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DOE/WIPP 91-007

Revision 0



**Evaluation of the Effectiveness  
and Feasibility of the  
Waste Isolation Pilot Plant  
Engineered Alternatives:**

**Final Report of the  
Engineered Alternatives Task Force**

**Volume I**

**July 1991**



**Waste Isolation Pilot Plant**

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## LIST OF ACRONYMS

ANL	Argonne National Laboratory
ALARA	As Low As Reasonably Achievable
CAM	Continuous Air Monitor
C of C	Certificate of Compliance
CEDE	Cumulative Effective Dose Equipment
CFR	Code of Federal Regulations
CH	Contact-Handled
CH-TRU	Contact-Handled Transuranic
DOE	United States Department of Energy
DRZ	Disturbed Rock Zone
EAMP	Engineered Alternatives Multidisciplinary Panel
EATF	Engineered Alternative Task Force
EPA	United States Environmental Protection Agency
FEIS	Final Environmental Impact Statement
FSAR	Final Safety Analysis Report
FSEIS	Final Supplemental Environmental Impact Statement
G	G Value for Radiolysis
HAN	Hanford Reservation
HEPA	High Efficiency Particulate Air
HSWA	Hazardous and Solid Waste Amendments of 1984
IDLH	Immediate Danger to Life and Health
IMPES	Implicit Pressure Explicit Saturation
INEL	Idaho National Engineering Laboratories
IT Corp.	International Technology Corporation
ITEO	International Technology Engineering Operations
LANL	Los Alamos National Laboratories
LDMU	Law of Diminishing Marginal Utility
LLNL	Lawrence Livermore National Laboratory

**LIST OF ACRONYMS  
(CONTINUED)**

<b>LLW</b>	<b>Low-Level Waste</b>
<b>MAUT</b>	<b>Multi-Attribute Utility Theory</b>
<b>MB 139</b>	<b>Marker Bed 139</b>
<b>MRE</b>	<b>Measure of Relative Effectiveness</b>
<b>NDE</b>	<b>Number of Drum Equivalents</b>
<b>NMD</b>	<b>No-Migration Determination</b>
<b>NMED</b>	<b>New Mexico Environmental Department</b>
<b>NMVP</b>	<b>No-Migration Variance Petition</b>
<b>NRC</b>	<b>Nuclear Regulatory Commission</b>
<b>NTS</b>	<b>Nevada Test Site</b>
<b>OPC</b>	<b>Ordinary Portland Cement</b>
<b>ORNL</b>	<b>Oak Ridge National Laboratories</b>
<b>PA</b>	<b>Performance Assessment</b>
<b>PNL</b>	<b>Pacific Northwest Laboratories</b>
<b>PREPP</b>	<b>Process Experimental Pilot Plant</b>
<b>PRRC</b>	<b>Petroleum Research and Recovery Center</b>
<b>QA</b>	<b>Quality Assurance</b>
<b>RCRA</b>	<b>Resource Conservation and Recovery Act</b>
<b>rf</b>	<b>radius factor</b>
<b>RFP</b>	<b>Rocky Flats Plant</b>
<b>RH</b>	<b>Remote-Handled</b>
<b>SAR</b>	<b>Safety Analysis Report</b>
<b>SEIS</b>	<b>Supplemental Environmental Impact Statement</b>
<b>SF</b>	<b>Scale Factor</b>
<b>SNL</b>	<b>Sandia National Laboratories</b>
<b>SRS</b>	<b>Savannah River Site</b>
<b>SWB</b>	<b>Standard Waste Box</b>
<b>TF</b>	<b>Treatment Facilities</b>
<b>TLV</b>	<b>Threshold Limit Values</b>
<b>TRAMPAC</b>	<b>TRUPACT-II Authorized Methods for Payload Acceptance and Control</b>
<b>TRU</b>	<b>Transuranic</b>

**LIST OF ACRONYMS  
(CONTINUED)**

<b>TRUPACT-II</b>	<b>Transuranic Package Transporter - II</b>
<b>TSD</b>	<b>Treatment, Storage, and Disposal</b>
<b>VR</b>	<b>Volume Reduction</b>
<b>WAC</b>	<b>Waste Acceptance Criteria</b>
<b>WACCC</b>	<b>Waste Acceptance Criteria Certification Committee</b>
<b>WERF</b>	<b>Waste Experimental Reduction Facility</b>
<b>WHB</b>	<b>Waste Handling Building</b>
<b>WIPP</b>	<b>Waste Isolation Pilot Plant</b>
<b>WPO</b>	<b>WIPP Project Office</b>

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## EXECUTIVE SUMMARY

The Engineered Alternatives Task Force (EATF) was established by the United States Department of Energy (DOE) WIPP Project Office (WPO) in September, 1989 (Hunt, A., 1990), to evaluate the relative effectiveness and feasibility of implementation of selected design enhancements (referred to as "engineered alternatives") for the Waste Isolation Pilot Plant (WIPP). These enhancements consist of modifications to existing waste forms and/or the WIPP facility, and other design variations such as passive marker systems. The purpose of this report is to summarize the methodologies and results of evaluation of the effectiveness of selected engineered alternatives relative to the existing repository design, and to discuss the feasibility of implementing these alternatives with respect to availability of technology, cost, schedule, and regulatory concerns.

Preliminary analyses of the long-term performance of the WIPP disposal system performed by Sandia National Laboratories (SNL) (referred to as "performance assessment") have identified two potential problems in demonstrating compliance with the applicable regulation 40 CFR Part 191 (EPA, 1985) that governs the disposal of transuranic radioactive waste. The first potential problem relates to gas generation. Lappin et al. (1989) discuss the possibility that up to 1,500 moles of gas can be generated per drum (or drum equivalent) of waste from anoxic corrosion, microbial degradation, and radiolysis, at rates that may be as high as 2.55 moles/drum/year. Although processes exist to dissipate excess gas pressure, these processes are currently believed to be slow relative to the current estimates of gas generation rates, resulting in gas pressures in storage rooms that may temporarily exceed lithostatic pressure. The consequences of exceeding lithostatic pressure are currently being evaluated by SNL (Lappin et al., 1989). Unless these evaluations demonstrate that either excess pressures will not occur, or that excess pressures will not degrade the performance of the disposal system, some type of waste form or facility modification may be required to either eliminate gas generation or reduce the rate of gas generation. For example, if the organics in the waste are incinerated and vitrified, then microbial gas generation can be eliminated.

A second potential problem in demonstrating compliance with 40 CFR Part 191 relates to the consequences predicted from future inadvertent human intrusion events. Preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 performed by SNL suggest that some of the current waste forms (under current interpretations of human intrusion provisions) may eventually be found to be unacceptable for disposal at the WIPP (Maretta et al., 1989). This may be due to uncertainties in key performance parameters of the waste forms. Key parameters that control the release of radionuclides during human intrusion scenarios are permeability of the waste storage rooms, radionuclide solubilities, and the availability of brine. Permeability of the storage rooms can be effectively reduced by the use of a grout backfill and/or shredding and cementation of the waste. Solubilities can be reduced by the use of grout backfill or the addition of lime to raise the pH of any brine that may come in contact with the waste.

The primary goal of the EATF is to develop and evaluate engineered alternatives that can mitigate the effects of, or eliminate, potential problems associated with the performance of the WIPP repository. The efforts of the EATF can be subdivided into two activities:

- Design analysis of the relative effectiveness of engineered alternatives
- Evaluation of the feasibility of implementing engineered alternatives.

The ongoing performance assessment studies by SNL involve the development and use of large complex probabilistic computer models. These models predict the cumulative release of radionuclides to the environment over 10,000 years. In contrast, the EATF analyses, which have been performed in parallel with the performance assessment analyses, utilize a model that calculates improvements offered by the engineered alternatives relative to the baseline design. Because performance is calculated relative to the baseline design, less complex codes can be used that do not incorporate all of the detail of the rigorous performance assessment models. With this approach, the EATF can quickly evaluate and screen a large number of alternatives in a relatively short time, that would not be feasible with complex probabilistic models. Alternatives which have been identified as beneficial by the EATF will then be evaluated by SNL using the performance assessment methodology. The EATF design analysis includes engineered alternatives that eliminate any adverse consequences of excess gas pressure in the storage room, and reduce the releases of radionuclides during human intrusion scenarios, should that be necessary.

As a first step in accomplishing the objectives of the EATF, a panel of experts, the Engineered Alternatives Multidisciplinary Panel (EAMP), was assembled. The EAMP identified and qualitatively ranked the effectiveness and feasibility of potential alternatives that address issues related to gas generation and human intrusion (Appendix A). Based on the ranking by the EAMP, the EATF recommended initial waste forms and backfill modifications for inclusion in the WIPP Experimental Test Program (DOE, 1990b).

The EATF has also selected various combinations of alternatives based on nine of the fifteen waste forms and three backfill modifications recommended for the WIPP Experimental Test Program (DOE, 1990b), and analyzed their relative effectiveness for enhancing the performance of the repository by using a design analysis model. In addition to the design analysis of engineered alternatives, the EATF has evaluated the feasibility of implementing these alternatives on the basis of status of development of technology, regulatory issues, cost, schedule, facility locations, and health and safety risks. The EATF also made an appraisal of optimal locations for waste processing facilities based on a comparative risk assessment of engineered alternatives. The discussion presented in this report is limited to Contact Handled-Transuranic (CH-TRU) waste because it constitutes a vast majority (~97 percent) of the overall TRU waste inventory (DOE, 1988c).

## DESCRIPTION OF ENGINEERED ALTERNATIVES

Analyses of the baseline design and 14 alternative designs were performed for undisturbed conditions, and for three human intrusion events that are described later. It should be noted that these 14 alternatives were selected to simulate a broad range of improvement in performance by different combinations of treatment of the major waste forms (i.e., sludges, solid organics, and solid inorganics), and by modifications to backfill material or the current facility design at the WIPP. Thus, these 14 combinations are merely a representation of the total spectrum of available alternatives, and do not imply that the final selection of an alternative will be limited to these 14 exact combinations. The baseline design and engineered alternatives that were analyzed are listed in Table ES-1 and described as follows:

Baseline Design: Sludges, solid organics, and solid inorganics are disposed of in their "as-received" (current treatment at the generator sites) state with a crushed salt backfill.

Alternative 1: Sludges are in their as-received state; solid organics and solid inorganics are shredded and cemented, and a crushed salt backfill is used.

Alternative 2: Same as Alternative 1, except the sludges are cemented.

Alternative 3: Sludges are cemented; solid organics and solid inorganics are shredded and cemented. A grout backfill is used.

Alternative 4: Sludges are cemented; solid organics are incinerated and the resulting ash cemented; and solid inorganics are shredded and cemented. A crushed salt backfill is used.

Alternative 5: Same as Alternative 4, but with grout backfill.

Alternative 6: Sludges are vitrified; solid organics are incinerated and vitrified; glasses are melted; and metals are separated out, melted, and disposed of as ingots. A salt backfill is used.

Alternative 7: Same as Alternative 6, but with a grout backfill.

Alternative 8: Same as Alternative 6, except it is assumed that metals are melted, and the radionuclides partition into a slag phase. The molten metal is drawn off from the melter and cast as ingots which are disposed of as low-level waste. Metals are thus removed from the inventory as low-level waste, but the contamination associated with the metals takes the form of a glass slag that is disposed of at the WIPP. Steel drums are replaced with some non-corroding material in Alternatives 8 and 9 so that both anoxic corrosion and microbial gas generation processes are essentially eliminated.

TABLE ES-1

**ENGINEERED ALTERNATIVES EVALUATED BY THE EATF RELATIVE TO THE BASELINE CASE**

<u>ALTERNATIVE #</u>	<u>SLUDGES</u>	<u>SOLID ORGANICS</u>	<u>SOLID INORGANICS</u>	<u>BACKFILL</u>	<u>WASTE CONTAINER</u>	<u>WASTE MANAGEMENT</u>	<u>FACILITY DESIGN</u>
BASLINE	As received	As received	As received	Salt	As received	As designed	As designed
ALTERNATIVE 1	As received	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 2	Cement	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 3	Cement	Shred/Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 4	Cement	Incin./Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 5	Cement	Incin./Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 6	Vitrify	Incin./Vitrify	Melt metals*	Salt	As received	As designed	As designed
ALTERNATIVE 7	Vitrify	Incin./Vitrify	Melt metals*	Cement grout	As received	As designed	As designed
ALTERNATIVE 8	Vitrify	Incin./Vitrify	Melt metals**	Salt	Non-ferrous	As designed	As designed
ALTERNATIVE 9	Vitrify	Incin./Vitrify	Melt metals**	Cement grout	Non-ferrous	As designed	As designed
ALTERNATIVE 10	As received	As received: Less Metals	Decontaminate Metals***	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 11	As received	Supercompact	Supercompact	Salt	As received	Single layer: 2000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 12	As received	Supercompact	Supercompact	Cement grout	As received	Single layer: 2000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 13	Vitrify	Incin./Vitrify	Melt metals**	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 14	As received	Supercompact	Supercompact	Salt aggregate Grout	As received	Compartmentalize waste, 2000 drums per room	Salt dikes: Waste Separation

\* Metals are melted into TRU waste ingots.

\*\* Metals are melted with glass/glass frit; radionuclides partition into the slag, and metals are eliminated from the WIPP inventory.

\*\*\* Metals are decontaminated by vibratory finishing and eliminated from the WIPP inventory.

**Alternative 9:** Same as Alternative 8, but with grout backfill.

**Alternative 10:** The waste container material is changed to a noncorroding material, and the shape is changed to rectangular; sludges are in their "as-received" state; solid organics are in "as-received" state less metals (i.e., small amounts of metals present in the solid organic waste, together with the mild steel containers, are separated from the solid organics as a preprocessing step); metals are decontaminated from solid inorganics and removed; the room dimensions are changed to 10'x31'x188' to eliminate backfill.

**Alternative 11:** Sludges are in their as-received state; solid organics and solid inorganics are supercompacted. The waste is placed in a monolayer. The room dimensions are altered to 6'x33'x300'. A salt backfill is used.

**Alternative 12:** Same as Alternative 11 but with grout backfill.

**Alternative 13:** Same as Alternative 8, except it is assumed that a rectangular waste container is used, and the room dimensions are altered to 10'x31'x188' to eliminate backfill.

**Alternative 14:** Sludges are in their "as-received" state; the solid organics and the solid inorganics are supercompacted. Three seven-packs of drums are placed in each "compartment" which is separated from other compartments by a salt aggregate grout composite. The compartmentalization reduces uncertainties related to the flow of brine through the waste stack and also sets an upper "engineered limit" on the inventory of radionuclides that can be released during any human intrusion event.

These 14 combinations of alternative waste forms and facility designs incorporate nine of the preliminary alternative waste forms recommended by the EATF for incorporation into the SNL bin-scale testing program (DOE, 1990b). Alternatives 1, 2, and 3 involve shredding and cementing of solid organics and solid inorganics, which affects gas generation rates but does not reduce the total gas generation potential. Alternatives 4, 5, 6, 7, 8, 9, and 13 involve thermal treatment (incineration or vitrification) of solid organics to eliminate the source of microbial gas generation. Alternatives 8, 9, and 13 do not have solid organics or metals present in the inventory and thus eliminate both of the sources of gas generation, namely from microbial processes and anoxic corrosion. Alternative 10 eliminates the metals from the inventory and hence the source of gas generation by anoxic corrosion. Alternatives 11, 12, and 14 involve supercompaction of the solid organics and solid inorganics and marginally increase the total gas generation potential based on conservative EATF assumptions.

Engineered alternatives are classified according to the degree of waste processing and its effect on gas generation potential (total number of moles of gas that can be generated) and gas generation rate as (Bertram-Howery and Swift, 1990):

- Level I Alternatives - "As received" (unprocessed) waste
- Level II Alternatives - Waste is processed to reduce gas generation rates with no effect on potential
- Level III Alternatives - Waste is processed to essentially eliminate potential for gas generation.

Examples of engineered alternatives are: waste management or facility design alternatives such as minimizing the space around the waste or changing room configuration, respectively (Level I); shredding and cementation of the waste which may reduce the rate of gas generation, but will not have any effect on total gas generation potential (Level II); and incineration or vitrification of the solid organic waste, which is expected to eliminate the potential for biological gas generation (Level III). The Level II and III classifications provide the framework for evaluating the feasibility of waste treatment alternatives relative to untreated waste (Lappin, 1990).

## DESIGN ANALYSES OF ENGINEERED ALTERNATIVES

### Design Analysis Model

The Design Analysis Model is a deterministic model which simulates the processes expected to occur following waste emplacement in the WIPP facility. The main program is used to analyze the relative effectiveness of various modifications to the waste forms and facility when compared to the current waste forms and WIPP baseline design.

The Design Analysis Model includes the modeling of the following processes under the isothermal conditions expected in the repository:

- Creep closure of the surrounding host rock
- Gas generation, consumption, and dispersion
- Brine inflow, consumption, and dispersion
- Panel seal leakage
- Consolidation of the shaft/seal system and advection of gas and brine through the shaft seals
- Diffusion and advection of gases into the host formation, and the underlying and overlying anhydrite beds
- Gas compressibility
- Waste compaction and resulting mechanical resistance to closure

- Development of a porous disturbed rock zone surrounding a storage room
- Radionuclide releases caused by three types of inadvertent human intrusion scenarios into the repository

The two main performance parameters that are used to compare the relative merits of each engineered alternative are: (1) the peak index pressure reached in the storage rooms during undisturbed conditions (no human intrusion), and (2) a measure of the cumulative release of radionuclides caused by human intrusion events.

For undisturbed conditions, the program estimates fluid pressure (brine and/or gas) within a typical waste storage room environment as a function of time. Coupling of creep closure, brine inflow and gas generation is incorporated into the model to simulate these interrelated processes over a 10,000-year period following the decommissioning of the repository.

For human intrusion events, three scenarios are considered (Marietta et al., 1989):

- A borehole that penetrates a waste-filled room and continues into or through a pressurized brine pocket assumed to exist in the underlying Castile Formation (E1 scenario)
- A borehole that penetrates the repository and stops (E2 scenario)
- Two boreholes that penetrate storage rooms in the same panel. One of these boreholes also penetrates a pressurized Castile brine pocket (E1E2 scenario).

The studies by Marietta et al. (1989) have determined that the three scenarios listed above constitute a reasonable set of possibilities based on investigation of more than thirty possible scenarios.

For the analysis of human intrusion events, a "Measure of Effectiveness" is calculated for each alternative design based on the cumulative release of twelve radionuclides (Lappin et al., 1989) into an overlying water-bearing strata (the Culebra Dolomite) over a 10,000-year period, plus the activity associated with the direct release of contaminated drill cuttings to the surface. A "Measure of Relative Effectiveness" (MRE) is then calculated for each alternative by dividing the measure of effectiveness for that alternative by the measure of effectiveness for the baseline design. Thus, an MRE greater than one indicates a decrease in performance and an MRE less than one indicates an increase in performance. These measures provide a convenient means of comparing the improvements offered by alternative designs relative to the baseline design, but do not represent absolute measures of repository performance.

### Analyses Performed

Specific analyses that were performed for analyzing various effects on room pressurization for undisturbed conditions include:

- Prediction of room pressurization for the baseline design
- Effects of supercompaction of waste, based on a single layer of 2000 drums and a triple layer of 6000 drums per room of supercompacted waste
- Effects of venting the repository for 100 years
- Effects of varying the rate and duration of microbial gas generation
- Effects of varying hydraulic properties of anhydrite beds
- Effects of varying initial brine inflow rate
- Predicted peak index gas pressures for the baseline design and 14 alternative combinations of waste forms and facility designs.

Analyses of human intrusion events include the calculation of MREs for 14 alternative combinations of waste forms and facility designs (listed earlier) including shredded and cemented, incinerated, and vitrified waste.

#### Results of Design Analyses

Predicted peak index pressures are used as a guide to rank the relative effectiveness of alternative designs in reducing concerns related to excess gas pressure for the undisturbed (no human intrusion) scenario. These peak index pressures are not necessarily the actual pressures that will exist in the storage rooms.

Results of the EATF's design analysis modeling for the undisturbed scenario, using SNL assumptions (Lappin et al., 1989) for gas generation rates, suggest the following:

- Gas pressures in storage rooms will exceed lithostatic pressure for the baseline design.
- Supercompaction of waste results in higher peak index gas pressures than the baseline (uncompacted) waste, based on either a monolayer of 2,000 drums or a triple layer of 6,000 drums of supercompacted waste per room.
- Venting the storage rooms will only be effective in reducing peak index gas pressures if the vent remains open for the entire gas generating period (i.e., an estimated period of approximately 800 years). Venting for only the first 100 years will result in higher peak index gas pressures than the baseline (non-vented) design. Venting will not allow gas pressure to build up, and therefore, will not offer any resistance to creep closure. This will result in lower void volumes in

the repository, and once the vents are closed after 100 years, the generated gas will occupy a smaller volume resulting in higher peak index pressures.

- Predicted peak index pressures are sensitive to the rate and duration of microbial gas generation.
- Predicted peak index pressures are only sensitive to the initial brine inflow rate if that rate exceeds a critical value. This critical value is higher than current estimates of actual brine inflow.
- Factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available for produced gases.
- Alternatives 1, 2, 3, 10, 11, 12, and 14, also generate pressures in excess of lithostatic due to the presence of organic materials. Thus, these alternatives appear to be ineffective in reducing peak index pressures, but they may have application in reducing the consequences if human intrusion occurs.
- Alternatives 4 through 7 involve thermal treatment of organic materials but do not remove metals completely. These alternatives do not exceed lithostatic pressure even though metals are present. This is because once the organic materials are destroyed by thermal treatment, the gas generation from anoxic corrosion is limited by the assumed coupling between anoxic corrosion and brine inflow (i.e., the pressure due to the gas generated by anoxic corrosion reduces the brine inflow, and as a result retards the process of anoxic corrosion).
- Alternatives 8, 9, and 13 that involve both thermal treatment of organic materials and removal of metals, do not exceed lithostatic pressure.

Results of design analysis modeling for the three human intrusion scenarios suggest the following improvements relative to the baseline design:

- Improvements in performance of one order of magnitude in the MRE are predicted for the Castile Brine (E1) scenario for shredded and cemented or supercompacted waste forms and two orders of magnitude for incinerated or vitrified waste forms. Critical parameters for this scenario are waste/backfill permeability, borehole radius and permeability, and radionuclide solubilities.
- Improvements of one to two orders of magnitude in the MRE are predicted for the repository breach (E2) scenario for shredded and cemented, and for incinerated and vitrified waste forms, provided that grout is used as a backfill. Critical parameters for this scenario are waste/backfill permeability, volume of contaminated brine trapped in the repository after repressurization, and radionuclide solubilities.

- Improvements of two to four orders of magnitude in the MRE can be gained for the dual borehole (E1E2) scenario using shredded and cemented, supercompacted, incinerated, vitrified, or melted metal waste forms, provided that grout is used as a backfill. Critical parameters for this scenario are waste/backfill permeability and radionuclide solubilities.

The results presented here are estimates and are subject to change as ongoing laboratory experiments, in situ testing with waste, other site characterization, and modeling activities continue to yield additional data that may alter the current understanding of the complex processes that will occur in the WIPP repository.

### FEASIBILITY OF IMPLEMENTING ENGINEERED ALTERNATIVES

The EATF has evaluated the feasibility of implementing selected waste treatment alternatives, and to a more limited extent has evaluated backfill materials and other alternatives such as waste management and WIPP facility design modifications. The results of the EATF provide a preliminary idea of the relative feasibilities of each alternative. The EATF recommends the use of such data only for comparative estimates, and not for arriving at a final decision regarding the choice of an alternative. Detailed assessments of the recommended technology are required before a final decision can be made regarding the feasibility of a particular engineered alternative.

### WASTE TREATMENT ALTERNATIVES

The EATF has considered the status of development of waste treatment technologies, and the cost, regulatory issues, schedule, health and safety risks, and potential locations for waste treatment facilities.

#### Status of Development

The status of development of waste treatment technologies is summarized as follows:

- **Vitrification** - Viable technology; additional development required before full scale transuranic (TRU) waste vitrification systems can be put into operation
- **Incineration** - Well developed for hazardous and low-level waste treatment; as of yet not fully developed for TRU waste
- **Cementation** - Well developed technology; uncertainty regarding long-term effects of the WIPP environment on the stability of cementitious materials

- **Compaction, Shredding, Melting Metals** - Commonly used technologies in industry (non-radioactive applications) and for low-level waste
- **Removal and Decontamination of metals** - Viable technology. Potential to achieve the effectiveness of a Level III alternative with a Level II alternative
- **Addition of pH Buffers to Waste** - Operational consideration with no process development required. Requires selection of effective buffers that will not interact or react with other waste components to either produce gas or increase the radionuclide solubility
- **Change Waste Container Material** - Requires evaluation of suitable materials that do not generate gas from anoxic corrosion or biological degradation, and can satisfy safety requirements for handling and transport

### Cost of Facilities

The cost and time required to implement Level II waste treatment facilities is less than for Level III facilities. The cost and size of treatment facilities have been estimated on the basis of "work-off periods." The EATF has defined this as the time projected to process all TRU waste generated by the year 2013, based on the volumes of waste estimated in DOE (1988c). Shorter work-off periods increase the facility costs while longer work-off periods reduce the costs. It is important to note that the costs presented in this report are rough cost estimates, and are computed from existing or planned DOE TRU waste treatment facility information that have been appropriately scaled to process all retrievably stored waste in 5, 10, or 20 years. The EATF computed operating cost estimates as a percent of capital cost (on an annualized basis). The EATF has concluded that there is a need for minimum size facilities which will operate in batch mode. Operating cost estimates for waste processing facilities are presented in categories as a means of communicating that estimates are rough and not based on bottom-up estimates (i.e., costs of equipment, material, and services have not been collected in minute detail).

### Schedules

Waste treatment implementation schedules also tend to be grouped by level of waste treatment required. For instance, Level II facilities require approximately 5-7 years to permit, construct and start up, whereas Level III facilities require about 8-11 years to implement. The size of the facility required for each level of treatment and the budgetary considerations also influence the schedule.

### Health and Safety Risks

The total risk associated with various waste treatments includes evaluation of risks from treating, handling, transporting, and emplacing waste in the WIPP. Within each category, risks components include occupational fatalities and injuries, 5- to 20-year occupational and public cancers, and 5000-year occupational and public cancers. Level II treatments would result in a slight increase in risk relative to the baseline design, and this increase would be independent of the number of facilities. In contrast to Level II treatments, for Level III treatments, the dominance of transportation risks favors treatment of wastes at multiple facilities before transporting the wastes to the WIPP. This is because the Level III treatment of waste before shipment substantially reduces the transportation risks, and this reduction more than compensates for the increase in occupational risks associated with Level III treatment. Long-term or late (5,000-year) risks due to human intrusion of the repository are by far the smallest component of total risk.

### Facility Locations

The EATF has evaluated potential waste treatment facility locations (e.g., at the WIPP, at individual waste generator/storage sites, or at centralized facilities). Information has been collected for several factors that should be considered for facility location. These factors are:

- Waste characterization for processing, transportation, and disposal
- Waste volumes and existing location
- Existing and planned facilities
- Transportation issues
- Risk assessment
- Schedule
- Cost
- Institutional and regulatory constraints

A logic diagram developed by the EATF has been used to consider factors that influence a decision between centralized and multiple facilities. The EATF has concluded that additional information such as the type of waste treatment required (based on the performance assessment studies), extent of waste characterization required, and more institutional information, is necessary for a firm decision. The EATF has investigated the pros and cons of a centralized facility versus facilities at multiple locations. The following factors have been found to be influential in choosing between multiple and centralized facilities:

- **Cost** - If cost is the deciding factor, a single integrated facility would be preferable, because economies of scale can be achieved with a single integrated facility.
- **Waste Characterization** - If the states receiving the waste mandate extensive characterization as per RCRA requirements, then waste characterization is likely to be expensive. Therefore, the preference would be for waste to be processed

at each site before transportation. If transportation only requires limited characterization (i.e., characterization for acceptance of payload), planned and existing capacity at the major storage/generator sites should be adequate.

- **Schedule** - The time required for simultaneous construction of smaller, multiple processing facilities at different locations is expected to be shorter than the time required to construct a large, single integrated facility having the same total capacity. Therefore, if schedule considerations are the primary deciding factor, then multiple processing sites are favored.
- **Risk Assessment** - Risks associated with Level II treatments are roughly comparable between multiple and centralized facilities, and are slightly greater than the baseline design. The risks from Level III treatments are dependent on the number of facilities, and show a range of slight increase to a slight decrease in risk as the number of facilities are increased from one to seven, respectively.

### BACKFILL ALTERNATIVES

Crushed salt derived from mining the WIPP waste disposal areas was considered as the baseline case for backfilling purposes. The addition of absorbents, or pH buffers (to raise the pH of repository brine) is an operational rather than a technological consideration. Selection of these additives will require further analyses. Grout is also a candidate for use as a backfill, but will require evaluation of longevity under conditions found in the WIPP. The cost of facilities at the WIPP site to prepare the salt additives, or grout, would be small compared to the cost of implementing waste treatment and other alternatives. Such a facility would not be on the overall WIPP schedule critical path, and regulatory impact is expected to be minimal.

### OTHER ALTERNATIVES

Alternatives involving waste management, facility design, waste container shape and material, and passive Institutional controls are collectively referred to as "other alternatives."

As is the case with backfill, the cost, schedule, and regulatory impact of incorporating other alternatives are expected to be minimal. Two potential exceptions are waste container shape and passive Institutional controls. Changing waste container shape and material will require testing for certification purposes for Type A Packaging Tests (DOT, 1989). The passive Institutional controls program initiated by Sandia National Laboratories (Bertram-Howery and Swift, 1990) has not matured to the point that schedule, regulatory, and cost impacts can be discussed with any degree of confidence.

Waste management and facility design will require documentation such as National Environmental Policy Act (NEPA) documentation, along with associated cost and schedule requirements. These cost and schedule impacts are not expected to be of the same magnitude as those for waste processing. It may be stated that technology exists for incorporation of all "other" alternatives, with the possible exception of passive Institutional

controls, for which requirements do not exist at this time. The mining of different repository configurations, minimizing space between waste containers, and repackaging waste into containers of different materials (and shapes) are all feasible from the technological and regulatory standpoints.

### OVERALL CONCLUSIONS OF THE EATF

The EATF has concluded that if performance assessment studies by SNL identify a problem in demonstrating compliance using the current waste forms and the baseline design of the WIPP, a number of engineered alternatives could be implemented by DOE to improve the repository performance. The combinations of engineered alternatives evaluated by the EATF include alternatives that have varying degrees of effectiveness for addressing possible gas generation and future inadvertent human intrusion scenarios. These combinations also differ from one another with respect to the availability of technology, cost, regulatory constraints, and schedule. Therefore, the exact choice of an engineered alternative can only be determined after the extent of the problem and the degree of effectiveness required have been identified by the performance assessment studies.

Table ES-2 describes the 14 combinations of alternatives evaluated by the EATF, and summarizes the overall findings of the EATF regarding the effectiveness of these combinations in addressing gas generation issues and human intrusion scenarios. The feasibility of implementing different alternatives with respect to availability of technology, cost, regulatory constraints, schedule, and health and safety risks is also summarized in Table ES-2. It should be noted that the levels of development presented in Table ES-2 are published estimates, and do not take into account various uncertainties that are likely to be encountered. For example, although there might be considerable experience with a particular process for nonradioactive materials, adaptation of the same process for handling radioactive waste is likely to cause unexpected modifications, subsequent delays, and added costs.

The capability of each alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, then the alternative is considered to be effective, and assigned a blank circle in Table ES-2. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table ES-2.

For example, from the results of the Design Analysis Model, the peak index pressures due to Alternative 2 exceed the lithostatic pressure, and therefore this alternative is assigned a dark circle in Table ES-2. Similarly, Alternative 4, which does not exceed the lithostatic pressure, is assigned a blank circle for its effectiveness in addressing peak index pressure.

The effect of an alternative on the gas generation rates has been summarized in Table ES-2 based on the knowledge of processes involved in these alternatives. An alternative is

TABLE ES-2  
SUMMARY OF EFFECTIVENESS AND FEASIBILITY OF ENGINEERED ALTERNATIVES

Treatment level <sup>b</sup>	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS						ALTERNATIVE FEASIBILITY					
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container	Peak Index Pressure	Gas Generation Rate		Human Intrusion			Level of Development	Treatment Facility Lifecycle Capital and Operating Cost 10 yr Work-Off Period (\$M)	Lifecycle Transportation Costs <sup>a</sup> (\$M)	Implmt. Schedule (yr)	Regulatory Requir.	Risk
							Microbial & Radiolytic	Anoxic Corrosion	E1	E2	E1E2							
II	1	AR	S&C	S&C	SLT	AR	●	○	○	○	●	○	H	270-380	71-170	5-7	*	△
	2	CMT	S&C	S&C	SLT	AR	●	○	○	○	●	○	H	310-420	71-180	5-7	*	△
	3	CMT	S&C	S&C	CGT	AR	●	○	○	○	○	○	H	310-420	71-180	5-7	*	△
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	○	●	●	○	H	610-820	71-110	8-11	**	△
	5	CMT	I&C	S&C	CGT	AR	○	○	○	○	○	○	H	610-820	71-110	8-11	**	△
III	6	VTR	I&V	MM	SLT	AR	○	○	○	○	○	○	M	830-1100	71-55	8-11	**	NE
	7	VTR	I&V	MM	CGT	AR	○	○	○	○	○	○	M	830-1100	71-55	8-11	**	NE
	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	■
	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	■
	13	VTR	I&V	MRM	N/A	NFR	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	■
III	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○	H	510-700	71-60	5-7	*	NE
I	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●	H	180-260	71-51	5-7	*	NE
	12	AR	SPT	SPT	CGT	AR	●	●	●	○	○	○	H	180-260	71-51	5-7	*	NE
	14	AR	SPT	SPT	SAG	AR	●	●	●	○	○	○	H	180-260	71-51	5-7	*	NE

AR - AS RECEIVED  
CMT - CEMENT  
VTR - VITRIFY  
S&C - SHRED & CEMENT  
I&C - INCINERATE & CEMENT  
I&V - INCINERATE & VITRIFY  
SPT - SUPERCOMPACT  
MM - MELT METALS  
N/A - NOT APPLICABLE

MRM - MELT AND REMOVE METALS  
DRM - DECONTAMINATE AND REMOVE METALS  
SLT - SALT  
CGT - CEMENT GROUT  
SAG - SALT AGGREGATE GROUT  
NFE - NON FERROUS  
NFR - NON FERROUS, RECTANGULAR  
● - NO EFFECT  
NE - NOT EVALUATED

○ - PARTIALLY EFFECTIVE  
○ - EFFECTIVE  
H - HIGH  
M - MEDIUM  
\* - RCRAHSWA, DOE ORDERS, NEPA, NESHAP  
\*\* - RCRAHSWA, DOE ORDERS, NEPA, NESHAP, CAA, CWA, TSCA, PSD, NAAQS, NSPS  
△ - SLIGHT RISK INCREASE RELATIVE TO BASELINE  
■ - SLIGHT RISK INCREASE FOR SINGLE FACILITY, TO SLIGHT DECREASE FOR 7 FACILITIES

<sup>a</sup> COSTS FOR ONE TO SEVEN PROCESSING FACILITIES

<sup>b</sup> CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

considered to be effective for addressing gas generation from a given mechanism, if it is expected to reduce the generation rates to near zero (i.e., it practically eliminates the potential for gas generation from that mechanism). This is denoted by a blank circle in Table ES-2. Similarly, if an alternative reduces the gas generation rate but does not completely eliminate it, it is considered to be partially effective (denoted by a shaded circle in Table ES-2). An alternative which is not expected to have any effect on the generation rates is termed ineffective, and assigned a dark circle in Table ES-2.

As an example, Alternative 6 which incinerates and vitrifies the solid organics, and vitrifies the sludges, practically eliminates gas generation from microbial/radiolytic processes, and reduces generation rates from this mechanism to zero. Therefore it is assigned a blank circle in Table ES-2 for addressing gas generation rates from microbial/radiolytic processes. However, the melting of metals into ingots (as done in Alternative 6) does not eliminate metals from the inventory, but helps to reduce the rate of gas generation from anoxic corrosion. This is denoted by a shaded circle in Table ES-2. Similarly, although supercompaction of the waste results in a marginal reduction in the total gas generation potential, it has no effect on the gas generation rate, and is therefore assigned a dark circle in Table ES-2.

The discrepancy between predicted peak index pressures and predicted effect on gas generation rates is a function of the simplifying assumptions inherent in model development. The Design Analysis Model includes various assumptions about gas generation rates from waste forms, creep closure rates, brine inflow, coupling of brine inflow and anoxic corrosion, and room response to gas pressure. These assumptions are based on data about the WIPP available at the time of model development, with almost all of the data obtained from SNL publications. Although these assumptions are reasonable at this time, they may change as ongoing experimental and modeling activities continue to provide additional data. If necessary, the Design Analysis Model can be updated to incorporate new assumptions as revised data become available.

Table ES-2 also summarizes the effectiveness of the 14 alternatives in addressing the three hypothetical human intrusion scenarios. The summary is based on the results obtained by the Design Analysis Model for the MRE of an alternative for these scenarios. As explained earlier, the MRE of an alternative needs to be less than 1 to signify an improvement in performance relative to the baseline design. Thereafter, the performance progressively improves as the MRE approaches zero. Although any value of MRE less than 1 signifies an improvement, the EATF has used a conservative upper limit of 0.5 for rating an alternative partially effective (denoted by a shaded circle). If the MRE is greater than 0.5 for a given scenario, the alternative is considered to be ineffective for addressing that particular scenario, and is assigned a dark circle in Table ES-2. Similarly, an MRE of less than 0.05 has been used to classify an alternative to be most effective (denoted by a blank circle in Table ES-2).

As an example, Alternative 7 is effective for all three intrusion scenarios, and is assigned a blank circle under each column. In contrast, Alternative 1 which is partially effective for scenario E1, effective for E1E2, and is ineffective for E2, is assigned a shaded circle, a blank circle, and a dark circle under the respective columns. As with predictions of effectiveness

for addressing gas generation, it should be noted that the results of the Design Analysis Model for human intrusion scenarios are also influenced by the assumptions inherent in model development.

Table ES-2 provides a quick reference for comparing the pros and cons of the various alternatives. It can be observed from Table ES-2 that, in general, alternatives that use only Level III processes (e.g., 8, 9, 13) are more effective than alternatives that use only Level II processes (e.g., 1, 2, 3), in addressing both gas generation and human intrusion. It should be noted, however, that the improved effectiveness is not obtained without paying a price. Level III alternatives tend to be more expensive, take longer to implement, and require facilities that are harder to permit than Level II alternatives. Consequently, the greater effectiveness of an alternative does not necessarily make it preferable over others. The selection of an alternative with the optimal effectiveness will depend upon the extent of any problem identified by performance assessment studies.

If a problem is identified by performance assessment, the data developed by the EATF will help to identify a list of candidate alternatives that would be sufficient to alter the performance parameters of concern in order to achieve the required performance. The objective would be to focus the choice of alternatives to a small group of candidate engineered alternatives for further evaluation. For example, if it is determined that merely lowering the gas generation rates will demonstrate compliance, one of Alternatives 1, 2, or 3 from Table ES-2 would be sufficient, and there would not be any need for Level III alternatives. If, on the other hand, it is determined that it is necessary to eliminate gas generation of any kind, then the group of candidate alternatives would be limited to Alternatives 8, 9, and 13. Similarly, based on the results of performance assessment, candidate alternatives can be chosen from Table ES-2 to address the human intrusion scenarios if the current design is predicted to result in noncompliance with any of the three intrusion scenarios.

Once a group of alternatives has been identified that has the effectiveness necessary to address the extent of the problem, Table ES-2 can be used to compare the feasibility of implementing each of them. The second part of Table ES-2 summarizes the feasibility of implementing each alternative design, in terms of availability of technology, cost, likely schedules for implementation, health and safety risks, and regulatory requirements. The availability of technology is summarized in terms of the level of development of technology for the treatment processes. In case of processes like vitrification, where additional development is required for application to TRU waste, the availability of technology has been rated as moderate. The capital costs listed for each alternative design reflect the range of costs estimated by the EATF for one to seven processing facilities. The health and safety risks associated with four alternatives relative to the baseline are summarized in Table ES-2. The risk analysis does not include all 14 alternatives, because the four options analyzed by the EATF represent the total range of treatments involved in the 14 alternatives. The regulatory issues associated with implementing each design are also presented in Table ES-2 in terms of the likely permitting requirements.

The process of narrowing the choice to one alternative from a set of effective alternatives will be primarily decided by the perceived importance of the factors listed under feasibility in Table ES-2. If cost is deemed to be the deciding factor, and the number of facilities is fixed in advance, the logical choice would be to select the least expensive alternative. In contrast, if the decision is constrained by schedule of implementation, then the alternative with the shortest estimated schedule may be chosen. Thus, once a list of effective alternatives are identified by the first part of Table ES-2, the final decision by DOE regarding the choice of a particular alternative can be made only after careful consideration of the different feasibility issues and their relative importance.

## 1.0 INTRODUCTION

The Engineered Alternatives Task Force (EATF) was formed by the Department of Energy (DOE) WIPP Project Office (WPO) to evaluate the feasibility and relative effectiveness of selected enhancements to the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico (Hunt, A., 1990). These enhancements (referred to as engineered alternatives) include modifications to existing waste forms and/or the WIPP facility and other design variations such as passive marker systems. Recommendations of the EATF will be forwarded by DOE to Sandia National Laboratories (SNL) for input into their experimental and Performance Assessment (PA) programs. Subsequent sections of this report describe the methodology used by the EATF to evaluate the relative effectiveness, the results of this evaluation, and the feasibility of implementing various engineered alternatives. An overview of the WIPP project in reference to the EATF effort and the framework of the EATF are described in this section.

### 1.1 WIPP CONCEPTUAL MODEL AND FACILITY OPERATIONAL OVERVIEW

The Waste Isolation Pilot Plant is located in southeastern New Mexico as shown in Figure 1-1. The WIPP is a proposed underground repository designed and constructed for the disposal of transuranic (TRU) radioactive wastes. TRU wastes are generated from DOE defense-related activities, including weapons production and research and development. Currently, these wastes are generated and/or stored at ten major DOE sites across the country (DOE, 1988c).

The majority of TRU waste is material that is contaminated with alpha emitting radionuclides (e.g., plutonium-239) with half lives greater than twenty years and concentrations greater than 100 nanocuries per gram (DOE, 1988c). TRU wastes are classified as either Contact-Handled (CH) or Remote-Handled (RH) (DOE, 1988c), depending on the dose rate at the surface of the waste container. CH-TRU waste containers have an external dose rate less than 200 mrem/hr at the surface of the container. The discussion in this report is limited to CH-TRU waste which constitutes a vast majority (~97 volume percent) of the overall TRU waste inventory although the modifications discussed could also be applied to RH-TRU waste. The WIPP repository and the waste to be stored at WIPP are described below.

#### 1.1.1 The WIPP Repository

Detailed descriptions of the geology and hydrology of the WIPP site have been published in numerous documents (DOE, 1990a; Lappin, 1988; Lappin et al., 1989). As shown in Figure 1-2, the WIPP repository is located 2,155 feet below the surface in a bedded salt (halite) formation of Permian age known as the Salado Formation. The basis for the selection of the WIPP site and an analysis of its environmental impacts were initially presented in the WIPP Final Environmental Impact Statement (FEIS) (DOE, 1980) and supplemented according to current understanding in the Final Supplemental Environmental Impact Statement (FSEIS) (DOE, 1990a). Figure 1-3 shows a three-dimensional layout of the repository in relation to the support facilities above the ground. The WIPP rooms and panels are being excavated in the salt beds of the Salado Formation. A panel consists of seven rooms and associated access drifts as shown in Figure 1-3. Figure 1-4 shows the stratigraphy at the repository horizon.

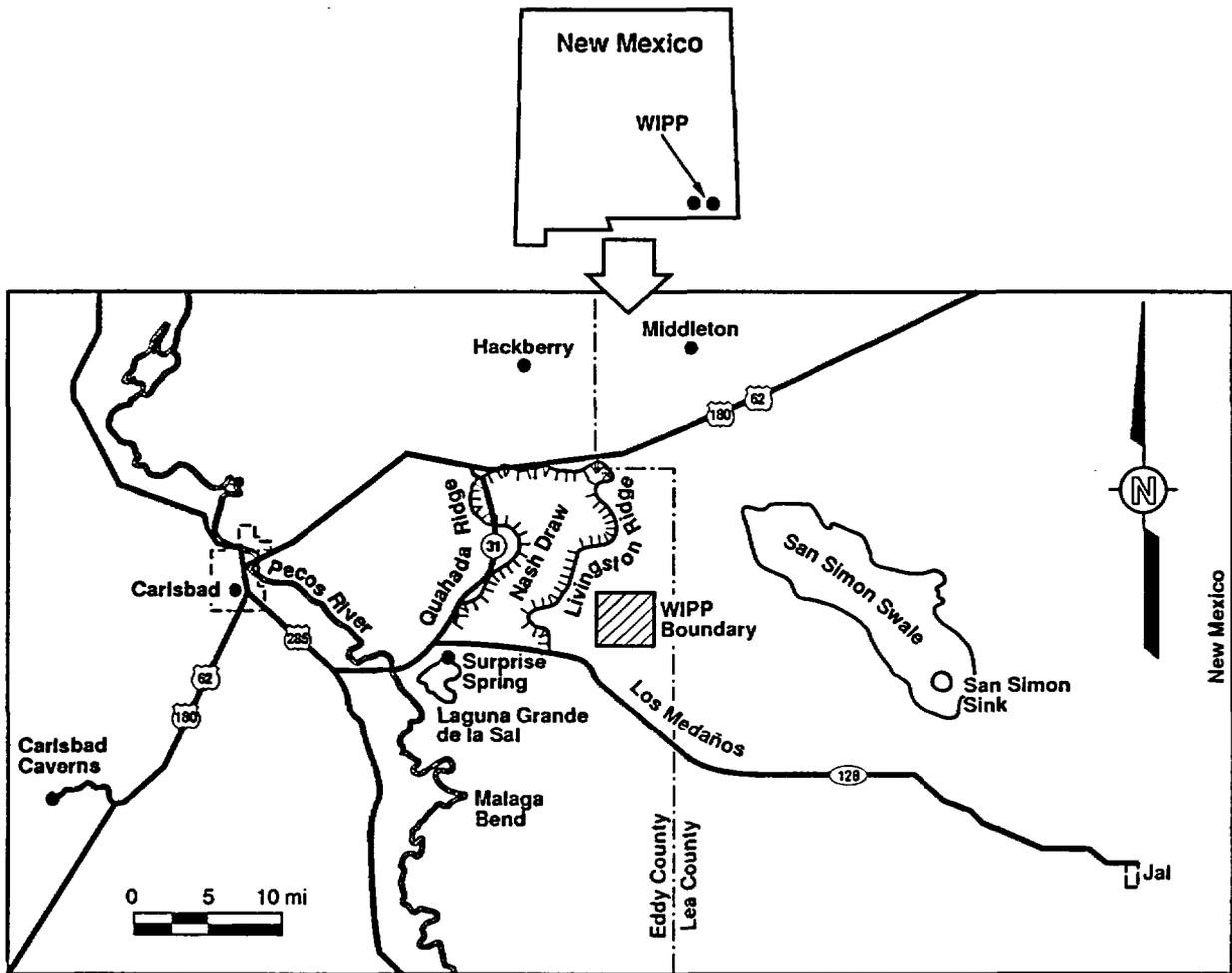


Figure 1-1  
WIPP Location in Southeastern New Mexico (Rechard, 1989)

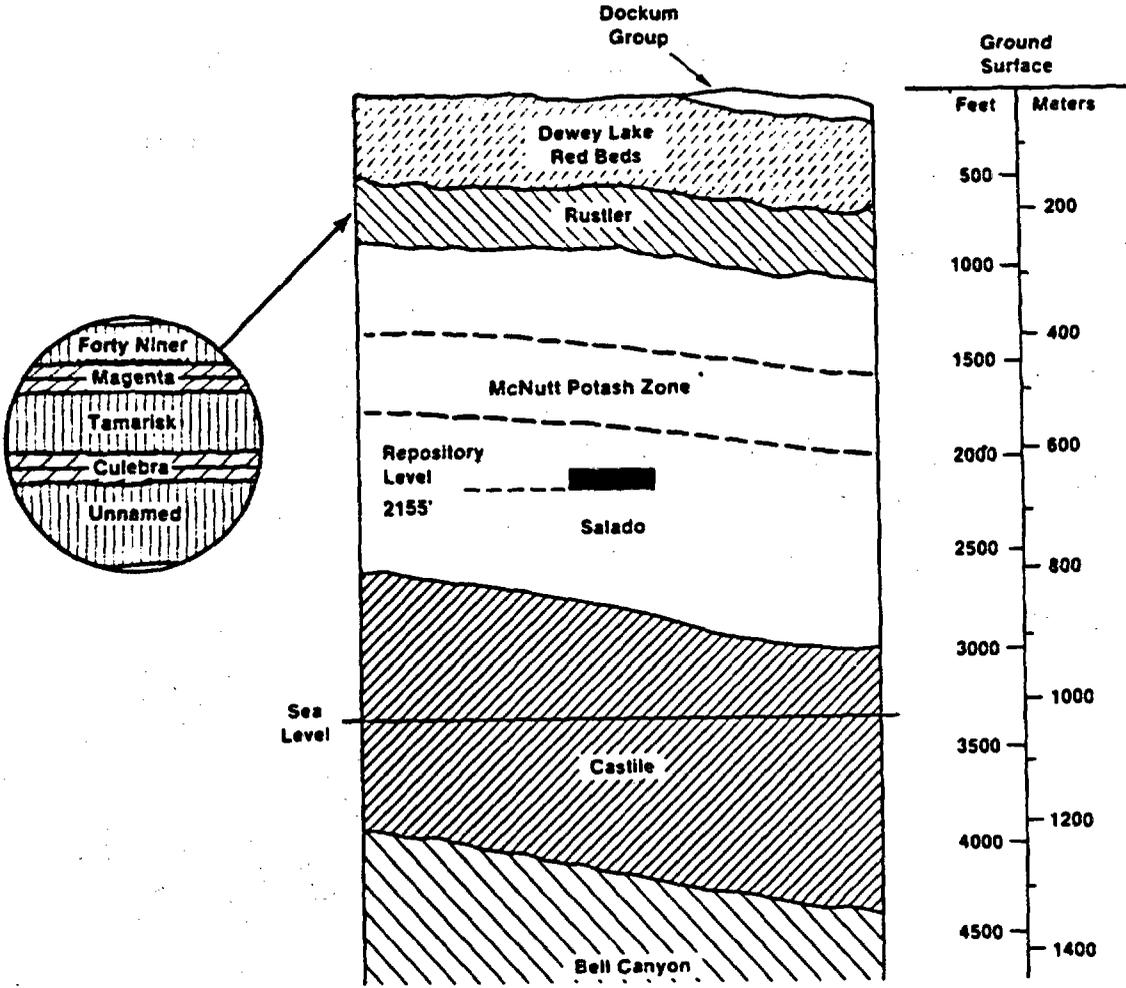


Figure 1-2. Level of WIPP Repository Located in the Salado Formation (Rechard, 1989).

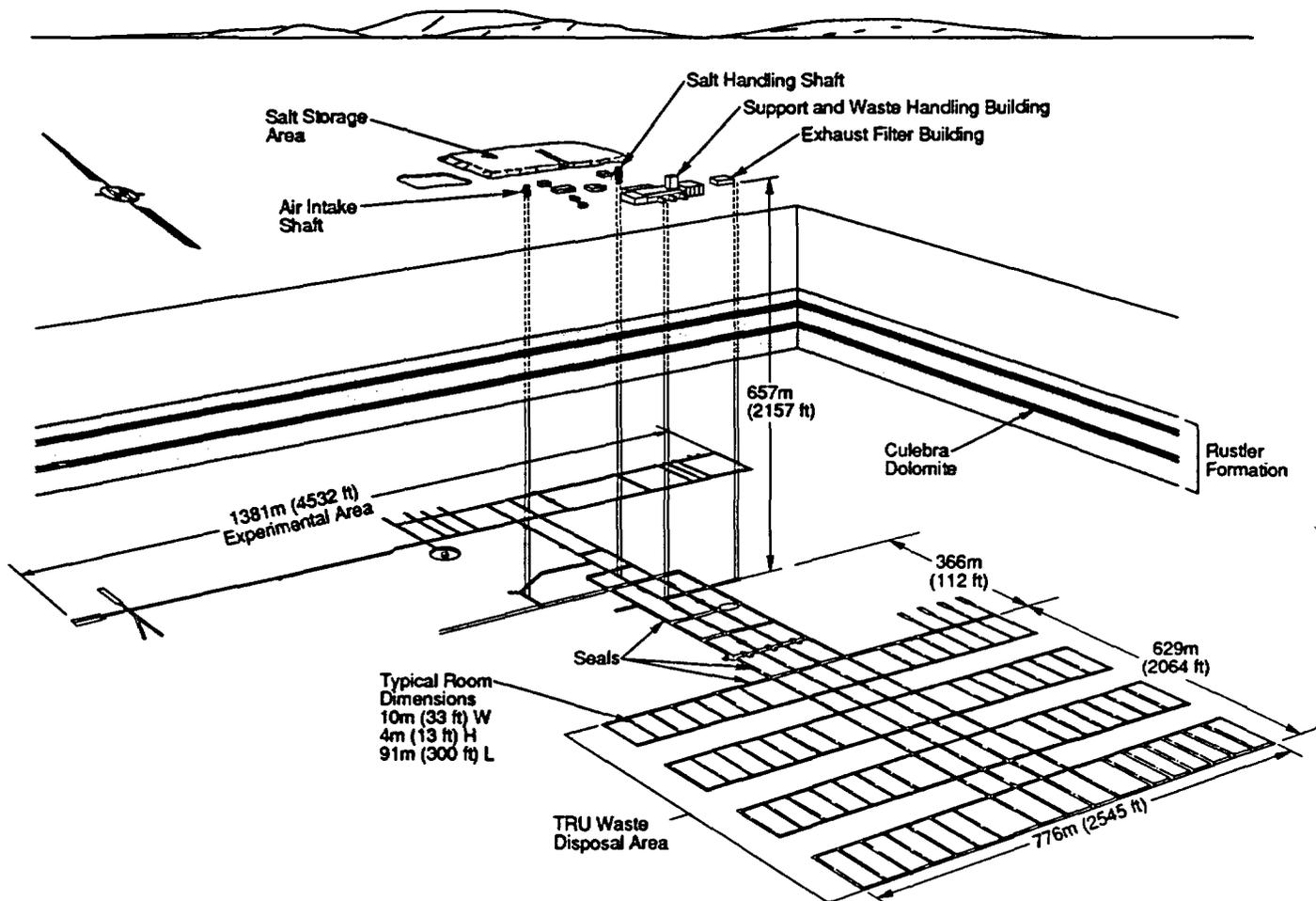


Figure 1-3  
Proposed WIPP Repository Showing Both TRU Disposal Areas  
and Experimental Areas (Nowak et al., 1990)

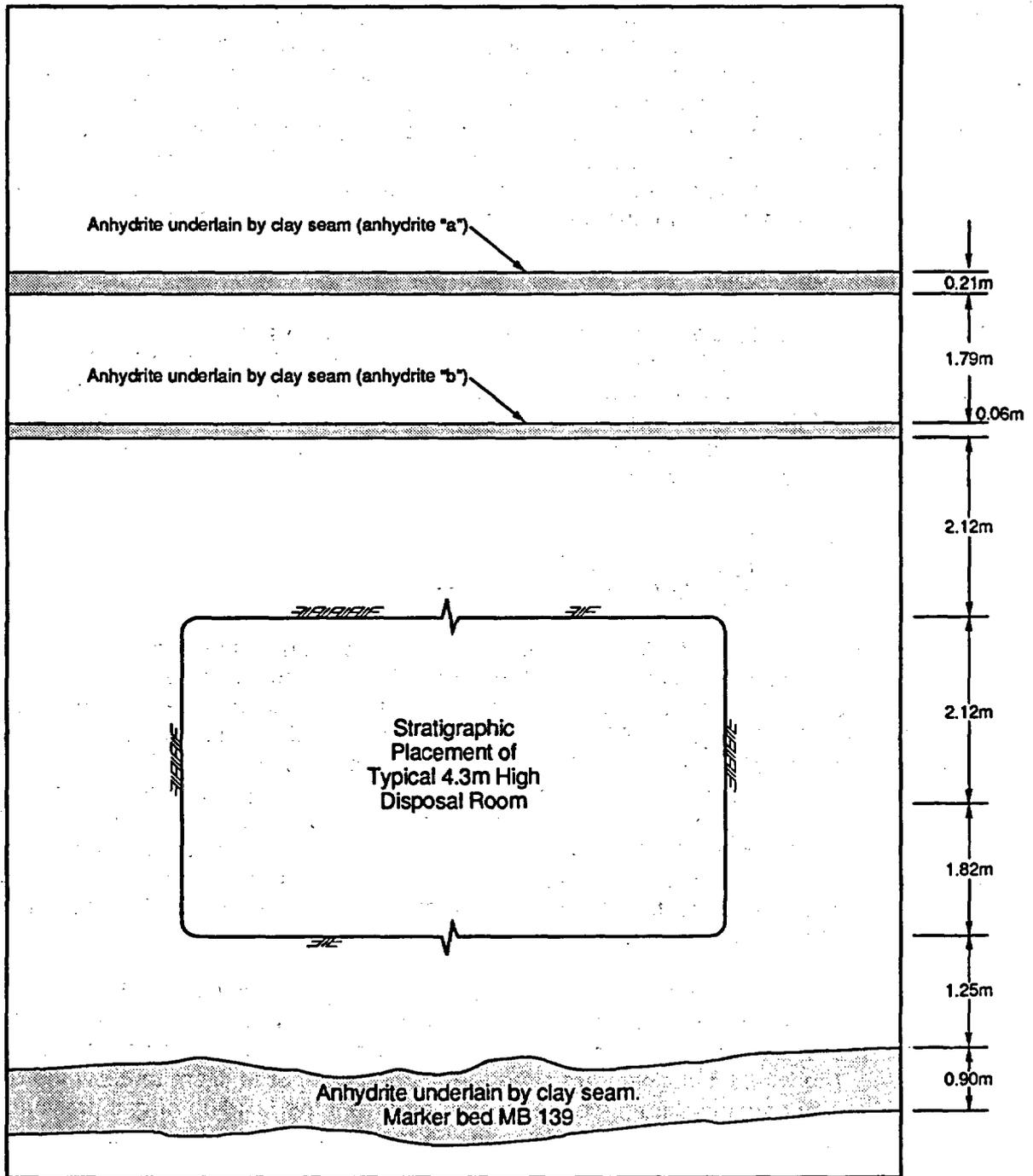


Figure 1-4  
Stratigraphy at the Repository Horizon [Modified from Lappin et al. (1989)]

After disposal of the waste in the WIPP storage rooms, closure of the repository occurs due to the creep (plastic flow) of the surrounding salt formation. This creep is in response to the pressure gradient that exists between the far-field pressure away from the repository (referred to as the lithostatic pressure or the pressure at the depth of the repository due to overlying rock) and the pressure in the repository (which is initially at atmospheric pressure). In a freshly excavated room under atmospheric pressure, this creep is of the order of a few inches per year. Under expected conditions, complete closure of the repository occurs due to creep, and the waste is safely and permanently isolated from the surrounding environment.

### 1.1.2 Waste Description

Transuranic waste to be disposed of at the WIPP consists of newly generated and/or retrievably stored waste in drums or boxes at major DOE facilities across the United States. Examples of processes that generate the waste are plutonium recovery operations, glove box operations, and the operation of on-site analytical and research and development laboratories. The waste destined for the WIPP site is either solid or solidified material and can be grouped under three major waste forms:

- Sludges
- Solid Organic (Combustible) Waste
- Solid Inorganic (Glass/Metal) Waste

Sludges are predominantly inorganic solidified wastes with some form of solidifying or stabilizing agent, usually a cement-based material. A small percentage of sludges designated as "organic sludges" may contain organic solvents in greater than trace (>1 weight percent) quantities (DOE, 1989e). Solid organic waste consists of organic materials (sometimes referred to as "combustible" waste) such as paper, plastic, tissues, plywood, etc. Solid inorganic waste consists of metals, glass, and a small percentage of other non-combustible material. All of the types of waste are in a chemically stable and non-reactive form (NuPac, 1989) and have been safely stored and handled at the waste generator and storage sites for over four decades. The wastes generated at the different sites are generally comparable, and can all be grouped under the three waste forms listed above (DOE, 1990c), with a few exceptions as noted in Table A-4 in Appendix A.

The waste is generally packaged in plastic bags (polyethylene and/or polyvinyl chloride) that are placed inside the waste containers (55-gallon steel drums or larger metal boxes) (DOE, 1989e). These different layers of confinement serve as barriers for radioactive materials in the waste. The waste containers are fitted with carbon composite filters to allow the diffusion of any hydrogen generated from the waste and to prevent the build-up of gas pressure in the containers, while retaining any particulates inside the containers (NuPac, 1989).

Waste characterization (the constituents and properties) of TRU waste is primarily based on process knowledge and records information, with supporting information from past and current sampling programs in place at the DOE sites. The available waste characterization information has been comprehensively summarized in a number of documents (e.g., DOE, 1989e; DOE, 1990c).

## **1.2 GOVERNING REGULATIONS**

A number of regulations govern the transportation packaging, waste acceptance, storage, and disposal of TRU wastes at the WIPP site. These are summarized in Table 1-1 and addressed in this section. An overview of some of the regulations is presented here, since any modifications recommended by the EATF must comply with these regulations.

### **1.2.1 Regulations Governing Transportation Packaging and Waste Acceptance**

The transportation packaging of radioactive waste is regulated under 10 CFR Part 71 (NRC, 1983). The shipping package to be used for the transportation of CH-TRU waste to the WIPP site is the Transuranic Package Transporter-II (TRUPACT-II) package. The TRUPACT-II is a double-contained, Type B package that can transport up to 14 drums or two metal boxes called Standard Waste Boxes (SWBs) per shipment. A Safety Analysis Report (SAR) for the TRUPACT-II package and its payload was submitted to the U.S. Nuclear Regulatory Commission (NRC) in 1989 (NuPac, 1989). Based on the analysis presented in the SAR, the NRC issued a Certificate of Compliance (C of C) for the TRUPACT-II package in August 1989. The C of C certifies that the TRUPACT-II package meets the requirements of 10 CFR Part 71. Transportation restrictions on the TRUPACT-II package and its payload are defined in the C of C. All waste to be disposed of at WIPP are also required to satisfy the WIPP Waste Acceptance Criteria (WAC), which imposes restrictions on various characteristics (DOE, 1989f).

### **1.2.2 Regulations Governing the Land Disposal of Mixed Waste**

A large portion of the CH-TRU waste to be emplaced at WIPP is mixed, defined as waste that is both radioactive and hazardous. The hazardous component of mixed TRU wastes must comply with the requirements of the Resource Conservation and Recovery Act (EPA, 1990a; 1990b; 1990c; 1990d; 1990e). These include standards for both hazardous waste generators and owners/operators of Treatment, Storage, or Disposal (TSD) facilities.

#### **1.2.2.1 Requirements of Hazardous Waste Generators**

40 CFR Part 261 (EPA, 1990a) defines hazardous wastes and provides lists of materials that are considered to be hazardous waste. In addition, Subpart B of 40 CFR Part 261 defines the criteria for identifying the characteristics of hazardous waste.

40 CFR Part 262 (EPA, 1990b) provides guidance for the generators of hazardous waste with regard to characterization. Specifically, 40 CFR Part 262.11 states that a generator must determine if a solid waste is a hazardous waste. This determination can be made based on the list in 40 CFR Part 261, Subpart D, or if it exhibits one of the characteristics discussed in 40 CFR Part 261, Subpart C. The generator can determine if a waste is a characteristic waste by testing [40 CFR Part 262.11(c)(1)] or by applying knowledge of the hazardous characteristics of the waste determined by the materials or the processes used to generate the waste [40 CFR Part 262.11(c)(2)].

TABLE 1-1

**REGULATIONS GOVERNING TRU WASTE DISPOSAL AT WIPP**

<b><u>REGULATION</u></b>	<b><u>ISSUE</u></b>	<b><u>REGULATORY AGENCY</u></b>
10 CFR Part 71	Transportation	NRC <sup>(1)</sup>
40 CFR Part 264	Standards for Owners and Operators of Hazardous Waste Treatment, Storage and Disposal Facilities	NM-ED <sup>(2)</sup>
40 CFR Part 265	Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities	NM-ED <sup>(2)</sup>
40 CFR Part 268	Land Disposal Restrictions	EPA-OSW <sup>(3)</sup>
40 CFR Part 191 Subpart A	Management and Storage of TRU Waste Prior to Disposal	EPA-ORP <sup>(4)</sup>
40 CFR Part 191 Subpart B	Disposal of TRU Waste	EPA-ORP <sup>(4)</sup>
WIPP WAC	Waste Acceptance at WIPP	WACCC <sup>(5)</sup>

<sup>(1)</sup>Nuclear Regulatory Commission<sup>(2)</sup>New Mexico Environment Department<sup>(3)</sup>Environmental Protection Agency Office of Solid Waste<sup>(4)</sup>Environmental Protection Agency Office of Radiation Programs<sup>(5)</sup>Waste Acceptance Criteria Certification Committee

### 1.2.2.2 Requirements of Owners/Operators of TSD Facilities

Standards for the owners/operators of TSD facilities are codified in 40 CFR Part 264 (EPA, 1990c) and 40 CFR Part 265 (EPA, 1990d). An owner/operator must obtain a detailed physical and chemical analysis of a representative sample of the waste. The analysis must contain all of the information required to safely manage the waste at the facility; it may include documented or existing published data. Owners/operators of TSD facilities are further required to verify that the waste shipped to the facility is the waste specified on the accompanying manifest. WIPP is currently developing a process for meeting waste analysis/verification requirements.

WIPP has prepared RCRA Permit Applications, Parts A and B (DOE, 1991). The State of New Mexico is reviewing the RCRA Part A and Part B permit applications to determine the status of the WIPP. If the WIPP is determined to be an interim facility, it will be subject to standards contained in 40 CFR Part 265 (EPA, 1990d). If a RCRA Part B permit is issued, the WIPP will be subject to the conditions imposed in the permit, based on those contained in 40 CFR Part 264 (EPA, 1990c).

### 1.2.2.3 Land Disposal Restrictions

The Hazardous and Solid Waste Amendments (HSWA) of 1984, which amend the RCRA, prohibit the land disposal of hazardous waste, unless the wastes meet treatment standards specified by the EPA. Land disposal of hazardous waste not meeting the treatment standards is permissible if the owner/operator can demonstrate, to a reasonable degree of certainty, that there will be no migration of hazardous constituents from the disposal unit (EPA, 1990e). In response to the No-Migration Variance Petition (NMVP) (DOE, 1990c) submitted by the DOE for WIPP, the EPA has granted a Conditional No-Migration Determination (NMD) (EPA, 1990f) for the test phase of the WIPP facility (a maximum of ten years). The NMD identifies specific waste characterization requirements applicable to waste to be used during the test phase of WIPP.

### 1.2.3 Regulations Governing the Performance of Nuclear Waste Repositories

The required long-term performance of a nuclear waste repository is governed by 40 CFR Part 191 Subpart B (EPA, 1985), which is currently under revision by the U.S. EPA. An evaluation of compliance with this regulation is referred to as a performance assessment (PA). The PA for the WIPP site is being conducted by Sandia National Laboratories for the U.S. Department of Energy. The methodology being used and the progress made to date appear in Lappin et al. (1989), Marietta et al. (1989), and in Bertram-Howery and Swift (1990). 40 CFR Part 191 Subpart B requires that the cumulative summed, normalized release of specific radionuclides present in the waste should not exceed a value of one over a 10,000-year period using the calculation methodology required by the EPA (EPA, 1985). A range of events and processes have to be considered in evaluating release from the repository. These include human intrusion scenarios that involve the possibility (and probability) of future inadvertent exploratory drilling activities into the repository for a period of 10,000 years after decommissioning. Probabilistic models are generally used in predicting the performance of a

disposal system over long time periods. The PA studies being conducted by SNL include lab-scale and full-scale experiments and the acquisition of field information to provide supporting data and input to the PA model (Brush, 1990; Molecke, 1990a; Molecke, 1990b; Molecke and Lappin, 1990). The PA studies are projected to be completed in 1994 (DOE, 1990d).

### **1.3 THE ENGINEERED ALTERNATIVES TASK FORCE (EATF)**

Preliminary analyses (DOE, 1990a) indicated that, given the current baseline design of the WIPP repository and the present waste forms at the sites, PA may not be able to demonstrate compliance with 40 CFR Part 191. In response to this concern, the DOE WFO formed the EATF in September 1989, to evaluate the feasibility of implementation and predict the effectiveness of various engineering modifications to the current waste forms and the WIPP facility design that would improve the long-term performance of the WIPP disposal system (Hunt, A., 1990). In order to maximize the benefits of the EATF evaluations and provide timely integration of EATF activities with the SNL performance assessment, these programs are being conducted in parallel. Program integration between PA and the EATF is described in the Program Plan for Engineered Alternatives (Hunt, A., 1990).

The purpose of the alternatives (or modifications) evaluated by the EATF is to mitigate the effects of, or eliminate, potential problems that might prevent WIPP from demonstrating compliance with the applicable regulations. An example of such a potential problem is gas generation from the waste (e.g., from microbial degradation of organic materials) that may result in overpressurization of the repository after closure. If overpressurization results in fracturing of the host rock, the fractures might become pathways for the migration of contaminated brine beyond the disposal unit boundary and may lead to noncompliance with some of the land disposal restrictions discussed earlier. Similarly, future inadvertent human intrusion into the repository (e.g., for drilling purposes) could potentially result in the release of radionuclides through drill cuttings in amounts exceeding the totals allowed by 40 CFR Part 191 and lead to noncompliance. An example of an engineered alternative to help mitigate the problem of gas generation from microbial degradation would be to incinerate the organics and vitrify them before disposal. The methodology used to evaluate the engineered alternatives that address potential problems, such as gas generation and human intrusion, are described in the following subsections.

#### **1.3.1 EATF Methodology**

The overall framework of the evaluation process of engineered alternatives is presented in Figure 1-5. The EATF activities can be subdivided under two headings:

- Design analysis of the effectiveness of engineered alternatives
- Evaluation of the feasibility of implementing engineered alternatives.

Analyses of the long-term performance of the WIPP disposal system performed by SNL have identified two potential problems with demonstrating compliance with applicable regulations.

The first potential problem relates to gas generation. Lappin et al. (1989) discusses the possibility that up to 1,500 moles of gas can be generated per drum of waste from a

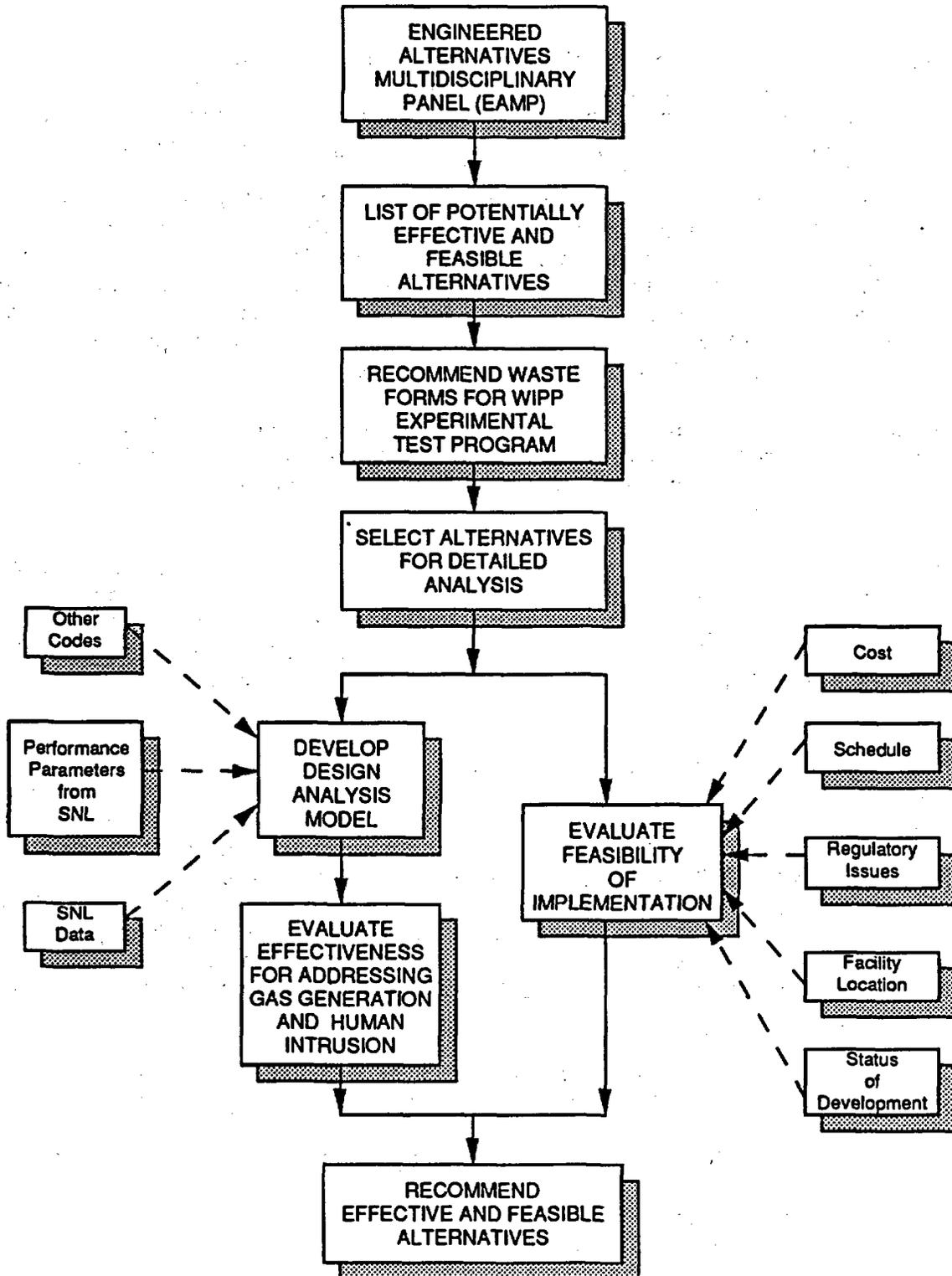


Figure 1-5. Engineered Alternatives Evaluation Process

combination of anoxic corrosion, microbial degradation, and radiolysis, at rates as high as 2.55 moles/drum/year. Anoxic corrosion rates of up to 1.7 moles of hydrogen per drum per year and microbial gas generation rates of 0.85 moles per drum per year are mentioned in the literature (Lappin et al., 1989). However, these gas generation rates can vary over large ranges. The current SNL estimate of 0.85 moles per drum per year of microbial gas generation is based on the arithmetic mean of 0.3 and 1.4 moles per drum per year; the range estimated from an earlier study (Molecke, 1979). Experiments planned in support of the performance assessment studies are expected to yield information on more realistic gas generation rates (Brush, 1990; Molecke, 1990a; Molecke, 1990b; Molecke and Lappin, 1990). As shown later in Section 4.0, existing processes to dissipate excess gas pressure are slow relative to the current estimates of gas generation rates, resulting in gas pressures in storage rooms that may temporarily exceed lithostatic pressure.

The effects of pressure on the gas generation rates is expected to be minimal, because the pressures at which the kinetics are affected are considerably (orders of magnitude) higher than what is expected in the repository. Therefore, pressure effects on gas generation rates have not been considered.

The consequences of exceeding lithostatic pressure are currently being evaluated by SNL (DOE, 1990d). If these evaluations fail to show that either excess pressures will not occur, or that excess pressures will not degrade the performance of the disposal system to the point that 40 CFR Part 191 Subpart B compliance is unachievable, then some type of waste form or facility modification may be required to either eliminate gas generation or reduce the rates of gas generation.

A second potential problem with demonstrating regulatory compliance relates to the consequences predicted from future inadvertent human intrusion events. Some of the preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 performed by SNL suggest that some of the current waste forms may not be acceptable for disposal at the WIPP (Marietta et al., 1989). This may be due to either: (1) conservative assumptions regarding intrusion events, (2) the current large uncertainties in key performance parameters, or (3) actual problems with higher than acceptable waste-form permeability or radionuclide solubility. Key parameters that control the release of waste elements during human intrusion scenarios are permeability of the waste storage rooms and radionuclide solubilities.

The first step in the evaluation of the alternatives was the identification of performance parameters that are critical to the long-term performance of the disposal system. These were determined based on existing PA analyses and the current understanding of the repository system (Marietta et al., 1989). The ten important performance parameters are the following:

- Radiolytic Gas Generation
- Biological Gas Generation
- Corrosion Gas Generation
- Permeability of the Waste and Backfill
- Waste Porosity
- Waste Shear Strength

- Waste Leachability
- Radionuclide Solubility In Brine
- Brine Inflow (seepage)
- Human Intrusion Probability.

### **1.3.2 Engineered Alternatives Multidisciplinary Panel**

Desirable engineered alternatives would be those that mitigate, to some degree, any potential adverse effects on the repository performance. A list of engineered alternatives that address potential problems related to gas generation and human intrusion was compiled, evaluated, and ranked by a multidisciplinary panel of experts [the Engineered Alternatives Multidisciplinary Panel (EAMP)] convened from several fields and disciplines. The panel activities are detailed in a separate report in Appendix A.

The EAMP evaluated engineered alternatives to current waste forms, waste management, backfill materials, facility design, passive marker systems, and several other disposal system features.

Qualitative rankings were assigned to each alternative based initially on three feasibility considerations:

- Regulatory compliance and permitting
- Availability of technology
- Schedule of implementation.

Following initial feasibility screening, each alternative was ranked according to effectiveness in mitigating undesirable effects associated with each of the ten performance parameters described before.

However in the final analysis, the EAMP ranking process was based on the five performance parameters which have been determined by SNL (Anderson, 1990) to be most critical. The condensed set of performance parameters consists of the following:

- Radiolytic Gas Generation
- Biological Gas Generation
- Corrosion Gas Generation
- Permeability of the Waste Stack  
(Waste Stack consists of waste and backfill between drums)
- Radionuclide Solubility In Brine.

To assess the cumulative effects of a particular alternative, the feasibility considerations were evaluated with respect to each of the five performance parameters for each of the three major waste forms:

- Sludges
- Solid Organic (Combustible) Waste
- Solid Inorganic (Glass/metal) Waste.

Within each of the three major waste form categories, the alternatives were ranked for the five performance parameters based on their effectiveness and feasibility (Appendix A). Using this method, the ranking considered the important factors contributing to the applicability of the alternatives: major waste form category, effectiveness relative to the five performance parameters, and the overall feasibility of each alternative. Based on the ranking by the EAMP, the EATF recommended initial waste forms and backfill modifications for inclusion in the WIPP Experimental Test Program (DOE, 1990b).

### 1.3.3 Selection of Engineered Alternatives

The EATF selected various alternatives based on nine of the fifteen waste forms and three backfill alternatives recommended for the WIPP Experimental Test Program. These alternatives were then analyzed for their relative effectiveness in enhancing the performance of the repository as compared to the current waste forms, by using a design analysis model. The alternatives that have been selected provide a broad range of solutions, if needed, for enhancing the performance of the repository. The basis for the EATF terminology for describing engineered alternatives is discussed in the following sections.

#### 1.3.3.1 Single Alternatives

The individual options recommended for evaluation by the EAMP (Appendix A) are defined by the EATF as "single alternatives". These alternatives include, but are not limited to, waste processing such as incineration (followed by cementation of ash/residue), supercompaction, and shredding (followed by cementation). An example of a single alternative, and a description of the consequences of its application, is the modification of the backfill by adding a sorbent such as bentonite (Butcher, 1990b); this potentially reduces the amount of free brine in the repository. Reduction of free brine inhibits the transport of radionuclides and reduces gas generation by mechanisms such as anoxic corrosion of metals. The complete list of single alternatives considered by the EAMP is presented in Table A-1 in Appendix A. It should be noted that the term "engineered alternative" as used by the EAMP in Table A-1 actually refers to a single alternative as described here.

#### 1.3.3.2 Combination Alternatives

The EATF has defined a "combination alternative" to be the combination of two or more "single alternatives" recommended for evaluation by the EAMP (Appendix A). In other words, single alternatives are the individual components that make up a combination alternative. Many single alternatives are limited in improving repository performance and can only be applied for one type of waste form. For example, incineration followed by solidification is only

applicable to solid organic waste forms. In contrast, the appropriate choice of single alternatives can make a combination alternative applicable to all types of waste forms. This also significantly improves the overall effectiveness as compared to the effectiveness of using only one single alternative. An example of a combination alternative is: sludges are cemented, solid organics and solid inorganics are shredded and cemented, and emplaced waste is backfilled with grout.

In later sections, the EATF has often categorized single alternatives according to their purpose. For example, the EATF uses the terms "waste treatment alternatives" and "backfill alternatives" to refer to the single alternatives that deal with the waste treatment component and the backfill component of a combination alternative, respectively.

### **1.3.3.3 Description of Engineered Alternatives Evaluated by the EATF**

All of the engineered alternatives evaluated by the EATF (with the exception of Alternative 1) fall in the category of "combination alternatives". These alternatives and the current baseline design evaluated by the EATF are presented in Table 1-2 and described below:

**Baseline Design:** Sludges, solid organics, and solid inorganics are disposed of in their "as-received" (current treatment at the generator sites) state with a crushed salt backfill.

**Alternative 1:** Sludges are in their "as-received" state; solid organics and solid inorganics are shredded and cemented, and a crushed salt backfill is used.

**Alternative 2:** Same as Alternative 1, except that the sludges are cemented.

**Alternative 3:** Sludges are cemented; solid organics and solid inorganics are shredded and cemented. A grout backfill is used.

**Alternative 4:** Sludges are cemented; solid organics are incinerated and the resulting ash cemented; and solid inorganics are shredded and cemented. A crushed salt backfill is used.

**Alternative 5:** Same as Alternative 4, but with grout backfill.

**Alternative 6:** Sludges are vitrified; solid organics are incinerated and vitrified; glasses are melted, and metals are separated out, melted, and disposed of as ingots. A salt backfill is used.

**Alternative 7:** Same as Alternative 6 but with grout backfill.

**Alternative 8:** Same as Alternative 6, except that it is assumed that metals are melted, and the radionuclides partition into a slag phase. The molten metal is drawn off from the melter and cast as ingots which are then disposed of as low-level waste. Metals are thus removed from the inventory as low-level waste, but the

TABLE 1-2

**ENGINEERED ALTERNATIVES EVALUATED BY THE EATF RELATIVE TO THE BASELINE CASE**

ALTERNATIVE #	SLUDGES	SOLID ORGANICS	SOLID INORGANICS	BACKFILL	WASTE CONTAINER	WASTE MANAGEMENT	FACILITY DESIGN
BASELINE	As received	As received	As received	Salt	As Received	As designed	As designed
ALTERNATIVE 1	As received	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 2	Cement	Shred/Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 3	Cement	Shred/Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 4	Cement	Incin./Cement	Shred/Cement	Salt	As received	As designed	As designed
ALTERNATIVE 5	Cement	Incin./Cement	Shred/Cement	Cement grout	As received	As designed	As designed
ALTERNATIVE 6	Vitrify	Incin./Vitrify	Melt metals*	Salt	As received	As designed	As designed
ALTERNATIVE 7	Vitrify	Incin./Vitrify	Melt metals*	Cement grout	As received	As designed	As designed
ALTERNATIVE 8	Vitrify	Incin./Vitrify	Melt metals**	Salt	Non-ferrous	As designed	As designed
ALTERNATIVE 9	Vitrify	Incin./Vitrify	Melt metals**	Cement grout	Non-ferrous	As designed	As designed
ALTERNATIVE 10	As received	As received; Less Metals	Decontaminate Metals***	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 11	As received	Supercompact	Supercompact	Salt	As received	Single layer: 2,000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 12	As received	Supercompact	Supercompact	Cement grout	As received	Single layer: 2,000 drums	New dimensions: 6'x33'x300'
ALTERNATIVE 13	Vitrify	Incin./Vitrify	Melt metals**	None	Non-ferrous/ Rectangular	Minimize space around waste	New dimensions: 10'x31'x188'
ALTERNATIVE 14	As received	Supercompact	Supercompact	Salt aggregate Grout	As received	Compartmentalize waste: 2,000 drums per room	Salt dikes: Waste Separation

\* Metals are melted into TRU waste ingots.

\*\* Metals are melted with glass/glass frit; radionuclides partition into the slag, and metals are eliminated from the WIPP inventory.

\*\*\* Metals are decontaminated by vibratory finishing and eliminated from the WIPP inventory.

contamination associated with the metal takes the form of a glass slag that is disposed of at the WIPP. Steel drums are replaced with some non-corroding material in Alternatives 8 and 9 so that both anoxic corrosion and microbial gas generation processes are essentially eliminated.

**Alternative 9:** Same as Alternative 8, but with grout backfill.

**Alternative 10:** The waste container material is changed to a noncorroding material, and the shape is changed to rectangular; sludges are in their "as-received" state; solid organics are in their "as-received" state less metals (i.e., small amounts of metals that are packaged with the solid organic waste, together with the mild steel container, are separated from the solid organics as a preprocessing step); metals are decontaminated from solid inorganics and removed; the room dimensions are changed to 10'x31'x188' to eliminate backfill.

**Alternative 11:** Sludges are in their "as-received" state; solid organics and solid inorganics are supercompacted. The waste is placed in a monolayer. The room dimensions are altered to 6'x33'x300'. A salt backfill is used.

**Alternative 12:** Same as Alternative 11, but with grout backfill.

**Alternative 13:** Same as Alternative 8, except it is assumed that a rectangular waste container is used, and the room dimensions are altered to 10'x31'x188' to eliminate backfill.

**Alternative 14:** Sludges are in their "as-received" state; the solid organics and the solid inorganics are supercompacted. Three seven-packs of drums are placed in each "compartment" which is separated from other compartments by a salt aggregate grout composite. The compartmentalization reduces uncertainties related to the flow of brine through the waste stack and also sets an upper "engineered limit" on the inventory of radionuclides that can be released during any human intrusion event.

It should be noted that any change of room dimensions (such as in Alternatives 10, 11, 12, and 13) may result in redesigning the equipment for RH-TRU waste emplacement, because the existing room dimensions were based on the size of the equipment.

#### 1.3.4 Classification of Engineered Alternatives

The engineered alternatives are classified according to the degree of waste processing and their effect on gas generation potential (total number of moles of gas that can be generated) and gas generation rate as:

- Level I Alternatives: "As received" (unprocessed) waste

- **Level II Alternatives:** Waste is processed to reduce gas generation rate with no effect on potential
- **Level III Alternatives:** Waste is processed to eliminate potential for gas generation.

Level I alternative examples include passive markers, facility design modifications, alternate waste containers, and backfill options. Level II alternatives include cemented sludges, and shredded and cemented solid organics and solid inorganics. Cementation of the waste will limit access of brine to the waste and will also raise the pH of any brine present in the room. High pH conditions should reduce anoxic corrosion and microbial gas generation rates, but will not reduce the total number of moles of gas that may eventually be generated by these processes. Level III alternatives eliminate gas generation potential completely. An example of a Level III alternative is: incineration and cementation of solid organics (this eliminates microbial gas generation potential). It should be noted that the classification is based upon single alternatives. Therefore, a combination alternative (such as Alternatives 1 to 14) is actually made up of single alternatives that belong to different classification levels.

#### **1.3.5 Criteria Used for Evaluation of Engineered Alternatives**

Criteria used to compare the alternatives were peak index pressures for undisturbed performance and a "Measure of Relative Effectiveness" for human intrusion. This "Measure of Relative Effectiveness" is based on the predicted 10,000-year cumulative release of radionuclides to the Culebra Dolomite (Figures 1-2 and 1-3) for Alternatives 1 to 14 compared to the baseline design. These peak index pressures and cumulative release estimates are for comparative purposes only, and not meant to be absolute values. The results of the engineered alternative evaluations and the design analyses will be provided as input into performance assessment. Probabilistic modeling by PA will yield absolute release estimates to evaluate compliance with 40 CFR Part 191.

In addition to the design analysis of engineered alternatives, the EATF has also evaluated the feasibility of implementing engineered alternatives on the basis of technical, cost, regulatory, and schedule criteria, and made assessments of various factors (including risk) that need to be considered for potential locations of waste processing facilities (i.e., comparisons of processing at centralized facilities versus individual storage/generator sites).

#### **1.4 LIMITATIONS OF THE EATF EVALUATION OF ENGINEERED ALTERNATIVES**

It should be noted that the EATF evaluation of engineered alternatives is based on currently available information. Thus, the design analysis of engineered alternatives reflects the current understanding of the processes that will occur in the repository, and the evaluation of feasibility is based on the current interpretation of applicable regulations. It should be noted that the EATF evaluations are limited by the information available today, and therefore do not

Include the uncertainties that remain unresolved at the time of this report. Some of these uncertainties and their potential effects are outlined below:

- The potential list of performance parameters that may require engineered alternatives is currently limited to only gas generation and human intrusion issues. Therefore, only these issues were considered in the selection of possible alternatives, and in the development of the Design Analysis Model. If other performance issues are identified later, the list of candidate alternatives may require modification, additional code development may be needed for the Design Analysis Model, and the feasibility of new alternatives may need to be investigated.
- The requirements of the repository, in terms of any performance improvements needed through engineered alternatives, have not been identified at the time of this report. These requirements will be identified from the PA studies. Therefore it is not possible for the EATF to recommend the best (optimal) alternative, because the extent of any improvement that may be needed is not known at this time. This limits the EATF to recommending a group of alternatives that collectively address any potential problem, rather than selecting one "best" alternative. Since the PA and EATF efforts are being conducted in parallel, the choice of an optimal alternative can be formalized only after the potential problems associated with the baseline design are quantified by the performance assessment. This issue is discussed in detail in Section 9.2.
- The design analysis of engineered alternatives is based on various assumptions regarding the different input parameters such as gas generation rate, creep closure rate, brine inflow rate, physical properties of modified waste forms, etc. These assumptions are based on the current information available in SNL studies and elsewhere. As experimental programs (DOE, 1990c) and planned analyses by SNL (DOE, 1990d) continue to provide new data, some of the EATF assumptions could change, and may lead to a need for updating the model in the future. Detailed discussion of this issue can be found in Section 4.
- The feasibility of implementing engineered alternatives is based on different assumptions for various criteria such as cost, schedule, regulatory considerations, and health and safety risk. Although items such as cost estimates developed by the EATF provide a means of rough comparison between alternatives, they should not be interpreted as absolute and precise values. The various assumptions are discussed in detail in Sections 6, 7, and 8.
- The extent of waste characterization required could dictate whether it would be necessary to treat the waste, regardless of the results of performance assessment. For example, if extensive RCRA sampling and analysis is required due to inadequate process knowledge, and if the cost of RCRA sampling is high

In comparison to treating the waste, then this might force a decision in favor of treatment even if the performance assessment does not identify any problems with the current waste forms. Unfortunately, the extent of characterization required is currently not well-defined. This issue is discussed in detail later in Section 6.

Thus, given the uncertainties involved, the analysis presented in this report is based on the best available information as of today. The uncertainties are discussed in further detail in appropriate sections of the report.

The subsequent sections of this report present the analysis of the effectiveness of engineered alternatives using the design analysis model, and the feasibility of implementation of engineered alternatives. Sections 2 through 4 deal with the activities related to design analysis and modeling. Sections 5 through 8 discuss the feasibility of implementing engineered alternatives. Section 9 provides a decision methodology that can be used to select an optimal engineered alternative, if one is needed.

## 2.0 OVERVIEW OF THE DESIGN ANALYSIS MODEL

This section explains the different processes that are expected to occur in the repository after waste emplacement, and also discusses the modeling approach and the various assumptions that have been used in the Design Analysis Model. The criteria used in the Design Analysis Model to evaluate the effectiveness of an engineered alternative for gas generation and human intrusion are also presented in this section.

### 2.1 GENERAL DESCRIPTION OF THE PROCESSES SIMULATED BY THE DESIGN ANALYSIS MODEL

The Design Analysis Model simulates processes occurring in the repository (rooms, panels, access drifts, and shaft seals) for the 10,000 year regulatory period defined in 40 CFR Part 191 (EPA, 1985). The behavior of the repository can be divided into the following phases:

- Repository under Atmospheric Pressure - Activities during this phase include waste/backfill emplacement followed by sealing of the panels. During this time atmospheric pressure is maintained within the repository.
- Repository Pressurization from Atmospheric to Peak Pressure - This phase is characterized by waste compaction under creep closure, brine inflow, gas generation, possible pressure build-up, and the processes associated with increasing gas pressure and presence of brine.
- Repository after Peak Pressure - This phase is characterized by the long-term processes that continue once peak pressures are reached in the repository, interrupted only by a human intrusion event. For some alternatives this phase may not be reached if, for instance, the pressure in the repository asymptotically approaches lithostatic pressure.

The processes simulated by the Design Analysis Model are discussed below.

#### 2.1.1 Repository under Atmospheric Pressure

The excavation of underground openings at the WIPP horizon results in a predictable disturbance of the equilibrium state of the Salado Formation. This deviation from equilibrium causes creep closure resulting in the formation of a disturbed-rock zone (DRZ). Creep closure is the viscoplastic response towards equilibrium by the rock under a deviatoric stress. Deviatoric stresses are the normal and shear stresses that remain after subtracting a hydrostatic stress, equal to the mean normal stress, from each normal stress component (Goodman, 1980). Closure rates have been measured at thirty locations throughout the WIPP, and are of the order of a few inches per year in a newly excavated room (Nowak et al., 1988).

The DRZ is defined as the zone of rock in which mechanical properties and hydrologic properties have changed in response to the excavation. The term "near-field" is used to describe the zone of rock within the DRZ, and the term "far-field" is used to describe the rock outside the DRZ in which intrinsic parameters such as porosity and permeability are undisturbed from pre-excavation values. The development of a DRZ has been confirmed by geophysical surveys and gas-flow tests, in addition to borehole observations. These three

observations have defined a DRZ extending laterally throughout the excavation and varying in thickness from 1 to 5 meters, depending on the size and age of the opening. Visual observations of Marker Bed 139 (MB139) underlying the repository (Figure 1-4) indicate that fractures in this unit are both preexisting and excavation induced. The anhydrites "a" and "b" overlying the repository (Figure 1-4) are probably also fractured. The "disturbed" zone exists above and below the repository, while the "intact" zone is undisturbed, and exists beyond the area affected by the excavations. The halite between the anhydrites above and below the floor of the repository is fractured.

A panel consisting of seven rooms and associated access drifts will be filled with the waste containers (either drums or boxes). In most of the engineered alternatives that were evaluated, a backfill material (e.g. salt) is used to fill the space around and between the waste containers. The waste and backfill material is referred to as "waste/backfill composite" or "composite". The purpose of adding the backfill is to minimize void volume in the room and also reduce the permeability of the composite. This reduction in permeability results in lower release of radionuclides in the case of human intrusion into the repository. A clearance is left between the backfill on top of the waste stack and the roof of a panel as an operational work space for backfilling.

During excavations and waste emplacement, atmospheric pressure is maintained within the repository. Since the atmospheric pressure is substantially lower than the lithostatic pressure in the surrounding rocks, a depressurization of the Salado Formation around the repository will occur. This will be manifested by a gradual decrease in pressure from the far-field pore pressure in the intact Salado to atmospheric pressure in a panel. Naturally occurring gas (nitrogen and methane) is present in brine from the Salado Formation, and has been observed to exsolve from the brine due to depressurization.

Underground experience at the WIPP with the presence and movement of brine within the Salado Formation has yielded an understanding of brine movement in salt. For example, the presence and movement of brine in the Salado Formation adjacent to the underground workings is evidenced by small "weeps" (brine encrustations) that commonly develop on the walls of an excavation shortly after it is mined. These "weeps" are a result of the difference in pressure between the surrounding halite and the atmospheric pressure within the rooms and cease over time. In general, the brine inflow rate is less than the evaporation potential caused by mine ventilation, resulting in humid, but brine free conditions in the repository.

In-situ brine flow experiments are used to measure the permeability of the Salado Formation. The brine flow rates into sealed boreholes are in the range of  $5 \times 10^{-8}$  to  $1 \times 10^{-7}$  liters/s as steady states are approached. These rates have been used to calculate far-field Salado permeabilities that fall within the range of  $10^{-21}$  to  $10^{-20}$  m<sup>2</sup>, using a poroelastic Darcy flow model (Lappin et al., 1989). On the basis of preliminary data, the far-field permeability of the anhydrites appears to be one to three orders of magnitude higher than that of the intact host salt.

Emplacement of the waste within a panel is followed by sealing of the access drifts and the shafts with a multicomponent seal system. The goal of the sealing system is to limit ground water from the overlying units from flowing down the shafts, limit brine and/or gas from flowing up the shafts. The panels seals will isolate the contaminants present in the waste from circulating in the air during the operational waste emplacement phase. This objective is accomplished by a combination of short-term and long-term seals as described below.

### 2.1.2 Repository Pressurization from Atmospheric to Peak Pressure

As long as the generated stress in the rooms is below lithostatic, the Salado will continue to creep due to deviatoric stresses, thereby reducing the room dimensions. As a result, the clearance above the waste composite will be eliminated and the void space within the waste/backfill composite will be reduced.

The creep that continues to compact the waste/backfill composite will be resisted by the combination of two different mechanisms. The first of these is the ability of the particular waste/backfill composite to resist compaction, manifested by its effective stress. The effective stress is the stress that is transferred between the solid particles of the waste/backfill composite. The other is the effect of gas pressure within the void spaces. The increasing gas pressure provides a second component of internal stress resisting creep. As creep ceases, the development of the DRZ ceases and may actually begin to reverse caused by healing of the fractures.

The brine will continue to seep into the panels due to a pressure differential between the panels and the Salado formation. Corrosion of drums and metals in the waste under anoxic conditions will consume large quantities of water in the brine (if present), producing hydrogen. Microbial activity by a potentially broad range of microbes, which may be aerobic, anaerobic, halophilic, or halotolerant, is assumed to consume cellulosic materials and perhaps other organic materials in the waste as well. This activity will produce carbon dioxide and methane, and may also produce nitrogen and hydrogen sulfide. The hydrogen sulfide will probably be removed by reacting with the metals or their corrosion products to form sulfide minerals. Radiolysis of brines, cellulosic materials, plastics, and rubbers, will consume water and degrade the organics to produce limited amounts of carbon monoxide, carbon dioxide, hydrogen, and oxygen. Carbon dioxide may be removed from the gas phase by reacting with cementitious materials present as part of the waste or backfill to form carbonate minerals (calcite, dolomite, magnesite, etc.). The combination of gas generation due to the mechanisms described above, and the decrease in void volume due to creep closure, will result in pressurization of the panel.

Increased gas generation will increase the partial pressures of the gases and their solubility in brine. This will cause additional gas to dissolve in the brine that may be present in the room. The increased concentration of gases in the brine will be the driving force for diffusion of gases into the intact Salado.

In addition to diffusion, advection into the Salado formation could occur as the gas pressure increases within the panel. This process involves the migration of gases under a pressure gradient from the room into the halite and anhydrites that make up the Salado formation. The ability of the Salado to advect gases will depend on: (1) the intrinsic permeability of each bed; (2) the relative brine and gas saturations of these beds; (3) any capillary or threshold-pressure effects involved in gas displacement of brine already present; and (4) the amount of localized depressurization which exists due to the operational phase. Ongoing work suggests the threshold-pressure within the intact Salado halites may be as high as 8 MPa. Therefore, the sum total of the threshold pressure and the in-situ pore pressure may prevent gas advection into the halite. However, if some fractures exist within the DRZ, connecting the panel to the anhydrite beds, gases will be dissipated due to the higher permeability (therefore lower threshold pressure) and lower pore pressure of the anhydrites. Advective processes would allow some gas to escape from the panels, thus lowering the pressure in the disposal rooms.

The proposed short-term seals consisting of concrete plugs and possibly clay materials are designed to function for approximately 100 years after decommissioning. The long-term seals are made of crushed salt that is chemically and mechanically compatible with the host rock formation. Creep closure of the surrounding intact host rock consolidates and densifies the crushed salt to a condition comparable to intact salt.

### 2.1.3 Repository after Peak Pressure

Gas generation due to microbial degradation of solid organic components of the waste such as paper, cloth, wood etc. would be terminated after peak pressure is reached. Any brine remaining in the panel would have been consumed by anoxic corrosion of the metals. No further brine inflow would take place because the pressures in the panel equal or exceed the far-field pressure of the Salado Formation. Since the water present in the brine would be consumed, reactions of carbon dioxide with cementitious materials would also cease, since these reactions require water.

The mechanical resistance to closure prevents further creep during the late phase, resulting in a cessation of waste/backfill compaction. This mechanical resistance is made up of two components: (1) the stress of compaction and (2) the interstitial fluid pressure. When the sum total of these components becomes greater than the lithostatic pressure, the deviatoric stress is eliminated and creep ceases. At this point, the void volume becomes fixed at a constant value.

Gas advection will continue as long as the pressure within the panel is such that a driving force into the Salado is maintained. Once the pressure in the repository is lithostatic, the driving force is terminated and the system reaches a steady state condition.

## 2.2 DESIGN ANALYSIS (COUPLED PROCESSES) MODEL

The components of the Design Analysis Model (the ROOM-SCALE model and the SHAFT-SEAL model) are defined according to the physical barriers that will exist following waste emplacement at the WIPP. These barriers and modeling regions (Figure 2-1) are:

- The host rock and panel seals surrounding the rooms and drifts. The seven rooms and the equivalent volume of five and one-half rooms existing in the access drifts within a panel (12.5 room equivalents), are modeled on a collective basis to most accurately approximate the conditions within a storage panel at each time step. The modeling is done using the ROOM-SCALE component of the Design Analysis Model as described in Appendix B.
- The shaft and panel seals. The permeabilities of the seals are obtained as a function of time using the SHAFT-SEAL component of the Design Analysis Model as described in Appendix C.

The Design Analysis Model considers the processes that are essential to predicting changes in performance resulting from the application of alternative repository designs and waste forms. The conceptualization of the repository including the physical orientation and the associated values for the Salado formation is shown in Figure 2-2. The simulation by the Design Analysis Model of the processes described earlier is summarized below.

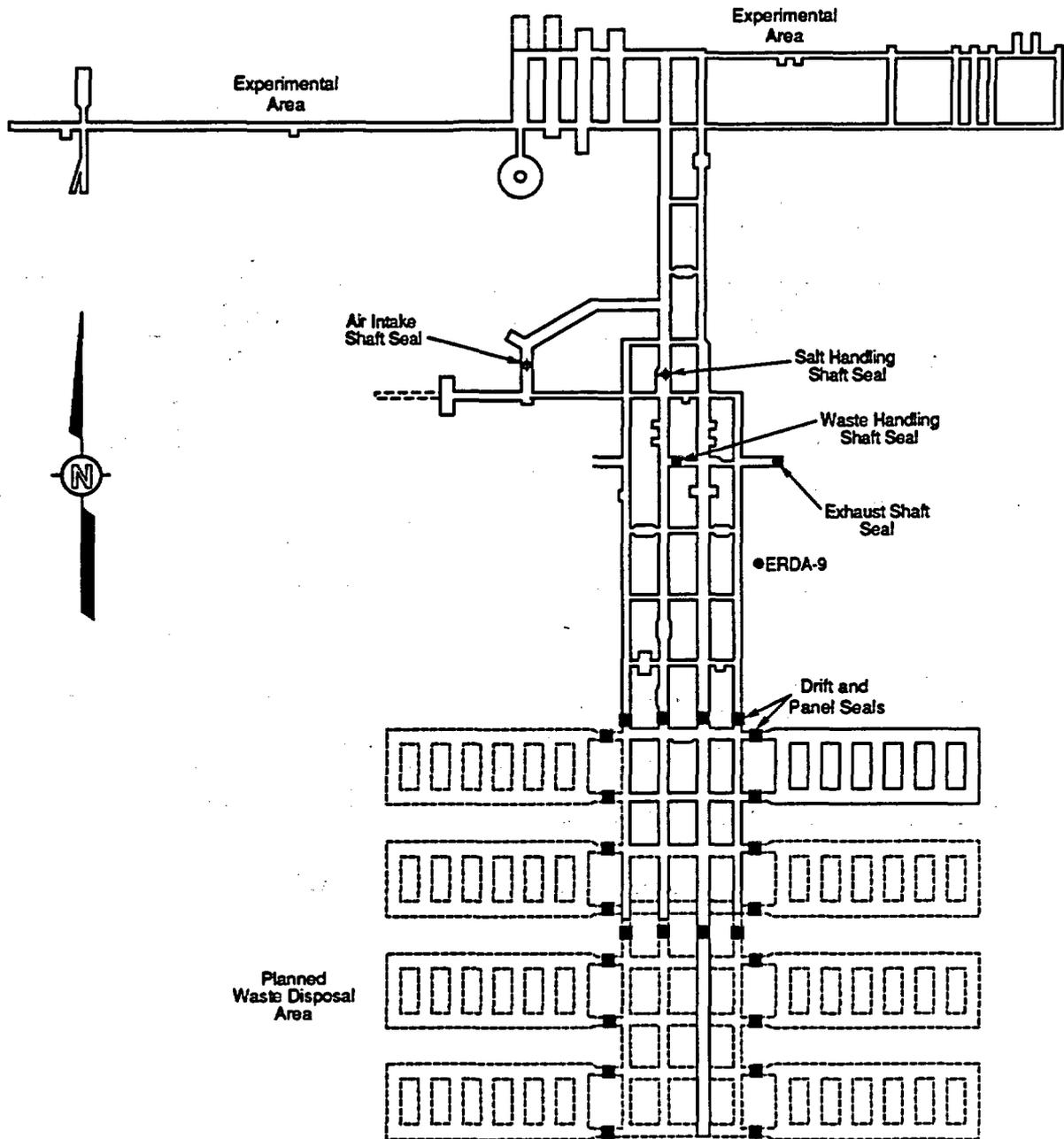


Figure 2-1  
Plan View with Proposed Seal Locations  
(Marietta et al., 1989)

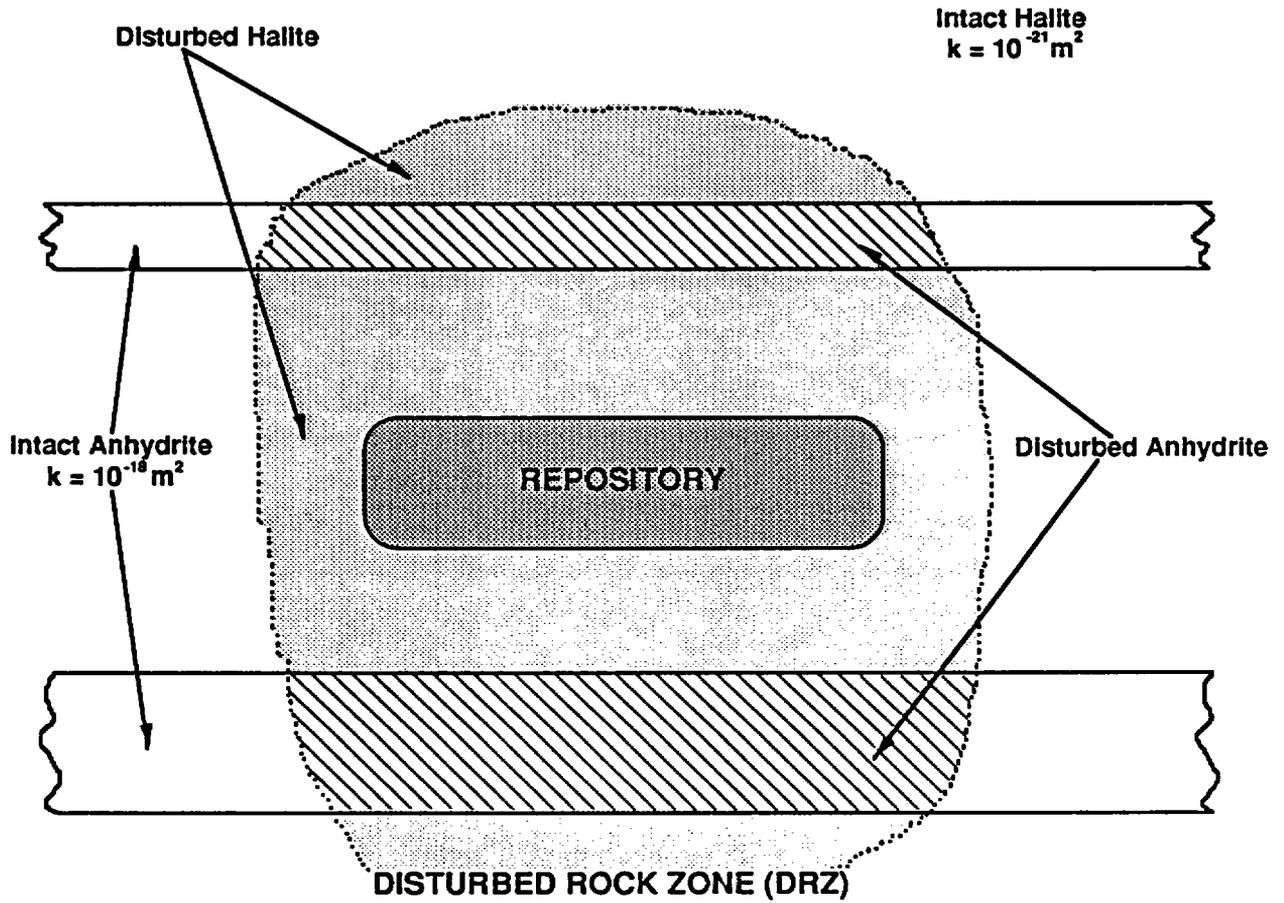


Figure 2-2. Conceptualization of Repository within Salado Formation

- Creep Closure of the Surrounding Host Rock (Appendix B, Section 2.4) - The Chabannes (1982) equation has been combined with a nonlinear regression equation based on several years of measured closure rates at 30 locations in the WIPP to predict creep closure rates of the host rock as a function of time. This equation expresses creep closure rates at each time step as a function of the room height, the room width, and the difference between lithostatic stress (14.8 MPa), and the internal stress in the panel. The internal stress is the sum of the effective stress of the waste/backfill composite and the fluid pressure inside the panel.
- Gas Generation and Consumption - There are four processes related to gas generation and consumption: anoxic corrosion, microbial gas generation, radiolysis, and dissolution of gases in brine. These are described below:

- Anoxic Corrosion (Appendix B, Section 2.13)

The dominant corrosion reaction is assumed to be the reaction of iron, usually in the form of mild steel, with water to generate amakanite and hydrogen according to the reaction:



This reaction generates one mole of hydrogen for every two moles of water consumed.

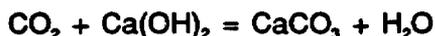
At each time step, brine in a storage room (if available) is assumed to react with iron or steel to generate hydrogen at a maximum rate of 1.7 moles of hydrogen/drum/yr (Lappin et al., 1989). This hydrogen generation rate requires the availability of  $5 \times 10^{-3}$  m<sup>3</sup> of water/drum/yr. If the brine (water) availability is less than the amount required for maximum hydrogen generation, the rate is scaled down based on the amount of water available for corrosion. This corrosion process is thus self-limiting since the hydrogen that is generated contributes to the pressurization of the room, which in turn inhibits brine inflow.

- Microbial and Radiolytic Gas Generation (Appendix B, Section 2.12) - The total potential for microbial gas generation, along with the rate of generation, have been modeled based on the data of Lappin et al. (1989). Based on the information provided therein, the following assumptions have been incorporated for modeling purposes:

- Since microbial activity and radiolysis utilize the same organic substrates, the gas generation rate of 0.85 moles/drum/year (Lappin et al., 1989) is assumed to represent both microbial and radiolytic gas generation.
- Microbial activity is not assumed to be limited by the availability of brine.

The microbial gas generation assumptions used in modeling the baseline case are explained in detail in Appendix B, Section 2.12, and can be summarized as follows:

- During the first 100 years after decommissioning of the repository, oxygen is completely consumed (aerobic microbial activity) with an equivalent molar production of carbon dioxide. Anaerobic microbial activity is assumed to commence only after this period of 100 years.
- Anaerobic microbial activity is assumed to ensue after 100 years at the rate of 0.85 moles/drum/year with a gas generation potential of 606 moles/drum (Lappin et al., 1989).
- Thus, anaerobic microbial activity begins 100 years after the start of the simulation, and lasts for a period of 713 years. The gases generated are assumed to be methane, carbon dioxide, and nitrogen in the ratio of 15:20:12.
- Dissolution of Gases in Brine - The moles of hydrogen, oxygen, and carbon dioxide dissolved in the brine present in a panel are evaluated at each time step (Appendix B, Sections 2.9 and 2.10). The moles of gas dissolved are calculated from phase equilibria relations using Henry's Law constants in brine (Reid et al., 1987). The Henry's Law constants and gas solubilities are evaluated from experimental correlations. The dissolution of nitrogen and methane is not considered since the brine already contains significant amounts of these gases (DOE, 1983).
- Brine Inflow (Appendix B, Section 2.3)
  - An initial brine inflow rate of 0.43 cubic meters/room/year (Nowak et al., 1988) is assumed. This is based on a constant room pressure of 1 atmosphere.
  - The rate of brine inflow is assumed to linearly decrease as fluid (brine and gas) pressure in the room increases, and approaches zero when the pressure in the room reaches lithostatic pressure (14.8 MPa). Lithostatic rather than hydrostatic is used since measurements have been made of pore pressures which exceed hydrostatic (Lappin et al, 1989). This approach couples brine inflow to creep closure and gas generation, because all of these processes affect fluid pressure in the room.
- CO<sub>2</sub>/Brine/Cement Interactions (Appendix B, Section 2.14 and Appendix E) - Carbon dioxide generated by microbial or radiolytic processes will partition into any brine present in the room. This dissolved CO<sub>2</sub> will then react with portlandite to produce calcite plus water according to the reaction shown below. Portlandite is a dominant phase in Portland cement and is available in the cementitious materials present in the waste.
  - The pH of any brine in the room is assumed to be buffered by portlandite that is present in the cement waste. CO<sub>2</sub> will react with portlandite to yield calcite and water according to the reaction:



- The reaction rate is assumed to be proportional to the volume of free brine in the room, and the reaction stops when either all of the portlandite or the brine/water in the room is consumed.
- Water that is generated by the above reaction is added to the total number of moles of water in the room.
- Diffusion of Gases into the Host Formation (Appendix B, Sections 2.2 and 2.11)  
Since undisturbed Salado brines at lithostatic pressure have significant amounts of dissolved  $N_2$  and  $CH_4$  (DOE, 1983), it is assumed that diffusion of these gases is negligible due to the lack of concentration gradients necessary to drive diffusive transport. Similar data were not available for  $H_2$  and  $CO_2$ , and therefore these gases have been considered for their diffusion into the host rock.
- Advection of Gases into the Host Formation, Across Seals, and into the Overlying and Underlying Anhydrite Beds (Appendix B, Section 2.6) - The host formation, panel and shaft seals, and the intact anhydrite beds are modeled as parallel routes for the advection of gases out of the panel. The following assumptions and information are being used for modeling purposes:
  - The permeability of the intact halite ranges from  $1 \times 10^{-21} m^2$  to  $1 \times 10^{-18} m^2$  with an expected permeability of  $3.4 \times 10^{-21} m^2$  (Rechard et al., 1990).
  - The permeability of the intact anhydrite beds is estimated to be 2 to 3 orders of magnitude greater than the halite ( $10^{-18}$ ), and as such is assumed to be the most probable pathway for gas advection (Lappin et al., 1989).

Other assumptions include:

- The halite between each room and the anhydrites is fractured such that there is hydrological communication between the rooms and the disturbed anhydrite.
- The anhydrite beds above and below the repository are extensively fractured due to excavation of the drifts and panels, and therefore all panels and rooms within each panel are in equilibrium with respect to gas pressure.
- The disturbed anhydrites above and below the repository are assumed to be saturated with brine at the time of WIPP decommissioning.
- The intact anhydrites, and the halite layers above and below the repository (outside the DRZ), are assumed to be saturated with brine at pore pressures of 10.36 MPa (70% of lithostatic) and 14.8 MPa (lithostatic), respectively. For the sake of modeling, the pressures in the intact Salado are chosen to provide the largest driving force for brine migration. Since there are measured values of the pore pressure approaching lithostatic, it has been chosen as the value for the far-field pressure of the brine.
- When the panel fluid pressure exceeds the assumed intact anhydrite pore pressure, the brine in the disturbed anhydrite is assumed to be driven into the undisturbed anhydrite.

- When the panel fluid pressure exceeds the assumed intact halite pore pressure, additional brine is driven from the disturbed anhydrite into the intact halite layer above and below the repository.
- The flow of brine from the disturbed anhydrites to the intact anhydrites and Salado layers, is assumed to be governed by Darcy's equation of flow through porous media.
- The volume from which the brine is expelled is assumed to provide an additional void volume for panel gases to occupy.

A program simulating two-phase flow is used to derive a parametric equation for the advection rate into the intact anhydrites when the panel fluid pressure exceeds 11.3 MPa (brine pore pressure of 10.36 MPa plus a threshold pressure of 0.94 MPa (Davies, 1989)). Concurrently with gas advection into the anhydrites, the advection of panel gases into the four shaft seals (conductance varying with time) is also simulated (Appendix B, Section 2.7). A viscosity correlation which is valid at both low and high pressures is used to estimate the viscosity of the gas mixture for use in the advection calculations.

- Gas Compressibility (Appendix B, Section 2.16) - The Lee-Kessler Equation of State (Reid et al., 1987) is used to estimate the compressibility of the gas mixture in a panel at each time step. The fluid pressure is updated based on the resulting value of compressibility. The fluid pressure is then used to estimate molar advection rates of gases, volume of brine inflow, creep closure rates, and gas solubilities in brine during the next time step.
- Waste/Backfill Composite Compaction and Resulting Mechanical Resistance to Closure (Appendix B, Section 2.15) - Stress/density relationships have been obtained for each waste form and backfill material from literature and experimental data. For each engineered alternative, an average density (based upon the mass fraction and density of each component) is calculated at various stress levels of compaction. The density of the waste/backfill composite is evaluated at each time step. The effective stress corresponding to this density is evaluated using the stress/density relationships of the composite. This effective stress is then used as input to the Chabannes equation (see discussion on creep closure above) as the mechanical component of resistance to creep closure.
- Development of a Zone of Enhanced Porosity Surrounding the Panel (Appendix B, Section 2.17) - The creep of the host rock creates an additional void volume within a zone of enhanced porosity which the panel gases will occupy. The rate and extent of creep closure will govern the magnitude of this void volume. This void volume is calculated at each time step as the product of the porosity of the Intact Salado (0.001) (Marietta et al., 1989, Table 3-9) and the difference between the initial panel volume and the panel volume at the current time step.
  - It is assumed that the zone of enhanced porosity does not contain brine.
  - It is assumed that all the pores in this zone are interconnected.

Future Human Intrusion into the Repository (Appendix B, Section 2.18) - Three human intrusion events (Figure 2-3) were evaluated to determine the relative effectiveness of each engineered alternative in reducing radionuclide releases. The three scenarios, the modeling procedure for each scenario, and the assumptions behind them are described as follows:

- The E1 scenario (Marietta et al., 1989) (Figure 2-3a) assumes a borehole penetration through a waste-filled panel and continuing into or through a pressurized brine pocket existing in the underlying Castile Formation (Figure 1-2). In actuality, the E1 scenario begins with the E2 scenario, but the amounts of brine located within the room are extremely small compared to the brine transported from the Castile through the waste, and therefore the E1 scenario neglects any effects from the E2 scenario. This event was modeled using a parametric equation relating flow rate through the waste/backfill composite to the hydraulic conductivity of the composite. This equation was developed by statistically regressing data resulting from a series of computer runs using the flow and transport code SWIFT III (Reeves et al., 1986).

The modeling associated with the E1 scenario is performed on a room basis, since only the area surrounding the actual borehole allows the brine to come in contact with the waste. In order to verify this, the SWIFT III was used to determine the velocities of the fluid flow through the waste/backfill composite. A bounding brine velocity was chosen such that in 5000 years a fluid particle would not be able to move a distance equal to the height of the room. This velocity defined a radius of influence used to calculate an effective wash-through volume. This volume was simulated as an ellipsoid, with the major axis along the borehole and the other axes into the room. If the conductivity of the waste/backfill composite was such that the effective radius was greater than the width of the room, the width of the room was chosen for one of the axes since the halite was considered to be impermeable. The other axis was allowed to continue to the edge of the room, but in no case did the effective radius exceed half of the length of one room. The assumption of an infinite reservoir of brine in the Castile allows a constant pressure of 16 MPa to be prescribed for the brine pocket.

- The E2 scenario (Marietta et al., 1989) (Figure 2-3b) assumes a borehole just penetrating into the repository, not passing through. This scenario is modeled using an analytical solution to the radial flow equation through a porous media, simulating the borehole and the panel as concentric circles. The halite is considered to be an impermeable boundary that is located at a sufficient distance to allow the volume of the cylinder to be the volume of a panel. Simplifying assumptions regarding the flow of gas and brine are made. In actuality, the gas phase would be located towards the top of the panel and the brine phase would be located towards the bottom of the panel. In fact, the amount of brine predicted by the model to be present in the panel at 5,000 years would not be enough to fill the borehole to reach the Culebra. The gas being less viscous and towards the top of the panel, would tend to escape preferentially to the brine, thereby reducing the room pressure.

For the purposes of comparing alternatives, a hypothetical "fluid" with the properties of brine is used. This fluid is comprised of the appropriate

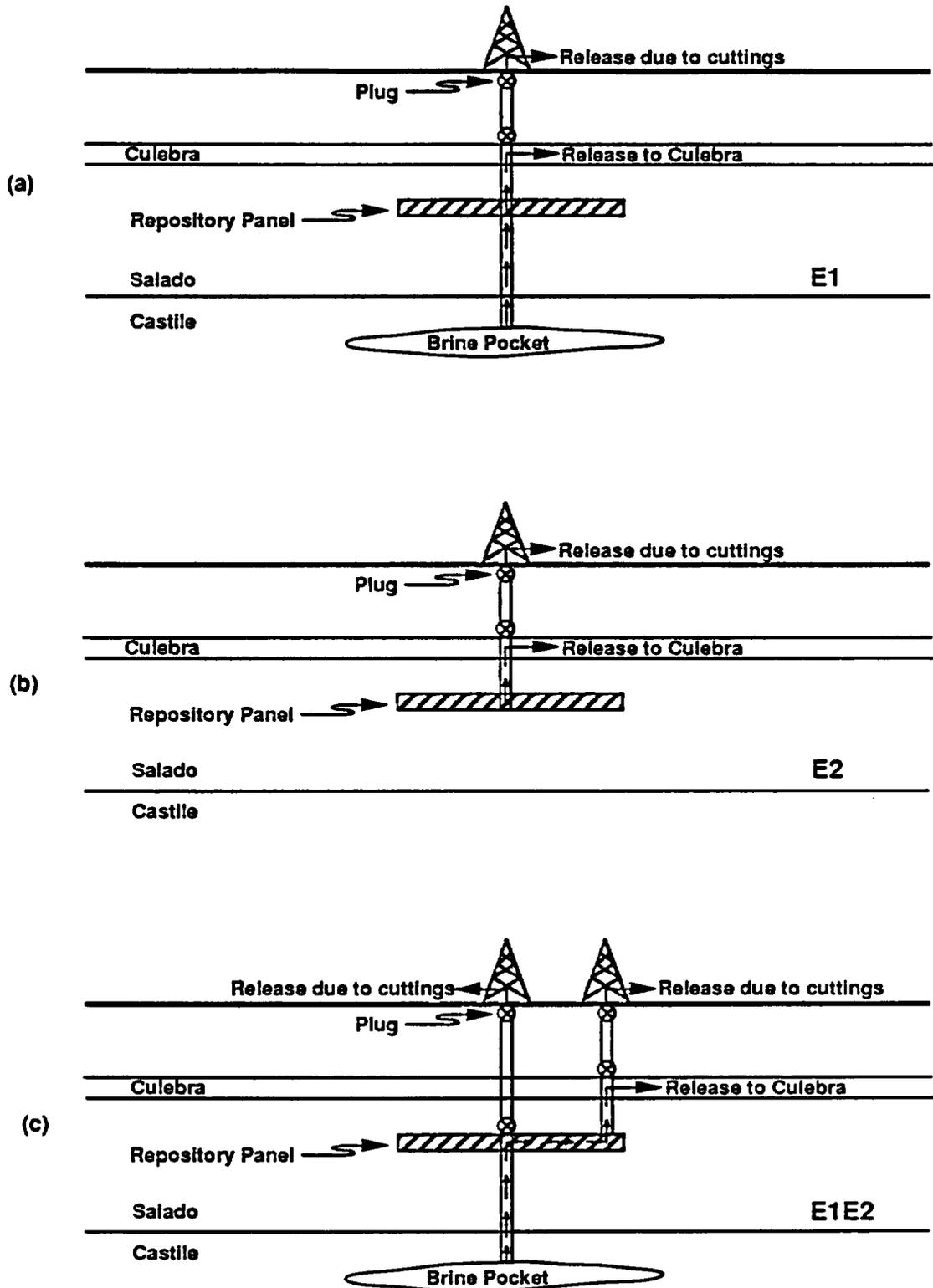


Figure 2-3. Human Intrusion Scenarios

volumetric proportions of gas and brine, which are predicted by the model for each alternative. This fluid is assumed to saturate the room and be transported to the Culebra through the borehole. The amount of radionuclides within the brine portion of the fluid that is released are then compared for each alternative.

- The E1E2 scenario (Marietta et al., 1989) (Figure 2-3c) assumes a combination of the first two scenarios; two boreholes penetrate the repository in the same panel. One borehole provides a pathway for brine flow from the Castile Formation brine pocket directly into the panel. This borehole is capped above the repository such that no brine can move vertically to the Culebra. The other borehole (occurring later in time) provides a pathway from the repository to the Culebra Dolomite. This pathway consists of a flow path through the panel from the E1 borehole to the E2 borehole. No credit is taken for any processes which may occur or change during the interim between the first and second boreholes. This scheme results in a pressurized flow path directly through the waste/backfill composite.

The flow rate through the waste is obtained from the analytical solution to the one-dimensional flow equation through porous media, assuming the two boreholes are separated by the length of one room (300 ft., 91.44 m). Any effects of the pressure in the room being greater than the pressure of the Castile brine pocket, are neglected due to the assumption of an infinite brine pocket. It should be noted that the E2 scenario is a part of the E1E2 scenario. This happens when the second borehole breaches the repository potentially releasing any gases and brine initially located there. This is neglected because the amount of brine originally located in the panel would be extremely small in comparison to the volume produced from the Castile brine pocket.

The following assumptions have been applied to all human intrusion scenarios:

- The intrusion occurs 5000 years after decommissioning.
- The diameter of the borehole is 0.14 meter based upon an average borehole area obtained from Marietta et al. (1989, Table 3-10).
- The hydraulic conductivity of the waste/backfill composite is the weighted geometric mean of the waste forms and backfill properties (explained in detail in Section 3.5.3).
- The borehole conductivity is  $1 \times 10^3$  meters/second (clean sand/gravel) obtained from Freeze and Cherry (1979, Table 2-2).
- Waste element solubilities have been assumed to be  $1 \times 10^4$  mol/liter from Marietta et al. (1989, Table 3-10).

The activity of each radionuclide at the time of intrusion is computed using the solutions to differential equations that represent mass balances for each radionuclide (Appendix B, Section 2.20). Based upon the radionuclide solubilities in brine and the volume of brine released, the cumulative activity of each radionuclide released

to the Culebra was determined. The objective of these human intrusion simulations is to calculate a number which is similar in functional form to the EPA Summed Normalized Release (EPA, 1985); the difference being that the Design Analysis Model calculates the cumulative release of radionuclides into the Culebra. Alternately, the EPA Summed Normalized Release specifies calculation of the cumulative activity of each radionuclide across the regulatory boundary, and in addition, employs scenario probability weighting to each release (EPA, 1985).

The Design Analysis Model does not consider probabilities of occurrence of scenarios; the scenario is assumed to occur and the effectiveness measure is evaluated. The value generated by the Design Analysis Model is the singular raw score for the effectiveness of each alternative design. Calculation of the measure of relative effectiveness is performed by dividing the effectiveness measure for the alternative by the effectiveness measure for the baseline case (Section 2.4). The baseline case uses "as received" waste with crushed salt backfill. "As received" waste is defined as follows:

- Sludges with some cement added as solidifying agents [i.e., current processes at the Rocky Flats Plant (RFP) for Content Code 111], but not a concreted monolith (DOE, 1989e).
- Solid organics and inorganics are in unshredded form, wrapped in multiple layers of plastic, inside a 90-mil rigid liner in a steel drum [i.e., current packaging at RFP and most other sites (DOE, 1989e)].

The improvement resulting from a waste form modification or a repository design alteration is determined by comparison with the baseline case. For the baseline case, the assumptions are as follows:

- Each room is assumed to be filled to capacity (considered to be 6,000 drums) with "as received" waste and backfilled with crushed salt.
- The initial room dimensions used in the calculations are 13 feet (3.96 m) high by 300 feet (91.44 m) long by 33 feet (10.06 m) wide (Lappin et al., 1989).
- A two-foot high clearance is assumed to be left above the waste/backfill composite in all rooms and drifts in the panel.
- The panel capacity (including the seven storage rooms and the surrounding access drifts as in Figure 2-1) is assumed to be approximately 12.5 times the capacity of one individual room.
- The panel and shaft seals are assumed to be in place.

### **2.3 CRITERIA FOR EVALUATION OF EFFECTIVENESS OF ALTERNATIVES FOR ADDRESSING GAS GENERATION**

Selected alternatives (described earlier in Table 1-2) were quantitatively evaluated using the Design Analysis Model for their effectiveness for addressing gas generation. The criteria of evaluation included Peak Index Pressure, Excess Gas Energy, and Additional Volume

Required. These three parameters are interrelated based upon the amount of gas pressure within a panel.

The Peak Index Pressure is the maximum pressure in a room predicted by the Design Analysis Model. This is based upon the gas generation properties of the final waste form resulting from a particular alternative, and also upon the resulting void volume in the room. The Peak Index Pressure for a particular alternative is compared with the lithostatic pressure to evaluate the effectiveness of that alternative with respect to gas generation. This is also expressed as a percentage of lithostatic pressure for purposes of comparison.

The Excess Gas Energy is based upon the amount of stored energy, which is represented by the gas which is in excess of lithostatic pressure. This is equal to the pressure in excess of lithostatic multiplied by the void volume which it occupies.

For alternatives in which the Peak Index Pressure does not exceed lithostatic, the Excess Gas Energy is zero. The closer this number is to zero, the better the alternative is in relation to minimizing the amount of excess energy in the system due to gas pressure.

The Additional Volume Required is a measure of the amount of additional volume that would be required for the pressure in a panel to return to lithostatic pressure. A further description of this parameter may be found in Section 4.0.

#### **2.4 CRITERIA FOR EVALUATION OF EFFECTIVENESS OF ALTERNATIVES FOR ADDRESSING HUMAN INTRUSION SCENARIOS**

A parameter called the "Measure of Relative Effectiveness" was defined for each alternative in order to quantitatively compare the different alternatives in relation to human intrusion by using the Design Analysis Model. This factor is a measure of the improvement in the performance of the alternative design, compared to the baseline design. The criterion used to measure this improvement is the estimated cumulative release of radionuclides to the Culebra Dolomite in the event of human intrusion. The ratio of the cumulative release of radionuclides for an engineered alternative to the release under baseline conditions is the "Measure of Relative Effectiveness" for that particular alternative. In other words:

$$\text{Measure of Relative Effectiveness} = \frac{\text{Cumulative Release of Radionuclides Using the Alternative Design}}{\text{Cumulative Release of Radionuclides Using the Baseline Design}}$$

For the baseline case, the Measure of Relative Effectiveness is 1. The lower the value of this factor, the more effective the alternative is in improving repository performance relative to the baseline case.

In summary, the Design Analysis Model has been developed by the EATF to simulate the behavior of the repository after waste emplacement. The model analyzes 14 combination alternatives (Table 1-2) relative to the baseline design with respect to their effectiveness for addressing possible gas generation and human intrusion issues. The results of the effectiveness evaluation of the 14 combination alternatives are discussed later in Section 4.0.

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### **3.0 PHYSICAL AND CHEMICAL PROPERTIES OF THE WASTE/BACKFILL COMPOSITE**

#### **3.1 INTRODUCTION**

Quantitative estimates of physical and chemical properties for the combination of waste and backfill are required for the Design Analysis Model to determine the relative effectiveness of an engineered alternative. In this section, the term "properties" refers to the physical and chemical properties of a homogeneous composite material consisting of waste and backfill (hereafter referred to as "waste/backfill composite" or "composite"). The properties of a particular engineered alternative are in most cases unique to that alternative; in some cases, similarities occur from one alternative to another. Properties of the composite such as density, porosity, hydraulic conductivity, and effective waste volume are quantified as a function of compaction stress level. The effective waste volume is defined as the volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack. This parameter is used in the Design Analysis Model to calculate radionuclide releases to the surface due to removal of drill cuttings (Appendix B, Section 2.22). In addition, gas generation potentials are provided to the Design Analysis Model.

The following sections briefly list the properties developed (Section 3.2), discuss the assumptions made in developing properties for the baseline case and for the different alternatives described earlier in Section 1.3 (Section 3.3), sources of data (Section 3.4), and finally, the quantification of the properties (Section 3.5 and 3.6).

Some of the important properties are coupled; an example is hydraulic conductivity and permeability. Assuming a fixed value for permeability, a mathematical relationship exists to determine hydraulic conductivity. Density and porosity are similarly related.

#### **3.2 COMPOSITE PHYSICAL AND CHEMICAL PROPERTIES**

The development of physical and chemical properties for each alternative assumes the waste/backfill composite to be a homogeneous mixture. Five physical and chemical properties of the waste/backfill composite are required as input to the Design Analysis Model:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

Investigations in radionuclide solubility (Rai et al., 1983; Felmy et al., 1989; Marietta et al., 1989) have shown variabilities of six orders of magnitude. The EATF has therefore assumed a value of  $1 \times 10^{-6}$  molar for all radionuclide solubilities.

### **3.3 WASTE FORM DISTRIBUTION**

The effectiveness of Alternatives 1 to 14 (Table 1-2) is evaluated relative to the baseline case. The baseline case is defined as "as received" waste emplaced in the current repository room design and backfilling with crushed salt. "As received" waste composition is assumed to comply with the Butcher (1989) classification of the waste destined for the WIPP, which can be generalized into the three major waste form categories.

The three major waste forms comprise most of the TRU waste inventory. On a volumetric basis, the proportions of the three major waste forms for the baseline case are assumed [based on DOE (1988c)] to be:

- 40 Percent Solid Organics (combustible)
- 40 Percent Solid Inorganics (glass/metal)
- 20 Percent Sludges.

These proportions were developed from the inventory description in Butcher (1989) by grouping waste types with similar physical properties. This proportional distribution for the baseline case is maintained for comparison of each alternative studied, ensuring no calculational bias. Specifying this ratio reduces the number of sensitivity runs necessary to establish the relative effectiveness of the alternatives. In addition to the proportional distribution of waste forms, the initial volume of waste contained in a repository room is assumed constant. Discussion with Westinghouse Engineering (Garcia, 1990) and review of Lappin et al. (1989) indicate variation in the assumed quantity of waste to be placed in WIPP repository rooms and drifts. In this analysis, the current repository design is assumed to contain 6,000 55-gallon drums of TRU waste per room.

The initial conditions for the baseline case waste distribution parameters are listed in Table 3-1. These values, along with the density of each component as a function of stress (from creep closure), are used in computing the composite physical and chemical properties.

### **3.4 DATA DEVELOPMENT FOR ALTERNATIVES**

The raw data necessary for computation of waste/backfill composite properties were obtained from several sources. These sources include:

**TABLE 3-1**  
**INITIAL CONDITIONS FOR THE BASELINE CASE**

<u>WASTE FORM</u>	<u>NUMBER OF 55-GALLON DRUMS PER ROOM<sup>1</sup></u>	<u>AVERAGE DRUM WEIGHT (kg)<sup>2</sup></u>
Solid Organics (combustible)	2400	77
Solid Inorganics (glass/metal)	2400	102
Sludges	<u>1200</u>	211
Total Drums	6000	

<u>Backfill Material</u>	<u>Quantity<sup>3</sup> (m<sup>3</sup>)</u>	<u>Void Space Between Drums<sup>4</sup> (m<sup>3</sup>)</u>
Crushed Salt	1215	402

<sup>1</sup> Number of drums is computed from the distribution of waste forms (pg. 3-2) and the total number of drums per room (pg. 3-2).

<sup>2</sup> Average drum weights are obtained from Butcher (1989).

<sup>3</sup> Volume of backfill is obtained by computing total initial room volume and subtracting the volume of 6000 55-gallon drums, the ventilation space, and the assumed volume resulting from inefficiencies in backfilling (see 4 below).

<sup>4</sup> Void space between drums is the assumed inefficiency in backfilling. For the baseline case it is assumed that half of the volume available for backfilling within the waste stack is not occupied by salt. In other words, backfilling between the drums is assumed to be only 50% efficient. This assumption results from uncertainties in backfill emplacement methodology and the slip sheets between layers of drums. It should be noted that at 100% backfilling efficiency, some void volume will still be present as a result of the porosity of naturally packed salt.

- Information such as mass reduction and volume reduction factors from processing facilities located at Los Alamos National Laboratories (LANL), Idaho National Engineering Laboratory (INEL), Rocky Flats Plant (RFP), Pacific Northwest Laboratory (PNL), and Savannah River Site (SRS)
- SNL (e.g., Molecke, 1979; Butcher, 1990a; Butcher 1990b; Butcher et al., 1990; Stinebaugh, 1979).

The following sections describe various waste treatments, and include data sources used for obtaining the properties of waste forms resulting from these treatments. The waste treatments described here are all single alternatives, and have been used as components of Alternatives 1 to 14, which were listed earlier in Table 1-2.

#### 3.4.1 Incineration

Incineration of the combustible components of TRU waste leads to an overall reduction in waste volume. Since the EAMP evaluated incineration on the basis of the Process Experimental Pilot Plant (PREPP) process, (Appendix A), the volume reduction factors reported in Table 3-2 are also based on the PREPP process (Halford, 1990). It should be noted that the process will not be operational, but the EATF has used the data from the process for the sake of consistency with the EAMP evaluations. The process involves shredding, incineration and cementation of solid organic and solid inorganic waste forms (in the PREPP process both waste and drums would be processed). Application of the PREPP process would result in volume reductions for both solid organic and solid inorganic waste forms.

The mass reduction factor in Table 3-2 applies only to solid organic waste and is based on work done at the Waste Experimental Reduction Facility (WERF). As the solid organic waste is incinerated, organics are oxidized to form combustion product gases consisting primarily of carbon dioxide and water which are removed from the waste stream. Solid inorganic waste, when incinerated, yields no appreciable mass reduction.

#### 3.4.2 Cementation

Cementitious materials in either grout (self-leveling mixtures) or concrete (mixtures containing aggregate which "slump") formulations are used in five applications:

- Cemented sludges
- Shredded and cemented solid organics (combustible)
- Shredded and cemented solid inorganics (glass/metal)
- Incinerated and cemented solid organics
- Grout backfill.

**TABLE 3-2**  
**INCINERATED WASTE CHARACTERISTICS**

<u>PARAMETER</u>	<u>WASTE FORM</u>	<u>RATIO</u>
Volume Reduction Factors <sup>1</sup>	Solid organics (combustible)	3:1
	Solid Inorganics (glass/metal)	2:1
Mass Reduction Factor <sup>2</sup>	Solid organics (combustible)	20:1

<sup>1</sup> Volume Reduction Factors are based on the PREPP process (Halford, 1990) which would entail shredding, incinerating and cementing solid organics and solid inorganics. In the PREPP process, both waste and containers would have been processed. The EAMP's qualitative assessment of incineration was also based on PREPP methodology.

<sup>2</sup> Mass Reduction Factor applies only to the incineration of solid organics. The mass reduction factor is based on WERF data (Hunt, L., 1990).

**NOTE:** Waste forms classified as "solid organics" or "solid inorganics" may contain significant amounts of other materials. For example, solid inorganic waste forms such as laboratory glassware may contain amounts of solid organics such as plastic bags containing the glass. Thus, in order to completely destroy all organic material, the "solid inorganics" are processed through the incinerator.

An example of sludge processing involves mixing the sludge with cement (dry powder) which absorbs free water (Petersen et al., 1987). Cementation of sludges (as defined in this report) results in a monolithic form which is assumed to possess physical properties similar to those of an ordinary Portland cement (OPC) monolith. Cementation of incineration residue or shredded waste is significantly different in that the addition of ash and/or shredded metal can alter some of the properties, such as density. For the purpose of this report, a mixture of ash, OPC, and shredded metal waste is assumed to have the same hydraulic conductivity as a mixture of OPC and ash. Physical properties for a salt aggregate grout backfill have been estimated on the basis of recommendations by the Expert Panel on Applications of Cement Materials for Use at the WIPP (Appendix G). For the purpose of this report, the physical properties of grout backfill are the same as those reported for Type 10 grout by Coons et al. (1987). Properties of single alternatives that involve cementation are listed in Table 3-3.

### 3.4.3 Vitrification

The term "vitrification" is used to refer to any process that results in a vitrified (glass) waste form as described below:

- "Vitrification of sludges" refers to melting the sludge; e.g., addition of energy using a microwave (Petersen et al., 1987) or an induction melter. Depending upon the composition of the sludge, silica may be added prior to melting.
- "Incineration and vitrification process" refers to incineration of solid organics and ash melting or fusing of residue into a glass matrix.
- Melting metals -- under proper conditions radionuclides can be partitioned into a silica-based slag. Partitioning involves reactive conditions for oxidizing radionuclides. Radionuclide oxides then separate from molten metal into the slag phase that can be subsequently vitrified (Heshmatpour et al., 1983).

The Materials Characterization Center at PNL and the Savannah River Site have developed experimental borosilicate glasses for the disposal of high-level nuclear waste (Barkatt et al., 1984). The EATF used the general information concerning borosilicate glasses to develop properties of vitrified waste forms. The density of glass used as a fusing agent is assumed to be that for Type 7740 Borosilicate Glass (McLellan and Shand, 1984). The density of vitrified sludges is assumed from RFP microwave melting studies (Petersen et al., 1987). These densities are given in Table 3-4.

### 3.4.4 Shredding

Processing waste by shredding is applicable to solid organic (combustible) and solid inorganic (glass/metal) waste forms only. The shredding procedure assumed for alternative evaluations

**TABLE 3-3**  
**PROPERTIES OF CEMENTED WASTE FORMS AND BACKFILL**

<b>SINGLE ALTERNATIVE</b>	<b>HYDRAULIC CONDUCTIVITY (m/s)</b>	<b>DENSITY<sup>(5)</sup> (kg/m<sup>3</sup>)</b>
Cemented Sludges <sup>(1)</sup>	$4.0 \times 10^{-10}$	1410
Shredded and Cemented: <sup>(2)</sup>		
Solid Organics	$1.3 \times 10^{-12}$	1760
Solid Inorganics	$1.3 \times 10^{-12}$	2010
Incinerated and Cemented Solid Organics <sup>(3)</sup>	$6.0 \times 10^{-14}$	1980
Grout Backfill <sup>(3)</sup>	$1.3 \times 10^{-12}$	1880
Salt Aggregate Grout Backfill <sup>(4)</sup>	$7.37 \times 10^{-14}$	2100

<sup>(1)</sup> This hydraulic conductivity is one order of magnitude less than "as received" sludge reported in Lappin et al., 1989.

<sup>(2)</sup> Hydraulic conductivities are based on EATF calculations.

<sup>(3)</sup> Hydraulic conductivity and density: Coons et al., 1987.

<sup>(4)</sup> Hydraulic conductivity is assumed to be one order of magnitude greater than host salt; density for undisturbed salt from Lappin et al., 1989.

<sup>(5)</sup> Densities reported are based on EATF calculations unless otherwise noted.

**TABLE 3-4**  
**VITRIFICATION PROCESS MATERIAL DENSITIES**

<b><u>MATERIAL</u></b>	<b><u>DENSITY</u> (kg/m<sup>3</sup>)</b>
Type 7740 Borosilicate Glass (McLellan and Shand, 1984)	2230
Vitrified Simulated Sludge Density (Petersen et al., 1987)	1900

consists of making repeated passes through multiple shredders. This process is assumed to achieve a volume reduction ratio of 1.2 to 1 (Looper, 1990). Waste material is the primary target of the shredding operation, although a fraction of the waste containers may also require this processing technique. Shredded waste materials and containers exhibit:

- Improved compaction capability
- Lower effective hydraulic conductivity (especially after compaction)
- Improved thermal treatment effectiveness.

#### 3.4.5 Supercompaction

Processing waste by supercompaction is applicable to solid organic (combustibles) and solid inorganic (metal/glass) waste forms. The RFP method of supercompaction involves low force precompaction of wastes in 35 gallon drums; the "pucks" are then supercompacted (force in excess of 2200 tons) and packaged for disposal in 55 gallon drums. Calculations by the EATF indicate a slight decrease in total metal (total waste metal is constant, the amount of container metal is reduced) is realized using the proposed RFP method of supercompaction. Physical properties for supercompacted wastes are developed on the basis of information reported from RFP and INEL and a conservative assumption concerning overpacks as outlined in Section 3.6.4. Volume reduction factors of 3:1, for both solid organics and solid inorganics due to supercompaction, were obtained by comparing drum weights before and after processing, and then converting to volumetric units using density data. The processed drum weights for supercompacted TRU waste were communicated to the EATF by Halverson (1988). Density data are obtained from supercompaction tests conducted by the INEL (Larsen and Aldrich, 1986).

#### 3.4.6 Decontamination

Decontamination of metals can be accomplished by thermal methods (refer to Section 3.4.3) or mechanical methods. The EATF has assumed the mechanical method of vibratory finishing as the treatment method for decontaminating metallic waste (see Table 1-2, Alternative 10). Metals can be sufficiently decontaminated by vibratory finishing, to be reclassified as low-level waste (Allen and Hazelton, 1985) and thus removed from the WIPP inventory. The resulting TRU waste form is a contaminated rinsing solution used in the vibratory finisher. The contaminated liquid is concentrated and then solidified by cementation (Allen et al., 1982). Physical properties for this waste form are assumed to be the same as those presented for grout backfill properties listed in Table 3-3.

### 3.5 PHYSICAL/CHEMICAL PROPERTY CALCULATION METHODOLOGY

Initial calculations supply input values for a spreadsheet designed to compute physical/chemical properties on a per-room or panel basis. Therefore, generating the effective properties resulting from a given combination alternative is reduced to specifying the basic input values for that

alternative in the spreadsheet; data files are then generated in the spreadsheet. The default values in the spreadsheet are those corresponding to the baseline case.

Spreadsheet input parameters are listed below:

- The distribution of waste components in an average room. This distribution is dependent on the number of drums of each waste form component (solid organics, sludges, and solid inorganics) present.
- The average weight per drum of each waste form.
- Volume reduction factors are unique to the particular alternative, and to the unprocessed waste form. They allow computation of the equivalent drum count which is the number of unprocessed drums required to produce a processed drum for the particular alternative. Equivalent drum counts for Alternatives 1 to 14 are presented in Table 3-5.
- The total volume of backfill, volume of backfill within the waste stack, and void volume within the waste stack. The void volume within the waste stack is an estimation of the void space within the waste stack resulting from inefficiency in the backfilling process. The void volume is used to estimate an initial waste stack density. The total volume of backfill is utilized in the computation of waste/backfill composite density. The volume of backfill within the waste stack is used in the computation of hydraulic conductivity of the waste/backfill composite.
- The density variations of each component as a function of closure stress, from 0 MPa to lithostatic pressure (approximately 14.8 MPa) in 1.35 MPa increments. The component density values are used in the computation of waste/backfill composite density, porosity, and hydraulic conductivity of the room contents.

The effects of an alternative on the waste/backfill composite properties are calculated with a computer spreadsheet. To compute physical and chemical properties of a single alternative, only those input values which deviate from the baseline case need to be modified in the spreadsheet. The remaining input variables are therefore unaltered from the baseline case. Some alternatives require no computation of various properties (i.e., OPC grout backfill is considered incompressible and therefore has constant density and hydraulic conductivity). The hydraulic conductivity of OPC grout backfill would be considered a fixed input value for all scenarios. Typically, a single alternative will affect properties of one or two waste components, and/or the backfill material. The physical properties of the waste/backfill composite for a particular alternative are computed in a spreadsheet; other parameters may also need to be entered into the spreadsheet (i.e., drum weight and/or distribution of waste forms). This spreadsheet computational methodology is used to evaluate the properties of each single alternative.

**TABLE 3-5**  
**UNPROCESSED DRUM EQUIVALENTS PER ROOM**

ALTERNATIVES	UNPROCESSED DRUM EQUIVALENTS PER ROOM	PROCESSED DRUMS PER ROOM
BASILINE	6,000	NA
ALTERNATIVE 1	6,803	6,000
ALTERNATIVE 2	6,803	6,000
ALTERNATIVE 3	6,803	6,000
ALTERNATIVE 4	11,250	6,000
ALTERNATIVE 5	11,250	6,000
ALTERNATIVE 6	22,580	6,000
ALTERNATIVE 7	22,580	6,000
ALTERNATIVE 8	56,155	6,000
ALTERNATIVE 9	56,155	6,000
ALTERNATIVE 10	8,395	6,000
ALTERNATIVE 11	4,284	2,000
ALTERNATIVE 12	4,284	2,000
ALTERNATIVE 13	56,155	6,000
ALTERNATIVE 14	4,275	1,995

Combination alternatives are evaluated by simultaneously incorporating input properties developed for two or more single alternatives into the spreadsheet. For example, drum weights of various waste forms may be taken directly from single alternative input, whereas distribution of various waste forms must be computed (and used as input) for each unique combination of alternatives.

### 3.6 QUANTIFICATION OF PHYSICAL AND CHEMICAL PROPERTIES

The physical and chemical properties used in the Design Analysis Model are evaluated over the range of closure stress expected in the repository. The properties of primary importance are:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

The waste/backfill composite in the WIPP repository is assumed to contain four components. These components are the backfill material (e.g., crushed salt, grout, etc.) and the three major categories of waste (solid organics, solid inorganics, and sludges) which are processed as described in Table 1-2. The physical and chemical properties of each component will be dependent on the particular single alternative or combination alternative being considered. The methodologies and assumptions used to characterize these properties are detailed in the following sections.

Although material compressibility is not a Design Analysis Model input property, it is a useful parameter upon which to base simplifying assumptions. Material compressibility is used to estimate effects of creep closure on the physical properties of waste/backfill composite. Waste and backfill materials in the WIPP repository will be subjected to triaxial compressive forces. Compressibility of these materials will affect all physical properties. The extent to which different materials consolidate is dependent on the strength of the material. Treated wastes such as grout or glass have compressive strengths in excess of lithostatic pressure (14.8 MPa, Lappin et al., 1989), and are assumed to be incompressible under the stresses expected in the repository.

It is important to note that effects of time on the physical properties of the waste/backfill composite are not considered in this analysis. Long-term (10,000 years) effects such as fatigue and degradation are not well quantified and are therefore considered inappropriate for these generalized calculations (these effects are more suitably considered in the SNL Performance Assessment of the WIPP facility). Therefore, the density, porosity, and hydraulic conductivity of OPC grout used as backfill or sorbent material are assumed to remain constant during the 10,000 year operating life of the WIPP.

### 3.6.1 Density

Density of the waste/backfill composite at any given stress level can be computed from the density of the individual components at that same stress level. The mass of each waste component is obtained from the mass distribution of the three major waste forms (Butcher, 1989), based on the sampling of RFP TRU wastes stored at INEL (Clements and Kudera, 1985). The quantity of backfill is estimated from current repository room design specifications (Lappin et al., 1989). Total mass for each alternative is assumed constant over the 10,000-year period for the computation of waste/backfill composite densities. This assumption simplifies the density calculations. It is understood that waste/backfill composite mass fluxes resulting from gas production/dissipation, and brine transport will vary the waste/backfill composite mass (e.g., by chemical degradation, physical erosion, and subsequent mass transfer into and out of the waste stack), though the extent to which these processes will occur is not well defined. Initial component volumes are known from the baseline design criteria, thus initial waste/backfill composite density is readily quantified.

The waste/backfill composite density resulting from alternative evaluations may or may not increase during the consolidation process. For the baseline case, waste component densities as a function of stress level were obtained from Butcher et al. (1990); crushed salt compressibility data were obtained from Stinebaugh (1979). The methodology of computing density of a multicomponent system is outlined in Butcher et al. (1990). This method utilizes component densities (or mass and volume) to compute waste/backfill composite density. Implicit in the calculation is the assumption that the components act independently.

The formulation can be summarized as follows; the volume occupied by component *i* at some stress level *x* is:

$$V_i(x) = \frac{M_i}{D_i(x)} \quad (3.6-1)$$

where,

*V<sub>i</sub>(x)* = volume of component "i" at stress level *x*  
*M<sub>i</sub>* = mass of component "i"  
*D<sub>i</sub>(x)* = density of component "i" at stress level *x*.

The total waste/backfill composite volume at stress level *x* is the sum of the component volumes:

$$TV(x) = \sum_{i=1}^n V_i(x) \quad (3.6-2)$$

where,

$TV(x)$  = total waste/backfill composite volume at stress level  $x$ .

The total waste/backfill composite mass is the sum of the "n" component masses, or:

$$TM = \sum_{i=1}^n M_i \quad (3.6-3)$$

where,

$TM$  = the total waste/backfill composite mass.

Therefore, the waste/backfill composite density at stress level  $x$  can be computed as follows:

$$RD(x) = \frac{TM}{TV(x)} = \sum_{i=1}^n \frac{M_i}{(M_i/D_i(x))} \quad (3.6-4)$$

where,

$RD(x)$  = density of waste/backfill composite at stress level  $x$ .

Equation 3.6-4 can be simplified by introducing a component weight fraction,  $W_i$ :

$$W_i = \frac{M_i}{TM} \quad (3.6-5)$$

After dividing the numerator and denominator of equation 3.6-4 by  $TM$ , the expression for the waste/backfill composite density becomes:

$$RD(x) = \sum_{i=1}^n \frac{1.0}{(W_i/D_i(x))} \quad (3.6-6)$$

In summary, waste/backfill composite density was computed at a given stress level by:

- Using densities as a function of stress level and weights for each component
- Utilizing the experimental densities of individual components such as metal, glass, sorbents and combustibles (all under pressure) as reported by Butcher et al. (1990)
- Using component mass proportions.

Table 3-6 contains waste/backfill composite densities as a function of stress for the 14 combination alternatives (Table 1-2) analyzed using the Design Analysis Model.

### 3.6.2 Porosity

Porosity is a measure of void space existing in a material and is defined as the ratio of void volume to total volume of the material (Equation 3.6-7). Within the repository, the waste/backfill composite porosity is dependent on waste characteristics, backfill materials, efficiency of waste emplacement, and the extent to which these materials compact during the consolidation process. Computation of waste/backfill composite porosity (assuming constant mass) can be made on either a volume or density basis (Butcher, 1989), for example:

On volume basis:

$$\text{Porosity} = \frac{(V_{\text{total}} - V_{\text{solid}})}{V_{\text{total}}} \quad (3.6-7)$$

On density basis:

$$\text{Porosity} = 1 - \frac{(\text{composite density})}{(\text{composite solid density})} \quad (3.6-8)$$

where,

$V_{\text{total}}$  is the total volume ( $V_{\text{solid}} + V_{\text{void}}$ ) of the room components at some stress level and  $V_{\text{solid}}$  is the total solid volume of all room components. Therefore, the quantity ( $V_{\text{total}} - V_{\text{solid}}$ ) represents  $V_{\text{void}}$ , the room void volume including the waste/backfill composite void volume minus the volume of the overlying air gap. It should be noted that Eqn. 3.6-7 has been developed on a room basis, and should not be confused with similar equations in Appendix B that were developed on a panel basis. Due to greater availability of density data for components, waste/backfill composite porosity is computed on a density basis. Table 3-7 presents the waste/backfill composite porosities as a function of stress for the 14 combination alternatives analyzed using the Design Analysis Model.

**TABLE 3-6**  
**COMPOSITE DENSITIES FOR COMBINATION ALTERNATIVES**  
**(kg/m<sup>3</sup>)\***

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	692	1260	1320	1830	1340	1860	1370	1890
0	796	1450	1510	1830	1540	1860	1580	1890
1.4	1300	1710	1700	1830	1730	1860	1990	1890
2.8	1500	1770	1740	1830	1770	1860	2070	1890
4.1	1610	1800	1760	1830	1790	1860	2120	1890
5.5	1700	1830	1780	1830	1810	1860	2170	1890
6.9	1760	1850	1790	1830	1820	1860	2200	1890
8.3	1810	1870	1800	1830	1830	1860	2230	1890
9.7	1860	1880	1810	1830	1850	1860	2250	1890
11.0	1900	1890	1820	1830	1850	1860	2270	1890
12.4	1930	1900	1830	1830	1860	1860	2280	1890
13.8	1970	1910	1830	1830	1870	1860	2300	1890
15.2	1990	1920	1840	1830	1870	1860	2320	1890
Solid	2280	2470	2480	2720	2640	2860	2470	2710

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14
0	692	1470	1990	746	1110	1540	2100	1070
0	796	1690	1990	747	1110	1540	2100	1070
1.4	1300	1900	1990	1050	1600	1540	2100	1710
2.8	1500	1940	1990	1310	1780	1540	2100	2070
4.1	1610	1960	1990	1450	1830	1540	2100	2110
5.5	1700	1990	1990	1540	1880	1540	2100	2140
6.9	1760	2000	1990	1610	1920	1540	2100	2160
8.3	1810	2010	1990	1660	1950	1540	2100	2180
9.7	1860	2020	1990	1700	1980	1540	2100	2200
11.0	1900	2030	1990	1740	1990	1540	2100	2210
12.4	1930	2040	1990	1760	2020	1540	2100	2220
13.8	1970	2050	1990	1790	2040	1540	2100	2230
15.2	1990	2050	1990	1810	2050	1540	2100	2250
Solid	2280	2120	2380	2280	2280	2700	2100	2520

\*See Glossary for explanation of each abbreviation.

NOTE: In Alternatives 3, 5, 7, and 9, the processed waste forms and grout backfill are assumed incompressible (compressive strengths greater than lithostatic pressure) and, therefore, have constant composite density. The initial zero in the stress column incorporates the void volume due to backfill inefficiency, but it does not include the clearance between the waste/backfill composite and the roof. The second zero in the stress column indicates that the inefficiency is no longer present due to compaction, and the densities are equal to what would be expected from natural packing of the material.

**TABLE 3-7**  
**COMPOSITE POROSITIES FOR COMBINATION ALTERNATIVES**

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	0.697	0.490	0.469	0.326	0.492	0.349	0.446	0.303
0	0.651	0.414	0.390	0.326	0.416	0.349	0.363	0.303
1.4	0.430	0.305	0.314	0.326	0.344	0.349	0.196	0.303
2.8	0.345	0.283	0.300	0.326	0.330	0.349	0.164	0.303
4.1	0.295	0.270	0.291	0.326	0.321	0.349	0.142	0.303
5.5	0.257	0.258	0.283	0.326	0.314	0.349	0.124	0.303
6.9	0.230	0.251	0.278	0.326	0.309	0.349	0.111	0.303
8.3	0.206	0.244	0.273	0.326	0.305	0.349	0.100	0.303
9.7	0.185	0.238	0.269	0.326	0.301	0.349	0.090	0.303
11.0	0.169	0.233	0.266	0.326	0.298	0.349	0.083	0.303
12.4	0.154	0.229	0.263	0.326	0.295	0.349	0.076	0.303
13.8	0.139	0.224	0.260	0.326	0.292	0.349	0.068	0.303
15.2	0.127	0.221	0.258	0.326	0.290	0.349	0.063	0.303

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14**
0	0.697	0.307	0.164	0.673	0.513	0.428	0	0.577
0	0.651	0.203	0.164	0.673	0.513	0.428	0	0.577
1.4	0.430	0.105	0.164	0.540	0.299	0.428	0	0.320
2.8	0.345	0.086	0.164	0.428	0.222	0.428	0	0.180
4.1	0.295	0.074	0.164	0.367	0.197	0.428	0	0.164
5.5	0.257	0.064	0.164	0.325	0.175	0.428	0	0.151
6.9	0.230	0.057	0.164	0.295	0.160	0.428	0	0.141
8.3	0.206	0.051	0.164	0.272	0.147	0.428	0	0.134
9.7	0.185	0.046	0.164	0.254	0.134	0.428	0	0.128
11.0	0.169	0.042	0.164	0.239	0.125	0.428	0	0.122
12.4	0.154	0.038	0.164	0.227	0.117	0.428	0	0.117
13.8	0.139	0.034	0.164	0.216	0.108	0.428	0	0.113
15.2	0.127	0.031	0.164	0.206	0.101	0.428	0	0.109

\*See Glossary for explanation of abbreviation.

\*\*Porosity computed on a compartment basis (three 7-packs).

NOTE: The initial zero in the stress column incorporates the void volume due to backfilling inefficiency. The second zero in the stress column indicates that this inefficiency is no longer present due to compaction. The resulting porosities are as would be expected due to naturally packed backfill.

### 3.6.3 Hydraulic Conductivity

Hydraulic conductivity is a measure of the permeability of a porous media. It is dependent on the properties of the media as well as the fluid. The hydraulic conductivity of the waste/backfill composite in an average WIPP repository room is dependent on the waste components, backfill material, and the brine present. In multicomponent systems, an effective hydraulic conductivity can be estimated by averaging the individual component hydraulic conductivities comprising the system. Three different averaging techniques exist:

- Arithmetic mean - applies to flow through a parallel configuration of components
- Harmonic mean - applies to flow through a series configuration of components
- Geometric mean - applies to flow through a randomly distributed configuration of components.

In practice, the effective hydraulic conductivity of randomly distributed components is estimated by using the geometric mean (of components). The geometric mean is preferred over arithmetic and harmonic means (parallel and series flow configurations, respectively), because it results in a better representation of randomly distributed components (Scheidegger, 1974).

In the baseline condition, hydraulic conductivity of solid inorganic and solid organic waste is assumed to vary with porosity and is estimated from a modified version of the Kozeny-Carman Equation (D'Appolonia, 1982). Components such as grout or glass are assumed incompressible under repository conditions (compressive strengths greater than lithostatic pressure) and thus have constant hydraulic conductivities.

It is important to note that fluid movement (hydraulic conductivity) in certain materials, such as glass, is due to diffusion or molecular transport as governed by Fick's Law rather than to Darcy's Law, which governs fluid flow through porous media. For the purposes of this report, vitrified waste forms and metal ingots are considered impermeable. Since fluid flow takes place through the path of least resistance (i.e., higher hydraulic conductivity), these waste forms are assigned a low hydraulic conductivity to limit their relative impact as components in the waste backfill composite. Lappin et al. (1989) reports the permeability of intact repository salt as  $10^{-22} \text{ m}^2$  (which is equivalent to a hydraulic conductivity of  $7.35 \times 10^{-16} \text{ m/s}$ ). Based on this and Butcher (1990a), a reference hydraulic conductivity of  $7.35 \times 10^{-16} \text{ m/s}$  has been assigned to "impermeable" waste forms for calculation purposes. Assigning a hydraulic conductivity one order of magnitude lower than the host rock minimizes the impact of these almost impermeable waste forms on the overall waste/backfill composite hydraulic conductivity and, in a conservative manner, puts more importance on the conductivity of the rest of the waste.

The components considered in the averaging process are the three primary waste forms and the backfill material within the waste stack. Backfill contained in the volume above the waste stack, and between the waste stack and the side walls in the rooms, is not considered because this region is a physical extension of the host rock.

The values of hydraulic conductivity for each component are estimated on the basis of available data in literature (Coons et al., 1987), personal communication (Butcher, 1990a), and representative equations (Case and Kelsall, 1987). Components with large void space which compact under compressive stresses will typically have hydraulic conductivities that vary with the degree of compaction. This variability can be estimated or computed from the porosity. For example, the hydraulic conductivity of crushed salt is assumed to be a function of porosity and is estimated as a function of compaction with a bilinear system of equations developed by Case and Kelsall (1987). Once the hydraulic conductivity of each component has been estimated, the effective hydraulic conductivity for the composite can be computed. The governing equation employing the geometric mean for averaging hydraulic conductivities is (Scheidegger, 1974):

$$\ln(K_{eff}) = \sum_{i=1}^n (F_i \ln(K_i)) \quad (3.6-9)$$

where,

$K_{eff}$  = effective waste/backfill composite hydraulic conductivity at stress level  $x$   
 $F_i$  = volume fraction of component  $i$  at stress level  $x$   
 $K_i$  = hydraulic conductivity of component  $i$  at stress level  $x$ .

The component volume fraction and the hydraulic conductivity may be functions of stress level or the state of compaction. The component volume fraction is computed as the component volume divided by the waste/backfill composite volume at a particular stress level:

$$F_i(x) = \frac{V_i(x)}{TV(x)} \quad (3.6-10)$$

where,

$F_i(x)$  = volume fraction of component  $i$  at stress level  $x$   
 $V_i(x)$  = volume of component  $i$  at stress level  $x$  (including the void space within the waste/backfill composite)  
 $TV(x)$  = volume of waste/backfill composite at stress level  $x$ .

The component and waste/backfill composite volumes are obtained from estimated values of component masses and densities:

$$V_i(x) = \frac{M_i}{D_i(x)} \quad (3.6-11)$$

$$TV(x) = \sum_{i=1}^n V_i(x) \quad (3.6-12)$$

where,

$M_i$  = mass of component "i"  
 $D_i(x)$  = density of component "i" at stress level x.

The procedure allows computation of an effective hydraulic conductivity for the average contents of a WIPP repository room at various stress levels. Table 3-8 contains the hydraulic conductivities for the 14 combination alternatives.

#### 3.6.4 Gas Generation Potential

Evaluation of design alternatives to the baseline waste disposal system requires estimation of the total potential for gas generation. Gas generation potential is the sum of three processes:

- Radiolytic gas generation
- Biological gas generation
- Corrosion gas generation.

Total potential is dependent on parameters such as brine inflow (for anoxic corrosion), radioactivity per unit volume of waste (for radiolysis), and mass of organic materials per unit volume of waste (for biological degradation). Lappin et al. (1989) report potentials of 894 moles of hydrogen/drum for anoxic corrosion of waste containers and metal waste, and 606 moles of total gas/drum for biological degradation and radiolysis. These constituent potentials are used to compute the total potential. These values are subject to validation by gas generation experiments in the WIPP Experimental Test Program (Molecke, 1990a; Molecke, 1990b).

The gas generation potential for the 14 combination alternatives analyzed by the Design Analysis Model are presented in Table 3-9. It should be noted that alternatives that involve either densification of waste (e.g., supercompaction) or removal of a waste component (e.g., incineration of solid organics), will result in volume reduction. This volume reduction helps to include more drum equivalents of unprocessed waste per room compared to the baseline design (presented earlier in Table 3-5). Since the volume reduction increases the mass of waste that can be stored in a room relative to the baseline, the total gas generation potential per room for some of the alternatives could be more than the baseline. Thus, a comparison of gas generation in terms of

**TABLE 3-8**  
**COMPOSITE HYDRAULIC CONDUCTIVITIES FOR**  
**COMBINATION ALTERNATIVES**  
 (m/s)\*

STRESS (MPa)*	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
0	4.12E-04	1.10E-09	7.30E-10	3.01E-12	3.15E-10	1.50E-12	7.47E-13	1.04E-14
1.4	1.55E-05	7.62E-11	6.55E-11	3.01E-12	2.70E-11	1.50E-12	9.41E-14	1.04E-14
2.8	3.61E-06	4.57E-11	4.28E-11	3.01E-12	1.74E-11	1.50E-12	5.84E-14	1.04E-14
4.1	1.42E-06	3.30E-11	3.26E-11	3.01E-12	1.32E-11	1.50E-12	4.26E-14	1.04E-14
5.5	6.63E-07	2.52E-11	2.61E-11	3.01E-12	1.05E-11	1.50E-12	3.27E-14	1.04E-14
6.9	3.77E-07	2.10E-11	2.25E-11	3.01E-12	9.09E-12	1.50E-12	2.73E-14	1.04E-14
8.3	2.25E-07	1.79E-11	1.98E-11	3.01E-12	7.96E-12	1.50E-12	2.32E-14	1.04E-14
9.7	1.23E-07	1.46E-11	1.67E-11	3.01E-12	6.71E-12	1.50E-12	1.88E-14	1.04E-14
11.0	4.52E-08	1.03E-11	1.24E-11	3.01E-12	4.96E-12	1.50E-12	1.28E-14	1.04E-14
12.4	1.83E-08	7.63E-12	9.55E-12	3.01E-12	3.82E-12	1.50E-12	9.17E-15	1.04E-14
13.8	6.10E-09	5.23E-12	6.89E-12	3.01E-12	2.75E-12	1.50E-12	6.00E-15	1.04E-14
15.2	2.75E-09	4.07E-12	5.57E-12	3.01E-12	2.22E-12	1.50E-12	4.54E-15	1.04E-14

STRESS (MPa)*	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14**
0	4.12E-04	7.46E-13	1.04E-14	1.80E-07	4.85E-05	7.72E-09	7.35E-16	2.45E-07
1.4	1.55E-05	4.58E-14	1.04E-14	5.48E-08	1.49E-06	7.72E-09	7.35E-16	3.44E-08
2.8	3.61E-06	2.79E-14	1.04E-14	8.91E-09	1.99E-07	7.72E-09	7.35E-16	2.94E-09
4.1	1.42E-06	2.04E-14	1.04E-14	3.44E-09	1.11E-07	7.72E-09	7.35E-16	2.92E-09
5.5	6.63E-07	1.58E-14	1.04E-14	1.83E-09	6.79E-08	7.72E-09	7.35E-16	2.90E-09
6.9	3.77E-07	1.33E-14	1.04E-14	1.14E-09	4.87E-08	7.72E-09	7.35E-16	2.89E-09
8.3	2.25E-07	1.15E-14	1.04E-14	7.81E-10	3.58E-08	7.72E-09	7.35E-16	2.89E-09
9.7	1.23E-07	9.51E-15	1.04E-14	5.67E-10	2.32E-08	7.72E-09	7.35E-16	2.88E-09
11.0	4.52E-08	6.94E-15	1.04E-14	4.28E-10	9.81E-09	7.72E-09	7.35E-16	2.87E-09
12.4	1.83E-08	5.30E-15	1.04E-14	3.31E-10	4.64E-09	7.72E-09	7.35E-16	2.87E-09
13.8	6.10E-09	3.77E-15	1.04E-14	2.58E-10	1.78E-09	7.72E-09	7.35E-16	2.86E-09
15.2	2.75E-09	3.02E-15	1.04E-14	2.03E-10	9.43E-10	7.72E-09	7.35E-16	2.86E-09

\*See Glossary for explanation of each abbreviation.

\*\*Hydraulic conductivity computed on a compartment basis (three 7-packs).

TABLE 3-9

**GAS GENERATION POTENTIAL FOR EACH COMBINATION ALTERNATIVE  
(moles/unprocessed drum equivalent)**

	BASELINE	ALT 1	ALT 2	ALT 3	ALT 4	ALT 5	ALT 6	ALT 7
Anoxic Corrosion	894	943	943	943	1093	1093	516	516
Microbial Degradation and Radiolysis	606	606	606	606	0	0	0	0
<b>Total</b>	<b>1500</b>	<b>1548</b>	<b>1548</b>	<b>1548</b>	<b>1093</b>	<b>1093</b>	<b>516</b>	<b>516</b>

	BASELINE	ALT 8	ALT 9	ALT 10	ALT 11	ALT 12	ALT 13	ALT 14
Anoxic Corrosion	894	0	0	53	1053	1053	0	1053
Microbial Degradation and Radiolysis	606	0	0	453	606	606	0	606
<b>Total</b>	<b>1500</b>	<b>0</b>	<b>0</b>	<b>506</b>	<b>1659</b>	<b>1659</b>	<b>0</b>	<b>1659</b>

the total potential is misleading, due to the unequal number of unprocessed drum equivalents for the alternatives and the baseline design.

In order to provide a reasonable comparison between the gas generation potentials for the baseline and the alternatives, the values presented in Table 3-9 are expressed in terms of moles per unprocessed drum. The values for Alternatives 1, 2, and 3 are higher than the baseline because it is assumed that 25 percent of the drums will be damaged, and therefore will also be shredded and cemented in addition to the waste itself. Since the drums are made of mild steel, the shredding and cementing of 25 percent of the drums would result in a net increase in the total metal inventory, thereby increasing the potential for gas generation by anoxic corrosion. Although the potential is higher compared to the baseline, it should be noted that shredding and cementing the waste will decrease the rate of gas generation and will also reduce the permeability of the waste/backfill composite. In alternatives 11, 12, and 14, the EATF has conservatively assumed a supercompaction process in which drums of solid organics and inorganics are supercompacted and overpacked in metal containers. The overpack represents an increase in the quantity of metal in the TRU waste inventory. Consequently, use of an overpack increases the gas generation potential (due to anoxic corrosion) per drum equivalent (see Table 3-9). It should be noted that the process proposed for supercompaction at RFP will employ an in-drum precompaction operation (Barthel, 1988) which results in a reduction of metal per drum equivalent. Thus, in actual practice, the inventory of container metal destined for the WIPP will actually be decreased.

Alternatives which eliminate both metals and solid organics from the inventory (e.g., Alternatives 8, 9, and 13), are not expected to generate any gas, and thus they can accommodate a very large number of unprocessed drum equivalents per room with no effect on the total potential. It should be noted that alternatives which result in densification of waste would also need a smaller number of rooms for waste disposal. Other assumptions used in estimating gas generation potentials are listed in Section 2.0 and Appendix B.

### 3.6.5 Effective Waste Volume

The effective waste volume is used to determine the radionuclide content in drill cuttings removed from the repository during human intrusion events (Appendix B, Section 2.22). The effective waste volume is the volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack. The term "drill cuttings" refers to the waste/backfill composite which would be brought to the surface with circulating drilling fluid during an inadvertent human intrusion event. The effective waste volume evaluation requires determination of the waste/backfill composite density as a function of stress, as per Equation (3.6-6). These calculations differ from each other only in that the waste/backfill composite density calculation neglects backfill on the sides of the waste stack. If penetration through the backfill on the sides of the waste stack occurs, the waste stack is assumed to remain intact and the cuttings are assumed not to contain any radionuclides. The backfill above the waste stack is considered because it would be mixed with extracted waste in the event the waste stack is breached by drilling activities.

### 3.7 SUMMARY

Input variables required by the Design Analysis Model include the physical and chemical properties of the repository contents following waste and backfill emplacement in the WIPP. The contents are assumed to be a homogeneous waste/backfill composite. This composite consists of four components:

- Sludges
- Solid organics (combustible)
- Solid inorganics (glass/metal)
- Backfill material.

The properties required by the Design Analysis Model for evaluation of the effectiveness of engineered alternatives include:

- Density
- Porosity
- Hydraulic conductivity
- Gas generation potential
- Effective waste volume.

Density of the waste-backfill composite is computed by assigning weights to the individual component densities as illustrated with Equation (3.5-6). The porosity of the composite is a function of the composite density. An estimate of the hydraulic conductivity of the waste/backfill composite is the geometric mean of the component hydraulic conductivities. Gas generation (radiolytic, microbial and corrosion) potentials are computed from the equivalent number of unprocessed drums emplaced in a room, taking into account the effect of waste treatment on components. With the exception of total gas generation potential, the physical properties vary with pressure resulting from creep closure. Properties for the three major waste forms and the backfill materials are obtained from available literature, applicable relationships or equations, and through personal communication with waste process facility personnel. Using the above evaluation process, physical properties of the waste/backfill composite in an average WIPP repository room are computed for use as input to the Design Analysis Model.

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## 4.0 RESULTS OF DESIGN ANALYSIS

Several analyses of room behavior during undisturbed conditions and human intrusion events have been performed using the Design Analysis Model. These analyses include:

### Undisturbed Performance (No Human Intrusion)

- A prediction of peak index gas pressures during undisturbed conditions, using baseline assumptions on gas generation rates and potentials (Section 4.1.1).
- An analysis of the effects of supercompaction of waste on room pressurization (Section 4.1.2).
- An analysis of the effects of venting excess gas pressure from the storage rooms during the first 100 years following repository decommissioning (Section 4.1.3).
- A sensitivity study to determine the effects of varying the microbial gas generation rate on room pressurization (Section 4.1.4).
- A sensitivity study to determine the effects of varying the undisturbed pore pressure and permeability of the anhydrite beds (Marker Bed 139, anhydrites "a" and "b") on room pressurization (Section 4.1.5).
- A sensitivity study to determine the effects of varying the initial brine inflow rates on room pressurization (Section 4.1.6).
- An estimate of the effects of 14 representative combinations of alternative waste forms on the peak storage room gas pressures (Section 4.1.7).

### Human Intrusion Scenarios

- A determination of the relative effectiveness of 14 representative combinations of alternative waste forms for reducing the consequences of human intrusion events (Section 4.2).

## 4.1 ANALYSIS OF DESIGN DURING UNDISTURBED PERFORMANCE

One-dimensional modeling of the performance of the disposal system under normal undisturbed conditions (no human intrusion) is described in Marietta et al. (1989) and Lappin et al. (1989), and two-dimensional modeling of undisturbed performance is described in Rechar et al. (1990). These analyses show that no releases to the accessible environment occur during a 10,000-year period of undisturbed performance.

The generation of large amounts of gas from microbial, chemical, or radiolytic processes may result in some or all of the following phenomena:

- Dissipation of excess gas pressure by advection out into the host rock via the anhydrite beds and clay seams
- Expansion of the storage rooms by reverse creep of the host rock
- Fracturing of the host rock by gas pressures that exceed lithostatic pressure
- Fracturing of the anhydrite beds and clay seams.

It is advantageous to avoid fracturing of the host rock because it may not be possible to accurately predict the direction and magnitude of the fractures which may become pathways for the migration of contaminated brine. The prediction of fracturing, and any subsequent fracture propagation, is being investigated by SNL (DOE, 1990d).

A preliminary analysis of the potential for expansion of the storage rooms by gas generation has been performed by SNL, using a simplified homogeneous isotropic model that predicts the response of the host rock to a room containing fluid pressure in excess of lithostatic pressure. Preliminary results from the model suggest that the room will indeed expand to accommodate any excess moles of gas that are generated by the waste (Lappin et al., 1989, Section 4.10.3). If this analysis proves to be correct, concerns regarding gas generation will be minimal, since the storage room will inflate to accommodate the volume of gas that is generated, as long as the rate of generation was less than the maximum rate of expansion that the host rock will allow. Planned analyses (DOE, 1990d) by SNL that refine the reinflation model to incorporate the actual stratigraphy (including anhydrite beds and clay seams) of the repository horizon may either confirm that the room will expand, or may conclude that fracturing will occur but will be restricted to the anhydrite beds, or that excess gas pressure will generate fractures with unpredictable lengths and directions in the host rock.

An additional concern regarding gas generation is that it may significantly contribute to pressurization of the storage rooms and prop open voids in the waste, thus preventing creep closure from compacting the waste. If this occurs, the permeability of the waste may not significantly decrease from the initial permeability at the time of emplacement.

Definition of a threshold pressure above which the performance of the disposal system is reduced is a complex problem involving the response of a heterogeneous nonisotropic multi-layered system to pressures in excess of the confining stress. This threshold pressure determination is under development by SNL (DOE, 1990d) and has not yet been established. For these reasons, the Design Analysis Model has been used to predict room pressurization as a function of time to evaluate the relative effectiveness of various alternative designs in reducing peak room pressure, should that prove to be necessary.

A common assumption underlying the following design analyses is that the room will not re-expand in response to pressures in excess of lithostatic. This assumption can easily be changed in future simulations when the current uncertainties regarding subsequent room pressurization are resolved.

#### 4.1.1 Prediction of Room Pressurization Using Baseline Assumptions

The Design Analysis Model was used to predict the pressurization of a typical storage room as a function of time for the baseline design, current waste forms and crushed salt backfill, as defined in Table 3-1. The goal of this analysis is to predict the timing and magnitude of peak index gas pressure that will occur. If it is determined that the peak index pressures predicted for the baseline design are in excess of those allowable, engineered alternatives can be selected to avoid potential problems associated with excess pressures. The allowable limits for peak index pressures will be determined from on-going modeling and experimental investigations at SNL (DOE, 1990d). When these limits are established, definitive conclusions regarding the acceptability of the baseline design and/or the need for engineered alternatives can be made.

Index pressure versus time curves for the baseline design are shown in Figure 4-1. The lower of the three curves shows the partial pressure of hydrogen generated by anoxic corrosion. The middle curve shows the sum of the partial pressures of  $\text{CO}_2$ ,  $\text{N}_2$ , and  $\text{CH}_4$ , which are the gases generated by both radiolytic and microbial degradation of organic materials (Brush, 1990). The upper curve shows the total pressure, which is the sum of the partial pressures of all gas components.

The partial pressure of hydrogen reaches a peak that coincides with the total pressure reaching lithostatic pressure (Figure 4-1). When lithostatic pressure is reached, brine inflow stops so there is no longer any brine available for anoxic corrosion to proceed. Hydrogen generation is thus self-limiting as a result of the assumed coupling between brine inflow, room pressure, and anoxic corrosion. That is, brine inflow and creep occur at a rate that is proportional to the difference between lithostatic and room pressures. Brine is required, and is also consumed, by anoxic corrosion. Based on these assumptions, when lithostatic pressure is reached, brine inflow and, hence, anoxic corrosion rates approach zero. Although a maximum hydrogen generation limit of 1.7 moles/drum/year is used (Lappin et al., 1989), the corrosion rate is always less than this bounding rate because of limited brine availability. When lithostatic pressure is reached, only about 54 percent of the metals in the inventory is expected to have corroded.

Microbial generation, on the other hand, is assumed to proceed at a constant rate that is independent of brine availability (Lappin et al., 1989). Aerobic conditions are assumed to persist for 100 years after closure, during which oxygen is converted to carbon dioxide via microbial activity with no significant change in pressure. Anaerobic degradation of organic materials occurs from 100 to approximately 815 years after closure at a constant rate of 0.85 moles/drum/year, generating a total of 606 moles/drum (Lappin et al., 1989) of gases composed of  $\text{CO}_2$ ,  $\text{N}_2$ , and  $\text{CH}_4$  at a molar ratio of 20:12:15. At approximately 815 years

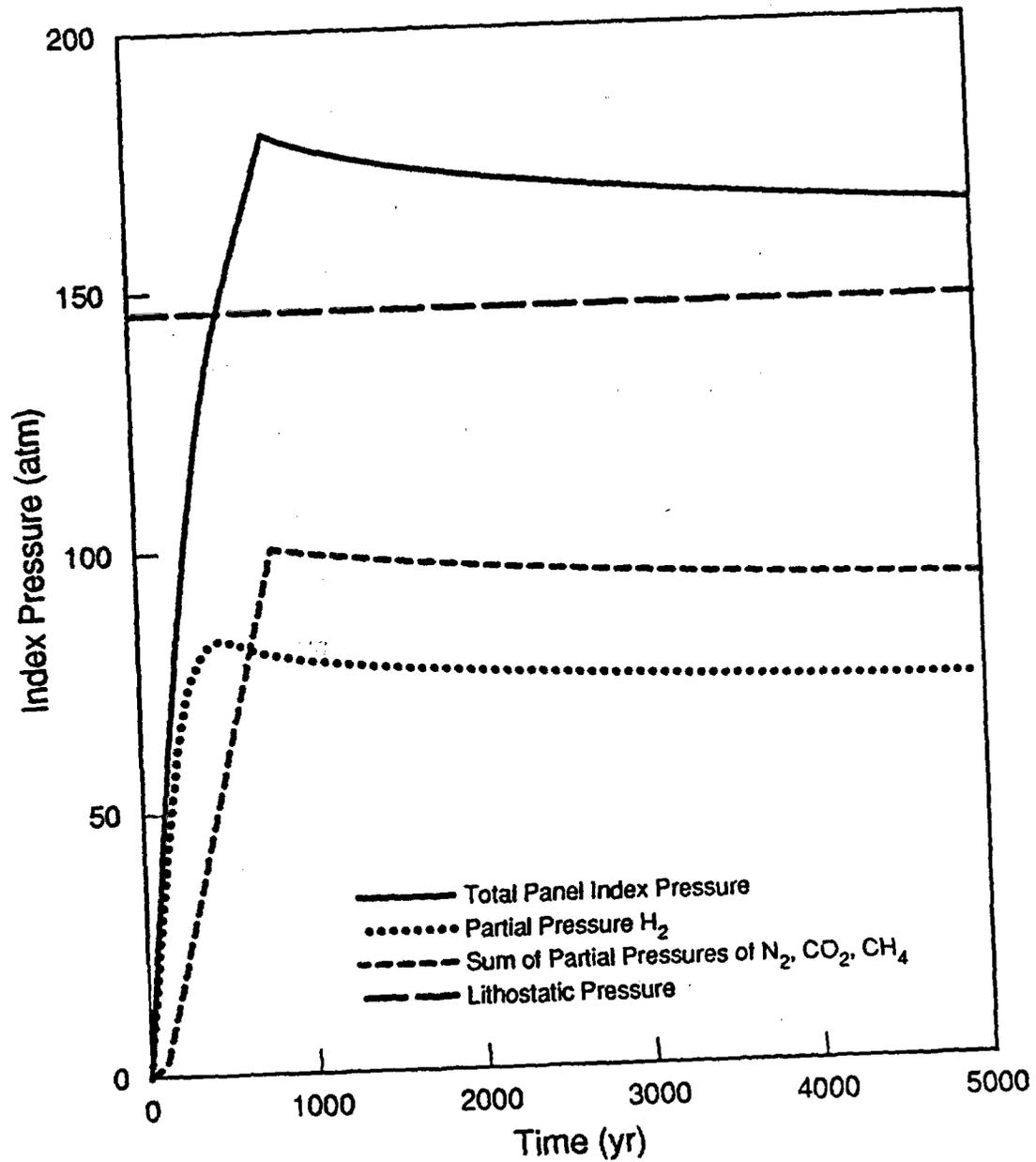


Figure 4-1  
Index Pressure Versus Time Curves for the Baseline Case

after closure, the substrate is depleted and microbial gas generation is assumed to stop. These assumptions are reflected in the partial pressure curve for microbial gases in Figure 4-1, which show a small rise during the first 100 years caused by the conversion of oxygen to carbon dioxide, followed by a linear increase in the partial pressures of these gases from 100 years to approximately 815 years.

The upper curve showing total pressure is the sum of the two lower curves. It shows an initial steep slope during the first 300 years, during which brine inflow occurs and hydrogen generation from anoxic corrosion is the dominant gas generation process. When lithostatic pressure (146 atmospheres) is reached at approximately 500 years, brine inflow and anoxic corrosion rates approach zero, which causes a slight decrease in the slope of the total pressure curve. This lower pressurization rate from continued microbial activity prevails until approximately 815 years when organic materials are consumed, and all gas generation ceases. At this point, a peak index pressure of 180 atmospheres (atm) is reached, followed by a gradual decline in pressure caused by continued advection of fluid (gas and brine) into the intact anhydrite beds and diffusion of gases into the intact host rock.

At this point in the discussion, it should be noted that although the Design Analysis Model calculates absolute pressures, these results are very sensitive to assumptions regarding gas generation rates and durations, brine inflow rates, creep closure rates, initial void volume, re-inflation of the rooms, and the degree of coupling between these processes. Thus, the absolute pressures presented here should be viewed as an index by which alternatives can be compared and ranked for effectiveness, rather than a prediction of the actual pressures that will exist in the storage rooms. As experimental programs continue to provide data, and the understanding of these processes increase, some of these assumptions will undoubtedly change, yielding different quantitative results. However, the objective of the EATF design analysis activity is to predict relative changes in performance offered by alternative designs. These relative changes in performance are less subject to modification by increased understanding than are the absolute pressures presented here. For this reason, the term peak index pressure is used to indicate that the absolute values are subject to change, but the relative rankings may not be.

#### 4.1.2 Effects of Supercompaction on Room Pressurization

An analysis was performed to evaluate the effects of supercompaction of waste on room pressurization. For this analysis, two waste emplacement configurations were considered; a single layer of 2,000 drums of supercompacted waste containing the equivalent contents of 4,284 drums of unprocessed waste, and a triple layer of 6,000 drums of supercompacted waste containing the equivalent contents of 12,856 drums of unprocessed waste. Figure 4-2 shows the results in terms of index pressures versus time curves for the monolayer and triple layers of supercompacted waste, along with a similar curve for the baseline configuration of 6,000 drums of uncompacted waste for comparison. These curves show that a room filled with a monolayer of supercompacted waste reaches a peak index pressure that is roughly 24 percent higher than the baseline case, and a triple layer of supercompacted waste reaches a peak index pressure that is greater than twice the baseline case.

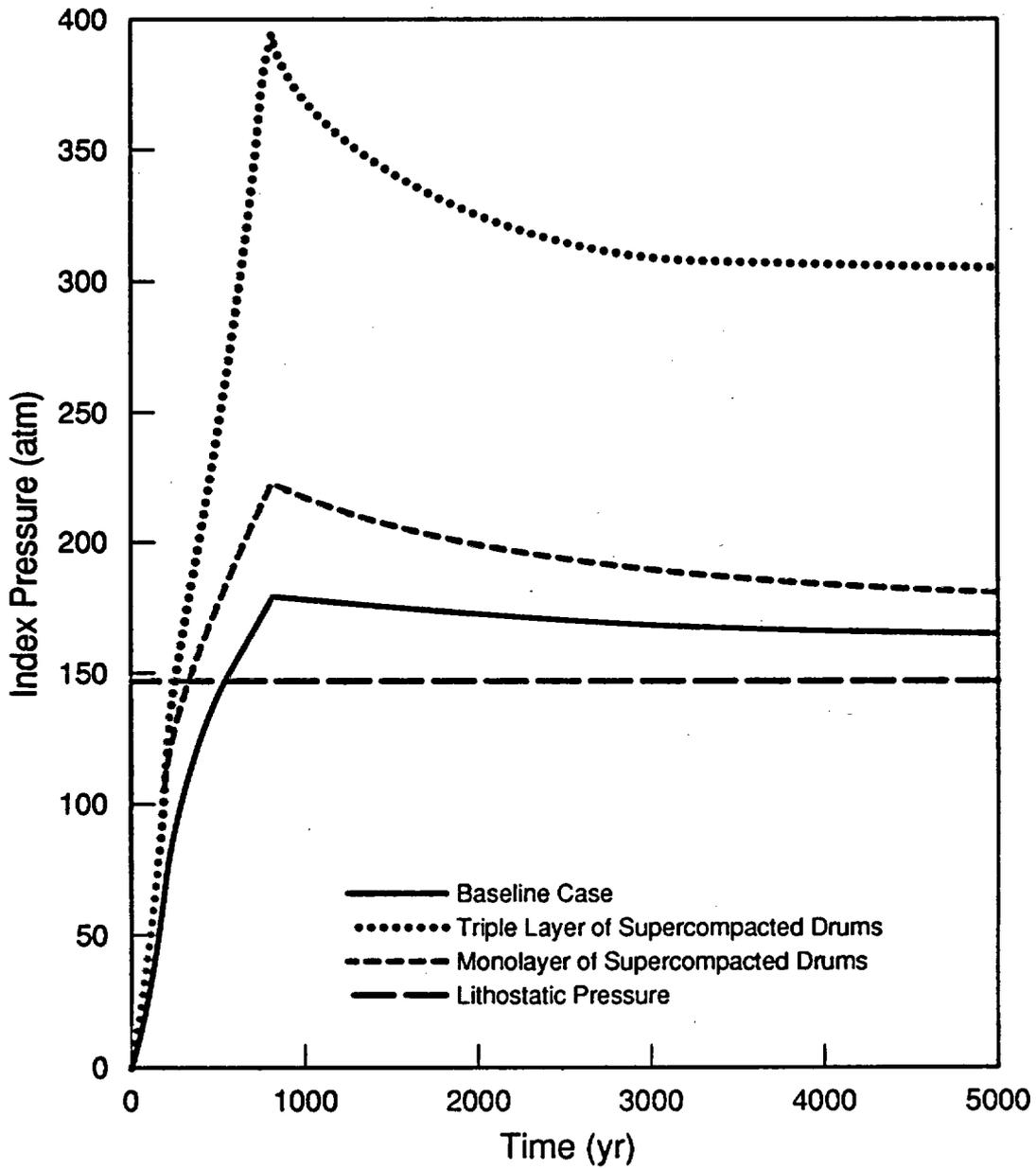


Figure 4-2  
Index Pressure Versus Time Curves for Supercompacted and Baseline Waste Forms

The main reason for the higher predicted peak index pressures for supercompacted waste is the decrease in initial void volume. Moles of gas that are generated occupy a smaller void volume, resulting in rapid pressurization. Although this rapid pressurization minimizes brine inflow, thus decreasing in the total moles of hydrogen generated by anoxic corrosion, these fewer moles of hydrogen occupy a smaller void volume. Even though fewer moles of hydrogen are generated, the partial pressure of hydrogen still remains high. In addition, microbial gas generation continues, which is assumed to be independent of brine availability, and is also pressurizing a smaller volume.

An additional factor is present in the case of the triple layer. In this case, there is a greater than two-fold increase in the mass of organic materials on a per-room basis, resulting in an equivalent increase in the microbial gas generation rate and gas generation potential per room.

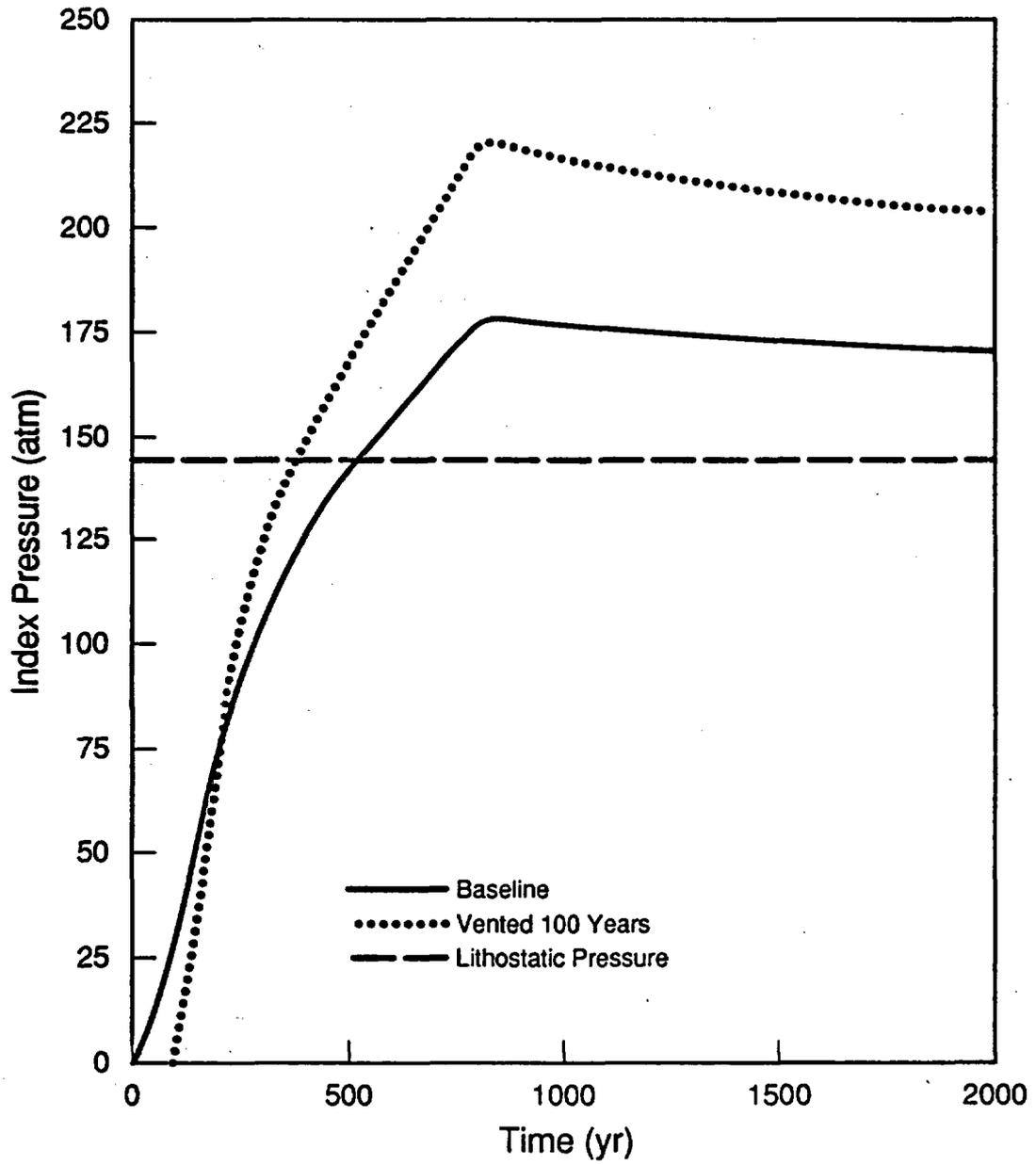
These results suggest that supercompaction is not effective in reducing peak index pressures. Changing the stack configuration from a triple layer to a monolayer can lower the peak pressure by reducing the mass of organics per room, but the decrease in initial void volume caused by supercompaction still yields higher predicted pressures than the baseline case.

Supercompaction can, however, be effective in lowering the permeability of the waste, which can decrease the consequences of human intrusion scenarios as discussed in Section 4.2.

#### 4.1.3 Effects of Venting the Repository for 100 Years

An analysis was performed to evaluate the effects of venting excess gas pressures from the repository during the first 100 years following decommissioning. A period of 100 years was chosen because it was assumed that some type of active controls would be required to maintain an open vent from the repository to the surface, and 40 CFR Part 191 (EPA, 1985) requires that active institutional controls cannot be assumed for longer than this period of time.

To evaluate the effectiveness of venting the repository, a simulation was performed that maintained a room pressure of one atmosphere during the first 100 years after decommissioning the repository. After 100 years, the storage rooms were allowed to pressurize in accordance with the baseline assumptions regarding gas generation, creep closure, brine inflow, etc. The results of this simulation is shown in Figure 4-3, along with the results of the baseline design. These results show that the peak index pressures that occur at approximately 815 years are 23 percent higher in the vented case than the baseline case. In the vented case, fluid pressure in the room does not build up during the first 100 years, providing no resistance to closure during this period. This results in lower storage room porosity at 100 years. In addition, this permits higher creep closure rates and, thus, results in a smaller void volume compared to an unvented repository. When the vent is closed at 100 years, microbial gas generation continues for approximately 715 years and is pressurizing a smaller void volume, resulting in higher pressures. From this analysis, it can be concluded that venting will be ineffective in reducing peak index gas pressures unless the vent remains open for the entire gas generating period.



**Figure 4-3**  
**Index Pressure Versus Time Curves Evaluating the Effectiveness of Venting the WIPP Repository**

Venting the repository could also potentially increase the cumulative inflow of brine to the storage rooms during the venting period. This increased inflow would result from maintaining a high pressure gradient toward the excavation during the venting period.

Venting may raise additional concerns with respect to compliance with the no-migration requirement (EPA, 1990e) of the Resource Conservation and Recovery Act (RCRA). Compliance with RCRA requires that there be no migration of specific volatile organic compounds past the Rustler/Salado contact in concentrations that are in excess of applicable health-based standards.

#### 4.1.4 Effects of Varying Microbial Gas Generation Rates on Room Pressurization

Two significant factors that affect the pressurization of the storage rooms are the total number of moles of gas that are generated and the rates at which they are generated. The baseline assumptions regarding microbial gas generation are that microbial degradation of the organic component of the waste will yield a total of 606 moles/drum, and will be generated at a rate of 0.85 moles/drum/year for a period of approximately 715 years following the establishment of anaerobic conditions (Lappin et al., 1989). There are, however, large uncertainties in these assumptions that will be resolved by the bin-scale experimental program (Molecke, 1990a) and the laboratory experimental program (Brush, 1990). These two experimental programs are designed to provide the project with realistic estimates of the total gas generation rates and potentials anticipated from the disposal of TRU waste in the WIPP environment. Since these data are currently unavailable, a sensitivity study was performed using the Design Analysis Model to evaluate the effects of varying these assumptions on the pressurization of the storage room environment. Four cases were evaluated:

- The baseline rate of 0.85 moles/drum/year and baseline duration of approximately 715 years
- One-half of the baseline rate and twice the baseline duration
- One-quarter of the baseline rate and four times the baseline duration
- Twice the baseline rate and one-half the baseline duration.

In all of the cases, the total baseline potential of 606 moles/drum from microbial gas generation was maintained.

Index pressure versus time curves for these four cases are shown in Figure 4-4, and include the contribution to gas generation from anoxic corrosion. These results show that both the peak index pressure and the timing of the peak are very sensitive to variations in the assumed microbial gas generation rate and duration, even though the total number of moles generated was held constant. In general, lower rates (with proportionally longer durations) result in higher and later peak index pressures. As an example, when the generation rate is reduced by a factor of four, the peak index pressure increases from 180 to 204 atmospheres and is delayed from 800 to 3,000 years (Figure 4-4). This is caused by the coupled nature of creep closure

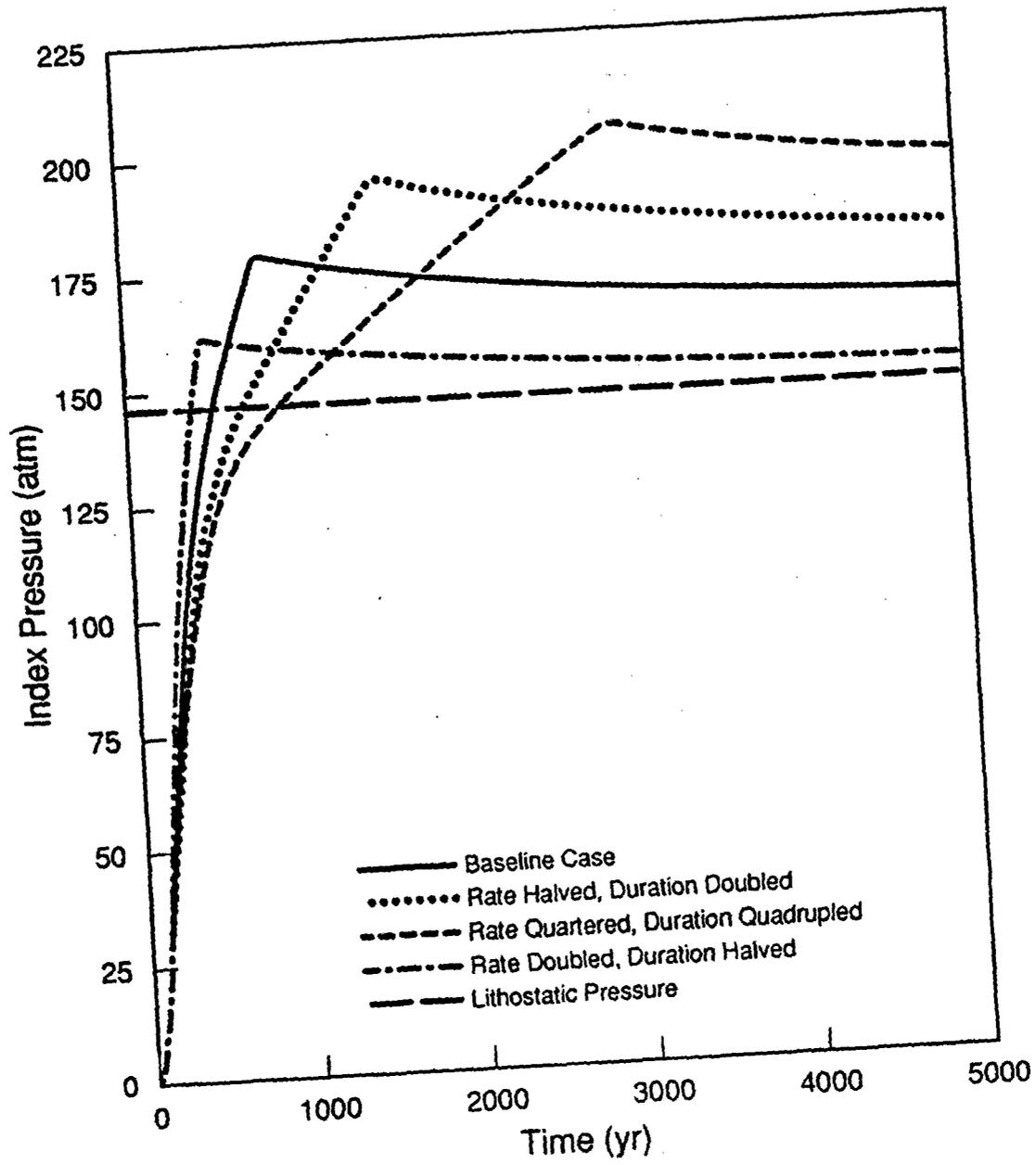


Figure 4-4  
Index Pressure Versus Time Curves Varying Rates and Duration of Microbial Gas Generation

and gas generation. When the generation rate is assumed to be low, creep closure proceeds faster and results in rapid establishment of low room porosity. Continued gas generation then pressurizes a smaller volume, yielding higher pressures.

The lowest peak index pressures were achieved in the case where the rate was doubled. In this case, the room rapidly pressurized with gas, which props open voids and reduces the amount of creep closure required to bring the room to lithostatic pressure. This also allows the room to retain a larger percentage of the initial void volume, providing a larger volume for gas to occupy. This suggests that peak index pressures can be reduced if the majority of the gas is generated during the period immediately following decommissioning, when the gas pressure in the room is still below lithostatic pressure.

These results indicate that the void volume available for any generated gas is directly proportional to the rate of gas generation. However, since the peak index pressures are inversely proportional to the available void volume, they are also inversely dependent on the rate of gas generation. Thus, an increase in the gas generation rate is expected to result in a lower peak index pressure. Lowering gas generation rates may not be effective in reducing peak index pressures unless the gas generation potential (total number of moles generated) is also reduced. These results highlight the need for more accurate gas generation rates than are currently available, so that the acceptability of the current unprocessed waste forms can be determined.

#### 4.1.5 Effects of Varying Anhydrite Bed Hydraulic Properties on Room Pressurization

A sensitivity analysis was performed on two hydraulic properties of anhydrite beds to evaluate their effects on room pressurization. The two major properties evaluated were the permeability and the far-field pore pressure of the intact anhydrite beds. A set of runs using the Design Analysis Model were completed, varying permeability over three orders of magnitude ( $10^{-17}$  to  $10^{-20}$ ). Figure 4-5 shows the results of these sensitivity runs in terms of index room pressure versus time curves for the assumed permeabilities of the anhydrite beds. This figure shows that only for the most extreme case (a permeability of  $10^{-17}$ ) does the peak index room pressure change significantly. It should be noted, however, that even though there is a reduction of the peak index pressure, it remains well above the lithostatic pressure of 146 atm. This reduction is attributed to the increased flow of brine from the disturbed to the intact anhydrite beds, providing a larger gas expansion volume, rather than a significant increase of advection of gases into the intact anhydrites (see Appendices B and D). In other words, the higher permeability allows the pressure to build up in the room, and drives a greater amount of the brine from the disturbed zone into the intact anhydrite beds, increasing the available void volume for pressurization.

The second set of sensitivity runs performed considered the effects of varying the far-field pore pressure of the intact anhydrite beds. For this analysis, the far-field pore pressure was varied from 60% to 90% of lithostatic pressure in 10% increments. Figure 4-6 shows the results of these sensitivity runs in the same format as the permeability sensitivity. This figure shows that while the rate of pressure decay changes with the assumed far-field pore pressure,

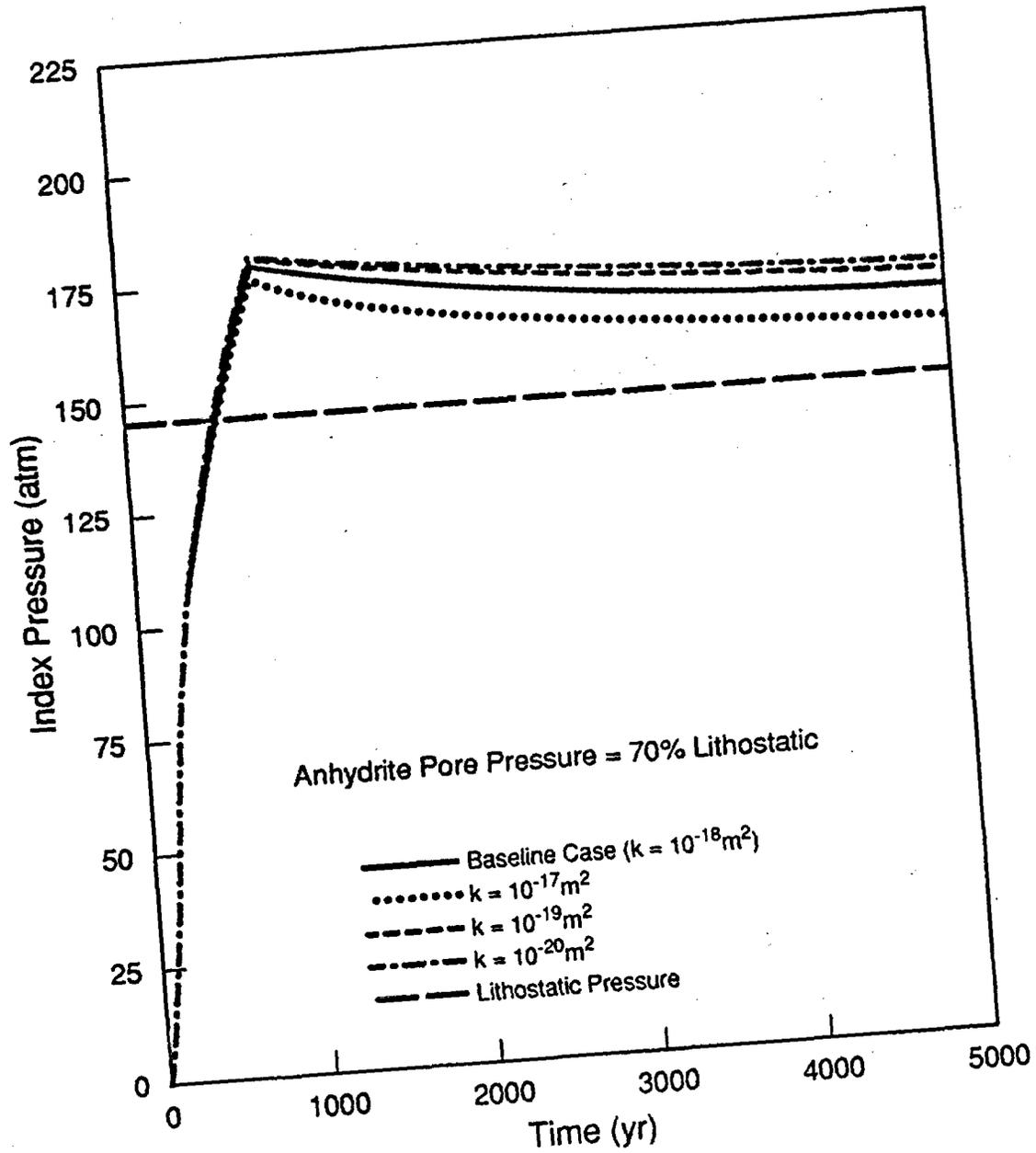


Figure 4-5  
Index Pressure Versus Time Curves Varying Permeability of the Anhydrite Beds

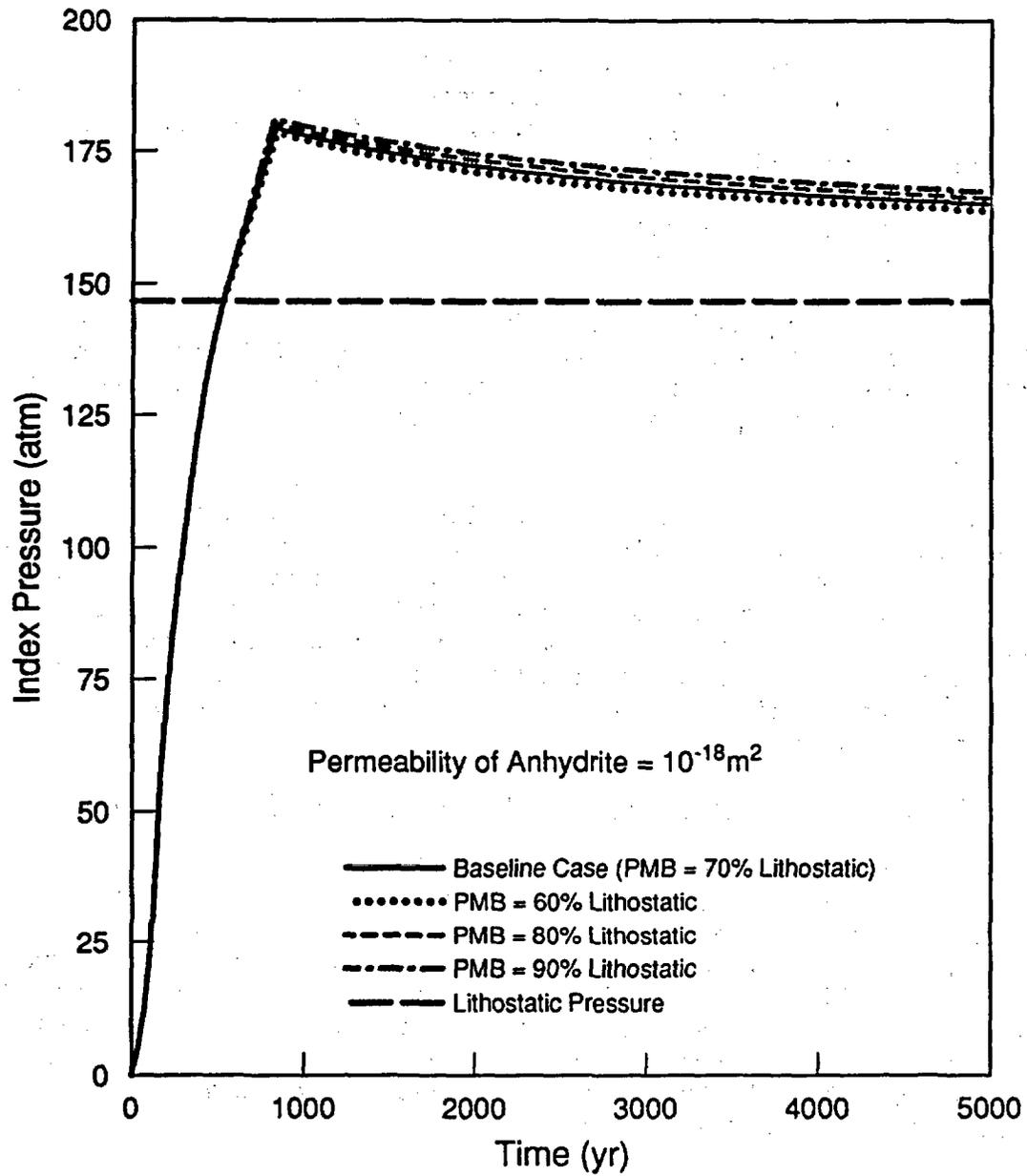


Figure 4-6  
Index Pressure Versus Time Curves Varying Far-Field Pore Pressure (PMB) in the Anhydrite Beds

the overall peak index pressures are not significantly affected by varying this parameter over this range.

The results of the sensitivity analyses indicate that the gas advection rates are relatively small compared to the gas generation rates, even under conditions reflecting increased permeability and decreased far-field pore pressure. It should be noted that the following processes impact the gas advection rates but are not incorporated into this model.

- Localized depressurization
- Gas exsolution from brines.

It is apparent from the plots that the advection rate into the anhydrite beds increases linearly with the decrease in far-field pore pressure and log-linearly with the increase in permeability. But for the case of varying the far-field pore pressures, this change is only apparent once gas generation ceases at approximately 815 years and the room slowly begins to return to lithostatic pressure.

These results suggest that while the anhydrite beds are a conduit for gases to advect out of the repository, the low rate of advection (relative to gas generation) may not be effective in reducing peak index pressure to values below lithostatic. However, engineered alternatives that lower gas generation rates to values similar to the rate at which gas can advect away from the storage rooms may be effective in reducing peak index pressures. It should be noted that the results of the model are limited by the assumptions inherent in the model. Therefore, caution should be exercised in interpreting the results until a better understanding is obtained for the gas advection pathways.

#### 4.1.6 Effects of Varying the Initial Brine Inflow Rate on Peak Index Pressure

Small volumes of brine have been observed seeping into brine monitoring holes at several locations in the underground excavations (Deal and Case, 1987). Most of the brine that is currently seeping into the excavations evaporates and is removed by the ventilation system; however, there is concern that some volume of brine may accumulate in the storage rooms during the period between decommissioning and repressurization. The baseline initial brine inflow rate of 0.43 cubic meters/room/year was chosen because it is the largest published value for that parameter (Nowak, et al., 1988). However, there is considerable uncertainty in that value. Published estimates of brine inflow rates vary over a considerable range due to uncertainties in the following processes or parameters:

- Far-field permeability
- The validity of a Darcy model for flow in low-permeability salt. The EATF recognizes that the phenomenon of brine inflow may be attributed to several different mechanisms. However, for the sake of consistency, the brine inflow rate based on the SNL modeling approach has been used.
- The contribution from near-field dewatering versus far-field flow

- The contribution from preferential flow along anhydrite and clay seams
- The role of the disturbed zone surrounding the excavation in controlling brine inflow
- The role of the exsolution of dissolved gases in driving brine inflow.

Due to the uncertainty in brine inflow rates, a sensitivity study was performed to evaluate the effects of varying this parameter on room pressurization.

The results of this analysis are shown in Figure 4-7. Five initial inflow rates were chosen: the baseline rate, one-half of the baseline rate, one-quarter of the baseline rate, twice the baseline rate, and four times the baseline rate. These results indicate that the peak index pressure reached assuming the baseline rate, one-half of the rate, and one-quarter of the rate, are all similar. Only when the baseline rate is doubled or quadrupled does the peak index pressure increase significantly. This phenomena is due to the assumed coupling between brine inflow and anoxic corrosion, as discussed in Section 4.1.1. A maximum hydrogen generation rate limit of 1.7 moles/drum/year (Lappin et al., 1989) is assumed; however, this limit is not reached if the baseline or lower initial brine inflow rates are assumed. Under these conditions, hydrogen generation is limited by brine availability so that brine inflow and hydrogen generation stop when lithostatic pressure is reached. When the initial brine inflow rate is raised above the baseline value, hydrogen generation becomes limited by the 1.7 moles/drum/year maximum rate. Under these conditions, both brine and steel are present in the storage rooms when lithostatic pressure is reached so that hydrogen generation continues after brine inflow stops, yielding higher peak index pressures. These results suggest that peak index room pressures are only sensitive to the initial brine inflow rate if that rate is above some critical value that is somewhere between the assumed rate of 0.43 cubic meters/room/year and twice that value. It is doubtful that the actual value is above 0.43 cubic meters/room/year, because revised inflow rates published after the Nowak, et al. (1988) value are considerably lower. For instance, the SEIS analyses were based on a brine inflow rate of 0.1 cubic meters/room/year (Lappin et al., 1989, page 4-14).

#### 4.1.7 Estimate of the Effects of Alternatives on Peak Index Pressure

The baseline case and 14 combinations of alternatives, shown earlier in Table 1-2, were analyzed using the Design Analysis Model to estimate the peak index gas pressures that will exist in the storage rooms. The goal of these analyses is to provide a relative ranking of the effectiveness of alternatives in reducing peak index pressures, should that be necessary.

These 14 combinations of alternatives include the primary waste forms recommended by the EATF for incorporation into the WIPP Experimental Test Program (DOE, 1990b). Alternatives 1, 2, and 3 involve shredding and cementing of solid organics and metals, which reduce gas generation rates but do not reduce the total gas generation potential. Alternatives 4, 5, 6, 7, 8, 9, and 13 involve thermal treatment (incineration or vitrification) of solid organics to eliminate the source of microbial gas generation. Alternatives 8, 9, and 13 do not have solid

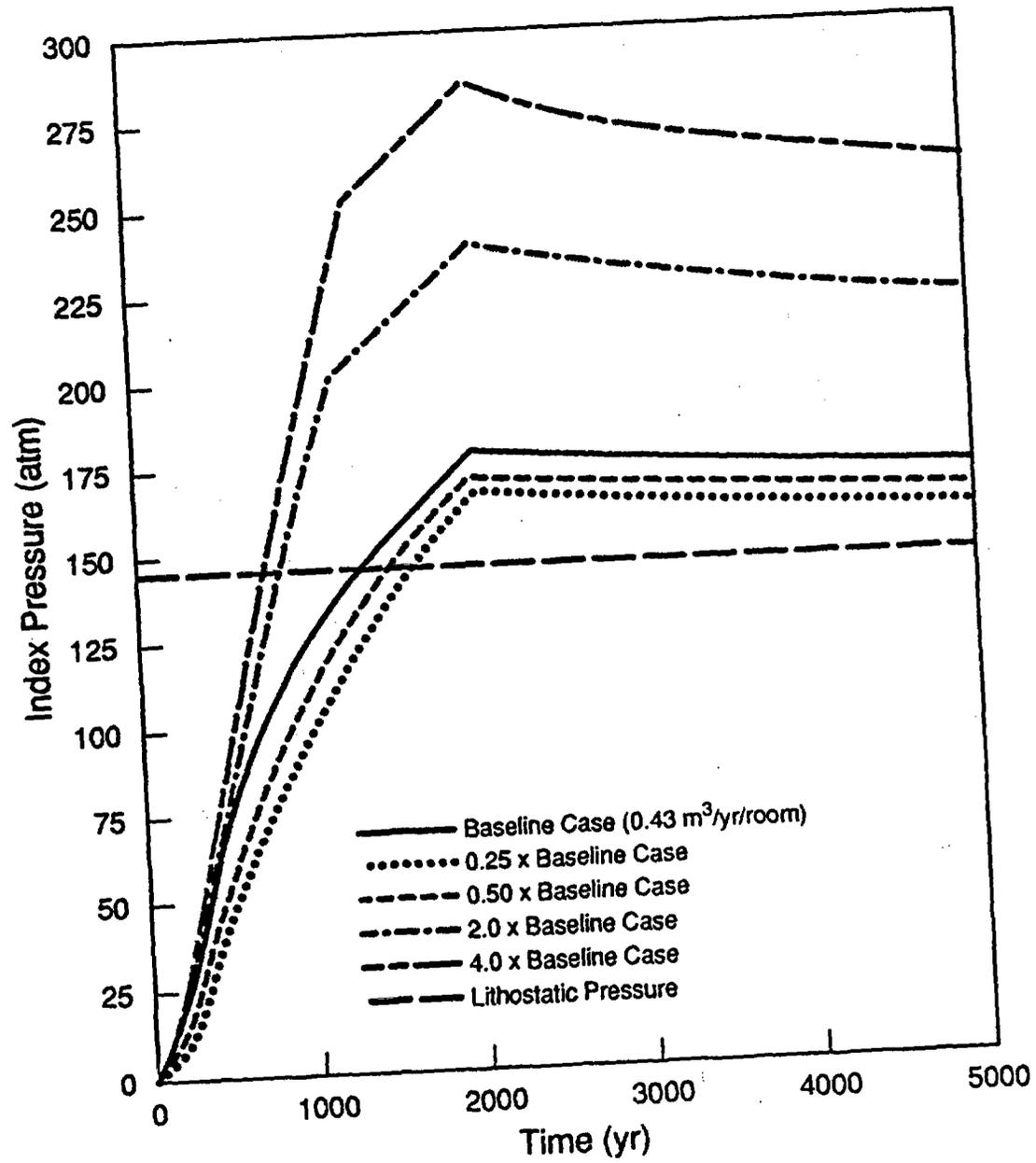


Figure 4-7  
Index Pressure Versus Time Curves Varying the Initial Brine Inflow Rate

organics or metals present in the inventory, and thereby eliminate both the microbial and the anoxic corrosion sources of gas generation. Alternative 10 eliminates the metals from the inventory and, hence, the source of gas generation by anoxic corrosion. Alternatives 11, 12, and 14 involve supercompaction of the solid organics and inorganics but do not reduce the total gas generation potential.

Predicted peak index room pressures for the baseline design and 14 alternative combinations of waste forms are shown in Table 4-1. The two principal factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available in the room for pressurization. Also shown in Table 4-1 is a tabulation of peak index pressures expressed as a percentage of lithostatic pressure, excess gas energy, and additional volume required. Excess gas energy is defined here as the excess peak index pressure (peak index pressure minus lithostatic pressure) multiplied by the void volume that the excess pressure occupies. Additional volume is defined as the additional void volume required to reduce the peak index pressure to lithostatic pressure.

The alternatives that involve thermal treatment of solid organics (Alternatives 4 through 9, and 13) show peak index pressures of 146 atm, which corresponds to lithostatic pressure.

For these alternatives, thermal treatment has completely eliminated microbial gas generation so that the main gas generation process is the production of hydrogen from the anoxic corrosion of ferrous metals and aluminum (metallic waste and steel drums and boxes) in the room. The assumed coupling between anoxic corrosion and brine inflow provides a self-limiting mechanism for hydrogen generation, where the generation rate and brine inflow approach zero as the fluid pressure in the room approaches lithostatic (as discussed in Section 4.1.1). Although anoxic corrosion contributes to room pressurization, the process halts when lithostatic pressure is reached.

The coupling of brine inflow and anoxic corrosion assumes that brine is required to be present for corrosion to proceed, and that the brine available for corrosion is finite in volume and is consumed in the process of generating hydrogen. If an additional source of water is present, such as diffusion of water vapor through a disturbed zone surrounding a room, and if corrosion can proceed in the presence of water vapor, then it is possible that hydrogen generation may still occur after lithostatic pressure is reached. The hydrogen generation rate under these conditions will be considerably lower than the rate in a brine-saturated environment, and will be limited either by the diffusion rate of water vapor through the disturbed zone or the corrosion rate of metals in a humid environment.

The assumed coupling between brine inflow and anoxic corrosion is a reasonable assumption at this time, however, it does require experimental verification. Experiments have been initiated by SNL to quantify corrosion rates of steel drum alloys in both brine-saturated and humid environments (Brush, 1990), and a prediction of the extent and degree of interconnected porosity existing in a disturbed zone surrounding a panel is also planned by SNL (DOE, 1990d). The analyses presented in this report can be updated to reflect any revised assumptions that may result from these on-going experimental and modeling activities.

TABLE 4-1

**MAXIMUM GAS PRESSURE AND RELATIVE INDEX PRESSURE RESULTS**

<b>DESIGN</b>	<b><math>P_{max}</math> (atm)</b>	<b>PERCENTAGE OF LITHOSTATIC PRESSURE</b>	<b>EXCESS GAS ENERGY (KJ)</b>	<b>ADDITIONAL VOLUME REQUIRED (M<sup>3</sup>/PANEL)</b>
BASELINE	180	123	$3.76 \times 10^7$	2407
ALTERNATIVE 1	222	152	$6.24 \times 10^7$	3899
ALTERNATIVE 2	215	147	$5.97 \times 10^7$	3760
ALTERNATIVE 3	175	120	$3.65 \times 10^7$	2362
ALTERNATIVE 4	146	100	0	0
ALTERNATIVE 5	146	100	0	0
ALTERNATIVE 6	146	100	0	0
ALTERNATIVE 7	146	100	0	0
ALTERNATIVE 8	146	100	0	0
ALTERNATIVE 9	146	100	0	0
ALTERNATIVE 10	215	147	$4.39 \times 10^7$	2779
ALTERNATIVE 11	224	153	$4.31 \times 10^7$	2682
ALTERNATIVE 12	195	134	$3.53 \times 10^7$	2233
ALTERNATIVE 13	146	100	0	0
ALTERNATIVE 14	312	214	$5.40 \times 10^7$	2939

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\* $P_{max}$  = Peak Index Pressure.

Peak index pressures in excess of lithostatic are predicted for the baseline design and Alternatives 1, 2, 3, 10, 11, 12, and 14, all of which use shredded and cemented or supercompacted waste forms. These peaks range from 20 percent above lithostatic for Alternative 3, to 114 percent above lithostatic for Alternative 14. The model predicts that lithostatic pressures are reached within a few hundred years after decommissioning when hydrogen generation stops, but microbial gas generation is assumed to proceed at a linear rate for approximately 815 years. Although advection and diffusion of excess gas pressure away from the storage room is accounted for in the model, the assumed microbial gas generation rate of 0.85 moles/drum/year (Lappin et al., 1989) is much greater than the rate at which excess gas pressure can dissipate, resulting in a period following a few hundred years after decommissioning during which lithostatic pressures are temporarily exceeded.

Variations in the peak index pressures predicted for these first three alternatives shown in Table 4-1 are due to differences in void volumes and differences in the mass of organic materials per room. Alternatives 2 and 3 differ by the use of crushed salt versus grout backfill. Salt backfill initially possesses a higher void volume than grout backfill; however, salt will consolidate under a load to extremely low porosities, whereas a rigid grout will maintain a fixed porosity for a long period. Alternative 3 (grout backfill) reaches a lower peak index pressure than Alternative 2 (salt backfill) because the porosity in the grout contributes to the volume available for pressurization, whereas the initially high porosity in the crushed salt backfill rapidly decreases to low values in response to creep closure, providing a smaller total volume available for pressurization.

An additional factor affecting peak index pressures is the mass of organics per room. For the baseline design, a room is assumed to hold 6,000 55-gallon drums. Shredding and cementation of waste results in a volume reduction of 13 percent, so that a storage room filled with 6,000 drums of shredded and cemented waste will contain the equivalent of approximately 6,800 drums of unprocessed waste (see Section 3.5). The gas generation rates and potentials for Alternatives 1, 2, and 3 are thus assumed to be 13 percent higher than the baseline waste forms because of the greater number of equivalent drums of unprocessed waste.

Fractures may develop at some critical pressure above lithostatic, but if the volume of pressurized gas is small, then the fractures will not propagate very far before the driving force returns to zero at lithostatic pressure. However, if the volume of pressurized gas is large, then fractures may propagate greater distances before the driving force is dissipated. Thus, peak index pressure is a relative measure of the tendency to initiate fractures, and excess gas energy, being a product of excess pressure and volume, is a relative measure of the tendency to propagate fractures once they are initiated.

The excess gas energies, and additional volumes required for Alternatives 4 through 9, and 13, are zero since there is no excess pressure (i.e., peak index room pressures are not greater than lithostatic). For the baseline, and Alternatives 1, 2, 3, 10, 11, 12, and 14, the excess gas energies do not vary by more than a factor of two, and rank in the same relative order as peak index pressures.

The values for the Additional Volume Required, shown in Table 4-1, provide a means to evaluate the uncertainty in the predicted peak index pressures. According to the Ideal Gas Law, in a closed system at constant pressure containing a fixed number of moles of gas, the product of pressure (P) and volume (V) is equal to a constant. If V is small and P is large, a small uncertainty in V corresponds to a large uncertainty in P. As an example, if the additional volume required to return the peak pressures to lithostatic is very small relative to the total void volume of the panel at the time that the peak pressure is reached, the predicted peak pressures may well be an artifact of the uncertainties in the total panel void volume. However, if the additional volume required is a significant percentage of the total panel void volume, there is greater confidence in the predicted peak pressures. The values for the additional volume required, shown in Table 4-1, range from 19 percent (for Alternative 3) to 92 percent (for Alternative 14) and average 47 percent of the total void volume in the panel at the time of peak pressurization. This significant amount of additional void volume required to return the peak pressures to lithostatic suggests that the predicted peak pressures are not artifacts of uncertainties in the predicted void volumes.

These analyses of the effects of alternative waste forms on peak index room pressures suggest the following:

- The most important factors that affect peak index pressures are the mass of organic materials present in the room and the void volume available for pressurization.
- The baseline waste forms will generate peak index gas pressures that are in excess of lithostatic.
- Alternatives 1, 2, 3, 10, 11, 12, and 14 also generate pressures in excess of lithostatic due to the presence of organic materials. Thus, these alternatives appear to be ineffective in reducing peak index pressures, but they may have application in reducing the consequences of human intrusion events.
- Alternatives that involve thermal treatment of organic materials (Alternatives 4 through 7) do not exceed lithostatic pressure even though metals are present. This is caused by the assumed coupling between anoxic corrosion and brine inflow.
- Alternatives 8, 9, and 13 do not exceed lithostatic pressures because organics and metals have been removed.

#### 4.2 ANALYSIS OF HUMAN INTRUSION SCENARIOS

Analyses were performed to determine the relative effectiveness of 14 alternative combinations of waste forms, described in Table 1-2, for reducing the consequences of human intrusion events. Three human intrusion scenarios designated E1, E2, and E1E2 were simulated using the methodology described in Appendix B. These scenarios, described in Section 2.2 and depicted in Figure 2-2, are the same as those used in the Performance Assessment

Methodology Demonstration Report (Marietta et al., 1989) where more detailed descriptions of these scenarios appear.

For all three scenarios, releases due to the slow flow of contaminated brine into the Culebra Dolomite are added to the releases due to the rapid removal of drill cuttings from the repository horizon to the surface. Scenarios E1 and E2 each remove cuttings from a single penetration of a borehole, and the E1E2 scenario includes the removal of cuttings from two boreholes. The methodology used to estimate the releases due to the removal of cuttings is described in Appendix B, Section 2.22.

The two most important parameters that control releases from the repository due to the migration of contaminated brine are radionuclide solubilities and the hydraulic conductivity of the storage rooms. Releases due to the removal of cuttings are controlled by the volumetric waste loadings, the height of the waste stack, and the shear strength of the waste forms. The methodology for estimation of waste element solubilities and storage room conductivity is described in Appendix B, Section 2.21.

#### Discussion of Results of Human Intrusion Scenarios

For each engineered alternative, the Design Analysis Model was used to calculate measures of relative performance for each of the three human intrusion scenarios. Two measures of relative effectiveness were calculated for each alternative/scenario pair; one based on the slow release of contaminated brine, and one that sums the slow release of contaminated brine with the contribution from the removal of drill cuttings. The results of these calculations are shown in Table 4-2.

Of the three scenarios considered, the Castile Brine scenario (E1) releases the largest volume of contaminated brine. This is caused by the slow migration of a potentially large volume of brine from the Castile Formation up the borehole, through the storage room, and on up to the Culebra Dolomite. The immediate release of drill cuttings to the surface causes a change in the Measure of Relative Effectiveness (MRE) only in the third or fourth decimal place which is why the pairs of values for the E1 scenario in Table 4-2 are similar. (The MRE is calculated by dividing the Measure of Effectiveness for the alternative by the Measure of Effectiveness for the baseline case; an MRE greater than one indicates a decrease in performance, and an MRE less than one indicates an increase in performance relative to the baseline case).

The use of grout backfill instead of the reference crushed salt backfill, in all cases, results in an improvement in performance as indicated in the relative improvement of Alternative 5 over 4, Alternative 7 over 6, and Alternative 12 over 11, as shown in Table 4-2. This is most clearly demonstrated in the E2 scenario where the consequence is dominated by the release of contaminated brine that has accumulated in the storage room during the initial repressurization period. The use of a grout backfill results in lower permeability of the waste/backfill composite, providing a greater resistance to the flow of contaminated brine toward the borehole.

TABLE 4-2

**MEASURE OF RELATIVE EFFECTIVENESS RESULTS WITHOUT CUTTINGS  
AND MEASURE OF RELATIVE EFFECTIVENESS RESULTS  
WITH CUTTINGS FOR THE E1, E2, and E1E2 SCENARIOS**

<u>DESIGN</u>	<u>E1</u>	<u>E2</u>	<u>E1E2</u>
BASELINE	1.00(a) 1.00(b)	1.00(a) 1.00(b)	1.00(a) 1.00(b)
ALTERNATIVE 1	0.40(a) 0.40(b)	0.96(a) 0.96(b)	$6.4 \times 10^{-4}$ (a) $8.3 \times 10^{-4}$ (b)
ALTERNATIVE 2	0.38(a) 0.38(b)	0.92(a) 0.90(b)	$4.7 \times 10^{-4}$ (a) $6.5 \times 10^{-4}$ (b)
ALTERNATIVE 3	0.27(a) 0.27(b)	$2.1 \times 10^{-2}$ (a) $2.8 \times 10^{-2}$ (b)	$4.1 \times 10^{-4}$ (a) $2.1 \times 10^{-4}$ (b)
ALTERNATIVE 4	0.55(a) 0.56(b)	1.21(a) 1.19(b)	$2.0 \times 10^{-4}$ (a) $5.0 \times 10^{-4}$ (b)
ALTERNATIVE 5	0.39(a) 0.39(b)	$3.6 \times 10^{-2}$ (a) $4.7 \times 10^{-2}$ (b)	$2.1 \times 10^{-4}$ (a) $2.9 \times 10^{-4}$ (b)
ALTERNATIVE 6	0.25(a) 0.26(b)	$4.4 \times 10^{-2}$ (a) $7.1 \times 10^{-2}$ (b)	$3.4 \times 10^{-4}$ (a) $6.6 \times 10^{-4}$ (b)
ALTERNATIVE 7	$1.2 \times 10^{-2}$ (a) $1.3 \times 10^{-2}$ (b)	$3.3 \times 10^{-3}$ (a) $2.8 \times 10^{-2}$ (b)	$4.5 \times 10^{-7}$ (a) $5.5 \times 10^{-7}$ (b)
ALTERNATIVE 8	$4.6 \times 10^{-2}$ (a) $4.9 \times 10^{-2}$ (b)	0.14(a) 0.20(b)	$2.6 \times 10^{-4}$ (a) $1.5 \times 10^{-3}$ (b)
ALTERNATIVE 9	$2.9 \times 10^{-2}$ (a) $3.2 \times 10^{-2}$ (b)	0.11(a) 0.16(b)	$3.1 \times 10^{-7}$ (a) $1.4 \times 10^{-3}$ (b)
ALTERNATIVE 10	1.14(a) 1.15(b)	2.19(a) 2.17(b)	$2.0 \times 10^{-2}$ (a) $2.1 \times 10^{-2}$ (b)
ALTERNATIVE 11	0.66(a) 0.66(b)	0.67(a) 0.66(b)	0.71(a) 0.71(b)
ALTERNATIVE 12	0.41(a) 0.41(b)	$1.3 \times 10^{-2}$ (a) $2.4 \times 10^{-2}$ (b)	$6.6 \times 10^{-3}$ (a) $6.9 \times 10^{-3}$ (b)
ALTERNATIVE 13	$4.7 \times 10^{-3}$ (a) $8.2 \times 10^{-3}$ (b)	$1.7 \times 10^{-4}$ (a) $9.4 \times 10^{-2}$ (b)	$1.6 \times 10^{-4}$ (a) $2.1 \times 10^{-3}$ (b)
ALTERNATIVE 14	0.17(a) 0.18(b)	$2.7 \times 10^{-2}$ (a) $9.8 \times 10^{-2}$ (b)	$1.5 \times 10^{-4}$ (a) $1.6 \times 10^{-3}$ (b)

(a) Without drill cuttings.  
(b) With drill cuttings.

The greatest relative improvement for the E1 scenario is offered by Alternative 13, which is vitrified waste forms placed in nonferrous rectangular containers, thereby eliminating the need for backfill. The critical performance parameter for this scenario is the relative contrast in hydraulic conductivity between the material filling the borehole (sand and silt) and the material filling the storage room (waste and backfill). If the conductivities of these two materials are similar, a significant fraction of the brine flowing up from the Castile will interact with the waste, but if the conductivity of the materials in the storage room is low relative to the material filling the borehole (as it is for Alternatives 7, 8, 9, and 13), there is little waste/brine interaction.

The most dramatic improvement in performance for the E1E2 scenario occurs using Alternative 13. A three-order-of-magnitude improvement is predicted, with two sets of drill cuttings included. However, an improvement of eight orders of magnitude is predicted using Alternative 13 if the contribution from drill cuttings is neglected, indicating that the contribution from drill cuttings dominates the release. This contribution can further be reduced by changing the initial height of the waste stack from the reference design of drums stacked three layers high (nine feet) to a lower configuration, as demonstrated by Alternatives 11 and 12 where the drill cuttings cause a change in the MRE only in the fourth decimal place.

#### 4.3 SUMMARY OF RESULTS FOR DESIGN ANALYSES

The results of design analysis have shown that, if needed, a number of engineered alternatives could be implemented to improve the repository long-term performance. The combinations of engineered alternatives evaluated by the EATF include alternatives that have varying degrees of effectiveness to address possible gas generation and future inadvertent human intrusion scenarios. However, the exact choice of an engineered alternative can only be determined after the extent of the problem, and the degree of effectiveness required, have been identified by the performance assessment studies.

Table 4-3 summarizes the interpretations of the EATF regarding the effectiveness of 14 combinations of engineered alternatives in addressing gas generation issues and three human intrusion scenarios.

The effectiveness of an alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, the alternative is considered to be effective, and is assigned a blank circle in Table 4-3. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table 4-3.

As an example, from the results of the Design Analysis Model, the peak index pressures due to Alternative 2 exceed the lithostatic pressure and therefore this alternative is assigned a dark circle in Table 4-3. Similarly, Alternative 4, which does not exceed the lithostatic pressure, is assigned a blank circle for its effectiveness for addressing peak index pressure.

**TABLE 4-3  
INTERPRETATION OF THE RESULTS OF THE DESIGN ANALYSIS MODEL**

Treatment Level <sup>a</sup>	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS					
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container	Peak Index Pressure	Gas Generation Rate		Human Intrusion		
								Microbial & Radiolytic	Anoxic Corrosion	E1	E2	E1E2
II	1	AR	S&C	S&C	SLT	AR	●	○	○	○	●	○
	2	CMT	S&C	S&C	SLT	AR	●	○	○	○	●	○
	3	CMT	S&C	S&C	CGT	AR	●	○	○	○	○	○
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	○	●	●	○
	5	CMT	I&C	S&C	CGT	AR	○	○	○	○	○	○
III	6	VTR	I&V	MM	SLT	AR	○	○	○	○	○	○
	7	VTR	I&V	MM	CGT	AR	○	○	○	○	○	○
	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	○	○
	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	○	○
I/III	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○
	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●
I	12	AR	SPT	SPT	CGT	AR	●	●	●	○	○	○
	14	AR	SPT	SPT	SAG	AR	●	●	●	○	○	○

AR - AS RECEIVED	MRM - MELT AND REMOVE METALS	● - PARTIALLY EFFECTIVE
CMT - CEMENT	DRM - DECONTAMINATE AND REMOVE METALS	○ - EFFECTIVE
VTR - VITRIFY	SLT - SALT	● - NO EFFECT
S&C - SHRED & CEMENT	CGT - CEMENT GROUT	NFR - NON FERROUS, RECTANGULAR
I&C - INCINERATE & CEMENT	SAG - SALT AGGREGATE GROUT	NFE - NON FERROUS
I&V - INCINERATE & VITRIFY	SPT - SUPERCOMPACT	MM - MELT METALS
N/A - NOT APPLICABLE		

<sup>a</sup> CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

The effect of an alternative on the gas generation rates has been summarized in Table 4-3, based on the knowledge of processes involved in these alternatives. An alternative is considered to be effective for addressing gas generation from a given mechanism, if it is expected to reduce the generation rates to near zero (i.e., it practically eliminates the potential for gas generation from that mechanism). This is denoted by a blank circle in Table 4-3. Similarly, if an alternative reduces the gas generation rate but does not completely eliminate it, it is considered to be partially effective (denoted by a shaded circle in Table 4-3). An alternative which is not expected to have any effect on the generation rates is termed ineffective, and is assigned a dark circle in Table 4-3.

As an example, Alternative 6 which incinerates and vitrifies the solid organics, and vitrifies the sludges, practically eliminates gas generation from microbial/radiolytic processes, and reduces generation rates from this mechanism to zero. Therefore, it is assigned a blank circle in Table 4-3 for addressing gas generation rates from microbial/radiolytic processes. However, the melting of metals into ingots (as done in Alternative 6) does not eliminate metals from the inventory, but helps to reduce the rate of gas generation from anoxic corrosion. This is denoted by a shaded circle in Table 4-3. Similarly, supercompaction of the waste has no effect on the gas generation rate, and is therefore assigned a dark circle in Table 4-3.

The apparent inconsistency between predicted peak index pressures and predicted effect on gas generation rates is a function of the simplifying assumptions inherent in model development. The Design Analysis Model includes various assumptions about gas generation rates from waste forms, creep closure rates, brine inflow, coupling of brine inflow and anoxic corrosion, and room response to gas pressure. These assumptions are based on data about the WIPP available at the time of model development, with almost all of the data obtained from SNL publications. Although these assumptions are reasonable at this time, they may change as ongoing experimental and modeling activities continue to provide additional data. If necessary, the Design Analysis Model can be updated to incorporate new assumptions as revised data becomes available.

Table 4-3 also summarizes the effectiveness of the 14 alternatives in addressing the three hypothetical human intrusion scenarios. The summary is based on the results obtained by the Design Analysis Model for the MRE of an alternative for these scenarios. As explained in Section 4.2, the MRE of an alternative must be less than 1 to signify an improvement in performance relative to the baseline design. The performance progressively improves as the MRE approaches zero. Although any value of MRE less than 1 signifies an improvement, the EATF has used a conservative upper limit of 0.5 for rating an alternative partially effective (denoted by a shaded circle). If the MRE is greater than 0.5 for a given scenario, the alternative is considered to be ineffective for addressing that particular scenario, and is assigned a dark circle in Table 4-3. Similarly, an MRE of less than 0.05 has been used to classify an alternative to be most effective (denoted by a blank circle in Table 4-3). As an example, Alternative 7 is effective for all three intrusion scenarios, and is assigned a blank circle under each column. In contrast, Alternative 1, which is partially effective for scenario E1, effective for E1E2, and is ineffective for E2, is assigned a shaded circle, a blank circle, and a dark circle under the respective columns. As with predictions of effectiveness for

addressing gas generation, it should be noted that the results of the Design Analysis Model for human intrusion scenarios are also influenced by the assumptions inherent in model development.

Table 4-3 provides a comparison between the relative effectiveness of 14 combinations of engineered alternatives for addressing both gas generation and human intrusion issues. If a problem is identified by performance assessment, Table 4-3 will help focus the choice of an effective alternative to a small group of alternatives. As an example, if performance assessment determines that merely reducing gas generation rates will help demonstrate compliance, then either one of Alternatives 1, 2, or 3 would be sufficient, and there would be no need for any Level III combinations. Alternatively, if it is determined that it is necessary to eliminate gas generation of any kind in order to demonstrate compliance, then the choice of alternatives would be limited to Alternatives 8, 9, and 13. Similar logic can be applied to the human intrusion scenarios to arrive at a set of alternatives sufficient to address any problems identified by performance assessment.

It should be noted that although Table 4-3 provides comprehensive information about the effectiveness of engineered alternatives, it cannot be used to determine the final choice of an alternative, because it does not distinguish between the alternatives regarding the feasibility of implementing them. Once a group of alternatives have been identified that have the minimum effectiveness necessary to address the extent of the problem, a comparison of their overall feasibility is required to arrive at a final conclusion. The subsequent sections (Sections 5.0 through 8.0) provide a detailed discussion of the feasibility of implementing engineered alternatives with respect to various issues.

## 5.0 OVERVIEW OF FEASIBILITY EVALUATION OF ENGINEERED ALTERNATIVES

In addition to assessing the effectiveness of various engineered alternatives, the EATF has also evaluated the feasibility of implementing each combination of alternatives presented in Table 1-2.

### 5.1 TYPES OF ENGINEERED ALTERNATIVES EVALUATED

The engineered alternatives evaluated by the EATF for feasibility of implementation have been classified into three categories:

- Waste treatment alternatives
- Backfill alternatives
- Other engineered alternatives.

Modifications to waste container material or shape have been discussed under "Other Engineered Alternatives." Waste treatment alternatives are the most complex to implement, and require construction of specialized facilities or use of existing facilities in order to implement the alternative. Therefore, the EATF has focused a substantial part of its feasibility evaluation efforts in assessing the feasibility of waste treatment alternatives.

The remainder of this section identifies the criteria against which the feasibility of alternatives has been evaluated. Section 6.0 discusses the feasibility of waste treatment alternatives, and Sections 7.0 and 8.0 discuss the feasibility of backfill and other alternatives, respectively.

### 5.2 CRITERIA FOR EVALUATION OF FEASIBILITY

The feasibility of implementing waste treatment alternatives has been evaluated relative to four criteria: availability of technology, regulatory issues, cost, and schedule. The Program Plan for Engineered Alternatives (Hunt, A., 1990) identified the following critical issues requiring investigation:

- Status of Development - The technology must have the potential for full-scale demonstration in order to be considered a viable option.
- Existing Capacity Versus Treatment Need - The usable capacity of treatment of TRU waste will be considered.
- Regulatory Constraints to Implementation - Issues such as extended permit cycles and transportation.
- Institutional Constraints to Implementation - Issues such as local waste treatment facility restrictions.

- **Estimate of Implementation Costs - Cost effectiveness of the treatment.**
- **Implementation Schedules - Timeliness of treatment relative to overall program schedules.**
- **Potential Facility Locations.**
- **Worker, General Public, and Environmental Safety - Comparison of the risks of processing existing waste or changes in waste generating processes at the DOE sites, with transport of untreated wastes to WIPP.**

The feasibility of implementing backfill or other engineered alternatives (waste management changes, facility design modifications, and passive surface markers) has been evaluated by using the following information:

- **Status of development of technology**
- **Regulatory considerations**
- **Cost and schedule for full-scale implementation.**

In addition to assessing the effectiveness of various engineered alternatives, the EATF has also evaluated the feasibility of implementing each combination of alternatives presented in Table 1-2.

## 6.0 FEASIBILITY OF IMPLEMENTING WASTE TREATMENT ALTERNATIVES

### 6.1 INTRODUCTION

The EATF developed the following categories for assessing the feasibility of implementation of waste treatment alternatives based on criteria identified in the Program Plan for Engineered Alternatives (Hunt, A., 1990):

- Development Status of Waste Treatment Technologies (Section 6.3.1)
- Location of Stored Waste and Waste Generation Rates by Site (Section 6.3.2)
- Tabulation of Existing Treatment Capacity (Section 6.3.3)
- Waste Treatment Cost Estimates (Section 6.3.4)
- Implementation Schedule (Section 6.3.5)
- Regulatory Considerations (Section 6.3.6)
- Worker, General Public and Environmental Risk Assessment (Section 6.3.7).

The data collected for each of these categories have a dual function. First, the data collectively form the basis for selecting a potential treatment technology. Trade-offs of effectiveness in improving repository performance are qualitatively weighted relative to cost, schedule, regulatory concerns, and health effects. Once the treatment is selected, the data are then used in the site selection process. Location of wastes, cost of treatment, transportation cost, risk, and permitting constraints are all considered for selecting the location and number of treatment facilities.

The EATF findings on the feasibility of waste-treatment alternatives in Section 6.0 are organized into three sections. Section 6.2 reviews the components of Level II and Level III treatment facilities. Section 6.3 presents the preliminary data required to evaluate waste treatment alternative feasibility. Results may then be factored into the decision methodology presented in Section 6.4 to select locations for treatment facilities, as well as the decision methodology for selecting treatment alternatives presented in Section 9.0.

The EATF mission of providing a preliminary analysis of alternative feasibility precluded detailed collection or development of information such as facility costs, implementation schedules, or institutional or regulatory requirements. The more quantitative data required in selection of a waste treatment, if waste treatment is determined to be required, is best collected once the WIPP performance assessment issue(s) become defined. Where appropriate, the EATF has identified additional information that should be developed before a final decision on waste treatment.

### 6.2 WASTE TREATMENT FACILITY DESCRIPTION

Waste treatment requires a facility or facilities that consists of both treatment operations (e.g., shredder, incinerator, solidification systems) and an array of support functions. Support functions for waste treatment include administration, maintenance, receiving, shipping, storage, etc. This section provides a brief description of the various waste treatment facility

components and potential operations which may be required to treat TRU waste prior to disposal at the WIPP.

### **6.2.1 Support Functions of a Waste Treatment Facility**

Facility structures and systems required to support the waste treatment operations are major contributors to the overall facility cost and schedule. Figure 6-1 depicts typical elements of a waste treatment facility. The elements common to most waste treatment facilities, independent of the treatment processes, are presented below.

#### **6.2.1.1 Unloading Bay**

This area provides space for unloading trucks carrying the TRUPACT-II or other authorized packages that are used to transport TRU waste to the waste treatment facility.

#### **6.2.1.2 Receiving Bay**

This area provides space and equipment for unloading waste containers from the shipping packages, inspecting the waste containers and the interior of the shipping package for surface contamination, and preparing the waste containers for temporary storage.

#### **6.2.1.3 Waste Storage Area**

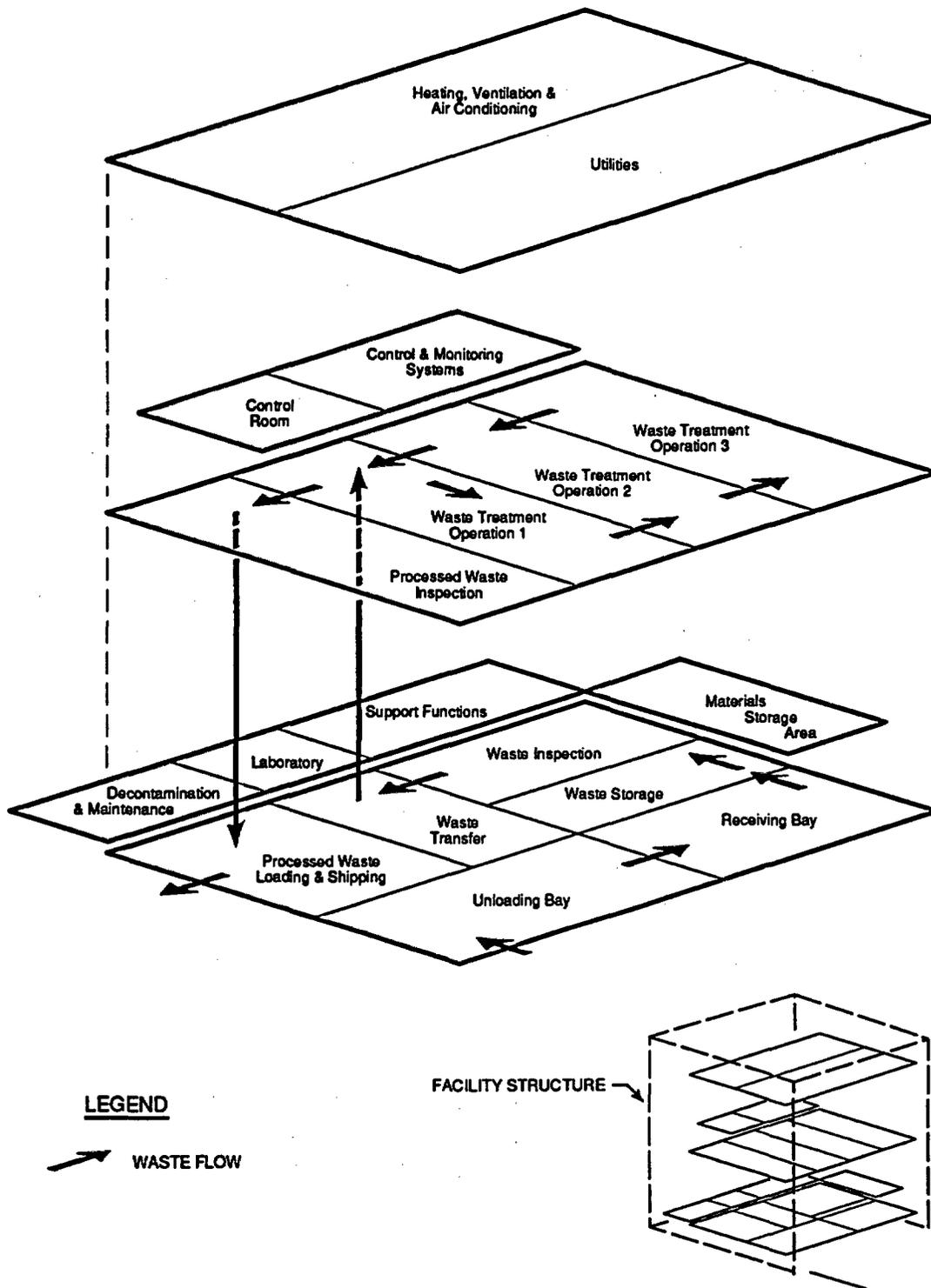
This area is storage space for incoming waste. The purpose of maintaining a stored waste inventory at the facility is to provide efficient flow of waste into the waste treatment area.

#### **6.2.1.4 Incoming Waste Inspection Area**

The heterogeneity of the incoming TRU waste forms suggests that some inspection or confirmation may be required to assure that the waste contents are appropriate for the specific waste treatment being conducted at the facility. Therefore nondestructive testing may be conducted before the waste is transferred to the waste treatment area. Testing might consist of real-time radiography, radionuclide assays, and weighing of the waste, as well as verifying transportation records.

#### **6.2.1.5 Waste Transfer Area**

This area serves as the loading point for waste entering the waste treatment area. The waste transfer area will either be an airlock, or have an airlock between itself and the waste treatment area. The airlock serves as a barrier between clean areas of the facility and potentially contaminated areas. If sampling of waste is required prior to treatment, this area could meet these needs.



**FIGURE 6-1**  
**WASTE TREATMENT FACILITY SCHEMATIC**

#### **6.2.1.6 Heating, Ventilation, and Air Conditioning (HVAC) Systems**

The HVAC systems control air flow and maintain temperature and negative pressure in all parts of the facility. These systems include high-efficiency particulate air (HEPA) filters to prevent TRU radionuclides from leaving the building with the ventilation air. All areas that contain TRU waste will be maintained at negative pressure relative to the exterior of the building. This assures that, in the unlikely event that radioactive materials contaminate an area of the facility, the contaminants will not be released to the environment.

#### **6.2.1.7 Control and Monitoring Systems**

These systems include fire protection and alarms, radioactive contamination monitoring, physical security, confinement control, utility instrumentation and control, and computer systems.

#### **6.2.1.8 Control Room**

Treatment processes may be controlled from a single control room, or individual control stations. For the more complex operations, waste treatment will probably be controlled via a central control room computer with local control options.

#### **6.2.1.9 Processed Waste Inspection**

After the waste has been treated, it is moved into an inspection area where it will be non-destructively tested or sampled to ensure that adequate treatment has taken place. Waste will be certified for shipment to WIPP in the processed waste inspection area.

#### **6.2.1.10 Processed Waste Loading**

This area is similar to the unloading and receiving bays. The waste containers will be prepared for loading (such as bundling drums into a seven-pack array) and loaded into the TRUPACT-II.

#### **6.2.1.11 Decontamination and Maintenance**

Equipment used to handle and treat the waste will require periodic maintenance and/or decontamination. This area of the facility serves as a decontamination and repair or maintenance function, and may consist of remote operations including a highbay area for maintaining large equipment.

#### **6.2.1.12 Laboratory**

Periodic sampling and analysis of incoming or outgoing waste will be required at the facility. A laboratory is necessary for analysis of the samples for certification purposes.

#### **6.2.1.13 Materials Storage Area**

Waste treatment may require bulk quantities of Portland cement, glass frit, or other materials associated with the process. This area will store and provide these materials to the waste treatment area. A separate area may also be reserved for spare parts, lubricating oils, and other materials and equipment as may be needed to support day-to-day operations.

#### **6.2.1.14 Utilities**

This function will be spread throughout the facility, and consists of: electrical, heating and cooling, water supply, emergency power, sanitary sewage systems; and process-related utilities such as emergency showers and personnel radiation detection. Recycling of wastewater may also occur within this function.

#### **6.2.1.15 Facility Structure**

A building will be required to house the waste treatment systems and supporting elements. Portions of the building, such as the waste treatment and receiving and loading areas, will probably require multistory construction to accommodate equipment and operations. Roads, parking, fences, and utility supplies complete the facility. The building would be designed and constructed to meet the requirements of DOE Order 6430.1A, General Design Criteria (DOE, 1987b), which includes an assessment of the hazard level of operation. It is expected that the facility will be considered a medium or high hazard facility as defined by this order.

#### **6.2.1.16 Other Support Functions**

These functions consist of administration, health physics, change areas, communications, and any unique operation required at the specific facility.

### **6.2.2 Treatment Operations**

Treatment operations, such as incineration, shredding, cementation, and vitrification, together with ancillary equipment such as off-gas systems, material hoppers, instrumentation and controls, and the supporting structures, represent the waste treatment portion of the facility. This area will be maintained at a negative pressure relative to other areas of the facility containing TRU waste.

The waste treatment alternatives considered feasible by the EATF result in five basic waste forms: glass or concrete monoliths, compacted waste, metal ingots, and the unprocessed waste form with pH buffers. The treatment operations needed to produce these basic products are:

- Vitrification
- Solidification (with a cement-based grout)
- Compaction
- Incineration (followed by vitrification or solidification)
- Metal melting (which produces metal ingots; a slag may be produced which can then be vitrified; see Section 6.3.1.9)
- Addition of pH buffers
- Shredding (as a precursor to other processes).

A treatment operation consists of the process equipment needed to produce the waste forms listed above, as well as support systems and structures directly associated with the particular treatment operation.

Figure 6-2 shows the treatment operations associated with each waste treatment alternative considered feasible by the EATF. One or more treatment operations are generally required to produce each waste form. For instance, a cemented waste form might require shredding, incineration, and cementation if the waste specification requires elimination of organics and solidification of the waste. These treatment operations, together with appropriate support elements, constitute the facility required to process TRU waste into the desired waste form. The facilities evaluated by the EATF include treatment operations capable of treating unprocessed waste forms as follows:

- Shred and cement solid organics
- Incinerate and cement solid organics
- Incinerate and vitrify solid organics
- Shred and cement solid inorganics
- Melt metals into TRU ingots
- Melt metals and eliminate from WIPP inventory (vitrified slag will be shipped to WIPP)
- Cement sludges
- Vitrify sludges
- Decontaminated metal with residue solidification.

### **6.3 DESCRIPTION OF FACTORS CONSIDERED IN IMPLEMENTING TREATMENT ALTERNATIVES**

The EATF assembled information on the feasibility of implementing waste treatment alternatives at facilities consisting of components described in Section 6.2. This information is organized by factors considered in implementing treatment alternatives and is described below. Selection of a treatment technology requires integration of data on waste treatment technology status (Section 6.3.1), treatment cost (Section 6.3.4), schedule issues (Section 6.3.5), regulatory considerations (Section 6.3.6), and the assessment of risk (Section 6.3.7). Once a treatment technology or technologies are selected, siting of treatment facilities requires analysis of location of waste and waste-generation rates (Section 6.3.2), current or planned treatment capacity (Section 6.3.3), waste transportation costs versus capital and operating costs for

WASTE TREATMENTS	TREATMENT OPERATIONS							
	SHRED	COMPACT	CEMENT OR GROUT	INCINERATE	VITRIFY	MELT METALS (INGOTS)	MELT METALS (SLAG)	ADD pH BUFFERS, SALT OR SORBENTS
<u>Sludges</u>								
VITRIFICATION				•				
CEMENTATION		•						
ADD pH BUFFERS							•	
<u>Solid Organics</u>								
COMPACT		•						
SHRED AND CEMENTATION	•		•					
SHRED, ADD SALT, COMPACTION	•	•					•	
SHRED AND ADD BENTONITE	•						•	
INCINERATION AND CEMENTATION	•		•	•				
INCINERATION AND VITRIFICATION	•			•	•			
ADD pH BUFFERS							•	
<u>Solid Inorganics</u>								
SHRED AND COMPACTION	•	•						
SHRED AND CEMENTATION	•		•					
SHRED, ADD SALT, COMPACTION	•	•					•	
VITRIFICATION <sup>1</sup>					•	•		
MELT METALS <sup>2</sup>						•		
SHRED AND ADD BENTONITE	•						•	
ADD pH BUFFERS							•	
DECONTAMINATE METALS <sup>3</sup>	•		•					•

<sup>1</sup> Metals are Melted with Glass/Glass Frit; Radionuclides Partition into the Slag and Metals are Eliminated from the WIPP Inventory

<sup>2</sup> Metals are Melted into TRU Waste Ingots

<sup>3</sup> Solidify Process Residue by Cementation

FIGURE 6-2  
TREATMENT OPERATIONS

various numbers of facilities (Section 6.3.4), required treatment schedules versus construction schedules for various numbers of facilities (Section 6.3.5), permitting facilities and regulations governing shipment of wastes (Section 6.3.6), and differences in public and occupational health-based risk for various numbers of facilities (Section 6.3.7).

### **6.3.1 Development Status of Waste Treatment Technologies**

The waste treatment alternatives recommended by the EATF for inclusion in the WIPP Experimental Program (DOE, 1990b) range from relatively simple operations, such as the addition of pH buffering materials to the waste, to the more complex waste treatment technologies, such as vitrification or incineration. While most of these alternatives are technologically feasible, others will require development for application to TRU waste. This section presents the development status of the technologies necessary to produce the combinations of waste forms described in Table 1-2, as well as the status for all the technologies necessary to produce the waste forms identified by the EATF.

#### **6.3.1.1 Vitrification**

A small commercial glass furnace has been tested at Mound Laboratories (Mound) for application to nuclear power plant solid wastes. It has been used for the demonstration of the incineration/vitrification of combustible wastes, ion exchange resins, filter cartridges, and sludges (Klingler and Armstrong, 1986).

Microwave melting of sludge wastes is another method of generating a vitrified waste form. Microwave systems are being tested at Rocky Flats Plant (RFP) (Petersen et al., 1988) and Oak Ridge National Laboratory (ORNL) (White et al., 1989). These vitrification systems appear to be viable technologies, but additional development will be required before operation of full scale systems is possible, since tests have been run on only TRU waste analogs. Development here is primarily a function of scale up of existing equipment, as well as feed preparation, metering, and control of radioactive materials.

#### **6.3.1.2 Incineration**

The EPA considers incineration a demonstrated technology for hazardous waste. Incineration has also been demonstrated internationally for radioactive applications, but the practical application to TRU waste has been limited in the U.S.

The DOE has used incineration for volume reduction of low level wastes in a number of locations, such as the Waste Experimental Reduction Facility (WERF) at Idaho National Engineering Laboratory (INEL) (McFee and Gillins, 1986) and the TSCA Incinerator at the Oak Ridge Reservation K-25 Plant (Kroll and Rogers, 1989). A commercial low level waste incinerator operated by the Scientific Ecology Group (SEG) of Westinghouse Electric Corporation is accepting waste at Oak Ridge, Tennessee (Dalton and Arrowsmith, 1990). The Los Alamos National Laboratory (LANL) Controlled Air Incinerator (CAI) has been used for demonstrating TRU waste incineration since 1976, but is currently not operational due to

mechanical system upgrades and regulatory issues (Vavruska et al., 1989). The CAI has a capacity of 45 kilograms per hour and is designed to process liquid and packaged solid waste that is low in solid inorganic content.

In summary, hazardous and low level waste incineration are well developed technologies. However, there are no TRU waste incinerators currently operating in the United States due to either technical or regulatory factors.

#### 6.3.1.3 Cementation

Cementation to stabilize or solidify materials is a well demonstrated technology for TRU waste and other low-level nuclear wastes. Types of cementation agents vary somewhat, and are dependent on the material to be solidified. Similarly, the capacities of the demonstrated systems range from simple "in-drum" operations in which waste and solidification agents are mixed and solidified in the final disposal package, to large continuous operation systems. However, the longevity of cemented waste forms in the WIPP environment is uncertain and will require additional studies and modeling for confirmation of applicability. The EATF assembled a panel of cement experts who suggested that properly formulated cemented waste forms will probably be durable for long periods of time. The details of the Cement/Grout Panel deliberations are presented in Appendix G.

The United Kingdom Atomic Energy Authority has selected cementation as the process for treating stored intermediate-level wastes, which include TRU waste (Lee and Wilding, 1989). In Sweden, metallic low level waste has been solidified in Envirostone, a commercial product using gypsum with an organic binder (Sjoberg et al., 1985). The EATF has found 21 separate applications of cementation used by the DOE for either low level or TRU waste solidification (IT Corp., 1989). There are several commercial suppliers of radioactive waste cementation systems and at least one cementation service available to commercial nuclear power plants. Cementation is a well developed technology, although development of specific cementitious formulations may be required for use in the WIPP environment.

#### 6.3.1.4 Shredding

Shredding technology is fully demonstrated, and commercially available shredders can be incorporated into facilities designed for TRU waste handling. It should be noted that shredding equipment can require extensive maintenance. Many of the proposed waste treatment technologies either require or can be enhanced if preceded by shredding. For example, addition of pH buffers to waste packages would be enhanced if preceded by shredding.

#### 6.3.1.5 Metal Melting

Scrap metal melting is an integral part of steel industry practice worldwide. Some melting techniques, such as induction heating, may be particularly suitable for melting TRU contaminated metals. A plasma process, which melts materials using heat from a plasma furnace, is in the demonstration stage (Peters and Ross, 1989; Peters et al., 1990) and may

be useful for melting metal wastes mixed with glass, combustibles, soils, and other materials. Metal melting experimental efforts at ORNL (Heshmatpour et al., 1983) have produced partition factors (mass of radionuclide in slag/mass of radionuclides originally in metal) that allow reclassification of metals as low level waste. In general, the application of melting metals as a waste treatment will require engineering development for scale up, application to specific types of metals, and containment of radioactive components.

#### 6.3.1.6 Compaction

Waste compactors are available from commercial suppliers. The EATF has identified three DOE compactor programs and several others appear to be in the planning phase. Low level waste compactors exist at the INEL (Gillins and Larsen, 1987) and at the West Valley Demonstration Project (WVDP) (Frank et al., 1988). The Supercompaction and Repackaging Facility (SaRF) at RFP is the first permanent installation for TRU waste in the United States (Barthel, 1988). A commercial low level waste supercompactor is operated by SEG at their facility in Oak Ridge, Tennessee, and mobile compactor services exist for nuclear power plants (Jossop, 1989). Waste compaction is therefore, considered a developed technology.

#### 6.3.1.7 Encapsulation

The use of polymers or bitumen to encapsulate radioactive waste is a relatively straightforward process. Encapsulation of radioactive waste in bitumen has been used by Duke Power Company (Jones et al., 1985). Low level radioactive waste encapsulation, using polyester as the encapsulation medium, has been developed in the United States (Dillman et al., 1985). Encapsulation of low and medium level waste in epoxy resins is being used in France (Gauthey, 1989). Although this alternative is a technologically proven waste solidification process, it has the potential for increasing biological and radiolytic gas generation due to addition of large quantities of organic binder materials, and is therefore not being recommended for TRU waste treatment at the present time.

#### 6.3.1.8 Addition of pH Buffers

Addition of buffers may be useful for increasing the pH of repository brine. Radionuclides tend to be less soluble at high pH conditions. A benefit of lowered solubility is decreased mobility of radionuclides in brine. The addition of pH buffers, such as cement, lime, or activated alumina is a relatively simple process in comparison to other waste treatment alternatives. Preshredding may prove beneficial to the mixing process. The shredding, solids metering, and mixing steps required for this operation are commercially practiced in nonradioactive waste operations and are therefore, judged to be well developed for TRU waste application.

#### 6.3.1.9 Metal Decontamination

Decontamination technology for converting metallic TRU waste to low level waste has been extensively studied at Pacific Northwest Laboratory (Allen and Hazelton, 1985). Several processes are available to decontaminate TRU waste forms to LLW. These processes include

electropolishing, hand scrubbing, chemical washes/sprays, strippable coatings, and Freon spray-cleaning (Allen and Hazelton, 1985). Electropolishing and vibratory finishing techniques are proven effective in decontaminating TRU wastes to levels below standards defining TRU waste (Allen et al., 1982). In fact, at the time these decontamination techniques were studied, the 10 nCi/g limit applied to TRU waste. Electropolishing will remove TRU contamination from all metals with the exception of those that form highly insulating oxides such as Zircalloy (Allen et al., 1982). Vibratory finishing will remove TRU contamination from almost all classes of metals and alloys and from a wide range of surface-contaminated nonmetallic TRU wastes including plastic, glass, and rubber (Allen et al., 1982). Metal waste forms that do not have exposed surfaces (e.g., pipes) may require preprocessing such as shredding.

The obvious benefit of decontamination is that metals can be removed from the WIPP waste inventory, thus eliminating any anoxic corrosion potential. Decontamination processes can reduce TRU contaminated metals into LLW. These processes generate a secondary waste in the form of an aqueous rinsing solution that may also contain some solids. These contaminated liquids would require some form of solidification treatment, such as cementation, prior to disposal at WIPP.

### 6.3.2 Location of Waste and Waste Generation Rates

The quantity of transuranic waste generated or stored at the various DOE sites directly influences any treatment facility siting decision. Treatment facility capacity is dependent upon both the quantity of waste to be treated and the time frame or work-off period over which all treatment must be accomplished.

Transuranic waste is stored and/or generated at ten major DOE sites nationwide located throughout the nation. The data for location and quantity of newly generated waste and data on waste currently in storage at each TRU waste generating or storage site has been extracted from the DOE Inventories, Projections and Characteristics Data Base (DOE, 1988c) which is updated annually. This version of the data base has been used by the EATF because it is the most current version that includes uncompact RFP wastes.

Transuranic waste at the DOE sites consists of: solid organics, combustibles, sludges, filters, noncombustibles, construction materials, and other miscellaneous materials. Sludges, solid organics, and glass and metals (solid inorganics) comprise approximately 85 percent by volume of the total TRU waste inventory. The remaining 15 percent of the inventory has been sorted into one of the three primary categories for the purposes of EATF work. Table 6-1 shows the quantities of waste currently in retrievable storage at INEL, Hanford, LANL, Savannah River Site (SRS), ORNL, and Nevada Test Site (NTS) plus the projected quantities expected to be generated during the next 26 years at these and other generator sites (DOE, 1988c). Table 6-2 shows the WIPP average annual expected emplacement rates (based on unprocessed wastes). The emplacement rates are based on Table 6-1 quantities, a five year WIPP test phase during which small quantities (EATF assumed 5 percent) of waste will be emplaced, plus a 20 year emplacement period during which the remainder of the production quantities of waste will be emplaced. These emplacement rates are representative of the

**TABLE 6-1**  
**TRU WASTE QUANTITIES AND LOCATIONS<sup>1, 2</sup>**

FACILITY <sup>3</sup>	SLUDGES		SOLID ORGANICS		SOLID INORGANICS	
	RETRIEVABLY <sup>4</sup> STORED	NEWLY <sup>5</sup> GENERATED	RETRIEVABLY STORED	NEWLY GENERATED	RETRIEVABLY STORED	NEWLY GENERATED
ANL-E	0	44	0	31	0	19
INEL	9193	479	13852	1007	12518	472
LANL	2261	2143	1604	2802	3427	3297
LLNL	0	87	0	2367	0	433
Mound	0	1017	0	60	0	120
NTS	12	0	353	0	254	0
ORNL	6	10	350	577	227	375
Hanford	583	635	4182	4555	5548	6043
RFP	0	9555	0	17017	0	9828
SRS	105	563	2242	12055	643	3456
<b>TOTALS</b>	<b>12160</b>	<b>14533</b>	<b>22583</b>	<b>40471</b>	<b>22617</b>	<b>24043</b>

<sup>1</sup> Source (DOE, 1988c).

<sup>2</sup> Quantities shown are in cubic meters.

<sup>3</sup> RFP = Rocky Flats Plant; INEL = Idaho National Engineering Laboratory; Hanford = Hanford Site; LANL = Los Alamos National Laboratory; SRS = Savannah River Site; ORNL = Oak Ridge National Laboratory; NTS = Nevada Test Site; LLNL = Lawrence Livermore National Laboratory; ANL-E = Argonne National Laboratory-East; Mound = Mound Laboratory.

<sup>4</sup> Retrievably Stored = TRU waste in storage generated between 1970 and the end of 1987.

<sup>5</sup> Newly Generated = TRU waste generated from 1988 through the end of 2013.

**TABLE 6-2**  
**AVERAGE ANNUAL UNPROCESSED TRU WASTE**  
**EMPLACEMENT QUANTITIES<sup>1, 2, 3</sup>**

FACILITY <sup>4</sup>	SLUDGES		SOLID ORGANICS		SOLID INORGANICS	
	RETRIEVABLY <sup>5</sup> STORED	NEWLY <sup>6</sup> GENERATED	RETRIEVABLY STORED	NEWLY GENERATED	RETRIEVABLY STORED	NEWLY GENERATED
ANL-E	0	2	0	1	0	1
INEL	437	23	658	48	595	22
LANL	107	102	76	133	163	157
LLNL	0	4	0	112	0	21
Mound	0	48	0	3	0	6
NTS	1	0	17	0	12	0
ORNL	0	0	17	27	11	18
Hanford	28	30	199	216	264	287
RFP	0	454	0	808	0	467
SRS	5	27	106	573	31	164
<b>TOTALS</b>	<b>578</b>	<b>690</b>	<b>1073</b>	<b>1921</b>	<b>1076</b>	<b>1143</b>

<sup>1</sup> Source (DOE,1988c).

<sup>2</sup> Quantities shown are in cubic meters/year.

<sup>3</sup> Annual quantities of emplaced waste are based on a 20 year WIPP operations period.

<sup>4</sup> RFP = Rocky Flats Plant; INEL = Idaho National Engineering Laboratory; Hanford = Hanford Site; LANL = Los Alamos National Laboratory; SRS = Savannah River Site; ORNL = Oak Ridge National Laboratory; NTS = Nevada Test Site; LLNL = Lawrence Livermore National Laboratory; ANL-E = Argonne National Laboratory-East; Mound = Mound Laboratory.

<sup>5</sup> Retrievably Stored = TRU waste in storage generated between 1970 and the end of 1987.

<sup>6</sup> Newly Generated = TRU waste generated from 1988 through the end of 2013.

annual waste treatment capacity that would be required in the event treatment becomes necessary.

### **6.3.3 Current or Planned DOE Waste Treatment Capacity**

Treatment-facility siting decisions and the site's ability to ship wastes are, in part, influenced by existing or planned treatment capacity. Waste shipped to the WIPP must comply with the requirements of the Waste Acceptance Criteria (WAC) (DOE, 1989f), which delineate the requirements for acceptance of TRU waste for emplacement and disposal in WIPP. Some of the DOE waste generation and storage sites have responded to these requirements by building (or by planning to build) inspection and limited processing facilities for certifying TRU waste to WIPP WAC requirements. While these facilities are not expected to have sufficient capacity should large volumes of TRU waste require treatment, it is possible that one or more of these facilities could suffice either as is or with some modifications, for treating waste. Such a facility could also be considered as the front-end of a larger processing facility. An example of a modification is addition of process operations to existing facilities (at the sites of large TRU waste generators such as RFP and SRS). The EATF has identified existing and planned waste processing facilities as a factor that should be included in the feasibility analysis of potential waste treatment alternatives. These facilities are described below.

#### **6.3.3.1 Size Reduction Facility (SRF)**

The SRF is an existing prototype facility (currently not in operation) located at LANL (DOE, 1988a). The facility is designed to reduce the volume of and repackage various types of metallic waste contaminated with TRU radionuclides. Through FY 1985, a total volume of 88 cubic meters of TRU waste has been reduced in volume by a factor of 6.7 to 1 (IT Corp., 1988).

#### **6.3.3.2 Treatment Development Facility (TDF)**

The TDF is an existing facility (currently not in operation) located at LANL and utilizes a dual chamber, controlled air incinerator for processing solid organic TRU wastes with a nominal capacity of 45 kilograms per hour (Hutchins, 1990). Ash from the incineration process is cemented in drums.

#### **6.3.3.3 Supercompaction and Repackaging Facility (SaRF)**

The SaRF, located at RFP, is designed to process two separate categories of TRU waste. Solid organic waste will be precompacted in a 30-ton compactor prior to supercompaction. Solid inorganics will be compacted directly in the 2,200-ton supercompactor. The SaRF will compact approximately 1,800 cubic meters per year (Barthel, 1988). The compacted material will be overpacked in 55-gallon drums for off-site disposal. SaRF is currently awaiting completion of NEPA documentation review prior to startup.

#### **6.3.3.4 Stored Waste Examination Pilot Plant (SWEPP)**

SWEPP will examine and certify INEL retrievably stored TRU waste for shipment to WIPP. Examination of waste containers includes weighing, real time radiographic examination, radionuclide assay, container integrity examination and radiological surveys (EG&G Idaho, Inc., 1982).

#### **6.3.3.5 Transuranic Waste Treatment and Storage Facility (TWTSF)**

The TWTSF, located at INEL, is in the conceptual design phase and when built is planned to be capable of examining, shredding, compacting and repackaging TRU waste (DOE, 1989a). Capacity to examine TRU waste will be the equivalent of 10,000 drums per year. Shredding and compaction capacity will be 4,000 cubic meters per year (this includes low level waste).

#### **6.3.3.6 Waste Receiving and Processing Facility (WRAP)**

The WRAP facility at Hanford is being constructed in two phases, designated Module I and Module II, projected to be completed in FY 1996 and FY 1999, respectively (DOE, 1987a). It is currently scheduled to perform nondestructive assay/examination, and process retrievably stored and newly generated TRU waste, as needed, for certification and shipment to WIPP. The process capabilities will include shredding, grout solidification, and size reduction of oversize boxes of waste. The WRAP facility is expected to process approximately 1000 cubic meters of TRU waste each year, based on waste processing estimates of 3550 cubic meters of retrievably stored waste and 9560 cubic meters of newly generated waste over a thirteen year period (DOE, 1987a).

#### **6.3.3.7 Waste Handling and Packaging Plant (WHPP)**

The WHPP is a planned facility at ORNL designed for the purpose of characterizing, processing, repackaging and certifying remote-handled and special-case TRU waste located at ORNL and other DOE sites (White et al., 1989). The facility will process both liquid and solid TRU wastes. The liquid processing portion of the facility creates sludges that will be solidified by yet-to-be-determined processes. Microwave evaporation-solidification methods are being considered, including melt-solidification of the sludges. Facility construction is not expected to start until FY 1996. The facility is expected to process approximately 500 cubic meters of solids, 1,000 cubic meters of liquid and sludge over 15 years, and 6 cubic meters of newly generated solids per year (DOE, 1989d).

#### **6.3.3.8 Transuranic Waste Facility (TWF)**

The TWF is a proposed facility to be located at SRS (Daugherty et al., 1987). Its purpose is to process noncertifiable, retrievably stored, and newly generated waste. The facility will provide capabilities for retrieving stored waste, remote venting/purging of waste drums, real-time radiography and assay of drums, shredding and solidification of selected wastes, and repackaging. A small amount of the total waste will be solidified in a small-scale solidification

glovebox. The total quantity of waste to be handled in the facility is approximately 595 cubic meters per year of retrievably stored waste, and 125 cubic meters of newly generated waste per year. The facility is scheduled to be completed in FY 1995.

#### **6.3.3.9 Future Use of Planned and Existing Facilities**

At the point in time that performance assessment determines what waste treatment is needed, if any, decisions can be made for the most effective use of facilities such as those noted above. If these facilities have adequate capacity to provide the needed waste treatment, or if these facilities could form the basis for waste treatment facilities at the respective sites, then cost and schedule benefits would be realized. The following summarizes how these facilities might contribute to waste treatment facility siting decisions:

**Hanford** - WRAP waste handling capacity may be adequate to serve as the front end of processing operations.

**LANL** - Small facilities inadequate for front end waste handling and processing of all LANL waste.

**ORNL** - Relatively small quantity of CH-TRU could be processed at WHPP.

**SRS** - TWF capacity may be sufficient to support process operations for part of SRS waste.

**RFP** - SaRF can support a compacted waste form. Current waste generating processes could be modified to support processing.

**INEL** - SWEPP, TWTSF may have enough capacity to serve as front-end to process operations.

#### **6.3.4 Waste Treatment Cost Estimation**

Costs associated with waste treatment include those for handling and transportation of wastes to and from the treatment facility, waste characterization required prior to transportation or treatment, treatment-facility capital, and operating costs. In all cases, the EATF mission of providing a preliminary analysis of feasibility precluded development of "bottoms-up" costs through aggregation of smaller cost components. The EATF recognizes that more detailed cost estimates are required before final decisions are made concerning and location of waste treatment facilities. Results of the EATF waste treatment cost study are presented in Section 6.3.4.5.

#### 6.3.4.1 Treatment Facility Capital Cost Estimation

The EATF evaluated TRU waste treatment facility costs by relying on published data and discussions with DOE waste generator site personnel knowledgeable of costs for planned and existing facilities. Table 6-3 lists cost estimates for several of the existing and planned DOE TRU waste treatment facilities discussed in Section 6.3.3. These data are provided to give an indication of the broad cost range of TRU waste treatment facilities. Factors influencing facility costs are discussed in the following paragraphs and in detail in Appendix J.

Preliminary facility costs were developed for the fourteen combination alternatives described in Table 1-2. The basis for these cost estimates are the individual treatment operation costs, plus the support function cost. The purpose of developing separate costs for treatment operations is to simplify estimating costs of waste treatment facilities which utilize more than one treatment operation. The basis cost and capacity for each treatment operation and the required support facility (support functions) is determined through literature review. The cost of the support facility and each treatment operation can then be scaled with respect to capacity (see Appendix J). In this manner, capital costs for one through seven facilities for each of the fourteen combination alternatives presented in Table 1-2 were determined. Basis costs are escalated to 1990 dollars (see Appendix J). The EATF has assumed that cost escalation factors for chemical processing plants are also applicable to TRU waste treatment facilities.

The capacity of a facility depends on the waste forms to be treated, the number of facilities available to process the inventory, operating time, and inventory work-off period. Treatment operations that produce Level II waste forms, such as cementation or shredding, intuitively are less expensive than those needed to produce Level III waste forms, such as incineration and vitrification. However, when these treatment operations are installed in their respective facilities, the building, alpha containment and support systems costs tend to reduce the cost differential between Level II and Level III facilities. The EATF did not factor in triple confinement of plutonium handling facilities (addressed in DOE 6430.1A General Design Criteria) in its cost estimates, for the following reasons: treatment operation costs for existing facilities (which form the basis for EATF cost estimates) are computed on a double-confinement basis; design and number of confinement barriers are predetermined on a case-by-case basis (DOE, 1987b). As a result, the cost differential between Level II and Level III is further reduced once triple confinement is factored into the design.

Capacity, as noted in Table 6-4, is designated as a percent of the total TRU waste generated through 2013 as projected by the IDB, 1988. This capacity is the sum of retrievably stored and/or newly generated waste from sites that feed the processing facilities for each of the seven options. An attempt was made to match treatment sites and waste locations in such a way that preference for treatment facilities is given to larger waste generating or storage sites in order to minimize waste transportation. Note that the siting options of Table 6-4 are examples, as other choices may also be appropriate. For instance, if only one facility were to be built, other sites besides WIPP are also candidates to host a central facility.

**TABLE 6-3**  
**EXISTING AND PLANNED DOE TRU FACILITY COST EXAMPLES**

Facility <sup>1</sup>	Facility Capacity (m <sup>3</sup> /yr)	Cost Treatment (Millions, 1990 dollars)	Level <sup>2</sup>
TWF, SRS (Westinghouse, 1990)	720	181 M	II
WRAP, Hanford Module 1 (Kaiser, 1989)	3850	54 M	II
WRAP, Hanford Module 2 <sup>3</sup>	TBD	150 M	II
TWTSF, INEL (DOE, 1989a)	5800	137 M	II
WHPP <sup>4</sup> , ORNL (DOE, 1989d)	200	238 M	III
TDF, LANL (Hutchins, 1990)	850	7 M	III
SaRF, RFP (Barthel, 1988)	1800	6 M	II
SWEPP, INEL (DOE, 1982)	4100	7 M	NA

<sup>1</sup>For complete facility descriptions see Section 6.3.3.

<sup>2</sup>For Treatment Level descriptions see Section 3.3.3.

<sup>3</sup>Personal communication, Chris Petersen, 1990.

<sup>4</sup>WHPP is a RH-TRU facility. Cost is included for comparison purposes only. Capacity based on Turner (1991).

TBD = To be determined.

NOTE: Facilities are intended for CH-TRU waste unless indicated otherwise.

TABLE 6-4

**POTENTIAL WASTE TREATMENT SITES AND WASTE  
DISTRIBUTION SCENARIOS FOR 1-7 FACILITIES**

Number of Facilities	Facility Location	Treats Waste From:	Quantity of Waste Treated, Percent
1	WIPP	All Sites	100.0
2	INEL	Hanford, INEL, LANL LLNL, NTS, RFP	83.9
	SRS	ANL-E, Mound, ORNL, SRS	16.1
3	INEL	Hanford, INEL	43.3
	RFP	RFP	26.7
	WIPP	LANL, LLNL, NTS, Mound, ANL-E, ORNL, SRS	30.0
4	INEL	INEL, LANL, LLNL, NTS	41.5
	RFP	RFP	26.7
	SRS	ANL-E, Mound, ORNL, SRS	16.0
	Hanford	Hanford	15.8
5	INEL	INEL	27.5
	RFP	RFP	26.7
	SRS	ANL-E, Mound, ORNL, SRS	16.0
	Hanford	Hanford	15.8
	WIPP	LANL, LLNL, NTS	14.0
6	INEL	INEL	27.5
	RFP	RFP	26.7
	Hanford	Hanford	15.8
	SRS	ORNL, SRS	15.1
	LANL	LANL	11.4
	WIPP	ANL-E, LLNL, Mound, NTS	3.5
7	INEL	INEL	27.5
	RFP	RFP	26.7
	Hanford	Hanford	15.8
	SRS	SRS	14.0
	LANL	LANL	11.4
	WIPP	ANL-E, LLNL, Mound, NTS	3.5
	ORNL	ORNL	1.1

Waste work-off periods of five, ten, and twenty years have been considered for each of these cases. Continuously operated facilities are assumed to operate 24 hours per day for 240 days per year, allowing approximately 125 days per year for maintenance. An exception to this rule is noted in the discussion on operating costs, Section 6.3.4.2. If more than one treatment operation is required in a single facility, the effect of capacity on the cost of each treatment operation is computed, and these costs are added to the support facility costs. Table 6-5 shows the total processing capacities of facilities needed to treat all waste in five, ten, or twenty year work-off periods. The data presented in Table 6-5 has been generated under the assumption that processing would begin in the year 2000.

The EATF also determined the need for minimum facility costs. Minimum facility costs are determined to preclude unrealistically low estimates. Low estimates result when the design capacity for continuous operation equipment becomes excessively small relative to the basis capacity of process operations. Treatment facility cost estimates are presented in Section 6.3.4.5

#### 6.3.4.2 Treatment Facility Operating Cost Estimation

The EATF has developed a method to estimate annual operating costs for continuous and batch operated TRU waste treatment facilities. This method is based on an empirical relationship between annual operating costs and facility capital costs. A review of literature (McKee et al., 1986; Ross et al., 1982) revealed that annual operating cost for continuous operation (24 hours/day, 200 days/year) is approximately 10 percent of facility capital cost. The EATF assumed operation for 240 days per year and thus estimates operating costs at 12 percent of capital costs.

Annual operating costs for batch processing facilities are estimated from operational requirements. A facility that does not operate continuously (based on capacity requirements) is defined as a batch operated facility. The EATF has assumed the minimum operation requirements of a batch operated facility to be one 8-hour shift per day, 240 days per year. Since operating costs for continuous operation is defined at 12 percent of capital, the annual operating costs for batch operated facilities are defined as a minimum of 4 percent of capital costs. Actual operating costs will vary between 4 and 12 percent of facility capital costs depending on the number of hours operated on a yearly basis. Operating cost estimates are present in Section 6.3.4.5.

#### 6.3.4.3 Waste Transportation Cost Estimation

The EATF has developed transportation cost estimates for each of the fourteen engineered alternatives described in Table 1-2, using the potential waste treatment site locations outlined in Table 6-4. Transportation costs are a result of transporting waste between sites and loading and unloading operations at storage and/or generator sites, treatment sites, and finally the WIPP. Three basic cost components have been defined by the EATF:

- Costs associated with loading waste into TRUPACT-IIs
- Costs associated with unloading TRUPACT-IIs
- Costs of transporting waste between sites.

Capital and maintenance costs for TRUPACT-IIs and tractor-trailer rigs are not included.

**TABLE 6-5**  
**TOTAL WASTE TREATMENT FACILITY**  
**CAPACITY REQUIREMENTS**  
**(m<sup>3</sup>/yr)**

THIS TABLE PRESENTS TOTAL PROCESSING CAPACITY OF FACILITIES NEEDED TO TREAT ALL WASTE IN 5, 10, OR 20 YEARS, BEGINNING IN THE YEAR 2000.

SITES	SOLID ORGANICS	SOLID INORGANICS	SLUDGES	TOTAL
<b>5 YEAR WORK-OFF</b>				
ANL-E	6	4	9	19
INEL	2972	2598	1934	7504
LANL	881	1345	881	3107
LLNL	473	87	17	577
Mound	12	24	203	239
NTS	71	51	2	124
ORNL	185	121	3	309
Hanford	1747	2318	243	4309
RFP	3403	1966	1911	7280
SRS	2859	820	133	3812
<b>TOTAL</b>	<b>12611</b>	<b>9332</b>	<b>5338</b>	<b>27280</b>
<b>10 YEAR WORK-OFF</b>				
ANL-E	3	2	4	9
INEL	1486	1299	967	3752
LANL	441	672	440	1553
LLNL	237	43	9	289
Mound	6	12	102	120
NTS	35	25	1	62
ORNL	93	60	2	155
Hanford	874	1159	122	2154
RFP	1702	983	956	3640
SRS	1430	410	67	1906
<b>TOTAL</b>	<b>6305</b>	<b>4666</b>	<b>2669</b>	<b>13640</b>
<b>20 YEAR WORK-OFF</b>				
ANL-E	2	1	2	5
INEL	743	650	484	1876
LANL	220	336	220	777
LLNL	118	22	4	144
Mound	3	6	51	60
NTS	18	13	1	31
ORNL	46	30	1	77
Hanford	437	580	61	1077
RFP	851	491	478	1820
SRS	715	205	33	953
<b>TOTAL</b>	<b>3153</b>	<b>2333</b>	<b>1334</b>	<b>6820</b>

Note: Numbers above are rounded figures.

Transportation costs are influenced by the location of waste relative to treatment facilities and the WIPP, and the final weight of processed waste form. Overall transportation costs are determined by the number of transports required to ship the entire TRU inventory from generator and/or storage sites to treatment locations first and then the WIPP. The number of transports determines the number of loading and unloading operations required as well as the total distance traveled.

Costs associated with transporting processed waste are not equivalent to the cost of transporting unprocessed waste. Processed waste will be much heavier than unprocessed waste, due to the reduction (or elimination) of void space. The increased weight of processed waste will reduce the volume of waste which can be shipped in TRUPACT-IIs, given the estimated 13,595 pounds (6,166 kilograms) per shipment payload restriction for three TRUPACT-IIs (Gregory, 1991). Although decreasing the waste volume per shipment will increase the number of transports relative to the baseline case (untreated waste), reductions in waste volume that result from processing will partially offset this increase by decreasing the total number of shipments required. The volume reduction for Level III options are sufficiently large enough that the number of transports is reduced from the baseline case. However, for Level II treatment alternatives (e.g., shredding and cementing), the volume reduction is not large enough to compensate for the effects of increased weight of the waste. This results in an increase in the number of transports relative to the baseline design for Level II treatment alternatives.

There are three shipping scenarios considered in computing waste transportation costs:

- Transportation of unprocessed waste to treatment facilities, followed by transportation of processed waste to the WIPP
- Transportation of unprocessed waste to the WIPP for treatment followed by disposal
- Transportation of processed waste to the WIPP, after treatment at the generator/storage site.

Site-to-site mileage estimates for the ten TRU waste generator/storage sites and the WIPP (Table 6-6) have been used to develop total TRUPACT-II miles (Table 6-7) required for each engineered alternative and siting option. Total TRUPACT-II miles are defined as the distance traveled in transporting all TRU waste to treatment locations and subsequently to the WIPP (including return trips with empty TRUPACT-IIs). Total TRUPACT-II mileage estimates take into account properties of processed waste in relation to TRUPACT-II payload restrictions. The methodology, assumptions, and numbers used by the EATF to generate transportation cost estimates are outlined in Appendix J. Waste transportation cost estimates are presented in Section 6.3.4.5.

#### **6.3.4.4 Waste Characterization Costs**

Characterization costs are needed in the evaluation of waste-treatment locations. As characterization costs, including construction of characterization facilities and sampling/analysis costs, approach treatment costs, it is anticipated that waste treatment becomes an increasingly viable option.

**TABLE 6-6**  
**ESTIMATE OF DISTANCES BETWEEN DOE FACILITIES**  
**(MILES)**

	ANL-E	INEL	LANL	LLNL	Mound	NTS	ORNL	Hanford	RFP	SRS
ANL-E										
INEL	1427									
LANL	1212	988								
LLNL	2173	936	1209							
Mound	343	1674	1333	2455						
NTS	1839	443	545	629	2065					
ORNL	626	1856	1485	2485	491	2030				
Hanford	1832	581	1133	855	2191	1019	2382			
RFP	1021	551	337	1255	1229	817	1344	1101		
SRS	767	2070	1664	2682	554	2198	240	2573	1582	
WIPP	1404	1484	352	1345	1460	1017	1493	1847	666	1447

REFERENCE: Site-to-site and site-to-WIPP (NuPac, 1989; Rand McNally, 1989).

**TABLE 6-7**  
**ROUND TRIP TRUPACT-II MILE ESTIMATES, 1-7 FACILITIES,**  
**FOR COMBINATION ALTERNATIVES 1-14**

Miles Traveled For Each Option and Alternative<sup>1, 2</sup>  
(Millions)

COMBINATION ALTERNATIVE	NUMBER OF FACILITIES <sup>3</sup>						
	1	2	3	4	5	6	7
1	32	105	64	89	74	75	75
2,3	32	112	68	95	79	80	80
4,5	32	72	46	59	48	48	48
6,7	32	40	29	31	25	25	25
8,9,13	32	25	19	17	13	12	12
10	32	44	30	34	27	27	27
11,12,14	32	40	27	30	24	23	23

<sup>1</sup> Values computed using Table 6-6 distance information, 10 cubic meters of unprocessed waste per transport (Batchelder, 1990), and waste volume (sum total of retrievably stored and newly generated) at each site.

<sup>2</sup> TRUPACT-II shipments are limited to 13595 pounds (Gregory, 1991) of waste.

<sup>3</sup> Refer to Table 6-4 for facility locations.

At the present time, the extent of waste characterization required before wastes can be emplaced at WIPP, is uncertain. It is for this reason that the EATF did not estimate characterization costs. The EATF did identify factors that affect characterization costs:

- Construction of additional facilities at DOE sites to provide capabilities for meeting TRAMPAC requirements and possibly RCRA sampling and analysis
- Resources for operating the above facilities
- Quantity of waste requiring characterization, i.e., extent of process knowledge
- Existing and planned characterization capabilities.

The degree of characterization required will depend on the regulations imposed (Section 6.3.6) and how much is known about the generation process of the waste. Compliance with TRAMPAC parameters will be required for transportation whereas RCRA compliance may be required for both transportation and disposal. Less is known about retrievably stored waste than newly generated waste categorized by content code (DOE, 1989e).

#### **6.3.4.5 Waste Treatment and Transportation Cost Estimate Results**

Results of the EATF waste treatment facility cost study are presented in Table 6-8. The table presents capital costs, annual operating costs, life cycle operating costs, and total project costs for each engineered alternative and potential treatment location described in Table 1-2 and Table 6-4, respectively. Life cycle operating costs represent the cost in 1990 dollars required to begin waste processing in the year 2000. The total project cost is the sum of capital cost and life cycle operating costs. Varying the period of time over which the total inventory of TRU waste is processed (5, 10, and 20 years) serves to illustrate the relationship between cost and treatment capacity. The results presented in Table 6-8 lead to the following observations:

- Level III treatment alternatives (thermal) are more expensive than Level II treatment alternatives by factors ranging from approximately two to four. Level III treatment operations are more expensive than Level II treatment operations for any given capacity.
- Treatment facility capital costs significantly increase with the number of individual treatment operations required to produce a particular waste form. That is, the more treatment operations required to produce a particular waste form the more expensive the facility.
- Multiple facilities (total system capacity is constant) are more expensive relative to a single facility by approximately 25 percent for five-year work-off periods and approximately 75 percent for 20-year work-off periods.

TABLE 6-8a

**FACILITY CAPITAL AND ANNUAL OPERATING COST<sup>1,2</sup> - FIVE-YEAR WORK-OFF  
(Cost in Millions)**

Combination Alternative		One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	390	410	440	460	470	480	510
	Annual Operations Cost	47	50	53	55	57	57	58
	Life Cycle Operations Cost	90	95	100	110	110	110	110
	1990 Project Cost	480	510	550	560	580	590	620
2,3	Capital Cost	440	470	500	520	540	550	570
	Annual Operations Cost	53	56	61	62	64	65	65
	Life Cycle Operations Cost	100	110	120	120	120	120	130
	1990 Project Cost	550	580	620	640	660	670	700
4,5	Capital Cost	870	920	990	1000	1000	1100	1100
	Annual Operations Cost	100	110	120	120	130	130	130
	Life Cycle Operations Cost	200	210	230	230	240	250	250
	1990 Project Cost	1100	1100	1200	1300	1300	1300	1400
6,7	Capital Cost	1200	1200	1300	1400	1400	1400	1500
	Annual Operations Cost	140	150	160	170	170	170	170
	Life Cycle Operations Cost	270	290	310	320	330	330	330
	1990 Project Cost	1400	1500	1700	1700	1800	1800	1800
8,9,13	Capital Cost	1500	1600	1700	1800	1800	1900	1900
	Annual Operations Cost	180	190	210	210	220	220	220
	Life Cycle Operations Cost	350	370	400	410	420	420	430
	1990 Project Cost	1900	2000	2100	2200	2200	2300	2400
11,12,14	Capital Cost	260	280	300	300	310	330	340
	Annual Operations Cost	31	33	36	37	38	38	39
	Life Cycle Operations Cost	60	63	68	70	72	73	74
	1990 Project Cost	320	340	360	380	390	400	420
10	Capital Cost	730	770	830	860	880	900	940
	Annual Operations Cost	88	93	100	100	110	110	110
	Life Cycle Operations Cost	170	180	190	200	200	210	210
	1990 Project Cost	900	950	1000	1100	1100	1100	1100

<sup>1</sup>Number above are rounded figures.

<sup>2</sup>1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

TABLE 6-8b

**FACILITY CAPITAL AND ANNUAL OPERATING COST<sup>1,2</sup> - TEN-YEAR WORK-OFF  
(Cost In Millions)**

Combination Alternatives	One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	210	220	240	250	260	300
	Annual Operations Cost	25	27	29	30	31	32
	Life Cycle Operations Cost	72	76	82	84	87	90
	1990 Project Cost	280	300	320	330	340	390
2,3	Capital Cost	240	250	270	280	290	340
	Annual Operations Cost	29	31	33	34	35	36
	Life Cycle Operations Cost	82	87	93	96	99	100
	1990 Project Cost	320	340	370	380	390	440
4,5	Capital Cost	470	500	540	550	570	640
	Annual Operations Cost	57	60	65	67	69	71
	Life Cycle Operations Cost	160	170	180	190	190	200
	1990 Project Cost	630	670	720	740	770	840
6,7	Capital Cost	640	680	730	750	770	880
	Annual Operations Cost	77	81	87	90	93	96
	Life Cycle Operations Cost	220	230	250	260	260	270
	1990 Project Cost	860	910	980	1000	1000	1200
8,9,13	Capital Cost	820	870	930	960	990	1100
	Annual Operations Cost	98	100	110	120	120	120
	Life Cycle Operations Cost	280	300	320	330	340	350
	1990 Project Cost	1100	1200	1300	1300	1300	1500
11,12,14	Capital Cost	140	150	160	170	170	210
	Annual Operations Cost	17	18	19	20	20	21
	Life Cycle Operations Cost	48	51	55	56	58	60
	1990 Project Cost	190	200	220	220	230	270
10	Capital Cost	400	420	450	470	480	550
	Annual Operations Cost	48	50	54	56	58	60
	Life Cycle Operations Cost	140	140	150	160	160	170
	1990 Project Cost	530	560	610	620	640	720

<sup>1</sup>Number above are rounded figures.

<sup>2</sup>1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

TABLE 6-8c

**FACILITY CAPITAL AND ANNUAL OPERATING COST<sup>1,2</sup> - TWENTY-YEAR WORK-OFF**  
(Cost in Millions)

Combination Alternatives	One Facility	Two Facilities	Three Facilities	Four Facilities	Five Facilities	Six Facilities	Seven Facilities
1	Capital Cost	120	130	130	150	160	210
	Annual Operations Cost	14	15	16	16	17	18
	Life Cycle Operations Cost	43	48	49	51	52	57
	1990 Project Cost	160	170	180	200	210	270
2,3	Capital Cost	130	140	150	160	170	220
	Annual Operations Cost	16	17	18	18	19	20
	Life Cycle Operations Cost	49	52	56	58	59	64
	1990 Project Cost	180	190	210	220	230	290
4,5	Capital Cost	260	270	290	300	310	410
	Annual Operations Cost	31	33	35	36	37	40
	Life Cycle Operations Cost	97	100	110	110	120	120
	1990 Project Cost	350	370	400	410	430	530
6,7	Capital Cost	350	370	400	410	430	570
	Annual Operations Cost	42	44	48	49	50	54
	Life Cycle Operations Cost	130	140	150	150	160	170
	1990 Project Cost	480	510	550	560	590	740
8,9,13	Capital Cost	450	470	510	530	550	740
	Annual Operations Cost	53	57	61	63	65	69
	Life Cycle Operations Cost	170	180	190	200	200	220
	1990 Project Cost	610	650	700	720	760	950
11,12,14	Capital Cost	77	81	87	100	110	160
	Annual Operations Cost	9	10	10	11	11	12
	Life Cycle Operations Cost	29	31	33	34	35	39
	1990 Project Cost	110	120	120	140	150	190
10	Capital Cost	220	230	250	260	280	370
	Annual Operations Cost	26	27	29	30	31	34
	Life Cycle Operations Cost	81	86	92	95	98	110
	1990 Project Cost	300	320	340	360	380	480

<sup>1</sup>Number above are rounded figures.

<sup>2</sup>1990 Project Cost = Sum of Capital Cost and Life Cycle Operations Cost.

- Cost is dependent on work-off period. Capital cost of facilities with a 20-year work-off period will cost less than those with a five-year work-off period. The system capacity required for a five-year work-off period is four times the system capacity required for a 20-year work-off period.

Results of the EATF waste transportation cost study are presented in Table 6-9 as life cycle transportation costs. These results illustrate the dependency of transportation costs on the level of treatment, and on the number and location of waste treatment facilities. These results have led to the following conclusions:

- A single treatment facility located at the WIPP results in transportation costs that are equal to the baseline case. No change in the baseline (current) transportation scheme would be required for this siting scenario.
- The significant increase in total TRUPACT-II miles and corresponding transportation costs associated with multiple Level II treatment facilities is a result of additional transports required to comply with TRUPACT-II payload limitations. These limitations force partial shipments of waste, thereby increasing the total number of shipments required. In discussions with site personnel (Gregory, 1991), the EATF has learned that efforts are under way to reevaluate the payload restrictions on the TRUPACT-II and develop modified designs that will be able to accommodate larger payloads. Such developments in the future will help to reduce the transportation costs estimated for Level II waste forms.
- Transportation costs and corresponding total TRUPACT-II miles for Level III engineered alternatives are less than Level II alternatives for a given treatment/siting scenario (except the one-facility option). This is due to the larger volume reductions associated with Level III treatment alternatives. The cost savings for transporting Level III waste forms as opposed to Level II waste forms partially offset the greater capital expenditures required for Level III treatment facilities.
- Transportation costs for Level III waste treatment alternatives decrease as the number of treatment facilities is increased. An increase in the number of treatment facilities reduces the volume of unprocessed waste requiring shipment to intermediate treatment locations, and thus results in a reduction of the overall transportation cost.

### 6.3.5 Implementation Schedules

The EATF relied on published data and discussions with DOE waste generator site personnel (rather than detailed development of schedules as part of facility conceptual design) to estimate waste-treatment implementation schedules. More detailed schedules can be developed only after conceptual designs of appropriate waste treatment facilities are completed. The schedules presented below are intended to provide a comparison between alternative

TABLE 6-9

**LIFE CYCLE TRANSPORTATION COSTS**  
**(Cost in Millions of 1990 Dollars)**

Combination Alternative	One Facility <sup>1</sup>	Two Facilities <sup>1</sup>	Three Facilities <sup>1</sup>	Four Facilities <sup>1</sup>	Five Facilities <sup>1</sup>	Six Facilities <sup>1</sup>	Seven Facilities <sup>1</sup>
1	71	230	140	190	160	170	170
2,3	71	240	150	210	170	180	180
4,5	71	160	100	130	110	110	110
6,7	71	90	63	68	55	55	55
8,9,13	71	57	42	37	29	27	27
10	71	99	66	74	60	60	60
11,12,14	71	89	60	65	52	51	51

<sup>1</sup>Refer to Table 6-4 for facility locations.

combinations. Overestimates or underestimates in categories such as technical feasibility studies are generally proportional to the complexity of the treatment alternative, and hence may change the absolute schedule, but should not change the relative differences between treatment alternatives.

Implementation schedules evaluated by the EATF for waste treatment facilities cover facility conception through start-up. Four components were included in the development of schedules: preconstruction, engineering, construction, and start-up. Table 6-10 lists tasks included in each category. The EATF has not assigned schedules to each task or category because many of the tasks, e.g., construction and engineering, overlap.

The schedule factors considered by the EATF to have the greatest uncertainty are regulatory/compliance issues (refer to Section 6.3.6), budget-cycle constraints, and technology demonstration using TRU waste. The EATF has not attempted to quantify the potential for extended permitting or review cycles, or the effect of budgetary constraints, but has instead used schedules published for DOE facilities. It should be noted that permitting time during various stages of waste processing facility development (preconstruction, engineering, construction, and start-up) can be extensive and difficult to quantify. The EATF has assumed that regulatory permitting issues are part of the preconstruction period of implementation schedules, and that permitting issues are not rate-limiting.

The time frames for demonstrating technical feasibility of various TRU waste treatment alternatives are difficult to determine due to the lack of published data. Although the effort involved in technology demonstrations are frequently underestimated, the EATF has assumed that this effort will proceed in parallel with other activities and not be a rate-limiting step. Initial demonstration will be required prior to a decision on waste treatment. Production of small quantities of modified waste forms for laboratory or field experiments is the likely driver for these early demonstrations. Pilot-plant demonstration is assumed to coincide with early design work on one or more treatment facilities and is assumed to culminate in time to be factored into final treatment facility design.

Table 6-11 provides examples of published construction schedules for DOE waste processing facilities. The table indicates a relationship between level of treatment and length of the construction schedule. These observations lead the EATF to conclude that implementation schedules for waste treatment alternatives will be influenced by the level of waste treatment (II or III) required. For example, construction of a Level II waste treatment facility requires between three and four years (refer to Table 6-11). Construction of a Level III waste treatment facility requires between four and six years. Because no other data exist, the upper bound on construction time for Level III treatment was selected from the construction time required for High-Level Waste (HLW) treatment facilities (DOE, 1989b).

The time required for preconstruction activities for Level II treatment facilities is assumed to be two to three years based on published overall project schedules for the Level II waste treatment facilities listed in Table 6-11. On the same basis, the time required for Level III facility preconstruction activities is assumed to be three to four years. The upper bound for

**TABLE 6-10**  
**SCHEDULING CONSIDERATION EXAMPLES**

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**Preconstruction -**

- Site Characterization
- Feasibility Study
- Environmental Assessment
- Environmental Impact Statement
- Preliminary Safety Analysis
- Applicable Permits

**Engineering -**

- Conceptual Design
- Preliminary Design
- Title I Design
- Title II Design
- Final Design

**Construction -**

- Procurement/Fabrication
- Construction
- Project Management
- Final Safety Analysis Report

**Start-Up -**

- Personnel Training & Qualifications
- Cold Testing
- Hot Start-Up

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TABLE 6-11

**EXAMPLES OF EXISTING AND PLANNED  
DOE FACILITY CONSTRUCTION SCHEDULES**

Facility <sup>1</sup>	Facility Capacity (m <sup>3</sup> /yr)	Construction Schedules <sup>2</sup> (years)	Treatment Level <sup>3</sup>
TWF, SRS (Westinghouse, 1990)	720	3	II
WRAP, Hanford Module 1 (Kaiser, 1989)	3850	3	II
TWTSF, INEL (DOE, 1989a)	5800	4	II
WHPP <sup>4</sup> , ORNL (DOE, 1989d)	200	5	III

<sup>1</sup>Complete facility descriptions in Section 6.2

<sup>2</sup>Facility construction schedules from (DOE, 1989b)

<sup>3</sup>For Treatment Level descriptions see Section 3.3.3

<sup>4</sup>WHPP is a RH-TRU facility. Capacity based on Turner (1991).

**NOTE:** Facilities are intended for CH-TRU waste unless indicated otherwise, information on RH is intended for comparison purposes only.

preconstruction activities is based on WHPP conceptual design (DOE, 1989d), which states that approximately four years will be required for site characterization activities.

The duration between completion of construction and full operation start-up is assumed to require six months to one year for Level II treatment facilities, and one to two years for Level III facilities based on DOE TRU and HLW facility schedules summarized in the Environmental Restoration and Waste Management Five-Year Plan (DOE, 1989b).

By summing the various schedule components, the EATF has developed rough estimates of implementation schedules for treatment facilities. Generic estimates of implementation schedules are:

Level II Waste Treatment	5-7 years
Level III Waste Treatment	8-11 years

No additional time is included for research and development.

Schedules are influenced by facility size, complexity, and the time required to complete preconstruction activities such as permitting, site characterization, and environmental assessments. The lower bound of the implementation schedule range applies to single treatment operation facilities with low waste treatment capacity, while the upper bound applies to facilities with multiple treatment operations and higher treatment capacity.

The estimated facility implementation schedules for each of the 14 combination alternatives evaluated by the EATF are presented in Table ES-2.

### 6.3.6 Regulatory Considerations

Regulatory requirements and institutional constraints governing new waste treatment facilities, as well as controlling the transportation and characterization of waste, were evaluated by the EATF for three reasons:

- Possibility that a treatment option may prove to be unfeasible because of insurmountable regulatory requirements
- Costs associated with regulatory compliance
- Impact on schedules from regulatory compliance.

Unfortunately, regulatory requirements and institutional constraints are the components of feasibility evaluated by the EATF over which DOE has the least control. Consequently, regulatory issues have the greatest degree of uncertainty in the EATF's quantification of these factors.

The following are regulatory/institutional factors identified by the EATF that affect waste treatment facilities, as well as the transportation and characterization of TRU wastes before and after waste treatment.

#### **6.3.6.1 Federal Regulations for Waste Treatment Facilities**

Current and previous DOE experience in building waste treatment facilities has been used by the EATF to assemble a list of federal regulations which affect the permitting process for waste treatment facilities (Table 6-12). Facility permitting complexity grows with the complexity of waste treatment being considered.

#### **6.3.6.2 Institutional Factors Affecting Waste Treatment Facilities**

The EATF defines Institutional factors as a condition (e.g., local regulation) which is unique to the site and has an effect on waste treatment. The EATF surveyed the DOE TRU waste generators for institutional and regulatory information regarding the siting of waste treatment facilities in those states that are hosts to major TRU waste generator sites. Information was provided by Hanford (Roberts, 1991); SRS (Dyches, 1991); RFP (O'Leary, 1990); ORNL (Mason, 1990); INEL (Solecki, 1991); and WIPP (Carrell, 1990; Kouba, 1990). This information encompassed the following:

- Applicable State Regulations
- State Jurisdictions
- Comparison of State and Federal Regulations
- Costs Associated With State Regulatory Compliance
- Effect on Schedule of State Regulation
- State/DOE Interfaces
- Institutional Sentiments Regarding New Waste Treatment Facilities.

The following conclusions were drawn from this information:

- Collectively, the respondents noted above do not anticipate institutional factors having adverse effects on siting new waste treatment facilities provided that storage of treated waste does not occur on site. Rocky Flats appears to be an exception regarding the construction of new waste treatment facilities, although add-ons to existing waste generating facilities might be more acceptable.
- Cost and schedule are not expected to be unduly affected by state or federal permitting requirements. Although in some cases RCRA permits can require several years to obtain, the permitting process is generally conducted in parallel with design, construction, and NEPA processes. Permitting costs are generally factored into the overall estimates, and extraordinary costs for permitting are not expected.

**TABLE 6-12**  
**POTENTIAL REGULATORY REQUIREMENTS**

<u>WASTE TREATMENT</u>	<u>REGULATORY REQUIREMENTS</u>
Cementation	RCRA, HSWA, NESHAP, NEPA
Compaction, Metal Decon	RCRA, NESHAP, NEPA
Thermal Treatments Incineration Vitrification Metal Melting	RCRA, CAA, CWA <sup>1</sup> , TSCA, NESHAP, PSD, NAAQS, NSPS, NEPA
Shredding/Sorting	RCRA, NESHAP, NEPA
Addition of pH Buffers	RCRA, NESHAP, NEPA

<sup>1</sup>For waste water discharged off site. Waste water retained on site may be regulated by certain states.

#### Definitions

RCRA	- Resource Conservation and Recovery Act of 1976
HSWA	- Hazardous Solid Waste Amendment of 1984
NESHAP	- National Emission Standards for Hazardous Air Pollutants 40 CFR Part 61
NEPA	- National Environmental Protection Act, 1969
CAA	- Clean Air Act, Air Quality Act and associated state implementation
CWA	- Clean Water Act
TSCA	- Toxic Substances Control Act
PSD	- Potential for Significant Deterioration (40 CFR Part 52.21)
NAAQS	- National Ambient Air Quality Standards
NSPS	- New Source Performance Standards

- Although some minor regulatory differences are apparent from state to state, these differences are not sufficient to affect the siting evaluation.
- There do not appear to be any significant conflicts between state and federal regulations, although ORNL reports that state regulations are generally more stringent than federal.

In summary, there appears to be cautious optimism at most DOE sites that Institutional and regulatory considerations would not be major factors for siting a waste treatment facility at their respective locations. This optimism must be tempered, given that these same facilities have little or no experience in permitting TRU-waste treatment facilities. Intuitively, the logistics of regulatory compliance at multiple sites versus a single site suggests that limiting the number of treatment facilities should simplify regulatory compliance. However, limiting facilities increases transport of wastes from other sites, which will dramatically increase public opposition to these facilities. Unfortunately, resolution is only possible through experience in permitting radioactive waste treatment facilities in candidate states. There is little likelihood that such data will exist at the time a decision on treatment and siting of facilities must be made. The best that can be expected is that the permitting process is begun concurrent with facility conceptual design and that the preliminary results of the process are available at the time of treatment and site selection.

#### 6.3.6.3 Regulations and Institutional Requirements Governing Waste Transport/Characterization

The waste transportation and waste characterization issues have the potential to limit siting options and to significantly influence costs of and schedules for waste treatment facilities. For example, characterization of TRU waste will be required to comply with the Nuclear Regulatory Commission (NRC) Certificate of Compliance for the TRUPACT-II, including the TRAMPAC requirements outlined in Appendix 1.3.7 of the Safety Analysis Report (NuPac, 1989). For example, the NRC Certificate of Compliance for the TRUPACT-II is explicit with regard to allowable hydrogen concentration (generated by radiolysis of organic material) permitted during the time waste is enclosed in the TRUPACT-II in order to ensure that excessive build-up of flammable gases is avoided. This criterion applies to hydrogen concentration in the innermost waste bag as well as between the layers of waste bags surrounding the waste (NuPac, 1989). Knowledge of how the waste is packaged is important to demonstrating that the waste will meet the NRC hydrogen concentration requirement. Similarly, knowledge of levels of flammable volatile organic compounds (VOC) and of gas generating materials is required. Significant quantities of waste may have to be characterized at each DOE site unless sufficient process knowledge exists to satisfy this requirement and regulatory bodies are amenable to accepting process knowledge in lieu of analysis.

The data presented in Table 6-13 was submitted in response to NRC requests for information concerning transportability of retrievably stored and newly generated waste (as is) under the Initial Certificate of Compliance (NuPac, 1989). This table represents the amount of waste (based on quantities reported in DOE, 1988c) in retrievable storage and newly generated,

TABLE 6-13

FIRST CERTIFICATE OF COMPLIANCE SHIPPABLE WASTE QUANTITIES<sup>1,2</sup>

SITE	RETRIEVABLY STORED		NEWLY GENERATED	
	Percent <sup>1</sup>	Volume, <sup>3</sup> (M <sup>3</sup> )	Percent	Avg. Volume (M <sup>3</sup> /yr)
ANL-E	-- <sup>4</sup>	--	0 <sup>6</sup>	0
Hanford	0 <sup>7</sup>	0	43	186
INEL	50	17782	80	60
LLNL	--	--	100	111
LANL	70	5104	75	238
Mound	--	--	100	46
NTS <sup>5</sup>	100	620	--	--
ORNL	0 <sup>6</sup>	0	0 <sup>6</sup>	0
RFP	--	--	95	1330
SRS	0 <sup>7</sup>	0	70	433

<sup>1</sup>The figures are based on input from CH-TRU waste generators response to the question, "What percentage of newly generated and/or retrievably stored waste at each site is shippable under the current TRUPACT-II C or C (August 1989)?" The results of the questionnaire assumes no changes to existing waste processes or packaging procedures at each site other than installation of a carbon composite filter and puncturing of rigid liners if present.

<sup>2</sup>Drez, 1989.

<sup>3</sup>Volume based on DOE 1988c, retrievably stored and average generation rate.

<sup>4</sup>-- Indicates no retrievably stored or newly generated waste at this DOE site.

<sup>5</sup>Excluding oversized boxes.

<sup>6</sup>Site uses heat-sealed bags (not allowed under TRUPACT-II Certification of Compliance).

<sup>7</sup>Insufficient knowledge of packaging and chemistry of waste to meet TRAMPAC requirements.

which could be transported at this time. This table illustrates the difficulty with meeting well-defined characterization requirements.

In addition to the NRC requirements for transporting TRU waste, RCRA requires characterization to meet the following requirements:

- Waste generator (40 CFR Part 262) - requires that a generator determine if solid wastes produced are a hazardous waste. The characterization is accomplished through process knowledge and/or sampling and analysis of the waste.
- Treatment/storage/disposal facility (40 CFR Part 265) - requires that WIPP verify that the waste shipped to WIPP is the waste specified on the accompanying manifest.
- Land disposal restrictions (40 CFR Part 268 and Hazardous and Solid Waste Amendments) - WIPP has been granted a Conditional No-Migration Determination for the test phase (maximum of 10 years) of WIPP, which specifies waste characterization requirements. These requirements are intended to provide the data needed to support a No-Migration Variance Petition for the operations phase of WIPP.

#### 6.3.7 Assessment of Risk

The final component of feasibility investigated by the EATF is the health-based risk to workers, the public, and the environment due to waste treatment. Engineered alternatives involving treatment of wastes can be expected to increase some short-term occupational and health-based risk due to waste treatment, with some corresponding level of reduction in long-term risk. The EATF examined in detail the risks inherent in treating and emplacing differently treated wastes at WIPP (Appendix I). The total risk of planned (no waste treatment) operations at WIPP is chosen as the baseline risk. The baseline risk is based on waste characteristics as defined by the Waste Acceptance Criteria (WAC) and on experience gained with wastes already produced, handled, and characterized (DOE, 1989f; Clements and Kudera, 1985). Among the many possible treatments of the wastes, a few options are chosen to represent the span of characteristics of treated wastes.

A risk assessment of the entire WIPP operation over its operating lifetime and the subsequent postclosure period includes risks for a variety of different operations, incidents, and accidents. Most prominent are those connected with the transportation of the wastes, the corresponding handling operations, and the emplacement of the wastes underground. Once a decision is made to treat the wastes, the risks of the additional handling and all treatment operations will have to be included.

The assessment includes transportation and occupational accidents, exposure to radiation either due to direct external exposure or incorporation of radiol isotopes by the inhalation or ingestion route, and exposure to hazardous components in the wastes. For all these risk

components, both routine exposures and exposures under accident conditions must be considered, and the corresponding risks to the public and the work force calculated. In addition, long-term risks to workers involved in the hypothetical human intrusion scenarios and to nearby residents must be included in the assessment. Increased handling due to waste treatment, and thus an increase in the work force, leads to an increase in the incidence of work-related accidents, potentially resulting in both injuries and fatalities. Also, some waste treatments will result in an increase, others in a decrease, in the number of TRUPACT-II transports to the WIPP. Transportation risks were found to have the largest number of expected fatalities and injuries of all risk components. It is important to keep in mind, however, that even for this component, consequences are low relative to risks faced by the general population.

The largest radiological risk components of the actual disposal operations are expected to arise from direct irradiations of the work crew, and are not expected to be strongly affected by implementation of engineered alternatives. This simplifying assumption arises from the fact that the same amount of radioactivity has to be handled and emplaced underground, regardless of its physical form. In the incident and accident scenarios, however, smaller risk components should be significantly reduced for some waste treatments. For example, untreated wastes have some volatile organic compounds (VOCs) in the inventory, for which the risks of both carcinogenic and noncarcinogenic health effects must be considered. Treatment of wastes to eliminate VOCs will essentially eliminate this risk, even if it is quite small.

Risks from disposal operations fall into two major categories, nonradiological accidents (e.g., forklift accidents) and worker exposure to radiological and toxic substances. For radiation exposures, the risks are primarily the small risk of cancer, as well as of genetic damages. Chemical toxicants potentially could have both carcinogenic and noncarcinogenic health effects. Any release from WIPP should be assumed to result in exposures of the public. Although strongly weakened by surface deposition and filtration and being further diluted by atmospheric dispersion, there are small risks to the public near the installation, risks that are expected to be substantially reduced by treatment of the wastes.

All components of the overall risk that involve treatment of the wastes lead to the potential for additional injuries and fatalities, which do not exist if the wastes were emplaced at WIPP untreated. Both the workers and the public have some small additional risk due to radiological and hazardous-material exposure, even though internal deposition in the plant, filtration, and environmental dilution are expected to reduce public exposures. Thus, it is mostly occupational risks that increase with waste treatment. Routine exposures can be assumed to be low due to the health and safety programs instituted at the treatment facility. The requirements of the ALARA (As Low As Reasonably Achievable) concept in particular are expected to be followed rigorously. Nevertheless, penetrating radiations will lead to a radiation exposure in the work place and consequently the potential for a small occupational risk of cancer and of genetic damage. Accidental events may increase these direct external exposures and their corresponding risks.

As an example, emissions of radioactive aerosols from the enclosures of the treatment devices during routine operations will lead to incorporation of radioisotopes by inhalation and ingestion, resulting in relatively small risks of cancer and genetic effects. The potential for such exposures is somewhat greater during routine maintenance operations, although personal respiratory protection and the enforcement of strict health and safety rules are expected to keep these risks low as well.

The result of the EATF Risk Assessment is a comparison, relative to the baseline (no waste treatment), of selected waste treatment alternatives and facility location options based on indices for overall risk reduction factors. One of the primary tasks of the EATF comparative risk assessment is to scale all components of the total risks to the level of activity required by the different treatment options. A total of four combination alternatives (1, 2, 4, and 8 as reported in Table 1-2) and four treatment location options (WIPP, three facilities, five facilities, and seven facilities, as reported in Table 6-4) have been evaluated. Table 6-14 presents the results of the EATF risk assessment activities in the form of consequence augmentation indices. Appendix I presents a complete discussion of the risk assessment methods, input data, and results in greater detail.

The consequence augmentation index ranges presented in Table 6-14 may be interpreted as follows: a number greater than unity (unity implies treatment and baseline risks are the same, giving a ratio of one) is considered to be an increase in risk relative to the baseline; a number less than unity implies a decrease in risk relative to the baseline. In fourteen of the sixteen treatment cases presented in Table 6-14 more risk is incurred relative to no waste processing. This finding is the combined result of additional risks incurred by waste processing activities and in some cases by increased transportation requirements. In the Level III treatments at five and seven facilities, the consequence augmentation index is less than 1, suggesting actual risk reduction. An index close to one indicates no overall difference in risk relative to the baseline.

Because transportation risks dominate, changes in risk for a given treatment due to the selection of different numbers of treatment sites are mostly due to increases or decreases in the distances over which wastes are transported. After treatment, increases or decreases in waste volume and weight, as well as restrictions in total weight for TRUPACT-II packages, may result in a different number of transports and transport miles from the originator to the treatment facility and from there to the WIPP. With transportation risks (nonradiological) contributing the largest numbers of fatalities and injuries to the total risk associated with WIPP operations, any change in transport miles will affect the total risk significantly.

Another contribution is the cancer risk due to the exposure of the public due to the routine operations, incidents, and accidents in the treatment facility. Different population distributions at different distances from the facility will result in different risks for different sites.

The following conclusions can be drawn from the EATF Risk Assessment:

- Baseline risks are small and increases resulting from the treatment/location options are also small

**TABLE 6-14**  
**CONSEQUENCE AUGMENTATION INDICES<sup>1</sup>**

COMBINATION <sup>2</sup> ALTERNATIVE	NUMBER OF WASTE TREATMENT FACILITIES <sup>3</sup>			
	1	3	5	7
1	1.38 - 1.42	1.47 - 1.55	1.36 - 1.46	1.32 - 1.42
2	1.41 - 1.45	1.54 - 1.62	1.44 - 1.54	1.40 - 1.50
4	1.60 - 1.64	1.32 - 1.50	1.12 - 1.34	1.08 - 1.30
8	2.03 - 2.09	1.26 - 1.30	0.85 - 0.90	0.80 - 0.85

<sup>1</sup>Table may be interpreted as follows (refer to Appendix I for in-depth discussion): ranges more than 1 indicate more risk relative to the baseline; ranges encompassing 1 indicate risk approximately the same as baseline; ranges less than 1 mean risk reduction relative to the baseline.

<sup>2</sup>See Table 1-2 for definition of combination alternatives 1, 2, 4, and 8.

<sup>3</sup>See Table 6-4 for location options of 1, 3, 5, and 7 facilities.

- Increases in overall risk due to Level II treatment options are independent of the treatment location
- Increases in overall risk due to Level III treatment options are minimized by treating nearest the generator/storage sites, due to reduced quantities of wastes requiring transport to WIPP
- Long-term risk components are very small and thus weighted as almost inconsequential. It is the balance between the short-term risk transportation and treatment components that dominate the comparison.

#### 6.4 FACILITY SITING

The objective of this section is to establish a basis for determining where facilities should be located once the decision is made to treat some or all of the wastes. As is the case in any decision analysis involving quantitative and qualitative parameters, this evaluation can be very complex. The EATF concentrated on identifying factors that favor either facilities at each major DOE site, or at a central location. A single facility at WIPP is considered the centralized location for the purposes of this evaluation. The evaluation cannot be finalized until additional information, such as the level of waste treatment required (if any) becomes available. Should performance assessment identify that design changes are needed to meet 40 CFR Part 191 requirements, a more detailed siting analysis will be required in order to finalize the siting decision.

Many pertinent issues needed for this assessment are nonquantifiable at this time. Issues such as waste characterization (for processing, transportation or disposal) that must be included in this assessment are not fully defined. The EATF took the approach of collecting relevant information and determined the potential impact of factors for which requirements are uncertain at this time. For this reason, the recommendations made regarding facility siting are presented in the following form: identification of factors (or conditions of factors) that favor a single facility at the WIPP and the factors favoring facilities in multiple locations.

##### 6.4.1 Basis for Determining Facility Location

The EATF considered several approaches to the siting evaluation of waste treatment facilities, ranging from multiattribute utility analysis to qualitative evaluations based on available information. Schedule and scope of work for the EATF dictated analysis of quantitative and qualitative factors versus more use of decision theory tools. The selected approach consisted of identifying the factors that influence preference between facility siting at individual DOE sites and a centralized location, gathering available data, and analyzing this data to establish qualitative results. Any of the ten sites of interest, in addition to WIPP itself, could be considered a potential location for a processing facility. This analysis has been simplified to

Limit the maximum number of sites for new waste processing facilities to the six largest DOE sites (Hanford, INEL, RFP, LANL, ORNL, SRS) and the WIPP.

Economies-of-scale will be used in the facility siting decision. In other words, a single large facility is preferred to several small facilities from the economic standpoint. Should the analysis identify existing conditions that preclude use of a single TRU waste processing facility, the analysis is then extended to multiple facilities. Such conditions are referred to as "No-Go Factors" and may be unique to individual sites of interest. "No-Go Factors" may be defined as conditions that preclude a TRU waste storage or generating site from hosting a TRU waste processing. Examples of potential "No-Go Factors" include:

- State and local regulatory controls
- Unique waste characteristics (e.g., decay heat, size)
- Extensive waste characterization followed by the need for preparation for transportation
- Institutional constraints (a factor unique to the site or its host state).

In support of the above approach, information on the following factors has been collected and analyzed:

Waste Characterization - Waste characterization or preparation required at individual sites prior to shipping waste off site

Waste Volumes and Locations - Waste generation rate and/or location of stored waste by site

Existing and Planned Facilities - Potential use of existing facilities as the core for a new facility

Transportation - TRUPACT-II miles required for a centralized or multiple locations

Risk - The risk to workers, the general public and the environment associated with the construction and operation of waste treatment facilities at one or more sites

Schedule - The time required to design and construct a single centralized facility versus multiple facilities

Economic Considerations

- Cost off-set for any planned facilities that are not required if a treatment facility is located at individual DOE sites

- Cost of multiple facilities
- Cost of a centralized facility
- Transportation cost factors
- Work-off period

Institutional Analyses - Factors unique to the specific major DOE sites (or their host states) that can or do affect the siting of facilities. Rather than providing absolute direction, these are factors for DOE to consider before making a final siting decision.

Decision models (see Section 6.4.2) have been developed to illustrate the effect of key parameters on the facility siting decision.

#### 6.4.2 Evaluation Methodology

The EATF has developed two facility-siting decision models. The first, presented in Figure 6-3, concentrates on identifying regulatory issues that limit each DOE site's ability to:

- Treat waste on site
- Accept waste from other sites for treatment
- Ship waste elsewhere for treatment.

This information must be determined for all potential host sites and collectively is used as input into the second decision model (Figure 6-4), which is used to optimize site locations. A coupled decision process is the principal component of the second decision model. The benefit of this two-model approach is that both individual site and the system (all sites) considerations are factored into the waste treatment facility siting decision.

##### 6.4.2.1 Decision Issues of Waste Characterization and Certification for Shipment

Factors which force certain siting options must be identified early in the evaluation process. As portrayed in Figure 6-4, waste characterization/certification requirements have the potential to limit such options because of the high cost of characterization. The first three decision nodes in the siting analysis are as follows:

##### **Characterization/Certification Issues that Preclude Shipping Untreated Waste?**

Shipment of waste from a DOE site is predicated upon satisfying state, federal and institutional transportation regulations. These regulations include TRUPACT-II Authorized Methods of Payload Control (TRAMPAC) (NuPac, 1989), WIPP Waste Acceptance Criteria (DOE, 1989f), and the requirement for RCRA characterization prior to waste shipment (see Section 6.3.6.3).

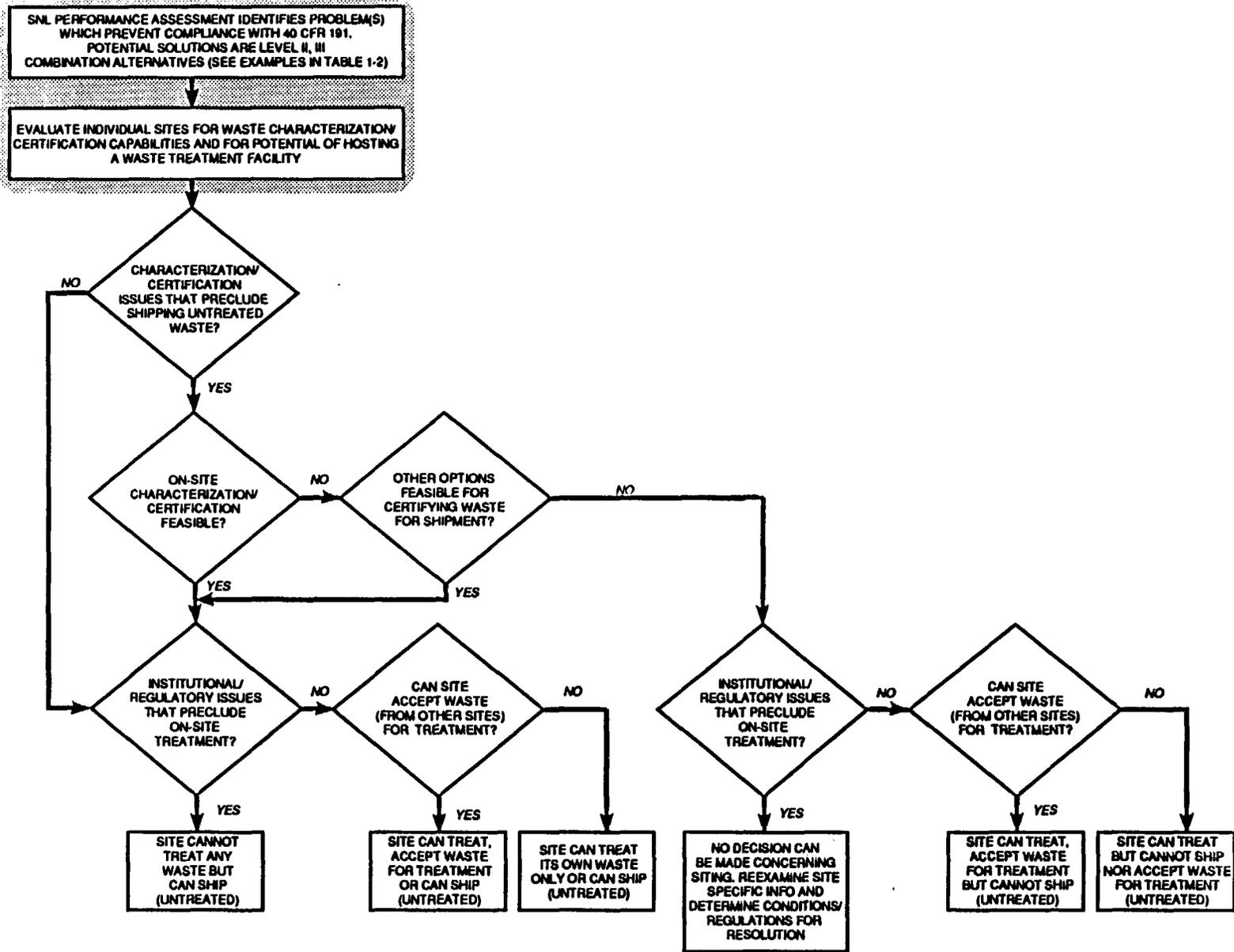


FIGURE 6-3 SITE-SPECIFIC FACTORS INFLUENCING DECISION TO LOCATE WASTE PROCESSING FACILITIES

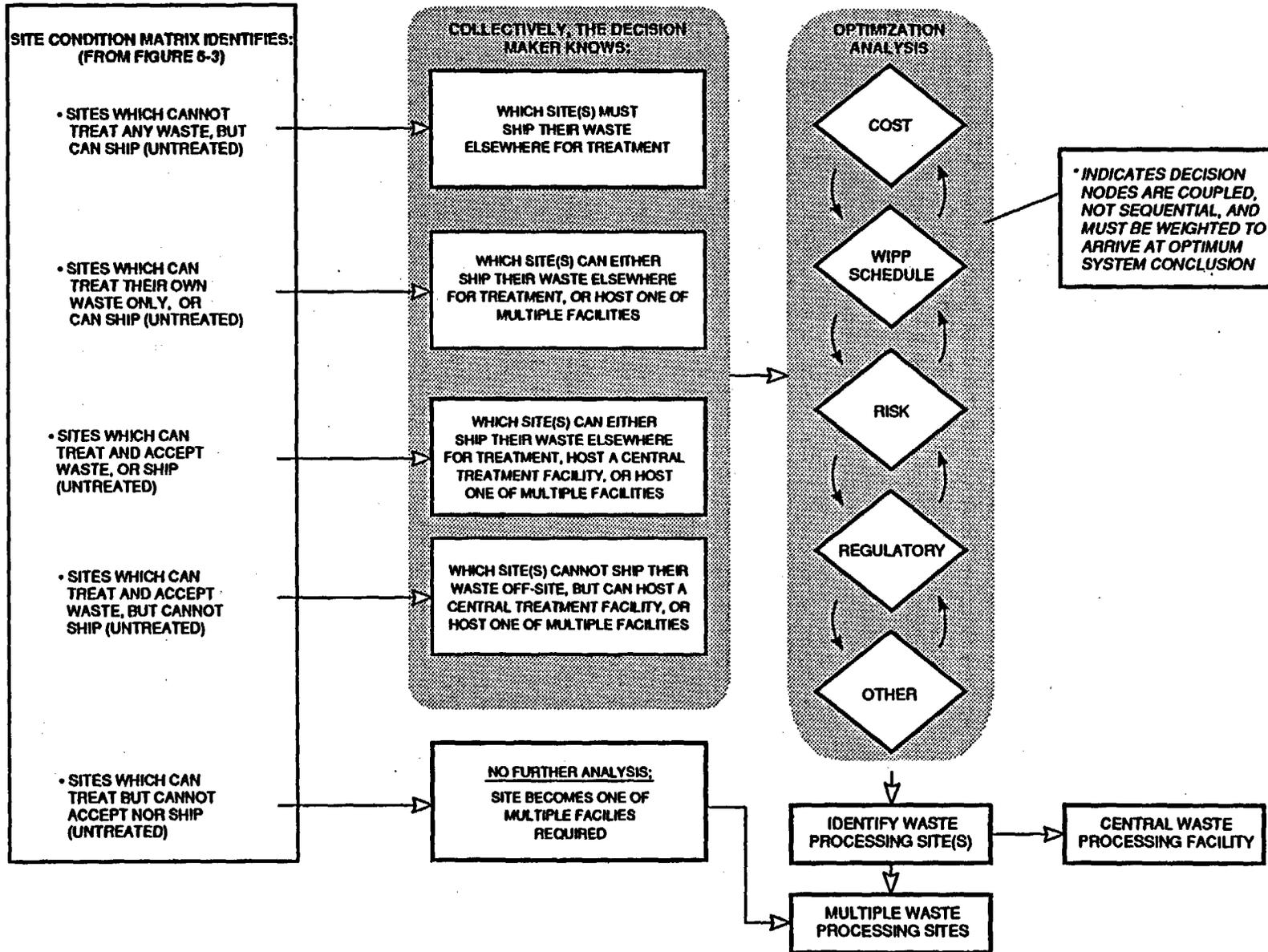


FIGURE 6-4  
SYSTEM LOGIC DIAGRAM FOR FACILITY SITING

For waste forms where there are no characterization/certification issues that preclude shipment, the siting options are limited only by institutional/regulatory issues that preclude on-site treatment.

#### **On-Site Waste Characterization/Certification Feasible?**

If waste characterization or certification issues preclude shipping untreated waste off-site, then the feasibility of characterizing waste on-site must be addressed. Feasibility is defined as a comparison of the cost of characterization (see Section 6.3.4.4) and availability of characterization facilities (see Section 6.3.3) versus the cost (see Section 6.3.4.1), schedule (see Section 6.3.5), and regulatory requirements (see Section 6.3.6) for treating wastes on site. The cost of characterization is dependent upon the level of understanding of waste composition, extracted from existing information such as process knowledge (how the waste was generated).

RCRA compliance is an example of one of the major factors affecting a facility's waste-characterization requirements. RCRA characterization potentially requires sampling a large number of waste containers, which may require expansion or construction of waste-characterization facilities. For wastes where additional data are required for certification prior to shipment, the cost of certification may be sufficiently close to the cost of treatment that the benefit in treating waste on-site is clear.

#### **Other Options Feasible for Certifying Waste for Shipment?**

In the unlikely event that regulatory requirements prevent on-site characterization/certification, all other options should be explored before a decision is made to treat wastes on site.

Options available depend upon the characterization/certification issue. If the concern is difficulty in compliance with regulatory requirements of the State of New Mexico before wastes can enter the state, then the siting option for wastes (from that particular site) may be limited to a treatment facility outside of New Mexico. Similarly, if the issue is one of TRAMPAC certifiability for shipment in TRUPACT-II, other transportation options may be investigated.

#### **6.4.2.2 Regulatory/Institutional Requirements That Prevent a Site From Treating Waste**

The first three decision nodes of Figure 6-3 lead the site to one of three conclusions:

- Characterization/Certification issues do not exist for a given site's waste
- Characterization/Certification issues exist and an on-site method for resolution is available
- Characterization/Certification issues exist and no on-site method for resolution is available.

Superimposed on the issue of whether a site can ship waste is the issue of whether the site can treat wastes. Note that in Figure 6-3 a parallel examination of institutional and regulatory factors influencing treatment is applied to two conditions: where characterization/certification issues do not prevent shipment off site, and where such issues prevent the site from shipping off site.

### **Institutional or Local Regulatory Factors Preclude On Site Waste Treatment?**

The analysis of institutional and local regulatory factors is focused on identification of constraints that might preclude construction or operation of a waste treatment facility on site. An example of such a factor is local opinion regarding waste treatment in general (See Section 6.3.6.2).

As indicated in Section 6.3.6, institutional and local regulatory factors currently are an area of considerable uncertainty and have the potential to change significantly over time. The fact that few radioactive-waste treatment facilities have been permitted suggest that a considerable effort will be required before adequate data are available to assess the time involved for permitting a facility at a given location. One approach to clarifying the institutional/regulatory issues is to initiate the permitting process at several candidate sites. On-site treatment is potentially removed as an option at sites where institutional requirements are insurmountable. (Note that such difficulty is not expected to be encountered.)

If waste cannot be shipped off site, and if institutional/regulatory factors preclude waste treatment, the site is at an impasse that must be resolved by negotiation with the appropriate regulatory agencies. If shipping is possible but institutional/regulatory factors preclude treatment on site, options are limited to waste treatment elsewhere. If waste can be shipped off site then, depending on the effect of institutional and regulatory constraints, options include waste shipment to another site for treatment or treatment on site.

### **Can A Site Treat Waste from Other Sites?**

In all cases, if institutional/regulatory issues do not prevent on-site waste treatment, a final decision can be made regarding the ability of the site to accept waste for treatment. The answer to this question (can the site treat waste from other sites) could be affected by institutional or local regulatory constraints other than those concerning treatment of the site's own waste. For instance, if a state has declared that it will not allow TRU waste within its borders unless generated there, the transportation of waste from other DOE sites is prevented. As in the previous decision node, additional analysis of institutional/regulatory requirements is required before candidate sites can be identified.

#### **6.4.2.3 Results of Site Categorization Evaluation**

As a result of the shipment and treatment analysis, each site is classified into one of five categories (excluding a situation where the site can neither ship nor process waste), which is presented in Table 6-15 and summarized as follows:

**TABLE 6-15**  
**LOGIC FOR SITE CATEGORIZATION**

DECISION	RESULTS
Ship waste to treatment site	<ul style="list-style-type: none"> <li>• Waste does not need to be characterized, or</li> <li>• On-site waste characterization is feasible, or</li> <li>• Other options are feasible, and</li> <li>• Institutional or regulatory factors preclude on-site waste treatment</li> </ul>
Waste treated on site or shipped to another location for treatment	<ul style="list-style-type: none"> <li>• Waste can be shipped off site, and</li> <li>• Institutional/regulatory factors do not preclude waste treatment on site, and</li> <li>• Site can treat other sites' waste</li> </ul>
<u>Site waste or other sites' waste can be treated on site, or ship waste off site for treatment (candidate for central facility)</u>	<ul style="list-style-type: none"> <li>• Waste can be shipped off site, and</li> <li>• Institutional/regulatory factors do not preclude waste treatment on site, and</li> <li>• Site can treat other sites' waste</li> </ul>
<u>Site waste treated on site; cannot ship untreated waste off site (candidate for central facility)</u>	<ul style="list-style-type: none"> <li>• Waste cannot be shipped off site, and</li> <li>• Site can treat other sites' waste</li> </ul>
Can only store its own treated waste on site; cannot ship untreated waste off site	<ul style="list-style-type: none"> <li>• Waste cannot be shipped off site, and</li> <li>• Site cannot treat other sites' waste</li> </ul>

- Sites that can only ship waste off site for treatment
- Sites that can only treat their own waste and cannot ship untreated waste off site
- Sites that can treat their own waste and waste from other sites but cannot ship untreated waste off site
- Sites that have the option to either treat their own waste on site or ship their waste off site for treatment
- Sites that have the option to either treat waste from any location on site or ship their waste off site for treatment.

Classification of each site into one of the five categories serves as input to the second decision model, where a decision of which DOE sites will host waste processing facilities is made.

#### **6.4.2.4 Selection of Site Specific Waste Treatment Locations**

The objective of the second part of the assessment is to determine optimum locations of waste treatment facilities, based on the results of the site categorization evaluation and is represented graphically by Figure 6-4. A data base of site-specific and system-wide information, including cost (Section 6.3.4), schedule (Section 6.3.5), risk (Section 6.3.7), regulatory considerations (Section 6.3.6), and other possible factors, will provide the technical support for conducting the analysis.

The following discussion provides an overview of the evaluation needed to establish optimum facility siting locations.

#### **Site Condition Matrix**

The starting point for this optimization analyses is the development of a site condition matrix which is developed from the site categorization evaluation. All DOE TRU waste sites fall into one of the five categories described in Section 6.4.2.3. A matrix can be developed by classifying each of the sites into one of these categories.

#### **Collective Knowledge Available to the Decision Maker**

The requirement for further optimization analysis is a function of the condition category to which a particular site belongs. Four out of the five categories described in Section 6.4.2.3 warrant siting optimization analysis. For a site that cannot ship untreated waste or accept waste from other sites for treatment, no further analysis is required; such a site would be required to treat its own waste before it can be shipped off site.

## **Optimization Analyses**

Based on the collective knowledge available to the decision maker, an optimization analysis can be used to reach a conclusion of which sites will host treatment facilities. The decision maker now knows which sites can or cannot treat wastes and which sites can or cannot accept waste. This information may then be used in a weighted factor analysis to arrive at a decision. Such an analysis emphasizes factors which more greatly influence a decision.

The following factors are involved in this analysis:

- The life cycle costs associated with the construction and operation of the waste treatment facilities
- The effects on WIPP schedules of locating waste treatment facilities at specific locations, and for the number of facilities constructed
- The health and safety risks associated with construction and operation of facilities at specific locations, and the risks of transporting waste to and from those locations
- The effect that regulations may have on optimum facility siting decisions
- Other factors not identified at this time.

In addition, there could be other factors selected as considered appropriate for inclusion in the analysis. The relative importance of each of these factors needs to be determined, and appropriate weighting needs to be applied to each so that their relative contributions to the siting decision can be collated.

When these factors have been evaluated for each site, a comparative analysis can be made to determine the optimum facility siting locations. The following discussions describe how these factors can be applied in the analysis:

### **Life Cycle Cost**

The cost of constructing and operating a waste treatment facility, and transporting waste to and from the facility, will vary depending on the DOE site chosen. Facility costs are a function of the quantity of waste that will be treated at the facility, which in turn is based on the total number of facilities constructed to treat all TRU waste. Facility costs can also be affected by planned or existing facilities that may support waste treatment at a DOE site. After the site-specific costs have been identified, a comparative analysis of the total life cycle costs for all facility locations can be made. The results can be factored into the overall analysis method chosen to optimize facility locations. Section 6.3.4 of this report provides capital and operating cost estimates if only a single, or as many as seven facilities, are constructed. Section 6.3.4.3 discusses the transportation considerations, using facility siting locations based on construction of up to seven facilities.

### Schedule Effects on Facility Siting

Schedule effects on the siting decision tend to be focused on how many facilities are constructed, and any considerations that are unique to a specific DOE site. If multiple facilities are planned, it may be possible to show that the first of these facilities would be in operation before a single larger plant is operational. This may improve the waste disposal schedule by making shippable wastes available to WIPP sooner. There could also be unique conditions at various DOE sites that would improve or hinder the overall schedule. For instance, the availability of an existing facility which could be used (in whole or in part) to support waste treatment at the site would advance the schedule and make the site attractive as a facility host. Conversely, if there are negative factors unique to a site, the schedule would be adversely affected. Data required in assessing schedules is provided in Section 6.3.5.

### Health and Safety Risks

Health effects due to treatment vary depending upon the number of treatment facilities and the type of treatment required. The assessment of risk in waste treatment relative to the risk in transportation and emplacement of untreated wastes is discussed in detail in Appendix I. As with the broader optimization analysis, the various components of the relative risk can be evaluated and weighted to arrive at total relative risks. The relative risks will then require an assignment of a weighting factor similar to those for the other components of the optimization analysis.

### Effect of Regulations

Regulations vary with time and can be assessed only at the time the siting decision is being made. As an example, regulations should be evaluated to assure that restrictions for building a single facility are not insurmountable. Restrictions could be in the form of transportation requirements, or emissions criteria that would be more easily achieved by numerous smaller facilities. In Section 6.3.6.1, the EATF has identified federal regulations that apply to the treatment of waste.

### **Identification of Optimum Treatment Locations for Each Site's Waste**

The completion of the optimization evaluations will result in:

- Optimum waste treatment site locations
- Designation of waste treatment site locations for all waste requiring treatment.

If as a result of the facility siting analyses only one site is identified as suitable, then all waste will be treated at this centralized facility. If more than one site is optimum, then DOE will have the option of designating multiple facility locations.

#### **6.4.2.5 Data Uncertainties**

This report provides much of the data needed to assess where waste treatment facilities should be located. However, uncertainties exist that must be resolved before a final siting

decision can be made. The various uncertainties are included in the discussion of the various decision nodes presented in Sections 6.4.2.2 and 6.4.2.3.

The acceptable level of uncertainty for the various components is a function of how each component is weighted in the optimization analysis. For components weighted heavily, the acceptable level of uncertainty will be lower than for components assigned a relatively lower weight. The acceptable level of uncertainty should be analyzed as part of the overall evaluation of siting options.

## **6.5 SUMMARY OF RESULTS FOR FEASIBILITY OF IMPLEMENTING WASTE TREATMENT ALTERNATIVES**

### **6.5.1 Feasibility of Waste Treatment**

The EATF findings indicate that a broad range of waste treatments are feasible. Technologies exist to produce a broad range of processed waste forms (e.g., compacted, vitrified) from TRU waste and research efforts are ongoing in many areas.

There are, however, issues such as regulatory compliance, budget (waste treatment costs may range from tens of millions to over one billion dollars), and schedule (up to eleven years for Level III treatment) which complicate the feasibility of waste treatment. Such factors present obstacles but are not considered to be insurmountable if waste treatment is necessary. Waste processing will involve small additional short-term risks, but long term performance is improved for many alternatives.

The EATF considers waste treatment to be feasible but much work will be necessary before it can be implemented.

### **6.5.2 Facility Siting**

Facility siting has been summarized by the EATF in the form of two cases: factors favoring a single site (at the WIPP) or multiple locations for waste processing facilities. This facility siting evaluation is based on the information collected and presented in Section 6.4. As noted in the various subsections of 6.4, firm requirements (or their effect) have not been delineated for factors that influence facility siting decisions. Specifically, final requirements needed for decision parameters are:

- Extent of waste characterization
- Finalization of transportation requirements
- Definition of regulatory requirements (specifically facility permitting) in order to establish costs and schedules for compliance
- Whether or not waste treatment is necessary (to comply with 40 CFR Part 191 or 40 CFR Part 268 requirements).

Table 6-16 summarizes the influence of factors presented in Section 6.4 on facility siting. Note that as directed in the EATF Program Plan (Hunt, 1990), qualitative assessments of factors and their influence on siting are made where quantitative information is not available.

TABLE 6-16

**SUMMARY OF DECISION FACTORS FAVORING A  
SINGLE OR MULTIPLE FACILITY**

<b>DECISION FACTOR</b>	<b>CONDITIONS FAVORING FACILITY AT WIPP</b>	<b>CONDITIONS FAVORING MULTIPLE FACILITIES</b>
<b>Waste Characterization</b>	Current characterization plans sufficient for transportation	Extensive characterization (RCRA, NRC) required prior to transporting
<b>Transportation</b>	Current transportation scheme already in place  Minimizes TRUPACT-II miles and transportation cost if Level II treatment	Minimizes TRUPACT-II miles and transportation cost if Level III treatment
<b>Waste Location</b>		Consideration of buried TRU waste  Precludes additional preparation for transportation
<b>Planned and Existing Facilities</b>		Planned and existing facilities exist at major sites and could be utilized as front-end to waste processing facility
<b>Total Cost for Waste Treatment Facilities</b>	Economy of scale realized for single facility	
<b>Institutional Factors and Regulatory Concerns</b>	Permitting requirements anticipated easier for a single facility	Institutions may not be able to accept waste from other sites  RCRA requirements may force processing on site
<b>Implementation Schedule</b>		Anticipated that processed waste would begin arriving at WIPP earlier than if a single facility is built
<b>Risk Reduction (Note: Level II independent of location)</b>		Highest overall risk reduction at multiple sites for Level III treatment

The EATF has identified the following set of factors that favor a single waste processing facility (at the WIPP):

- Characterization - TRAMPAC characterization only (at planned or existing facilities)
- Cost - economy of scale achieved with a single integrated facility; transportation costs for Level II waste treatment are also minimized with a single facility
- Regulatory - permitting a single facility may be easier to accomplish.

Similarly, the following set of factors favors waste processing at multiple locations:

- Characterization - if extensive waste characterization is required, the cost differential between waste characterization and waste processing may be sufficiently small that treatment at multiple sites is preferred
- Transportation - transportation requirements are minimized for Level III treatment because of volume and mass reductions
- Schedule (WIPP) - it is anticipated that some of the multiple facilities would be operational more quickly than a single facility. Thus, processed waste would be sent to the WIPP in a more timely manner
- Risk Assessment (Safety) - the highest overall risk reduction (albeit small) for the alternatives examined was realized at multiple facilities for Level III treatment.

A specific "answer" on optimum facility siting cannot be ascertained due to data uncertainties in key decision parameters. Ground work in the form of a data base and a decision methodology have been completed to the point where a decision can be made as soon as the existing uncertainties are considered acceptable. Where uncertainties must be reduced, a decision awaits the collection of the required additional data.

### 6.5.3 Additional Data Requirements

The following information requirements identified by the EATF are needed before a waste treatment feasibility assessment (and facility siting decision) can be finalized:

- Waste treatment level (if any) defined by SNL performance assessment
- Extent of waste characterization
- Better understanding of institutional factors (influences whether or not site can be a host for a TRU waste treatment facility).

A recommendation for waste treatment cannot be made by the EATF at this time. This decision will be made as compliance issues of 40 CFR Part 191 pertaining to the current design are answered by the SNL performance assessment for the repository. Clearly, some work remains to be done before definitive conclusions can be drawn.

## 7.0 FEASIBILITY OF IMPLEMENTING BACKFILL ALTERNATIVES

The EATF evaluation of backfill alternatives emphasizes cement and salt-based backfills. Cement and salt-based backfill materials were recommended for inclusion in the WIPP experimental program by the EATF (DOE, 1990b). The following feasibility evaluation of backfill alternatives is based on development status, cost, schedule, and regulatory issues. Backfill alternatives are being evaluated in combination with various waste treatment techniques (Table 1-2). Initial work by the EATF indicates that regulatory considerations for backfill modifications will be minimal and should not impact the overall WIPP schedule (see Appendix A, Table A-6).

### 7.1 STATUS OF DEVELOPMENT

Three backfill modification alternatives have been recommended for inclusion in the WIPP Experimental Program (DOE, 1990b):

- Salt with Brine Absorbent - Addition of an absorbent, such as bentonite, introduces brine absorbing capability to reduce the potential for brine penetration into the waste.
- Salt with pH Buffer - Addition of a pH buffer, such as calcium oxide, will raise the pH of any brine coming in contact with the backfill. At elevated pH, radionuclide solubility, microbial activity, and corrosion of iron-based metals decreases (see Appendix G).
- Cement Grout - Cement grout backfill may offer several advantages, such as raising pH, or reducing permeability of waste storage rooms (Appendix G).

In addition to the above, the Expert Panel on Cementitious Materials recommended the following backfill:

- Salt Aggregate Grout - A grout with a high percentage of salt aggregate is anticipated to provide deformability, will be self-healing, and maintain low permeability under the anticipated 2,000 psi isostatic confining stress (Appendix G).

Mining technology exists to crush, blend, and transport salt and additives. Some engineering work will be required for backfill emplacement equipment. Similarly, grout backfill preparation and emplacement equipment does not involve research and development. Grouting in deep underground formations is common practice at DOE's Nevada Test Site (Ellis and Bendinelli, ND). The salt aggregate grout will require a development program.

### 7.1.1 Salt with Brine Absorbent

Mining of the WIPP facility produces bulk salt, which is stored above ground at the WIPP site. Granulation of this salt to a consistency required for efficient emplacement and the addition of a brine sorbent such as bentonite clay will not require a research and development program. Bentonite is expected to possess the beneficial characteristics of radionuclide sorption, and brine absorption (Butcher, 1990b).

### 7.1.2 Salt with pH Buffers

The addition of pH buffers to crushed salt backfill is similar to the addition of bentonite from the process standpoint. No process development is anticipated. Some additional investigations into the effectiveness of the pH buffers may be needed, depending on the specific requirements for such buffers in the WIPP underground environment.

### 7.1.3 Cement Grout

Many formulations of grout exist and other formulations can be prepared, depending on the specific application. An expert panel was convened by the EATF to qualitatively evaluate the use of cement or grout as a backfill medium. The panel concluded that the use of cementitious materials may be feasible for use as backfills in the WIPP underground environment. The report of the expert panel's findings is presented in Appendix G.

### 7.1.4 Salt Aggregate Grout

A grout formulation containing a high percentage of salt aggregate and brine (to provide hydration water) has not been produced to date (Appendix G); however, concretes with aggregate contents as high as 95 percent have been used in underground applications at the Nevada Test Site (Appendix G). It is anticipated that such a grout will have properties approaching those of host rock at the WIPP, and potentially allows more rapid closure.

## 7.2 BACKFILL PREPARATION FACILITY DESCRIPTION

The preparation of backfill requires equipment for bulk material crushing, blending, and handling operations. Storage of raw materials such as cement, bentonite, and calcium oxide are also necessary. Equipment needed for material staging, handling, and mixing are commercially available. Dry material mixers and concrete batch plants are commonly used in the construction and mining industries. It is understood that materials such as salt are hygroscopic and will absorb water; for the purposes of specifying backfill equipment, salt is a "dry material." Specification of a backfill preparation facility requires only a designation of the appropriate capacities and design parameters for staging, handling, and mixing equipment.

### 7.2.1 Cement Grout Preparation Facility Description

The cement grout preparation facility operations include material handling, batching, and mixing of backfill. A commercially available concrete batch plant may be used for preparation of the cement grout. The major components of a concrete batch plant are: storage silos for cement, aggregates, fillers, or other additives; a batch mixing system for weighing and blending dry materials; pneumatic and/or conveyor systems to move dry materials; and mixing equipment for preparation of the grout mixture.

Concrete batch plants are commercially available in a wide range of sizes, from small mobile equipment to large stationary facilities. The location of the batch plant should be near shafts for transporting the cement grout underground in order to minimize the time between mixing and emplacement. Once prepared, the cement grout can be moved to agitating holding tanks or emplaced directly. Agitator holding tanks may be required for temporary storage to prevent settling prior to emplacement.

### 7.2.2 Dry Material Preparation Facility Description

A dry material preparation facility will be required for crushed salt (or crushed salt plus additives) backfill. The crushing of bulk materials (if needed) and mixing (for addition of additives) operations are the primary functions of the facility. A roller impact or hammer mill may be used to process bulk salt to a specified granular size. Bulk materials such as bentonite or calcium oxide (unslaked lime) may also require some pre-processing (to break chunks) prior to being mixed with crushed salt. Commercially available dry mixing equipment may be used to produce homogeneous mixtures of salt and additives.

## 7.3 BACKFILL EMPLACEMENT EQUIPMENT DESCRIPTION

The EATF assumed backfill emplacement occurring in parallel with waste emplacement: as waste is emplaced in one portion of the facility, retaining walls will be erected and backfill emplaced over the waste in other areas. Upon completion of backfilling, the retaining walls can be removed and the process repeated elsewhere. The backfill volume that can be emplaced at one time will depend on capacity and design of the emplacement equipment.

Emplacement will require containers for transportation of backfill material and equipment for placing it in and around the waste. Backfill materials must be transported from storage or feed locations to partitioned waste stacks. The backfill must be elevated above the retaining walls and placed between and over the waste containers. The emplacement equipment must be designed to direct the flow of backfill into void spaces within and around the waste stack. The physical size of emplacement equipment must be compatible with the repository.

Available methods for emplacing backfill may be described as mechanical, pneumatic, or a combination of both. Commercially available equipment such as conveyors, augers, and pneumatic systems may be specified with modifications for application at the WIPP. Concepts

presented here are preliminary in nature and are presented as examples of systems which may be used in the future.

### **7.3.1 Cement Grout Emplacement Equipment**

Hydraulic emplacement involves pumping cement grout from storage tanks, Moran Cars, or feed tanks to the partitioned waste stack. The storage or feed tank can receive cement grout from the above-ground batch plant via a system of pumps. The emplacement equipment might consist of an agitated feed tank or Moran Car from which cement grout will be pumped into place via a boom mounted truck. A telescopic boom would allow the operator flexibility in the placement of the cement grout. Cement grout should be emplaced at low pressures to avoid damaging waste containers.

Another method of grout emplacement will require conveyors in combination with augers for mechanical emplacement. Conveyors may be used for horizontal movement, whereas augers may be used for lifting grout. This method might consist of a conveyor moving cement grout from storage/feed tanks to the waste stack. An inclined auger could then lift cement grout to a conveyor extending over the waste stack. The final length of conveyor would be cantilevered and adjustable to allow the flow of cement grout to be directed to any portion of the waste stack. Cement grout could either free fall into the waste stack or be directed through a flexible hose. It is assumed that cement grout backfill will be free-flowing and unobstructed from filling void space within the waste stack. It is anticipated that some engineering development will be required to specify a grouting system.

### **7.3.2 Dry Material Emplacement Equipment**

Emplacement of dry materials can be accomplished by methods similar to emplacing cement grout. For mechanical emplacement, a feed hopper located near the waste stack would supply backfill to an auger/conveyor system, which moves backfill to sections of waste being backfilled. The backfill material could either free fall from the end of the conveyor/auger or be directed through a flexible hose. The flexible hose would allow control over emplacement, as well as reduce potential dust problems resulting from re-suspended particles (Pfieffe, 1985). It is assumed that dry backfill will adequately fill void space within the waste stack if this method of emplacement is used.

Dry backfill material could also be pneumatically emplaced. The backfill could be crushed to an appropriate size and blown over the waste stack. The backfill is then allowed to settle in to void spaces within and around the waste stack. This method may require isolating the waste stack to avoid ventilation problems resulting from suspended particulates. Furthermore, special equipment may be required to avoid worker exposure to dust. Low pressure emplacement will be necessary to prevent damaging waste containers. An engineering development program will also be required for the dry material emplacement system.

## **7.4 COST OF FACILITIES AND EQUIPMENT**

The EATF has calculated rough cost estimates for cement grout and crushed salt backfill preparation facilities. Capital cost estimates for material preparation facilities have been obtained from vendors of industrial construction equipment. Actual cost estimates are not practical since backfilling methods and requirements have not been specified. In order to account for this uncertainty, a 50 percent contingency factor has been added to the preparation facility capital costs for emplacement equipment.

In order to specify a design capacity for a backfill preparation facility at the WIPP, a basis volume of backfill must be assumed. The volume in each room available for backfill is estimated to be approximately 2,100 cubic yards [design basis room volume (13x33x300 feet) less the volume of 6,000 drums and a 2-foot air gap]. The design basis volume of backfill is assumed to be one-third of the total backfill volume, approximately 700 cubic yards. If the basis volume is to be backfilled in one shift (eight hours), a capacity of approximately 90 cubic yards per hour is required.

Small scale backfilling equipment is being used for test purposes at the WIPP. This equipment includes a small capacity screen and conveyor. Screening/blending (preparation) equipment for salt-bentonite backfill is available with a capacity of approximately 2 cubic yards per hour (Stenson, 1989). A portable conveyor elevator for emplacing dry backfill is also available (Gonzales, 1990). This equipment is to be used in experimental programs such as backfilling demonstrations and alcove experiments. The existing equipment may supplement the additional equipment required for backfilling operations. The cost of the existing equipment has not been included in EATF cost estimates.

### **7.4.1 Cement Grout Backfill Capital Costs**

A capital cost estimate for a cement grout preparation facility was obtained from a vendor of industrial construction equipment (Prange, 1991). Many options are available for batch plants, and the actual costs will vary with the options specified. The batch plant cost reported here represents a facility capable of preparing cement grout at a rate of 110 cubic yards per hour. An estimate of the total capital cost for a cement grout backfill preparation facility and associated emplacement equipment is prescribed in Table 7-1.

Larger capacity, stationary batch plants are also available. These facilities are capable of producing larger amounts of cement grout backfill more rapidly. Larger capacity, stationary batch plants will cost approximately \$750,000 (Prange, 1991). The capacity of larger facilities is considered to be beyond the needs of the WIPP backfilling efforts during the disposal phase.

### **7.4.2 Dry Material Backfill Capital Costs**

Capital cost estimates have been prepared for both crushed salt and crushed salt plus additives backfill preparation facilities. These capital cost estimates are based on industrial

TABLE 7-1

**BACKFILL PREPARATION FACILITIES AND  
EMPLACEMENT EQUIPMENT CAPITAL COSTS**

BACKFILL ALTERNATIVE	COST (THOUSANDS, 1990 DOLLARS)
Crushed Salt	225
Crushed Salt plus Additives*	290
Cement Grout	435

\*Additives include pH buffers and sorbents.

TABLE 7-2

**BACKFILL OPERATING COSTS<sup>(1)</sup>**

ALTERNATIVE <sup>(2)</sup>	BACKFILL MATERIAL	ANNUAL COSTS (THOUSANDS, 1990 DOLLARS)
Baseline	Salt	1,200
1	Salt	1,000
2	Salt	1,000
3	Cement-Grout	1,900
4	Salt	620
5	Cement-Grout	1,100
6	Salt	310
7	Cement-Grout	570
8	Salt	120
9	Cement-Grout	230
10	NA <sup>(3)</sup>	NA
11	Salt	1,100
12	Cement-Grout	1,500
13	NA	NA
14	Salt Grout	4,800

<sup>(1)</sup> Includes Labor, raw materials, required supplies.

<sup>(2)</sup> Refer to Table 1-2 for complete alternative description.

<sup>(3)</sup> NA - Not Applicable, these alternatives do not use backfill.

construction equipment from a commercial vendor (Prange, 1991). The capital cost estimate for crushed salt includes costs for an impact mill capable of processing 300 to 500 tons of backfill per hour. The capital cost for crushed salt plus additives includes cost for the same impact mill, in addition to cost for a conveyor pugmill plant with variable capacity, depending on the required mix time. The emplacement equipment required for crushed salt and crushed salt plus additives is assumed to be the same. The capital cost estimates for dry backfill preparation facilities and emplacement equipment are shown in Table 7-1.

The capacity of equipment used in the mining and construction industries is far greater than backfilling needs at the WIPP. Larger capacity equipment could be used to produce backfill in quantities large enough to stockpile. This could reduce the total operating time of the preparation facility, as well as enable simultaneous backfilling campaigns or more continuous backfilling operations.

#### 7.4.3 Operating Costs

Annual operating costs of backfilling for each of the 14 combination alternatives has been estimated on the basis of backfill material requirements and emplacement costs. The baseline backfill requirement is calculated to be enough to fill 121 equivalent waste disposal rooms over a 25-year period. The Test Phase has not been considered. Each disposal room will require approximately 2,100 cubic yards of backfill. Emplacement of dry backfill is assumed to be 50 percent efficient in filling void space between drums, whereas grout is assumed to be 100 percent efficient in filling available void volume. An increase or decrease in total disposal volume is estimated from the number of equivalent drums per room (Table 3-5) for each combination alternative. For example, combination Alternatives 4 and 5 result in disposal of 11,250 unprocessed equivalent drums per room. Thus, in comparison to the baseline, the original disposal volume required for combination Alternatives 4 and 5 is decreased by the ratio of 6,000 to 11,000 (that is, original design volume times the ratio of unprocessed drum equivalents to processed drum equivalents).

Concrete emplacement costs for commercial applications have been used as the basis for estimating cement grout backfill operating costs (Kosel, 1991). Estimated concrete emplacement costs have been escalated by 20 percent as a contingency factor to account for the unique requirements of application at the WIPP. These emplacement costs include labor, raw materials, and any necessary supplies (other than cement grout ingredients). Emplacement costs for crushed salt have been estimated from concrete emplacement costs by subtracting materials cost. Labor costs are assumed to be the same for cement grout emplacement and crushed salt emplacement. The operating costs for cement grout backfill and crushed salt backfill are assumed to bound all possible backfill alternative operating costs. The estimated operating costs for the 14 combinations of alternatives are shown in Table 7-2.

## **7.5 IMPLEMENTATION SCHEDULES**

The EATF has concluded that implementation schedules for backfill alternatives will have no impact on the overall WIPP schedule. Backfill preparation facilities are commercially available and can be erected on-site in relatively short periods of time. Off-the-shelf emplacement equipment which may need modification will require additional time above commercial ordering lead times. Overall, the backfill preparation facilities and emplacement equipment should be available before the WIPP Experimental Program has been completed, and are therefore not considered critical schedule items.

## **7.6 SUMMARY**

The feasibility of implementing backfill alternatives has been evaluated by the EATF on the basis of development status, cost, schedule, and regulatory considerations. Equipment necessary for preparation of cement grouts, dry material crushing, blending, and handling are commonly used in the mining and construction industries (including nuclear applications at NTS). Backfill preparation equipment and facilities are commercially available and may be used with minor modifications for WIPP purposes. Backfill emplacement equipment may require an engineering development program. Material handling and transportation equipment is also commercially available and may be adequate for backfill emplacement. Capital and operating costs for backfill alternatives are relatively inexpensive in comparison to waste treatment. Backfill preparation facilities and emplacement equipment are estimated to cost less than one million dollars for all backfill alternatives. Lead time for ordering commercially available equipment defines the implementation schedules for backfill preparation facilities; additional schedule time must be allowed for modification or development of emplacement equipment. Regulatory requirements for backfill alternatives are minimal and should not impact the overall WIPP schedule. It is not known at this time whether a cement grout, salt (or salt and additives), or a high salt aggregate grout is the best choice for use at the WIPP. A development program will be necessary to specify an optimal composition for backfill material. The EATF concludes that all backfill alternatives presented in this report are feasible for implementation at the WIPP.

## 8.0 FEASIBILITY OF IMPLEMENTING OTHER ALTERNATIVES

This section provides a brief description of alternatives for WIPP waste management, facility design, waste container shape and material, and passive institutional controls. With the exception of waste containers, the nature of these alternatives dictates that they will be located or implemented at the WIPP site. Some of these alternatives may have regulatory impacts (e.g., facility redesign) whereas others will have minimal regulatory impact. The same observation can be made concerning cost. Some alternatives are potentially expensive, while others have minimal effects on total project costs.

### 8.1 STATUS OF DEVELOPMENT

Alternatives included in the categories of waste management and facility design modifications are not expected to require research and development. An engineering development effort will be required in most cases. For the most part, these alternatives are variations of existing operations or previous constructions and were judged to require only sound engineering or operations planning. For instance, minimizing space around the waste in WIPP is an operational consideration.

Facility design alternatives, such as changing the waste disposal room configuration, are variations of current mining practices which are commonly applied in the mining industry. Exceptions that will require further development are modifications to the waste container material and compartmentalization of the waste. The former may require the development of manufacturing techniques that will allow use of the material chosen, while waste compartmentalization may require development of special backfill materials. The preferred approach may be to investigate materials similar to shaft and drift sealing materials. Shaft sealing studies involving various sealing materials, such as concrete and salt, are underway. (DOE, 1989c). Passive institutional controls are the subject of extensive work recently initiated by Sandia National Laboratories (Bertram-Howery and Swift, 1990). The program has not reached the level of maturity required to discuss regulatory, technological, cost, and schedule considerations, and therefore passive institutional controls have not been evaluated by the EATF.

### 8.2 WASTE MANAGEMENT ALTERNATIVES

#### 8.2.1 Minimize Space Around Waste

The WIPP waste disposal room dimensions were chosen so that retrieval of waste after a five-year demonstration period would not be precluded by premature room closure (DOE, 1989c). Space must exist between the waste stack and the walls and ceiling of the rooms immediately after waste emplacement to compensate for closure. The current design includes backfilling this space with crushed salt, while leaving a ventilation space above the backfill. By minimizing the space around the waste stack, room consolidation and repressurization may occur more quickly, thereby reducing the potential for brine inflow. At the same time, it should be noted that retrievability will be significantly curtailed and any gases generated by radiolysis,

biodegradation, or anoxic corrosion will pressurize the room more quickly as total void volume of the room is decreased.

Space around the waste can be minimized further by changing the waste container shape. The interstitial space within the waste stack and along its edges represents approximately 15 percent of the total waste stack volume. Reduction of interstitial space can substantially reduce the waste disposal void volume, which in turn reduces the time for room reconsolidation. The potential modifications to the waste container shape and material are discussed in Section 8.4.

### **8.2.2 Waste Segregation**

Waste segregation could prove beneficial in reducing or isolating potential problems (e.g., gas generation) within the WIPP. Segregating high gas-generating waste forms to specified locations within the WIPP will isolate the area over which other engineered alternatives may be required (i.e., alternative backfills) to reduce the gas generation rate of that segregated waste. Another segregation method may involve separating the inorganic sludges containing nitrates from the solid organic waste to slow down biological processes in the solid organic waste.

The decision to implement waste segregation requires changes in waste handling practices and an administrative effort for success. Regulatory and institutional consideration will not be as significant relative to other alternatives. The additional costs (above baseline disposal operating costs), resulting from increased waste handling and administrative efforts to implement the alternative, are expected to be small.

## **8.3 FACILITY DESIGN ALTERNATIVES**

### **8.3.1 Compartmentalize Waste**

The EATF has extended the alternative "Seal Individual Rooms", as discussed by the EAMP, to the concept of compartmentalizing waste. Much latitude in assumptions can be taken when formulating an approach for compartmentalizing the waste. The key objective is to segregate a known quantity of curies in an isolated compartment. The benefit of this waste management practice ensures that only a fixed (within regulatory constraints) quantity of TRU isotopes would be released if human intrusion occurred. The EATF concluded that one promising approach would be compartmentalizing waste using salt dikes to separate compartments containing three 7-packs of waste. This design was evaluated as part of Combination Alternative 14, described in Table 1-2.

Based on the report of Cement/Grout Expert Panel (Appendix G), the EATF has concluded that a salt-aggregated concrete could be formulated for use in waste separation. If a specific quantity of curies is placed in each compartment, only that amount could be washed out with the drill cuttings. Thus, the amount of curies placed in each compartment would be such that 40 CFR Part 191 will not be violated if human intrusion occurs sometime in the future.

### 8.3.2 Modified Room Dimensions

Although some design changes would be required, there should not be any significant regulatory or institutional actions required to proceed with this change. Mining new room dimensions does not present any additional risk of worker radiological exposure or industrial hazard. In fact, by eliminating the need for backfill around the waste stack, some radiological exposure to workers is eliminated because backfill emplacement operations taking place in close proximity to the waste would no longer be necessary.

Cost increments for mining waste disposal rooms to different dimensions will be small and will depend on whether smaller or larger rooms are needed to achieve the purpose of this alternative. More substantial cost increases could result if remote-handled waste emplacement equipment must be redesigned due to narrower room dimensions, and the ventilation system adequacy must be reanalyzed.

## 8.4 WASTE CONTAINERS

### 8.4.1 Waste Container Materials

Waste containers commonly in use are manufactured of mild steel, though some sites have used stainless steel. Given that a majority of steel in the WIPP waste inventory is in the form of waste containers, use of an alternative container material will substantially reduce gas generation potential due to anoxic corrosion. The EATF convened an expert panel to recommend alternative container materials. The Waste Container Materials Panel report is presented in Appendix H. The materials considered by the panel included copper and its alloys, titanium, ceramics, and cement-based materials.

### 8.4.2 Waste Container Shape

Minimizing the space around the waste stack has the benefit of minimizing potential conduits for brine immediately adjacent to the waste stack. The use of waste containers that can be tightly packed was investigated by the EATF. The EATF considers rectangular or hexagonal containers as most effective in eliminating void spaces between containers, relative to the present ringed, cylindrical waste drums and standard waste boxes. Hexagonal containers have an advantage in that geometries are similar enough to the cylindrical waste containers that they can fit into TRUPACT-II shipping package, while rectangular containers are easier to fabricate.

### 8.4.3 Cost Estimates for Alternative Containers

The cost of manufacturing (materials and fabrication) alternative containers is estimated to range from one to thirty-five times that of mild steel containers, depending on the material used (see Appendix H). Metal alloys such as titanium, zirconium, and high-nickel fall into the high end of the cost range; copper, stainless steel, polymers, glass, and ceramics are on the low end of the cost range.

It should be noted that some materials may require significant development costs to meet specific design criteria (e.g., mechanical properties, manufacturability). Further, significant costs may also result from construction of new manufacturing facilities. Estimation of these costs will be required before a decision can be reached as to the use of alternative containers.

#### **8.4.4 Implementation Schedules**

An implementation schedule for use of an alternative container requires definition of the following variables (see Appendix H):

- Time required to establish the effectiveness of the container in meeting gas generation requirements
- Time required to develop fabrication capabilities and to produce a full-scale prototype container.

Ceramic and glass materials do not require time to establish a program to determine gas generation potential. However, metal, cement, and polymers can require from one to five years for studies concerning gas generation potential. Note that microbial gas generation research is not included in the schedule estimate.

Stainless steel containers have been produced for the nuclear industry. However, a development program may be required for containers manufactured of other materials. Development time estimates are: two years for other metals; three to eight years for ceramics; two to four years for glass and cement (Appendix H).

#### **8.4.5 Regulatory Issues**

The single regulatory consideration for alternative containers is compliance with Department of Transportation (DOT) Type A requirements which is a Waste Acceptance Criteria at WIPP (DOE, 1989f). Compliance with DOT Type A requirements entails satisfactory completion of Type A Packaging Tests (DOT, 1989). These tests are designed to ensure the mechanical integrity of containers during standard handling operations and potential accident scenarios.

## 9.0 SUMMARY OF EATF FINDINGS AND RECOMMENDATIONS FOR APPLYING EATF RESULTS

The results of the EATF can be applied for final selection of engineered alternatives that improve the performance of the WIPP repository. Sections 1.0 through 8.0 and Appendices A through J, of this report present the data developed by the EATF related to the effectiveness and feasibility of various engineered alternatives. The data developed provide the knowledge base required for assessment and comparison of various candidate alternatives.

The EATF has also developed a methodology by which these data can be evaluated, and a decision can be made regarding which single alternative or combination of alternatives is preferred for a given performance problem. The recommended methodology includes an assessment of the limitations or uncertainties in the existing data. Identification of these uncertainties will help to assess the significance of simplifying assumptions. It will also help to prioritize any additional data requirements, so that the uncertainties in the most critical data sets are reduced to acceptable levels.

The following sections summarize the data developed by the EATF, present the recommended methodology for selecting an optimal alternative, identify additional data requirements at each step of the selection process, and present the conclusions of the EATF to date.

### 9.1 SUMMARY OF DATA DEVELOPED BY THE EATF

The EATF evaluated 14 alternatives with respect to their effectiveness for addressing gas generation and human intrusion issues (see Sections 2.0 to 4.0), and the feasibility of implementing them with respect to status of technology, cost, schedule, regulatory issues, and health and safety risks (see Sections 5.0 to 8.0). Table 9-1 lists the 14 alternatives and summarizes their evaluation.

The capability of each alternative for addressing gas generation has been summarized in terms of the effect of an alternative on the peak index pressure, and its effect on the gas generation rates by either microbial/radiolytic processes or by anoxic corrosion. If the peak index pressures due to an alternative (as estimated by the Design Analysis Model) do not exceed the lithostatic pressure, then the alternative is considered to be effective, and assigned a blank circle in Table 9-1. On the contrary, if the peak index pressure exceeds the lithostatic pressure, the alternative is considered to be ineffective, and is assigned a dark circle in Table 9-1. Similarly, the effect of each alternative on gas generation rates, and on the three human intrusion scenarios, are also presented in Table 9-1. These results have been discussed earlier in Section 4.3.

In addition to summarizing the effectiveness of alternatives, Table 9-1 also presents the feasibility of implementing each alternative in terms of the availability of technology, cost, likely schedules for implementation, regulatory requirements, and the health and safety risk relative to the baseline. The availability of technology is summarized in terms of the level of development of technology for the treatment processes. In case of processes like

**TABLE 9-1  
SUMMARY OF EFFECTIVENESS AND FEASIBILITY OF ENGINEERED ALTERNATIVES**

Treatment level <sup>b</sup>	ALTERNATIVE DESCRIPTION						ALTERNATIVE EFFECTIVENESS						ALTERNATIVE FEASIBILITY					
	Number	Sludges	Solid Organics	Solid Inorganics	Backfill	Waste Container	Peak Index Pressure	Gas Generation Rate		Human Intrusion			Level of Development	Treatment Facility Lifecycle Capital and Operating Cost 10 yr Work-Off Period (\$M)	Lifecycle Transportation Costs <sup>a</sup> (\$M)	Implmt. Schedule (yr)	Regulatory Requir.	Risk
								Microbial & Radiolytic	Anoxic Corrosion	E1	E2	E1E2						
II	1	AR	S&C	S&C	SLT	AR	●	○	○	○	●	○	H	270-380	71-170	5-7	*	△
	2	CMT	S&C	S&C	SLT	AR	●	○	○	○	●	○	H	310-420	71-180	5-7	*	△
	3	CMT	S&C	S&C	CGT	AR	●	○	○	○	○	○	H	310-420	71-180	5-7	*	△
II/III	4	CMT	I&C	S&C	SLT	AR	○	○	○	●	●	○	H	610-820	71-110	8-11	**	△
	5	CMT	I&C	S&C	CGT	AR	○	○	○	○	○	○	H	610-820	71-110	8-11	**	△
III	6	VTR	I&V	MM	SLT	AR	○	○	○	○	○	○	M	830-1100	71-55	8-11	**	NE
	7	VTR	I&V	MM	CGT	AR	○	○	○	○	○	○	M	830-1100	71-55	8-11	**	NE
	8	VTR	I&V	MRM	SLT	NFE	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	▣
	9	VTR	I&V	MRM	CGT	NFE	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	▣
III/II	10	AR	AR	DRM	N/A	NFR	●	●	○	●	●	○	H	510-700	71-60	5-7	*	NE
	13	VTR	I&V	MRM	N/A	NFR	○	○	○	○	○	○	M	1100-1400	71-27	8-11	**	▣
I	11	AR	SPT	SPT	SLT	AR	●	●	●	●	●	●	H	180-260	71-51	5-7	*	NE
	12	AR	SPT	SPT	CGT	AR	●	●	●	○	○	○	H	180-260	71-51	5-7	*	NE
	14	AR	SPT	SPT	SAG	AR	●	●	●	○	○	○	H	180-260	71-51	5-7	*	NE

AR - AS RECEIVED  
 CMT - CEMENT  
 VTR - VITRIFY  
 S&C - SHRED & CEMENT  
 I&C - INCINERATE & CEMENT  
 I&V - INCINERATE & VITRIFY  
 SPT - SUPERCOMPACT  
 MM - MELT METALS  
 N/A - NOT APPLICABLE

MRM - MELT AND REMOVE METALS  
 DRM - DECONTAMINATE AND REMOVE METALS  
 SLT - SALT  
 CGT - CEMENT GROUT  
 SAG - SALT AGGREGATE GROUT  
 NFE - NON FERROUS  
 NFR - NON FERROUS, RECTANGULAR  
 ● - NO EFFECT  
 NE - NOT EVALUATED

● - PARTIALLY EFFECTIVE  
 ○ - EFFECTIVE  
 H - HIGH  
 M - MEDIUM  
 \* - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP  
 \*\* - RCRA/HSWA, DOE ORDERS, NEPA, NESHAP, CAA, CWA, TSCA, PSD, NAAQS, NSPS  
 △ - SLIGHT RISK INCREASE RELATIVE TO BASELINE  
 ▣ - SLIGHT RISK INCREASE FOR SINGLE FACILITY, TO SLIGHT DECREASE FOR 7 FACILITIES

<sup>a</sup> COSTS FOR ONE TO SEVEN PROCESSING FACILITIES

<sup>b</sup> CLASSIFICATION BY TREATMENT LEVELS IS SOMEWHAT GENERALIZED; FOR EXAMPLE, ALTERNATIVE 1 INCLUDES BOTH LEVEL I AND LEVEL II TREATMENTS.

vitrification, where additional development is required for application to TRU waste, the availability of technology has been rated as moderate. The capital costs listed for each alternative reflect the range of costs estimated by the EATF for one to seven processing facilities. The regulatory issues associated with implementing each alternative are presented in terms of the likely permitting requirements, and the schedules for each alternative are presented in terms of the number of years likely to implement the alternative. Risks are presented as a qualitative assessment relative to the "baseline" (all wastes transported and emplaced "as received"). Because backfill has no influence on the assessment of risk, alternative combinations 3, 5, and 9 have the same relative risk increases or reductions as alternative combinations 2, 4, and 8 respectively.

The information presented in Table 9-1 provides a matrix that can be used as a quick reference for comparing the pros and cons of the various alternatives. It can be observed from Table 9-1 that, in general, Level III alternatives (e.g., 8, 9, 13) are more effective than Level II alternatives (e.g., 1, 2, 3), in addressing both gas generation and human intrusion. It should be noted, however, that the improved effectiveness is not obtained without paying a price. Level III alternatives tend to be more expensive, take longer to implement, and require facilities that are harder to permit than Level II alternatives. Consequently, the greater effectiveness of an alternative does not necessarily make it preferable over others, because the selection of an alternative with the optimal effectiveness will depend upon the extent of any problem identified by performance assessment studies.

## 9.2 METHODOLOGY FOR FINAL SELECTION OF AN ALTERNATIVE

The 14 alternatives that have been evaluated were selected to provide a broad range of improvement in performance by treatment of all three major waste forms (sludges, solid organics, and solid inorganics). While it is expected that these 14 alternatives would be sufficient to address any potential issues of gas generation and human intrusion, this does not imply that the choice of an optimal alternative is limited to the 14 alternatives evaluated by the EATF. For example, if performance assessment determines that merely destroying the solid organics would be sufficient to demonstrate compliance, then thermal treatment of the organics should provide the necessary improvement in performance, and there would be no need of any treatment of the sludges and solid inorganics. In other words, it is possible that one of the single alternatives forming the combination alternatives 1 through 14, could be selected as an optimal alternative.

The EATF has developed a methodology for selecting an optimal alternative using the results of evaluation of the 14 alternatives. The decision process for using the EATF results are presented in Figure 9-1. This figure outlines the usefulness of the EATF evaluations in relation to the overall framework of the system, and provides a tool for reaching a final decision.

As shown in Figure 9-1, the decision process starts with an assessment of the current design with respect to demonstration of compliance with 40 CFR Part 191, 40 CFR Part 268, and any other applicable regulations. If compliance can be demonstrated using the current design, then there would be no need for an engineered alternative. On the contrary, if the current design fails to demonstrate compliance, then performance assessment will identify which performance

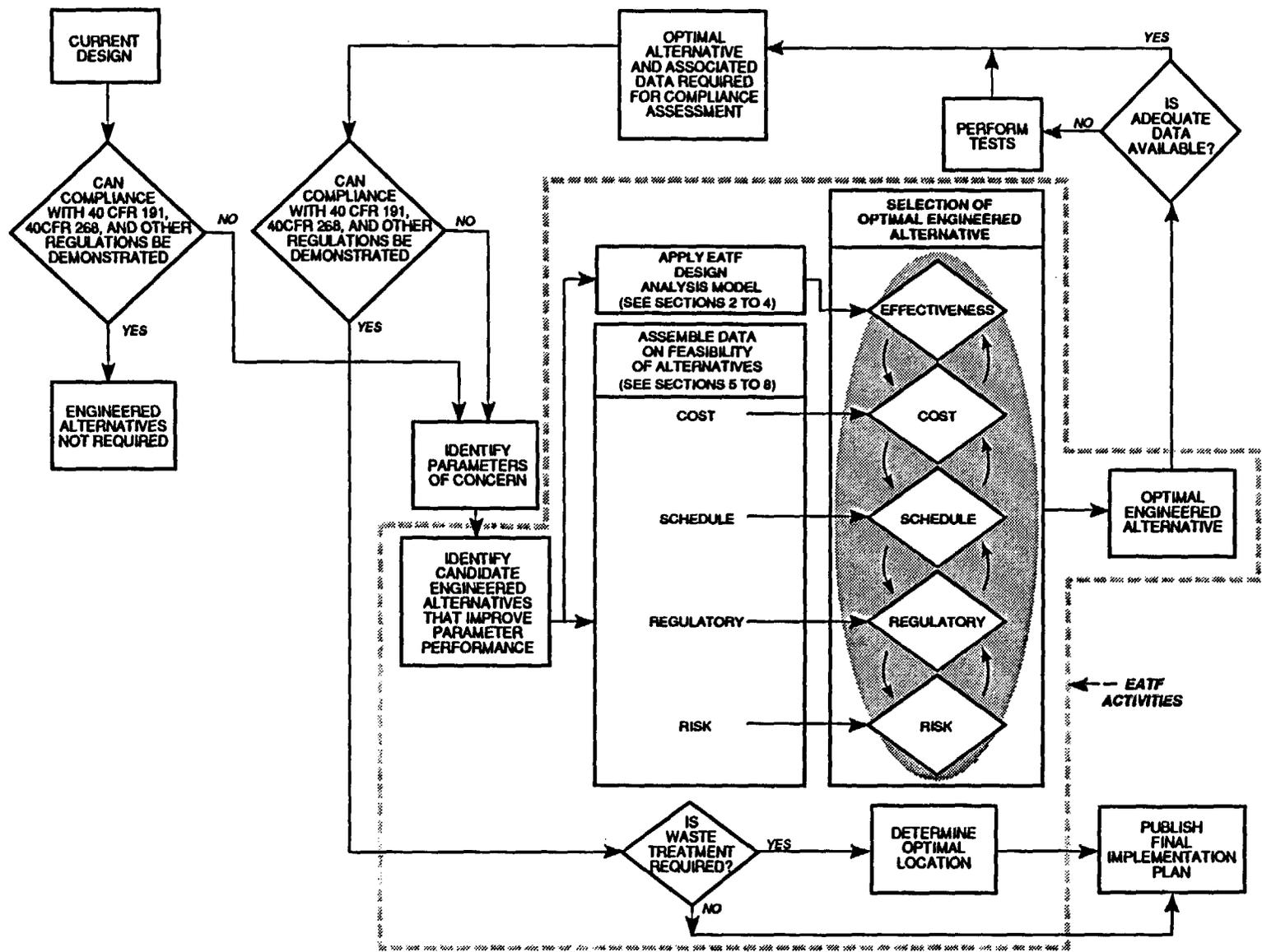


Figure 9-1 Methodology for using EATF results

parameters (e. g., permeability, radionuclide solubility, microbial/radiolytic gas generation, etc.) are the cause for concern.

### 9.2.1 Identification of Candidate Engineered Alternatives

Once a problem is identified by performance assessment, the data developed by the EATF will help to identify a list of candidate alternatives that would be sufficient to alter the performance parameters of concern in order to achieve the required performance. The objective would be to focus the choice of alternatives to a small group of candidate engineered alternatives for further evaluation. For example, if it is determined that merely lowering the gas generation rates will demonstrate compliance, one of Alternatives 1, 2, or 3, from Table 9-1 would be sufficient, and there would not be any need of any Level III alternatives. If, on the other hand, it is determined that it is necessary to eliminate gas generation of any kind, then the group of candidate alternatives would be limited to Alternatives 8, 9, and 13. Similarly, based on the results of performance assessment, candidate alternatives can be chosen from Table 9-1 to address the human intrusion scenarios if the current design is predicted to result in noncompliance with any of the three intrusion scenarios.

### 9.2.2 Evaluation of Candidate Alternatives

Once a group of candidate alternatives has been identified, the next step is to utilize the EATF results to assemble the data required for optimization of candidate alternatives. The specific tasks involved are discussed in the following sections.

#### 9.2.2.1 Application of the EATF Design Analysis Model

The effectiveness of the candidate alternatives with respect to various effectiveness criteria such as peak index pressure from gas generation, and the MRE for the three intrusion scenarios, can be estimated by the EATF Design Analysis Model. The results for the 14 alternatives analyzed by the EATF were presented earlier in Section 4.0. A similar analysis is required for each candidate alternative. It should be noted that if the underlying assumptions in the model change as additional data are obtained, or if the data base of model input parameters is expanded, then the Design Analysis Model should be updated and the effectiveness of the alternatives estimated using the revised assumptions.

#### 9.2.2.2 Assemble Data for Evaluation of the Feasibility of Candidate Alternatives

In addition to the analysis of the effectiveness of an alternative, data are required for the evaluation of the feasibility of implementing each candidate alternative. As mentioned earlier, feasibility refers to the combination of criteria such as cost, schedule, regulatory issues, and health and safety risks. These criteria are discussed below:

- Application of EATF Cost Analysis - The factors considered by the EATF for cost analysis include the capital cost of new treatment facilities, operating cost of facilities, cost of alternative materials (e. g., backfill, waste container, etc.) cost

of waste characterization/certification (if applicable), and the cost of waste transport. The cost of implementing different alternatives was estimated in Section 6.0 for waste treatment, Section 7.0 for backfill alternatives, and Appendix H for alternate waste container materials. The applicable information in each of these sections will help to develop the cost for implementing each alternative. The level of detail required in cost analyses depends upon the level of precision required. It should be noted that the costs presented in this report are not "bottom-up" costs (i.e., specific costs of equipment, material, and services have not been specified). Instead, these costs have been compiled from various DOE publications. These costs provide an excellent comparison between alternatives. However, if cost is of primary importance in the selection of optimal alternatives, then additional cost analysis may be required to reduce uncertainties to an acceptable level.

- Application of EATF Schedule Analysis - The schedules for implementing candidate treatment alternatives can be estimated from the EATF results presented in Section 6.0. The schedules estimated by the EATF include preconstruction, engineering, construction, and start-up, and are based upon results from various DOE publications. The regulatory issues have been assumed to be part of the preconstruction period of implementation schedules. The EATF feels that regulatory/compliance issues and budgetary constraints that delay construction, present the greatest uncertainties in the estimation of schedules. The acceptability of these estimates depends upon the relative importance assigned to schedule concerns during the selection of an optimal alternative (Section 9.2.3). Thus, the uncertainties involved must be weighed against the relative importance of schedule concerns, to decide if additional data are required to make a decision.
- Application of EATF Regulatory Analysis - The EATF analysis presented in Section 6.0 shows that significant uncertainty exists in the area of regulatory compliance, and therefore it is difficult to estimate the time periods required for licensing a facility. The EATF has considered the experience of other projects in various states, and also the different state and federal regulations that affect the permitting process. It has been observed that, in general, the timeframe required for facility permitting varies with the type of facility being considered (i.e., Level II or Level III), and the proposed facility location.

As discussed in Section 6.0, waste characterization may be required to comply with the State of New Mexico or RCRA requirements. The extent of waste characterization required by RCRA will have a significant influence on the choice of an alternative, especially if the cost of such characterization is comparable to the cost of processing the waste. Presently, the extent of characterization required by RCRA is not well defined. This increases the uncertainties of estimating the requirements for regulatory compliance. Although the various factors that affect the regulatory issues have been explained in Section 6.0, the EATF has refrained from presenting precise estimates of facility permitting time.

- **Application of EATF Risk Assessment** - The risks associated with implementing candidate alternatives can be compared with the baseline design using the results of the risk assessment summarized in Section 6.0 and discussed in detail in Appendix I. Although the analysis presented in Section 6.0 relates to Alternatives 1, 2, 4, and 8, and does not include all 14 alternatives, the four options analyzed by the EATF represent the total range of treatments involved in the 14 alternatives. For example, the waste treatment involved in Alternatives 3, 5, and 9 is identical to that of Alternatives 2, 4, and 8, except for different backfills. Because backfills used have no influence on the risk assessment, risk associated with Alternatives 3, 5, and 9 are assumed to be identical to those for Alternatives 2, 4, and 8, respectively.

The results of the EATF risk assessment demonstrate that Level II treatments result in a slight increase in risk relative to the baseline design, and this increase is generally independent of the number of facilities. In contrast, for Level III treatments, the dominance of transportation risks favors treatment of wastes at multiple facilities before transporting the wastes to WIPP. This is because the Level III treatment of waste before shipment substantially reduces the transportation risks, and this reduction more than compensates for the increase in occupational risks associated with the Level III treatment of waste.

Since risk is an abstract quantity, the results of any risk analysis are often used by equating risk to some tangible quantity (e. g., the number of lives saved by an unit decrease in absolute risk). However, the use of such an approach is not recommended for the results of the EATF risk assessment for reasons outlined below.

The EATF analysis has involved estimating the risks of alternatives as ratios relative to the baseline case. This approach was used to cancel the uncertainties that are common to the baseline case and the alternatives. In theory, one could take the relative risk reduction ratios estimated by the EATF, and combine these numbers with the absolute baseline risk provided in the FSEIS/FSAR to arrive at an absolute risk for each alternative. However, it should be noted that this would only serve to bring back the uncertainties present in the FSEIS/FSAR calculations, and therefore not advisable.

If it is not possible to make a decision without the absolute risk values for the alternatives, then the EATF recommends either one of two optional approaches. The first approach involves an estimate of the absolute baseline risks using a more rigorous method than the one used in the FSEIS/FSAR. This should reduce the uncertainties, and the EATF results of relative risk could then be combined to arrive at absolute risks for the alternatives. The second approach is less rigorous, and involves expressing the value of relative risk reduction for each risk component (e.g., transportation fatalities, etc.) in terms of a tangible quantity such as the number of lives saved, etc. Once each of the eight components

considered by the EATF has been expressed in terms of a tangible quantity, they could then be aggregated using societal weights for each component to arrive at a tangible value of risk reduction for each alternative.

The limited scope of this study should be noted while applying the results of the risk assessment. As explained in detail in Figure I.ES-1 in Appendix I, the different combinations of alternatives and treatment locations fall into four different risk groups. While a more rigorous analysis might change the numerical values of the risk reduction factors within each of the four groups, it is unlikely to result in reclassification of any option from one group to another.

### 9.2.3 Selection of an Optimal Engineered Alternative

Once the data on the effectiveness and feasibility of candidate alternatives have been compiled, the next step is to use the data to select an optimal alternative. As shown in Figure 9-1, the optimal alternative should be decided by simultaneous consideration of five different components for each alternative. These are effectiveness, cost, schedule, regulatory considerations, and the health and safety risk associated with an alternative. While a relative measure of these factors can be obtained for each alternative using the results of the EATF, their relative importance must be evaluated in any final decision process. Unless the relative importance of these factors is established, the results of the EATF for each factor will remain mutually exclusive, and therefore cannot be aggregated for optimizing the choice of an alternative.

The interactive processes that are expected to be involved in such an optimization process are illustrated below with an example. Assuming that the candidate alternatives are limited to Alternatives 3 and 4, the analysis of the EATF would provide the following results:

Effectiveness - Alternative 4 would reduce peak index pressures to lithostatic. Alternative 3 would be ineffective in reducing pressures to lithostatic, and the maximum peak index pressures predicted for this alternative are 20 percent higher than the lithostatic pressure. In general, Alternative 3 may be more effective against human intrusion, whereas Alternative 4 is more effective for addressing gas generation.

Cost - Project costs for Alternative 4 are expected to be substantially higher than for Alternative 3.

Schedule - Alternative 3 would take 5-7 years for implementation, whereas Alternative 4 would take 8-11 years.

Regulatory Considerations - Since Alternative 4 involves thermal treatment, it would be expected that the regulatory requirements for this alternative would be more extensive than Alternative 3.

**Risk** - If the number of waste treatment facilities is less than or equal to three, then the risks due to the two alternatives are roughly equal. For more than three treatment facilities, the risk due to Alternative 4 is marginally less than Alternative 3.

Given the above results, the relative importance of the above factors has to be determined in influencing the decision. For example, it must be decided whether the improvement in effectiveness using Alternative 4 is worth the additional cost as well as the more extensive regulatory requirements. If schedule is the most important factor, Alternative 3 would seem to have an advantage over Alternative 4.

The decision maker should also take note of the uncertainties involved in the EATF evaluations and, based on the relative importance of a factor, it should be decided if a more detailed analysis is warranted. For example, future experimental data regarding properties of modified waste forms might show that Level II alternatives such as Alternative 3 would not exceed the lithostatic pressure. Therefore, if the relative importance of effectiveness is considered to be greater than the other factors, then it would be advisable to carry out additional analysis of alternatives using revised properties of modified waste forms as input to the Design Analysis Model, and thus minimize the uncertainties before selecting an optimal alternative. Similarly, if the EATF estimates of project costs for the candidate alternatives are roughly equivalent, and cost is the most important factor, then it would be advisable to estimate "bottom-up" costs for each candidate before reaching a decision.

In summary, the decision methodology proposed by the EATF can serve as a "guide" in the process of selecting an optimal alternative. However, this optimization process involves the aggregation of the EATF results based on the relative importance of influential factors. It is beyond the scope of the EATF to make a judgement on the relative importance of the five factors mentioned previously, and therefore the EATF has left the process of selecting an optimal alternative to the eventual decision maker.

Thus, there are three tasks that must be completed as part of any final selection of an optimal alternative. Since the EATF formulated the list of alternatives in the early part of 1990, the list of alternatives might require a review and update in the future as new technologies continue to evolve. The relative importance of the five factors involved in selecting an optimal alternative should also be decided by some sort of weighting or prioritization. Finally, the existing data developed and presented by the EATF in this report should be reviewed to understand its uncertainties and limitations. The completion of these tasks, together with the methodology described in Figure 9-1, should guide the selection of an optimal alternative, in case one is needed.

#### 9.2.4 Verification of Compliance for Optimal Alternative

Once an optimal alternative has been selected, compliance with the applicable regulations must be demonstrated. An assessment of compliance for the alternative by the use of performance assessment codes will require adequate data regarding the properties of the waste forms resulting from the alternative. If such data are not available, experiments should be conducted to obtain the required data. The data for the optimal alternative will be used as input to the

performance assessment codes to verify if the selected alternative can indeed demonstrate compliance with all applicable regulations. If compliance is demonstrated, optimal locations for implementing the alternative can be determined using the EATF facility siting logic described in Section 6.4. In case the optimal alternative fails to demonstrate compliance with applicable regulations, the parameters of concern associated with the alternative must be identified, and the whole selection process repeated until compliance can be demonstrated.

### **9.3 CONCLUSION OF THE EATF**

The EATF has concluded that a number of engineered alternatives could be implemented to improve repository performance if WIPP performance assessment determines that either gas generation or human intrusion presents a problem in demonstrating compliance. Waste treatment is generally the most effective type of engineered alternative, but is by far the most difficult to implement. Within waste treatment, Level III treatments are the most effective in addressing multiple performance parameters, but tend to be the most expensive, the most difficult and time-consuming to implement, and have the greatest regulatory requirements. Level II treatments are less expensive, faster, require less extensive permitting, and utilize off-the-shelf technology, but are less effective in addressing multiple performance parameters. Depending upon the performance parameter, Level I alternatives such as alternative backfills, alternative waste containers, or modified repository design should be thoroughly evaluated and eliminated before any decision is made to treat the waste.

The present uncertainty in the degree to which the baseline WIPP design complies with 40 CFR Part 191 and 40 CFR Part 268 precludes specific recommendations at this time. The broad range of potential alternatives, with significant variations in cost, implementation schedules, regulatory requirements, etc. between alternatives, requires that performance improvements are better defined before the EATF can make specific recommendations. The decision methodology provided (see Section 9.2 for optimal alternative selection and Section 6.4 for treatment site selection) provides a means to evaluate options once the needed improvement in performance is known. In the interim, there is the option of using the decision methodology to perform sensitivity analyses or to evaluate potential alternatives based upon preliminary results of the WIPP performance assessment.

## 10.0 MEMBERS OF THE EATF

The Engineered Alternatives Task Force is comprised of WIPP-management and more than 50 technical personnel from the DOE, DOE-contractors, and commercial organizations (Figure 10-1). The core EATF team includes staff from DOE-WPO, Westinghouse Waste Isolation Division (WID), International Technology Corporation (IT), and Sandia National Laboratories. The work of the task force was supported by input from several "expert panels" that addressed specific technical issues. The Engineered Alternatives Multidisciplinary Panel (Appendix A), the Cement/Grout Expert Panel (Appendix G), and the Waste Container Materials Panel (Appendix H) were three such expert panels convened to provide technical guidance to the EATF.

External and internal DOE peer reviews were used to develop and refine the EATF Program Plan, the Design Analysis Model, data on the feasibility of alternatives, and this EATF Final Report. Comments from the DOE/HQ WIPP Task Force staff and the National Academy of Sciences WIPP Panel were particularly instrumental in formulating the approach taken by the EATF. The Independent Review Panel, composed of the now-deceased Dr. Doug Brookins [Professor of Geochemistry and prior contributor to WIPP and Office of Civilian Radioactive Waste Management (OCRWM) programs], Dr. Eric Nuttall (Professor of Chemical Engineering and contributor to modeling of geological repositories), Mr. Donald Shaw (expert in rock mechanics and prior contributor to modeling of WIPP), and Dr. Robert Budnitz (expert in probabilistic risk assessments) reviewed a draft version of this EATF Final Report and suggested numerous improvements.

The work of the EATF was supported by the technical staff at Westinghouse and IT Corporation. Text processing and graphics support at IT produced high-quality documentation. Administrative support was provided by Kathleen Logan and Cindy Morrison of IT and Rhonda Molgaard of Westinghouse. Contracts support was provided by Peter Tackett of Westinghouse and Ron Freeny and Linda Baker of IT.

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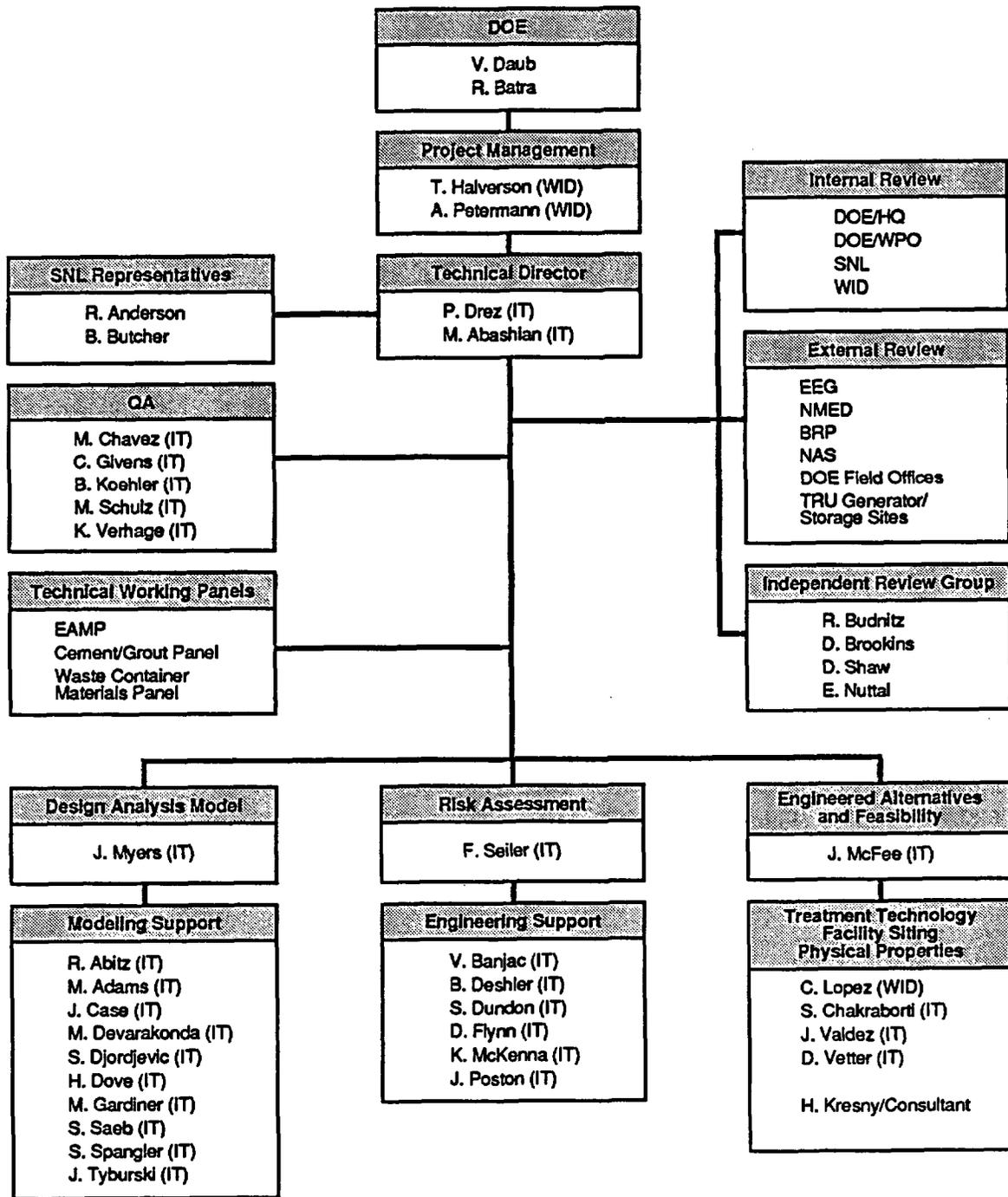


Figure 10-1  
Engineered Alternatives Task Force Project Organization

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## 12.0 GLOSSARY

**Accessible Environment** - The accessible environment means to (1) the atmosphere, (2) land surfaces, (3) surface waters, (4) oceans, and (5) all of the lithosphere that is beyond the controlled area (see 40 CFR Part 191.12[k]).

**Activity** - The number of nuclear disintegrations occurring in a given quantity of material per unit time.

**Advection** - The transport of fluid by bulk motion through a porous solid due to a difference in absolute fluid pressure across the solid.

**Alpha Particle** - A positively charged particle made up of two protons and two neutrons (therefore, identical to a Helium atom). Emitted in the radioactive decay of certain nuclides, it is the least penetrating of the three types of radiation: alpha, beta, and gamma.

**AIRDOS** - A computer code used to calculate health risks due to the atmospheric dispersal of radioactivity.

**Anhydrite** - A mineral consisting of anhydrous calcium sulfate ( $\text{CaSO}_4$ ). It is equivalent to gypsum without water, and is denser, harder and less soluble than gypsum.

**Anoxic** - Without oxygen.

**Argillaceous** - Pertaining to, largely composed of, or containing clay-sized particles or clay forming minerals.

**Argillaceous Rocks** - Rocks containing appreciable amounts of clay.

**Attribute** - the value of utility assigned to a particular component of the risk.

**Backfill** - Material (such as crushed salt or grout) placed around the waste containers to fill the open spaces in the room.

**Becquerel (Bq)** - The SI unit of radioactivity. One Bq equals one disintegration per second.

**Bell Canyon Formation** - A sequence of rock strata (sandstones, shales and limestones) that form the uppermost unit of the Delaware Mountain Group; of significance because it is the first regionally continuous water-bearing formation beneath the WIPP underground workings (Lappin et al., 1989).

**Bentonite** - A commercial term applied to clay materials containing montmorillonite (smectite) as the primary mineral.

**Biomass** - The dry weight of living matter, including stored food, present in a species population and expressed in terms of a given area or volume of the habitat.

**Borehole** - (1) A manmade hole in the wall, floor, or ceiling of a subsurface room used for verifying the geology, observation, or the emplacement of waste canisters. The horizontal wall holes are used for remote-handled transuranic (RH-TRU) waste; (2) A hole drilled from the

surface for purposes of geologic or hydrologic testing, or to explore for resources, sometimes referred to as a borehole.

**Brine Pocket** - Pressurized brine of unknown origin but of limited extent contained in fractured anhydrite within the Castile Formation located 210 m below the WIPP repository.

**Cancer Risk Coefficient** - The factor used to convert radiation dose in Sievert (Sv) to Latent Cancer Fatalities. Numerical value taken from the BEIR III (National Research Council, 1980) Report is equal to  $0.028 \text{ Sv}^{-1}$ .

**Carcinogens** - A substance that causes or enhances the processes which turn a normal cell into a cancerous cell.

**Castile Formation** - A formation of evaporite rocks (interbedded halite and anhydrite) of Permian age that stratigraphically underlies the Salado Formation.

**Cement/Cementitious Material** - A dry substance with the capacity to absorb fluid.

**CH-TRU Waste** - Contact-Handled TransUranic waste, packaged TRU waste whose external dose rate does not exceed 200 mrem per hour.

**Cloudshine** - The exposure from cloudshine is the direct external dose from the passing cloud of atmospherically dispersed radioactive material.

**Committed Effective Dose Equivalent (CEDE)** - The weighted sum of the dose equivalent to organs or other tissues that will be received following an intake of radioactive material for a 50-year period following that intake.

**Compaction** - Mechanical process by which the pore space in the waste is reduced prior to waste emplacement.

**Composite** - A single, homogeneous mixture of waste and backfill material which has physical and chemical characteristics resulting from the incorporation of a particular engineered alternative.

**Compressibility** - The property of a substance capable of being reduced in volume by application of pressure; quantitatively, the reciprocal of the bulk modulus.

**Conceptual Model** - The set of hypotheses and data that postulate the description and behavior of the disposal system.

**Concrete** - A mixture of grout and some type of aggregate (such as stone pebbles or salt rock).

**Conservative** - When used with predictions or estimates, a conservative estimate is one in which the uncertain values are used in a way that maximizes their negative or undesirable impact on the system.

**Continuous Air Monitor (CAM)** - Instrument that continuously monitors the air for certain present concentrations of toxic substances or radioactivity.

**Controlled Area** - The controlled area means (1) a surface location, to be identified by passive institutional controls; that encompasses no more than 100 km and extends horizontally no more than 5 km in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and (2) the subsurface underlying such a surface location (40 CFR Part 191.12[G]).

**Creep** - A very slow deformation of solid rock resulting from constant stress applied just below the elastic limit; refers to the geologic phenomenon experienced as salt under high compressive loading begins to deform plastically.

**Creep Closure** - Closure of underground openings, especially openings in salt, by plastic flow of the surrounding rock under pressure.

**Culebra Dolomite Member** - The lower of two dolomite units (the other being the Magenta Dolomite Member) within the Rustler Formation that are locally water bearing; the first laterally continuous unit above the repository to display significant permeability (Lappin, et al., 1989).

**Curie** - The SI unit of activity. One curie (Ci) equals  $3.700 \times 10^{10}$  nuclear disintegrations per second.

**Darcy** - An English standard unit of permeability, defined by a medium for which a flow of 1  $\text{cm}^3/\text{s}$  is obtained through a section 1  $\text{cm}^2$  for a fluid viscosity of 1 cP and a pressure gradient of 1 atm/cm. (One Darcy is equal to  $9.87 \times 10^{-11} \text{ m}^2$ ).

**Darcy's Law** - The law which states that the rate at which a fluid flows through a permeable substance per unit area is equal to the permeability (a property of the substance through which the fluid is flowing) times the pressure drop per unit length of flow, divided by the viscosity of the fluid.

**Decay (radioactive)** - Process in which a nucleus emits radiation in the form of ionizing and/or particle radiations undergoing spontaneous transformation into one or more different nuclei.

**Decontamination** - The removal of unwanted material (especially radioactive material) from the surface of, or from within, another material.

**Delaware Basin** - The part of the geologic Permian Basin in southeastern New Mexico and adjacent parts of Texas where an ancient sea deposited thick layers of evaporites approximately 200 million years ago. It is partially surrounded by the Capitan Reef.

**Design Analysis Model** - The main program used to analyze the relative effectiveness of various modifications to the WIPP facility and waste forms when compared to the WIPP disposal system reference design and current waste forms.

**Deterministic** - Pertaining to an exact mathematical relationship between the dependent and independent variables in a system.

**Dewey Lake Red Beds** - A formation that overlies the Rustler Formation and is composed of reddish brown marine mudstones and siltstones interbedded with finegrained sandstone.

**Diffusion** - Is the transport process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient, from higher concentrations to lower concentrations.

**Diffusion Coefficient** - The proportionality constant in Fick's Law of Diffusion defined as the amount of solute material per unit time that diffuses through a unit cross-sectional area under a unit concentration gradient; with fundamental dimensions of area per unit time.

**Diffusive** - Characterized by the transfer of chemical components from a region of higher to one of lower concentration.

**Dispersion Function** - Function that models the dispersion of a substance through the environment.

**Disposal Phase** - The 20 year period by which DOE proposes to permanently emplace TRU wastes in the WIPP.

**Dolomite** - A sedimentary rock consisting primarily of the mineral dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ); commonly associated with limestone.

**Dose** - A general term denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose. (The SI unit of absorbed dose is the gray; the old unit is the rad.)

**Drift** - A horizontal mine passageway.

**E1** - An event or scenario: intrusion of a borehole through a disposal panel into a pressurized brine occurrence in the Castile Formation (Marietta et al., 1989).

**E1E2** - The combined scenario involving a borehole intrusion into a disposal panel and into pressurized brine followed by the intrusion of another borehole into the same panel.

**E2** - An event or scenario: intrusion of a borehole into a disposal panel (Marietta et al., 1989).

**Effectiveness Measure** - A parameter used in the analysis of human intrusion events which provides a convenient means of comparing improvements offered by alternative designs over the baseline design. The "Effectiveness Measure" is calculated for the baseline design, as well as for each alternative design and is proportional to the cumulative release of twelve individual isotopes into an overlying water-bearing strata (the Culebra Dolomite) over a 10,000-year period, plus the activity associated with the direct release of contaminated drill cuttings to the surface.

**Effective Waste Volume** - The volume of the waste/backfill composite minus the volume of the backfill along the sides of the waste stack; parameter used in the Design Analysis Model to calculate radionuclide releases to the surface due to the removal of drill cuttings.

**Exposure** - A measure of the ionization produced in air by gamma or x-ray radiation. It is the sum of the electrical charges on ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the Roentgen.

**Fick's Law** - The law which states that the rate of diffusion of matter across a plane is proportional to the negative of the rate of change of the concentration of the diffusing substance in the direction perpendicular to the plane; in other words, a species "i" diffuses (moves relative to the mixture in the direction of decreasing mole fraction "i").

**Fissile** - Describing a nuclide that readily undergoes fission (splitting) by absorption of neutrons within discrete energy bands.

**Fugacity** - An idealized vapor pressure; equal to the vapor pressure when the vapor behaves as an ideal gas.

**40 CFR Part 191** - EPA standard for managing and disposing of spent nuclear fuel, high-level, and transuranic wastes. Subpart A deals with managing and storing of wastes, while Subpart B covers long-term isolation and disposal.

**40 CFR Part 268** - EPA regulation governing land disposal restrictions; consists of five subparts as follows: Subpart A - General; Subpart B - Schedule for Land Disposal Prohibition and Establishment of Treatment Standards; Subpart C - Prohibitions on Land Disposal; Subpart D - Treatment Standards; and Subpart E - Prohibitions on Storage (Code of Federal Regulations, p. 748).

**Gamma** - Penetrating electromagnetic radiation emitted in some nuclear decays.

**GBq** - GigaBecquerel ( $10^9$  Bq).

**Gray** - The SI unit of absorbed dose. One gray is produced by the absorption of one Joule of energy in a mass of one kg.

**Groundshine** - The exposure from groundshine is the direct external dose from radioactive material that has deposited on the ground after being dispersed from an accident site.

**Grout** - The material which results when a cement is combined and well mixed with a fluid.

**Half-life** - The average time required for an unstable element or nuclide to lose one-half of its radioactive intensity in the form of alpha, beta, or gamma radiation.

**Halite** - The mineral rock salt, NaCl.

**Hazard Index (HI)** - The ratio between the daily intake of a chemical and an acceptable reference level.

**Hazardous Waste** - Restricted nonradioactive wastes that exceed standards or do not meet other requirements of 40 CFR Part 268 with regard to toxicity or mobility reduction (DOE, 1990d, Vol. 1, p. 1-1).

**Headspace** - Gas volume in a closed waste drum.

**HEPA Filters** - High Efficiency Particulate Air Filters.

**Hydraulic Conductivity** - The rate of aqueous flow, in volume per time, through a cross-section of area under a unit hydraulic gradient at the prevailing temperature.

**Hydraulic Diffusivity** - The ratio of the hydraulic conductivity to the specific storage with fundamental dimensions of area per unit time.

**Immediate Danger to Life and Health (IDLH)** - Level or concentration of toxic agent that causes an immediate danger to life and health.

**Isotope** - A species of atom having the same number of protons but differing in the number of neutrons in its nucleus. In most instances, an element can exist as several isotopes differing in the atomic mass. Isotopes can be either stable isotopes or radioactive isotopes (also called radioisotopes or radionuclides).

**Isotropic** - Having the same properties in all directions.

**Joule** - SI unit of energy, equal to the energy expended by a force of 1 Newton over a distance of 1 meter.

**kg** - Kilogram

**km** - Kilometer

**Lithostatic Pressure** - Subsurface pressure caused by the weight of overlying rock or soil (14.8 MPa at the WIPP repository level).

**m** - Meter

**MB 139** - Marker Bed 139: One of 45 siliceous or sulfatic units within the Salado Formation consisting of about 1 m of polyhalitic anhydrite and anhydrite. MB 139 is located within the WIPP horizon.

**MBq** - MegaBecquerel ( $10^6$  Becquerel).

**mJ** - Milli-Joule ( $10^{-3}$  J). Subunit of energy.

**Morbidity** - An early morbidity, premature death due to causal agent.

**MPa** - Megapascal ( $10^6$  Pa)

**Newton** - SI unit of force: 1 N is the force needed to accelerate a mass of 1 kg by  $1 \text{ m s}^{-2}$ .

**Nuclide** - A species of atom characterized by the number of protons (Z), number of neutrons (N), and energy state.

**Occupational Risks** - Risk of occupational work due to the treatment, transport, handling, or emplacement of Contact-Handled transuranic waste at the WIPP.

**Pa** - Pascal; basic unit of pressure produced by a force of 1 Newton applied over an area of  $1 \text{ m}^2$ .

**Panel** - Within the WIPP, a panel consists of seven underground rooms connected by 33-ft-wide drifts at each end.

**Particulates** - Fine liquid or solid particles such as dust, smoke, or fumes found in the air or in emissions.

**PE-Bq** - A radioactive hazard index factor; relates the radiotoxicity, a given activity, of TRU radionuclides to that of Plutonium-239.

**Performance Assessment** - The process of assessing the compliance of a deep, geologic waste repository with the Containment Requirements of 40 CFR Part 191 Subpart B. Performance assessment is defined by Subpart B as an analysis that (1) identifies the processes and events that might affect the disposal system, (2) examines the effects of these processes and events on the performance of the disposal system, and (3) estimates the cumulative releases of radionuclides, considering the associated uncertainties, caused by all significant processes and events. These estimates are incorporated into an overall probability distribution of cumulative release to the extent practicable (40 CFR Part 191.12(q)).

**Permeability** - A measurement of the ability of a rock or soil to transmit fluid under hydraulic gradient dependent upon the interconnectedness of the interstices.

**Permian Basin** - A region in the south-central United States, where during Permian times (248 to 286 million years ago), basin configuration created many shallow sub-basins which resulted in the position of vast beds of marine evaporites.

**Person-sievert** - A unit of population dose, equivalent to man-sievert.

**Polyhalite** - A hard, poorly soluble evaporite mineral:  $K_2MgCa_2(SO_4)_4 \cdot 2H_2O$ .

**Porosity** - The porosity of a rock or soil is its property of containing interstices or voids and may be expressed quantitatively as the ratio of the volume of its interstices to its total volume.

**Portlandite** - Calcium hydroxide,  $Ca(OH)_2$ ; a mineral belonging to the brucite group.

**Potentiometric Surface** - The surface of the hydraulic potentials of an aquifer. It is usually represented as a contour map in which each contour indicates how high the water would rise in a well tapping that aquifer at any point on that contour.

**rad** - An old measure of radiation dose absorbed by a tissue or other material. 1 rad corresponds to the absorption of 10 mJ/kg of material.

**Radioactive Waste** - Solid, liquid, or gaseous material of negligible economic value that contains radionuclides in excess of threshold quantities.

**Radioactivity** - The property of certain nuclides of spontaneously emitting particles or energy or of undergoing spontaneous fission.

**Radiolysis** - Chemical decomposition by the action of radiation.

**Radionuclide** - see Isotope.

**Radionuclide Inventory** - A list of the types and quantities of radionuclides in a container or source. Amounts are usually expressed in activity units: curies or curies per unit volume.

**RADTRAN** - Computer code used to calculate radiological risks of transportation (Madsen et al., 1986).

**Reference Level** - The level at which no observable effects are obtained from a certain chemical exposure.

**Rem** - An old unit for dose equivalent. It is numerically equal to the absorbed dose in rads multiplied by a quality factor of the radiation type.

**RH-TRU Waste** - Remote-Handled TRansUranic waste. Packaged TRU waste whose external surface dose rate exceeds 200 mrem per hour, but not greater than 1,000 rem per hour.

**Risk** - The product of probability and consequence. The radiological risk of a scenario is the population dose equivalent resulting from that scenario multiplied by that scenario's probability of occurrence and the risk coefficient such as a cancer risk coefficient.

**Risk Assessment** - Qualitative or quantitative evaluation of health and environmental risks resulting from exposure to chemical, radioactive, or physical agents.

**Room** - An excavated underground cavity; within the WIPP, a room has the following dimensions; width = 33 ft; height = 13 ft; and length = 300 ft.

**Rustler Formation** - A sequence of Upper Permian age clastic and evaporite rocks that contains two dolomite marker beds (the Magenta and the Culebra Dolomite members), and overlies the Salado Formation.

**s** - Second

**Salado Formation** - A sequence of Upper Permian age evaporite rocks containing 45 numbered "anhydrite" marker beds (MB 101 through MB 145) interbedded with halites of varying purity and accessory minerals such as clay and polyhalite.

**Scenario** - A combination of events and processes that represent a possible future condition of the repository; factors examined include geologic and groundwater systems that could contribute to the escape of radionuclides from the repository, and release into the accessible environment.

**Sealing** - Formation of barriers within man-made penetrations (shafts, boreholes, tunnels, drifts).

**Shaft** - A manmade hole, either vertical or steeply inclined, that connects the surface with the underground workings of a mine.

**Sievert (Sv)** - The SI unit of radiation dose equivalent which is the product of the absorbed dose (in Gray), the quality factor of the radiation, and other factors.

**Solute** - The substance dissolved in a solvent.

**Specific Activity** - Total activity of a given radionuclide per gram of a compound, element, or radionuclide.

**Storativity** - The volume of water released by an aquifer per unit surface area per unit decrease in hydrologic head.

**TBq** - TeraBecquerel ( $10^{12}$  Bq).

**Threshold Limit Value (TLV)** - Basis for Hazard Index. A time-weighted average for an 8-hour period intended to protect workers over a career of exposure.

**Threshold Pressure** - The capillary pressure corresponding to full saturation under drainage conditions required to overcome capillary forces at the gas/brine interface and create an incipient interconnected gas filled pore network.

**Tortuosity** - Measurement of actual path of flow through a porous medium.

**Transmutation** - Any process by which a nuclide is transformed into a different nuclide, or more specifically, when transformed into a different element by a nuclear reaction.

**Transuranic Radioactive Waste (TRU Waste)** - Waste that, without regard to source or form, is contaminated with more than 100 nCi per gram of waste of alpha-emitting transuranic isotopes with atomic numbers greater than 92 and half-lives greater than 20 yr, except for: (1) HLW; (2) wastes that the DOE has determined, with the concurrence of the EPA Administrator, do not need the degree of isolation required by 40 CFR Part 191; or (3) wastes that the NRC has approved for disposal on a case-by-case basis in accordance with 10 CFR Part 61. Heads of DOE field organizations can determine that other alpha-contaminated wastes, peculiar to a specific site, must be managed as TRU waste.

**Treatment Facility** - Place(s) at which contact-handled waste is to be treated by different means either before, during, or after transportation.

**TRUPACT-II** - The DOT Type B package designed to transport Contact-Handled transuranic waste to the WIPP site. It is a cylinder with a flat bottom and a domed top that is transported in the upright position. Each containment vessel is nonvented and capable of withstanding a pressure of 50 psi (345 kPa). Capacity of each TRUPACT-II is fourteen 55-gallon drums (208 L), two standard waste boxes, or one box and seven drums.

**Utility Index** - The value of the Multi-Attribute Utility Theory function. This function describes the value assigned to a particular combination of attributes.

**Viscosity** - The resistance that a gaseous or liquid system offers to flow when it is subjected to a shear stress.

**Vitrification** - Term which implies the melting or fusing of residue into a glass matrix.

**Void Volume** - The total volume in a matrix not occupied by the matrix material.

**Waste Acceptance Criteria (WAC)** - The DOE document describing the criteria by which unclassified transuranic waste will be accepted for emplacement at the WIPP and the basis upon which these criteria were established (U.S. Department of Energy, 1989b).

**Waste Form** - The condition of the waste, its type, and physical form. Provides information on the waste contents, how the waste is processed, and on the chemistry of the constituents (TRUPACT-II Content Codes, p. v.).

**Waste Handling Building (WHB)** - The area at the WIPP which receives waste and where waste is assayed, if necessary, to prepare for emplacement.

*Rec'd WIPP letter dated  
7/3/91*

DOE/WIPP 91-007  
Revision 0



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**Final Report of the  
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Appendices**

**July 1991**



**Waste Isolation Pilot Plant**

*109.5*

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**Waste Isolation Pilot Plant**

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**LIST OF ACRONYMS**

<b>ANL</b>	<b>Argonne National Laboratory</b>
<b>ALARA</b>	<b>As Low As Reasonably Achievable</b>
<b>CAM</b>	<b>Continuous Air Monitor</b>
<b>C of C</b>	<b>Certificate of Compliance</b>
<b>CEDE</b>	<b>Cumulative Effective Dose Equipment</b>
<b>CFR</b>	<b>Code of Federal Regulations</b>
<b>CH</b>	<b>Contact-Handled</b>
<b>CH-TRU</b>	<b>Contact-Handled Transuranic</b>
<b>DOE</b>	<b>United States Department of Energy</b>
<b>DRZ</b>	<b>Disturbed Rock Zone</b>
<b>EAMP</b>	<b>Engineered Alternatives Multidisciplinary Panel</b>
<b>EATF</b>	<b>Engineered Alternative Task Force</b>
<b>EPA</b>	<b>United States Environmental Protection Agency</b>
<b>FEIS</b>	<b>Final Environmental Impact Statement</b>
<b>FSAR</b>	<b>Final Safety Analysis Report</b>
<b>FSEIS</b>	<b>Final Supplemental Environmental Impact Statement</b>
<b>G</b>	<b>G Value for Radiolysis</b>
<b>HAN</b>	<b>Hanford Reservation</b>
<b>HEPA</b>	<b>High Efficiency Particulate Air</b>
<b>HSWA</b>	<b>Hazardous and Solid Waste Amendments of 1984</b>
<b>IDLH</b>	<b>Immediate Danger to Life and Health</b>
<b>IMPES</b>	<b>Implicit Pressure Explicit Saturation</b>
<b>INEL</b>	<b>Idaho National Engineering Laboratories</b>
<b>IT Corp.</b>	<b>International Technology Corporation</b>
<b>ITEO</b>	<b>International Technology Engineering Operations</b>
<b>LANL</b>	<b>Los Alamos National Laboratories</b>
<b>LDMU</b>	<b>Law of Diminishing Marginal Utility</b>
<b>LLNL</b>	<b>Lawrence Livermore National Laboratory</b>

**LIST OF ACRONYMS  
(CONTINUED)**

LLW	Low-Level Waste
MAUT	Multi-Attribute Utility Theory
MB 139	Marker Bed 139
MRE	Measure of Relative Effectiveness
NDE	Number of Drum Equivalents
NMD	No-Migration Determination
NMED	New Mexico Environmental Department
NMVP	No-Migration Variance Petition
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
OPC	Ordinary Portland Cement
ORNL	Oak Ridge National Laboratories
PA	Performance Assessment
PNL	Pacific Northwest Laboratories
PREPP	Process Experimental Pilot Plant
PRRC	Petroleum Research and Recovery Center
QA	Quality Assurance
RCRA	Resource Conservation and Recovery Act
rf	radius factor
RFP	Rocky Flats Plant
RH	Remote-Handled
SAR	Safety Analysis Report
SEIS	Supplemental Environmental Impact Statement
SF	Scale Factor
SNL	Sandia National Laboratories
SRS	Savannah River Site
SWB	Standard Waste Box
TF	Treatment Facilities
TLV	Threshold Limit Values
TRAMPAC	TRUPACT-II Authorized Methods for Payload Acceptance and Control
TRU	Transuranic

**LIST OF ACRONYMS  
(CONTINUED)**

<b>TRUPACT-II</b>	<b>Transuranic Package Transporter - II</b>
<b>TSD</b>	<b>Treatment, Storage, and Disposal</b>
<b>VR</b>	<b>Volume Reduction</b>
<b>WAC</b>	<b>Waste Acceptance Criteria</b>
<b>WACCC</b>	<b>Waste Acceptance Criteria Certification Committee</b>
<b>WERF</b>	<b>Waste Experimental Reduction Facility</b>
<b>WHB</b>	<b>Waste Handling Building</b>
<b>WIPP</b>	<b>Waste Isolation Pilot Plant</b>
<b>WPO</b>	<b>WIPP Project Office</b>

**APPENDIX A**  
**REPORT OF THE WIPP ENGINEERED**  
**ALTERNATIVES MULTIDISCIPLINARY PANEL**

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## PREFACE

The WIPP Engineered Alternatives Multidisciplinary Panel, described in this report, was composed of individuals representing many disciplines and organizations. The primary Panel members included:

<u>Member</u>	<u>Discipline</u>	<u>Organization*</u>
Dr. Arun Agrawal	Metallurgy/Corrosion	Battelle Memorial Institute
Mr. Roger Hansen	Regulatory Compliance and Permitting	IT Corporation
Mr. Barry King	Microbiology	IT Corporation
Dr. Jon Myers	Geochemistry and Performance Assessment	IT Corporation
Mr. Milo Larsen	Waste Treatment	Haz Answers, Inc.
Mr. Mike McFadden	DOE/Institutional	U.S. Department of Energy WIPP Project Office
Mr. Vernon Daub	DOE/Institutional	U.S. Department of Energy WIPP Project Office
Mr. Jeff Paynter	Generator Waste Processing	EG&G Rocky Flats Incorporated
Mr. Kyle Peter	Generator Waste Processing	EG&G Rocky Flats Incorporated
Dr. Joe Tillerson	Rock Mechanics	Sandia National Laboratories
Mr. Bill White	Repository Operations	Westinghouse Electric Corporation Waste Isolation Division
Mr. Rod Palanca	Repository Operations	Westinghouse Electric Corporation Waste Isolation Division
Mr. Hans Kresny (Chairman)	Chairman and Facilitator	Solmont Corporation

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\*Current at the time the Panel convened in February, 1990.

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## EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico, is an underground repository designed for the geologic disposal of radioactive wastes resulting from the defense activities and programs of the United States Department of Energy (DOE). The performance of nuclear waste repositories is governed by U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985). The study conducted to demonstrate compliance with this regulation is called performance assessment. The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL). The EPA standard requires that DOE provide a reasonable assurance, based on performance assessment, that cumulative releases of radioactivity to the accessible environment will not exceed the standard's criteria. Preliminary performance assessment performed by SNL (DOE, 1990a) has indicated that the current design of the WIPP repository, together with the waste forms at the DOE storage and generating sites, may not demonstrate compliance with the EPA Standard. In view of this concern, and prompted by recommendations from the National Academy of Sciences (NAS) (DOE, 1988c) and other external review groups, the DOE established the Engineered Alternatives Task Force (EATF) in September, 1989 (Hunt, 1990).

The objective of the EATF is to identify potential engineering modifications (referred to as engineered alternatives) to the existing WIPP design and/or to the transuranic (TRU) waste forms, and to evaluate their effectiveness and feasibility in facilitating compliance with the EPA Standard. These alternatives would be designed to completely eliminate or reduce any problems which might cause non-compliance with the EPA Standard. As an example, if excess gas generation from corrosion of steel containers is identified by performance assessment to be an impediment to demonstrating compliance with the EPA Standard, an engineered alternative consisting of a different waste container material which does not generate gas could be considered. Gas generation in WIPP and other potential problems are referred to as "performance parameters" and are being addressed by the performance assessment studies (DOE, 1990d).

The performance assessment studies to date have identified a number of important performance parameters that are listed in a later section. However, until the studies are completed, it will not be known which of these performance parameters are most important to demonstrating compliance with the EPA Standard. The EATF is dealing with this uncertainty by integrating its efforts with the performance assessment studies and addressing all performance parameters identified by the studies. Recommendations of the EATF will be forwarded by DOE to SNL for input into the performance assessment efforts, as needed.

The specific steps involved in accomplishing the goal of the EATF were to:

- Identify and screen potential engineered alternatives.
- Develop design analysis models for the evaluation of relative effectiveness of engineered alternatives in comparison to the existing WIPP design and TRU waste forms.
- Determine the mitigating effect of engineered alternatives for each performance parameter using a quantitative design analysis model.

- Determine potential locations for implementing recommended engineered alternatives.
- Provide estimated schedules and costs for implementation of engineered alternatives.
- Recommend selected alternatives to DOE.

The EATF convened an Engineered Alternatives Multidisciplinary Panel (EAMP) with the objective of accomplishing the first step; the initial qualitative screening and ranking of potential engineered alternatives. The EAMP comprised a group of experts from different disciplines to ensure that appropriate technical expertise was available to make the qualitative judgments regarding each potential alternative. The engineered alternatives screened by the EAMP would be subsequently used by the EATF for quantitative evaluation using design analysis models.

The following disciplines were represented on the EAMP:

- DOE/Institutional
- Generator TRU Waste Processing
- Geochemistry
- Metallurgy/Corrosion
- Microbiology
- Performance Assessment
- Regulatory Compliance and Permitting
- Repository Operations
- Rock Mechanics
- Waste Treatment

The EAMP activities were carried out during November 1989 and February 1990. The EAMP members were briefed on WIPP, the EPA Standard 40 CFR Part 191 (EPA, 1985), the EPA land disposal restrictions in 40 CFR Part 268 (EPA, 1989), and the decision analysis methodology that was to be used. The EAMP also developed the criteria for screening and ranking the engineered alternatives. A total of 64 potential engineered alternatives suggested by the EATF and the EAMP were given preliminary scores by the EAMP for feasibility, and relative effectiveness in mitigating the effects of the performance parameters. These alternatives are listed in Table AES-1. Once the preliminary evaluations were completed, the EAMP took into consideration the heterogeneity of the TRU waste form and reevaluated the alternatives in terms of their ability to treat the different waste constituents (e.g., sludges, solid organics, etc.). The results of the EAMP formed the basis for recommendation of alternative waste forms for the WIPP Experimental Test Program (DOE, 1990b).

#### Methodology of Panel Evaluation

During the preliminary evaluations, ten performance parameters which might be important for demonstrating compliance with the EPA Standard were considered based on the performance assessment studies (Marietta et al., 1989). After further consultation with SNL's performance assessment group, the EAMP decided that the ten parameters could be condensed into a set

## TABLE AES-1

**POTENTIALLY USEFUL ENGINEERED ALTERNATIVES  
CONSIDERED BY THE ENGINEERED ALTERNATIVES  
MULTIDISCIPLINARY PANEL (EAMP)**

WASTE FORM MODIFICATION ALTERNATIVES

Compact Waste  
Incinerate and Cement  
Incinerate and Vitrify  
Wet Oxidation  
Shred and Bituminize  
Shred and Compact  
Shred and Cement  
Shred and Polymer Encapsulation  
Shred, Add Salt, and Compact  
Plasma Processing  
Melt Metals  
Add Salt Backfill  
Add Other Sorbents  
Add Gas Suppressants  
Shred and Add Bentonite  
Acid Digestion  
Sterilize  
Add Copper Sulfate  
Add Gas Getters  
Add Fillers  
Segregate Waste Forms  
Decontaminate Metals  
Change Waste Generating Process  
Add Anti-Bacterial Material  
Accelerate Waste Digestion Process  
Alter Corrosion Environment in WIPP  
Alter Bacterial Environment in WIPP  
Transmutation of Radionuclides  
Vitrify Sludges

BACKFILL ALTERNATIVES

Salt Only  
Salt Plus Gas Getters  
Compact Backfill  
Salt Plus Brine Sorbents  
Preformed Compacted Backfill  
Grout Backfill  
Bitumen Backfill  
Add Gas Suppressants

WASTE MANAGEMENT ALTERNATIVES

Minimize Space Around Waste Stack  
Segregate Waste in WIPP  
Decrease Amount of Waste Per Room  
Emplace Waste and Backfill Simultaneously  
Selective Vegetative Uptake

FACILITY DESIGN ALTERNATIVES

Brine Isolating Dikes  
Raise Waste Above the Floor  
Brine Sumps and Drains  
Gas Expansion Volumes  
Seal Disposal Room Walls  
Vent Facility  
Ventilate Facility  
Add Floor of Brine Sorbents  
Change Mined Extraction Ratio  
Change Room Configuration  
Seal Individual Rooms  
Two Level Repository

PASSIVE MARKER ALTERNATIVES

Monument Forest Over Repository  
Monument Covering the Entire Repository  
Buried Steel Plate Over Repository  
Artificial Surface Layer Over Repository  
Add Marker Dye To Strata

MISCELLANEOUS ALTERNATIVES

Drain Castile Reservoir  
Grout Culebra Formation  
Increase Land Withdrawal Area  
to Regulatory Boundary

WASTE CONTAINER ALTERNATIVES

Change Waste Container Shape  
Change Waste Container Material

of five parameters, since some of the ten parameters are interdependent and not mutually exclusive of one another (Anderson, 1990).

The original parameters and the five performance parameters upon which the EAMP based its final results are:

<u>Original Parameters</u>	<u>Condensed Set</u>
Radiolytic Gas Generation	Radiolytic Gas Generation
Biological Gas Generation	Biological Gas Generation
Corrosion Gas Generation	Corrosion Gas Generation
Porosity of Waste	Permeability of the Waste Stack
Permeability of the Waste Stack	Radionuclide Solubility in Brine
Brine Inflow	
Leachability of Waste	
Shear Strength of Waste	
Radionuclide Solubility in Brine	
Human Intrusion	

The EAMP considered engineered alternatives in seven categories. These categories, along with examples of engineered alternatives evaluated, are presented below:

<u>Category</u>	<u>Example</u>
Waste Form Modification Alternatives	Vitrify sludges
Waste Management Alternatives	Segregate waste in WIPP
Backfill Alternatives	Grout backfill
Facility Design Alternatives	Change room configuration
Passive Marker Alternatives	Monument covering the entire repository
Miscellaneous Alternatives	Grout Culebra Formation
Waste Container Alternatives	Change waste container material

The EAMP's activities were conducted according to a management decision process that quantifies normally subjective information (Daugbjerg, 1980). The 64 potential engineered alternatives considered by the EAMP were first subjected to a "must" criteria test (i.e., criteria which each alternative must satisfy in order to be considered for further evaluation by the panel). The following "must" criteria were defined by the EAMP:

Regulatory Compliance and Permitting - The alternative must have a likelihood to demonstrate regulatory compliance.

Availability of Technology - Technology must have been demonstrated at a minimum of laboratory scale, and must have the potential for full-scale implementation.

Schedule of Implementation - The alternative must be implementable within eight years for newly generated waste, and within 15 years for retrievably stored waste.

Any alternative which failed to satisfy all three criteria was eliminated from further consideration. The remaining alternatives were then judged according to two criteria; their

**effectiveness** in mitigating the effects of each of the five performance parameters, and their **feasibility** in terms of the three "must" criteria listed above. The EAMP decided that for feasibility considerations, the order of importance of the three criteria was Regulatory Compliance and Permitting, followed by Availability of Technology, and Schedule of Implementation. This relative order of importance was reflected appropriately in the weights assigned to these criteria during the scoring process. The scoring process is described in detail below. The effectiveness criterion was not divided into any subcategories. However, the effectiveness of an alternative was evaluated separately for each of the performance parameters.

The overall scores for each alternative were calculated by taking both effectiveness and feasibility into account. The EAMP judged that effectiveness and feasibility were of almost equal importance, with effectiveness being marginally more important than feasibility. On a scale of 0 to 10 (a score of 10 being the most effective), effectiveness was assigned a weight of 5.1 and feasibility was assigned a weight of 4.9. Feasibility was further subdivided into the three criteria previously used as "must" criteria above. These criteria were now used as weighted components of the overall feasibility criterion and formed the basis for ranking the relative feasibility of the alternatives that were not previously eliminated.

Thus, the weights assigned to each criterion was as follows:

• Effectiveness	5.1
• Feasibility	
- Regulatory Compliance and Permitting	2.4
- Availability of Technology	1.5
- Schedule of Implementation	<u>1.0</u>
Total Weightage	10.0

The effectiveness of the alternatives was evaluated on a scale of 1 to 10 for each of the performance parameters. The feasibility of the alternatives was also evaluated on a scale of 10 for each one of the three feasibility criteria. Finally, the scores on the 10 point scale were multiplied by the appropriate weights as listed above to get effectiveness and feasibility scores, and then summed together to get a total score for each alternative for any particular performance parameter. The feasibility of each alternative was assumed to remain the same irrespective of the performance parameter being considered for effectiveness evaluation.

Thus, if an alternative received an effectiveness score of 9 for mitigating radiolytic gas generation, 5 for regulatory compliance and permitting, 6 for availability of technology, and 7 for schedule of implementation, its total weighted score would be as follows:

$$\begin{array}{rcl}
 9 \times 5.1 & + & (5 \times 2.4 + 6 \times 1.5 + 7 \times 1.0) = 73.9 \\
 \text{Effectiveness} & & \text{Feasibility} \qquad \qquad \text{Total}
 \end{array}$$

After the preliminary evaluations were completed, the heterogeneity of the TRU waste was addressed by evaluating the effectiveness of all applicable alternatives for the three types of waste forms that are expected to comprise the majority of the WIPP inventory. These waste forms are sludges, solid organics (combustibles), and solid inorganics (glass and metals). The

scoring methodology was similar, except that the effectiveness of the chosen alternatives was judged separately for each of the three major waste forms. In addition, only the condensed set of five performance parameters was considered instead of the original ten.

### RESULTS OF PANEL EVALUATION

The results of the EAMP's screening of potential engineered alternatives indicate that numerous alternatives are available, if needed, to improve the performance of the WIPP repository. It should be emphasized that the screening process provides the basis for the quantitative design analyses of the engineered alternatives, and does not constitute an end result by itself. Therefore, the results must be considered preliminary to the follow-on design analyses and engineering studies to be conducted by the EATF.

In addition, it should be noted that a high scoring alternative is not necessarily an automatic choice over the others. In fact, the selection of an alternative is dependent on the extent of the problem (if any), as identified by the ongoing performance assessment studies. If the problem associated with a performance parameter is deemed to be minor by the performance assessment studies, even an alternative with low scores might be adequate to correct the problem.

The EAMP screening process eliminated all but 35 of the 64 engineered alternatives originally considered for evaluation. In addition, the EAMP added one alternative (cementation of the sludges) to the list, resulting in a total of 36 scored alternatives in six categories:

Waste Form Modification Alternatives	17
Waste Management Alternatives	2
Backfill Alternatives	6
Facility Design Alternatives	5
Passive Marker Alternatives	4
Waste Container Alternatives	2

The EATF has used the results of the EAMP and classified the waste form modification alternatives into seven generalized categories based on the similar final waste forms resulting from these treatments. These categories and the alternatives grouped into each category are:

- Vitrification of waste
  - Microwave melting (sludges only)
  - Plasma processing
  - Incinerate and vitrify (solid organics only)
  - Acid digest, calcine, and vitrify (solid organics only)
- Cementation of waste
  - Cementation of sludges into monoliths
  - Shred and cement (solid organics and inorganics)
  - Incinerate and cement (solid organics only)
- Compaction of waste (does not apply to sludges)
  - Compact
  - Shred and compact
  - Shred, add salt, then compact

- Encapsulation of waste (does not apply to sludges)
  - Shred and encapsulate with polymer
  - Shred and encapsulate with bitumen
- Preparation of Ingots from melted metal waste (applicable only to solid inorganics)
- Shredding of waste followed by addition of bentonite
- pH buffering of waste
  - Buffering by lime
  - Buffering by cement
  - Buffering by alumina

In addition, the EATF has included one more category in the above list which is not a waste form modification, but considered by the EATF to be an equally important group of alternatives. This new category is:

- Changing of waste container material.

In conjunction with the deliberations of the EAMP, the EATF has noted that there are some groups of alternatives which consistently received high scores for effectiveness, primarily because of their ability to eliminate the potential problem associated with a performance parameter. For example, all the different vitrification options (i.e., plasma processing, acid digestion, etc.) received consistently high effectiveness scores for the parameters associated with radiolytic gas generation, because they would (for all practical considerations) eliminate the potential associated with radiolytic gas generation. On the other hand, there are groups of alternatives which have been assigned low to moderate scores for effectiveness, because they can only slow down the rate processes associated with the parameter (instead of eliminating the potential). For example, any form of compaction of the waste was assigned low to moderate scores by the EAMP for corrosion gas generation, because these alternatives would only reduce the rate of corrosion gas generation but not eliminate it. Therefore, in order to develop a generalized set of recommendations for future design analysis, and for the WIPP Experimental Test Program, the EATF has divided the alternatives into two categories for each performance parameter:

- Alternatives which essentially eliminate the potential associated with a performance parameter
- Alternatives which only reduce or control the rate processes.

Alternatives belonging to both of the above categories were identified for the three gas generation parameters. The remaining parameters (permeability of waste stack and radionuclide solubility in brine) did not have any applicable alternatives belonging to the first category. In other words, the EAMP concluded that permeability and solubility can only be reduced or controlled but never completely eliminated.

Since the objectives of the WIPP Experimental Test Program and the design analysis modeling are primarily related to the effectiveness of an alternative, the EATF has summarized the panel

deliberations on the basis of effectiveness scores, and the two categories of alternatives mentioned above. It should be noted, however, that the feasibility of the alternatives is also being studied in detail as part of the overall EATF objectives.

Table AES-2 presents the set of alternatives which were consistently assigned high scores by the EAMP for their effectiveness for eliminating the potential associated with a performance parameter. Table AES-3 presents similar information for alternatives assigned low to moderate scores for effectiveness because they can only reduce the rate processes associated with a parameter, and cannot eliminate the potential. Since the extent to which the rate can be reduced or controlled is different for each alternative, the alternatives are listed in descending order of merit for each performance parameter.

It should be noted that since the properties of the final waste forms resulting from a lot of the alternatives are very similar, for the sake of brevity, alternatives in Tables AES-2 and have been grouped into one of the seven generalized categories described earlier. For example, all the different forms of compacting the waste have been grouped together as "compaction" in Table AES-3.

The EATF will perform design analyses of appropriate combinations of engineered alternatives from Tables AES-2 and AES-3 to quantify the improvement in repository performance using alternative waste forms. An example of such a combination for reducing the potential of radiolytic gas generation would be to cement the sludges, shredding and cementing the solid organics, and decontaminate the metals. Either grout or salt could be added in the repository as a backfill material. Similarly, decontamination of all corroding metals from the waste inventory, and changing the waste container material could be used to eliminate the potential of corrosion gas generation.

The EAMP considered ranking a set of combined alternatives based on their effectiveness and feasibility. However, it was decided that since the evaluation process was primarily qualitative, ranking the combinations merely on the basis of summation of their individual scores would not be meaningful, and therefore not advisable.

The results of the EAMP's evaluations will be used to:

1. Recommend waste form alternatives that should be included in the WIPP Experimental Test Program.
2. Provide a basis for identification of combinations of alternatives that should be quantitatively analyzed for relative effectiveness.
3. Provide a basis for evaluation of the relative cost and schedule ramifications for implementation of the most effective and feasible alternatives.

The final choice of alternative(s), and whether any alternatives are needed, will be decided in conjunction with the performance assessment studies when the extent of mitigation required is determined.

**TABLE AES-2**  
**WASTE FORM MODIFICATIONS FOR ELIMINATING POTENTIAL**

WASTE FORM			
PARAMETER	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
<b>Radolytic Gas Generation</b>	Vitrification	Plasma processing Incinerate and Vitrify Acid digest and Vitrify	Vitrification
<b>Biological Gas Generation</b>	Vitrification	Plasma processing Incinerate and Cement Incinerate and Vitrify Acid digest and Vitrify	Category does not pose biological gas generation problem
<b>Corrosion Gas Generation</b>	Vitrification	Category does not pose corrosion gas generation problem	Decontamination of corroding metals Change existing waste container material
<b>Permeability of the Waste Stack</b>	None	None	None
<b>Radionuclide Solubility In Brine</b>	None	None	None

TABLE AES-3

WASTE FORM MODIFICATIONS FOR  
REDUCING/CONTROLLING POTENTIAL

PARAMETER	WASTE FORM		
	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Radolytic Gas Generation	Cementation* pH Buffers	Incinerate and Cement Compaction pH Buffers	Decontamination Melted metals pH Buffers
Biological Gas Generation	Cementation* pH Buffers	Shred and Cement Compaction pH Buffers Shred, add bentonite	Category does not pose biological gas generation problem
Corrosion Gas Generation	Cementation* pH Buffers	Category does not pose corrosion gas generation problem	Vitrification pH Buffers Encapsulation Melted metals Shred and cement Compaction Shred, add bentonite
Permeability of the Waste Stack	Vitrification Cementation* pH Buffers	Vitrification Encapsulation Cementation Shred, add bentonite Compaction pH Buffers	Vitrification Melted metals Shred, add bentonite Encapsulation Shred and Cement Decontaminate metals Compaction pH Buffers
Radionuclide Solubility In Brine	Cementation* pH Buffers	Cementation pH Buffers Vitrification	Decontaminate metals pH Buffers Shred and cement Melted metals

\*Cementation into monoliths.

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP), a Department of Energy (DOE) project near Carlsbad, New Mexico, is intended as a geologic repository designed for the safe disposal of transuranic (TRU) radioactive wastes that have been generated by the defense activities of the U.S. government. The performance of nuclear waste repositories (such as WIPP) is regulated by the U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985) promulgated in 1985. The EPA Standard addresses the waste isolation capability of radioactive waste sites and includes specific requirements regarding containment of radioactivity, quality assurance, individual radiation protection for the public, and limits on groundwater radionuclide concentrations. The containment requirements mandate that radioactive waste disposal systems be designed to provide a "reasonable expectation" that cumulative releases of radionuclides over 10,000 years will not exceed specified levels, based on studies referred to as performance assessment. The assurance requirements were selected to provide confidence that containment requirements can be met and mandate active institutional controls (e.g., boundary markers, etc.) over disposal sites for as long a period of time as is "practicable" after disposal. However, for the purposes of assessing the performance of a geologic repository, these institutional controls are assumed not to contribute to waste isolation longer than 100 years following disposal.

Since TRU wastes to be emplaced in WIPP are also contaminated with hazardous chemical wastes, they are subject to regulations under the Resource Conservation and Recovery Act (RCRA). The land disposal of untreated hazardous wastes is prohibited by EPA Standard 40 CFR Part 268.6 (EPA, 1989), unless the DOE can obtain a variance for WIPP waste by demonstrating to the EPA that the wastes will not migrate from the disposal unit. A petition for a variance was submitted by the DOE to the EPA (DOE, 1990c), and the EPA granted a conditional No-Migration Determination in November, 1990 (EPA, 1990).

The performance assessment for WIPP is being conducted by Sandia National Laboratories (SNL) and is expected to be completed by 1994 (DOE, 1990d). However, preliminary performance assessment (DOE, 1990a) has indicated that the current design of the WIPP repository and the existing waste forms at the storage/generator sites may not be able to demonstrate compliance with the EPA Standard 40 CFR Part 191. In consideration of such an eventuality, the National Academy of Sciences (NAS) WIPP Panel recommended in March 1988, that DOE investigate the feasibility of possible technical "fixes" to the WIPP site and/or to the waste itself (DOE, 1988c). If the performance assessment studies cannot demonstrate compliance with the EPA Standard 40 CFR Part 191, then these "fixes" could be applied to successfully rectify any potential scenario of noncompliance.

The NAS provided examples of such "fixes" including:

- Getters to absorb gases
- Inhibitors to suppress bacterial activity
- Repository ventilation until closure
- Absorbers for brine reduction
- Waste processing into a dense, chemically stable form

- Brine drainage (sumps)
- Drum void space reduction.

Based on this recommendation by the NAS, and the recommendations of other external review groups, the DOE established the Engineered Alternatives Task Force (EATF) in September, 1989 (Hunt, 1990).

The objective of the EATF is to identify potential engineering modifications (referred to as "engineered alternatives") to the current design of WIPP and/or to the present waste forms in order to enhance repository performance. These alternatives would either eliminate or mitigate any problems associated with demonstrating compliance with the EPA Standard 40 CFR Part 191. As an example, if excess gas generation from corrosion of steel waste containers is identified by performance assessment as an impediment to demonstrating compliance with 40 CFR Part 191, an engineered alternative such as modifying the waste container material could be implemented. Potential problems such as gas generation are referred to as "performance parameters" and are being addressed by the performance assessment studies (DOE, 1990d).

The studies have identified a number of different performance parameters (Marietta et al., 1989). However, until the performance assessment studies are completed, it will not be known which specific performance parameters are most important to demonstrating compliance with the EPA Standard. The EATF is dealing with this uncertainty by integrating its efforts with the ongoing performance assessment studies at SNL and addressing all performance parameters identified in conjunction with these studies. While the studies are being conducted, the results of the EATF may provide one or more engineered alternatives to mitigate the effects of the identified parameter(s), if compliance with EPA Standard 40 CFR Part 191 cannot be demonstrated otherwise.

The various tasks of the EATF are to:

- Identify and screen potential engineered alternatives and evaluate their feasibility of implementation.
- Develop a deterministic design analysis model to evaluate the effectiveness of the engineered alternatives in comparison with the existing WIPP design and TRU waste forms.
- Evaluate the mitigating effect of potential engineered alternatives on waste forms and on repository performance for each performance parameter using the developed design analysis model.
- Provide estimated schedules and costs for implementation of engineered alternatives.
- Recommend potential locations for implementation of engineered alternatives.
- Recommend selected alternatives to the DOE.

The Engineered Alternatives Multidisciplinary Panel (EAMP) was formed to accomplish the first of the EATF Tasks; the qualitative initial screening and ranking of potential engineered alternatives. The composition of the EAMP is described in the following section.

## **1.2 COMPOSITION OF THE EAMP AND ITS OBJECTIVES**

In view of the technical expertise needed in the areas associated with the engineered alternatives, and in consideration of other important regulatory and operational issues associated with the WIPP repository, the following disciplines were represented on the panel:

- DOE/Institutional
- Generator Waste Processing
- Geochemistry
- Metallurgy/Corrosion
- Microbiology
- Performance Assessment
- Regulatory Compliance and Permitting
- Repository Operations
- Rock Mechanics
- Waste Treatment.

A description of the EAMP requirements and qualifications of panel members is provided in Attachment A. The specific objectives of the EAMP were to:

- Identify potential alternatives, and establish screening criteria that any potential alternative must satisfy in order to be considered for further evaluation.
- Establish criteria for the qualitative evaluation of each alternative regarding its mitigating effects on each performance parameter.
- Rank the screened engineered alternatives for their mitigating effects using the established criteria and decision analysis techniques.

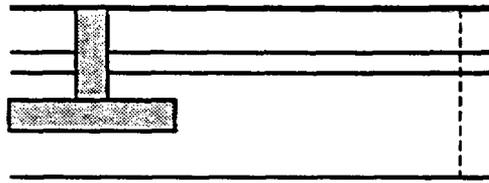
## **1.3 NONCOMPLIANCE SCENARIOS AND PERFORMANCE PARAMETERS**

The scenarios that were considered to be bounding conditions for selecting performance parameters consisted of both natural (undisturbed performance) and human intrusion events. Seven hypothetical scenarios were developed by SNL (Marletta et al., 1989), a base case scenario and six additional scenarios which may be expected to occur during the regulatory periods described in EPA Standard 40 CFR Part 191 (EPA, 1985). The performance parameters are based on these seven scenarios. The seven scenarios shown in Figure A-1 include:

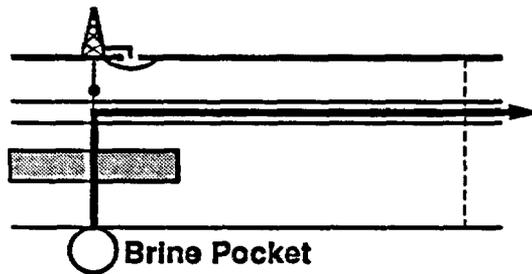
**Base Case** - This was defined as an undisturbed repository with gas generation, brine inflow from the Salado Formation, and normal creep closure of the salt.

**Human Intrusion** - Six cases were considered:

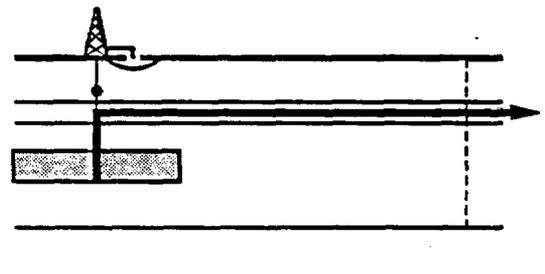
### Base Case Scenario



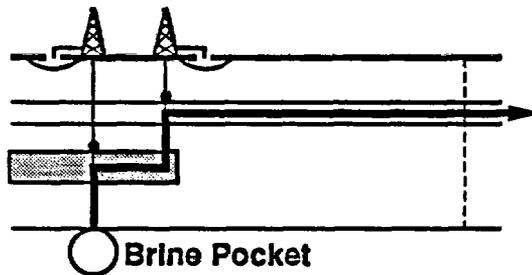
### Human Intrusion Scenarios



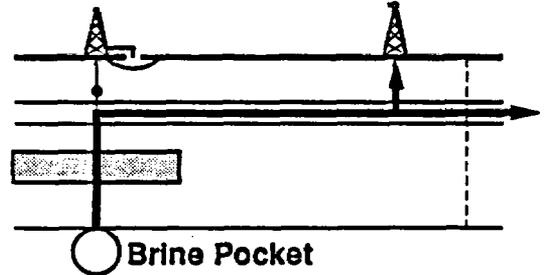
**SCENARIO 1**



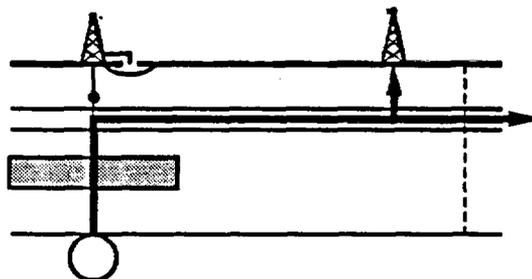
**SCENARIO 2**



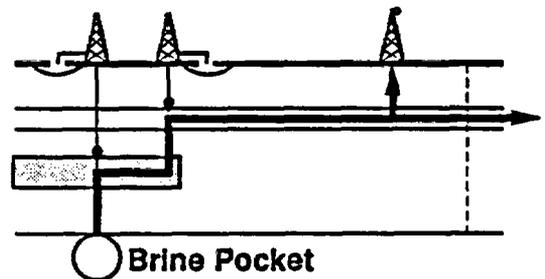
**SCENARIO 3**



**SCENARIO 4**



**SCENARIO 5**



**SCENARIO 6**

**Figure A-1**  
**Base Case and Intrusion Scenarios**

1. A single borehole is drilled through the repository to a postulated pressurized brine pocket. Before the borehole is plugged, release occurs directly to the surface. After the borehole is plugged, release also occurs along a horizontal pathway above the repository to the regulatory boundary.
2. Same as Scenario 1, except that drilling stops in the repository horizon.
3. Two boreholes are drilled, consisting of Scenarios 1 and 2, with the commensurate releases.
4. Same as Scenario 1, except that extraction of water takes place within the regulated boundary.
5. Same as Scenario 2, except that extraction of water takes place within the regulated boundary.
6. Same as Scenario 3, except that extraction of water takes place within the regulated boundary.

Under the above scenarios, there are three basic elements that have the potential to create the conditions that could lead to non-compliance with the EPA Standards. These basic elements are:

- Mobility of the waste
- The release path to the regulated boundary
- The release mechanisms that move waste to the accessible environment, or beyond the unit boundary in the case of the RCRA requirements.

The ten performance parameters associated with the three elements that have been identified based on the performance assessment studies are (Marietta et al., 1989):

<u>PERFORMANCE PARAMETER</u>	<u>SCENARIO(S)</u>
Radiolytic Gas Generation	Base Case
Biological Gas Generation	Base Case
Corrosion Gas Generation	Base Case
Waste Permeability	Base Case & Human Intrusion
Waste Porosity	Base Case & Human Intrusion
Waste Strength	Human Intrusion
Radionuclide Leachability	Base Case & Human Intrusion
Radionuclide Solubility	Base Case & Human Intrusion
Brine Inflow	Base Case & Human Intrusion
Human Intrusion Probability	Human Intrusion

The subsequent sections of this report describe the methodology used by the EAMP to accomplish its objectives of screening and ranking engineered alternatives with reference to the parameters listed above, the results of the EAMP deliberations, and finally, the conclusions reached by the EAMP and the EATF regarding the effectiveness of engineered alternatives.

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## 2.0 METHODOLOGY USED TO EVALUATE ENGINEERED ALTERNATIVES

The EAMP activities were carried out during November 1989 and February 1990. The panel members were briefed on WIPP, the EPA Standard 40 CFR Part 191 (EPA, 1985), the EPA land disposal restrictions in 40 CFR Part 268 (EPA, 1989), the performance parameters, and the decision analysis methodology that was to be used. The EAMP, in conjunction with the EATF, prepared a list of potential engineered alternatives (described in Attachment B) in seven different categories. The 64 potential engineered alternatives are listed in Table A-1. The seven different categories are listed below with an example for each category:

<u>Category</u>	<u>Example</u>
Waste Form Modification Alternatives	Vitrify sludges
Waste Management Alternatives	Segregate waste in WIPP
Backfill Alternatives	Grout backfill
Facility Design Alternatives	Change room configuration
Passive Marker Alternatives	Monument covering the entire repository
Miscellaneous Alternatives	Grout Culebra Formation
Waste Container Alternatives	Change waste container material

After developing the criteria against which to screen and rank the engineered alternatives, each alternative was subjected to a preliminary evaluation which considered ten parameters for alternative effectiveness and three for alternative feasibility. A brief description of the preliminary evaluation and results is provided in Attachment C. Once the preliminary evaluations were completed, the EAMP incorporated the heterogeneity of TRU waste in the evaluation process by examining the applicability of each alternative for each one of the three major constituents of TRU waste. These three constituents of TRU waste are as follows:

- Sludges
- Solid Organics (Combustibles)
- Solid Inorganics (Glass and Metals).

This was necessary because not all alternatives apply to all types of waste. As an example, compaction does not apply to sludges. Also, based on an update from SNL (Anderson, 1990), only five performance parameters were considered instead of the original ten because some of the ten parameters are interdependent, and therefore could be combined into one parameter. The five parameters were:

- Radiolytic Gas Generation
- Biological Gas Generation
- Corrosion Gas Generation
- Permeability of the Waste Stack
- Radionuclide Solubility (in Brine).

The remaining parameters that were considered by the EAMP during the preliminary evaluations are inherent in the above parameters. For instance, leachability and solubility are

TABLE A-1

POTENTIALLY USEFUL ENGINEERED ALTERNATIVES CONSIDERED BY THE  
ENGINEERED ALTERNATIVES MULTIDISCIPLINARY PANEL (EAMP)

WASTE FORM  
MODIFICATION ALTERNATIVES

Compact Waste  
Incinerate and Cement  
Incinerate and Vitrify  
Wet Oxidation  
Shred and Bituminize  
Shred and Compact  
Shred and Cement  
Shred and Polymer Encapsulation  
Shred, Add Salt, and Compact  
Plasma Processing  
Melt Metals  
Add Salt Backfill  
Add Other Sorbents  
Add Gas Suppressants  
Shred and Add Bentonite  
Acid Digestion  
Sterilize  
Add Copper Sulfate  
Add Gas Getters  
Add Fillers  
Segregate Waste Forms  
Decontaminate Metals  
Change Waste Generating Process  
Add Anti-Bacterial Material  
Accelerate Waste Digestion Process  
Alter Corrosion Environment in WIPP  
Alter Bacterial Environment in WIPP  
Transmutation of Radionuclides  
Vitrify Sludges

BACKFILL ALTERNATIVES

Salt Only  
Salt Plus Gas Getters  
Compact Backfill  
Salt Plus Brine Sorbents  
Preformed Compacted Backfill  
Grout Backfill  
Bitumen Backfill  
Add Gas Suppressants

WASTE MANAGEMENT ALTERNATIVES

Minimize Space Around Waste Stack  
Segregate Waste In WIPP  
Decrease Amount of Waste Per Room  
Emplace Waste and Backfill Simultaneously  
Selective Vegetative Uptake

FACILITY DESIGN ALTERNATIVES

Brine Isolating Dikes  
Raise Waste Above The Floor  
Brine Sumps and Drains  
Gas Expansion Volumes  
Seal Disposal Room Walls  
Vent Facility  
Ventilate Facility  
Add Floor of Brine Sorbents  
Change Mined Extraction Ratio  
Change Room Configuration  
Seal Individual Rooms  
Two Level Repository

PASSIVE MARKER ALTERNATIVES

Monument Forest Over Repository  
Monument Covering the Entire Repository  
Buried Steel Plate Over Repository  
Artificial Surface Layer Over Repository  
Add Marker Dye To Strata

MISCELLANEOUS ALTERNATIVES

Drain Castle Reservoir  
Grout Culebra Formation  
Increase Land Withdrawal Area  
to Regulatory Boundary

WASTE CONTAINER ALTERNATIVES

Change Waste Container Shape  
Change Waste Container Material

related, as are porosity and permeability. Brine inflow and waste strength are dependent, to a large extent, on permeability. The EAMP also re-evaluated the backfill alternatives in terms of their ability in mitigating the effect of the five performance parameters. The following subsections describe in detail the criteria established and the decision analysis technique used by the EAMP.

## 2.1 ESTABLISHMENT OF SCREENING CRITERIA

The evaluation criteria was based upon a management decision process that quantifies normally subjective information (Daugbjerg, 1980). The 64 potential engineered alternatives were first subjected to a "must" criteria test for initial screening (i.e., criteria which each alternative must satisfy in order to be considered for further evaluation). The following "must" criteria were defined by the EAMP:

- Regulatory Compliance and Permitting - The alternative must have the likelihood to demonstrate regulatory compliance including local, state, or federal permits to operate, based in part on past experience with other similar facilities/processes, including public opinion considerations.
- Availability of Technology - The alternative must have been demonstrated at a minimum of laboratory scale and must have the potential for full-scale implementation in the future.
- Schedule of Implementation - The EAMP assumed that waste disposal at WIPP should begin no later than 8 years from 1989 for newly-generated waste and 15 years for retrievably stored waste. Based on this assumption, it was decided that any alternative must be implementable within 8 years for newly-generated waste and 15 for retrievably stored waste.

Alternatives which failed to satisfy all the three "must" criteria were eliminated from further consideration. In addition, some of the alternatives which were deemed to be similar in nature were combined to eliminate redundancies. A list of the alternatives which were eliminated from further consideration and the reasons for their elimination are presented in Table A-2. The process of elimination resulted in 35 remaining alternatives which were considered for further evaluation. Also, the EAMP added an alternative (cementation of sludges) to increase the total to 36 evaluated alternatives. These alternatives are listed in Table A-3.

## 2.2 ESTABLISHMENT OF EVALUATION CRITERIA

The process of evaluation of the 36 alternatives was based on two basic criteria; effectiveness of the alternative in mitigating the effects of each performance parameter, and its feasibility.

### 2.2.1 Evaluation of Effectiveness

The effectiveness of each alternative in mitigating the effect of each of the ten original performance parameters was evaluated on a scale of 1 to 10 (a score of 10 being the most effective) in the preliminary evaluation. In cases where an alternative was judged to have no effect on a parameter (positive or negative), it was not given a score (represented by a "-" in the scoring column). On the other hand, if an alternative was judged to have an adverse

TABLE A-2

**ALTERNATIVES DELETED FROM FURTHER CONSIDERATION  
AND THE REASONS FOR THEIR DELETION**

<u>ALTERNATIVES</u>	<u>REASONS FOR DELETION</u>
Wet Oxidation	Technology Not Demonstrated For Solid Waste
Sterilization of Waste Package	Not Feasible To Maintain Long Term Effectiveness
Add Copper Sulfate	Potential for Hydrogen Generation by Galvanic Coupling of Deposited Copper
Add Anti-Bacterial Material	Unable To Identify A Long Term Anti-Bacterial Material
Accelerate Waste Digestion	Technology For Fast Waste Digestion Not Demonstrated
Transmutation of Radionuclides	Technology Not Demonstrated for Large Waste Amounts
Change Generating Process	Scope Is Too Broad To Be Evaluated
Selective Vegetative Uptake	Not Been Laboratory Demonstrated For TRU Waste
Brine Sumps and Drains	Brine Flow Will Stop After Reconsolidation of Salt
Seal Disposal Room Walls	Technology Has Not Been Demonstrated
Vent Facility	Not Regulatory Feasible After Institutional Control
Artificial Surface Layer	Not Possible To Identify A Feasible Concept
Drain Castile Reservoir	Technologically Not Feasible
Grout Culebra Formation	Technologically Not Feasible
Increase Land Withdrawal Area	This Is Not An Engineered Alternative
Add Salt Backfill	Considered Under Backfill Alternatives
Add Brine Sorbents	Considered Under Backfill Alternatives
Add Gas Suppressants	Considered Under 'Add Gas Getters'
Add Fillers	Considered Under Backfill Alternatives
Alter Bacterial Environment	Considered In Evaluation of Other Alternatives
Decrease Waste Per Room	Considered Under Backfill Alternatives
Simultaneous Emplacement of Waste/Backfill	Considered Under Compact Backfill
Gas Suppressants as Backfill	Considered Under Salt Plus Alkali In Backfills
Preformed Compacted Backfill	Considered Under Compact Backfill
Brine Isolating Dikes	Considered Under Sealing Individual Rooms
Raise Waste Above Floor	Considered Under Add Sorbents To Backfill
Gas Expansion Volume	Indeterminate Unless Total Volume of Gas Is Known
Add Floor Of Brine Sorbent	Considered Under Backfill Alternatives
Segregate Waste Forms	Alternative Is Not A Stand-Alone Process

## TABLE A-3

**ALTERNATIVES CONSIDERED FOR FURTHER  
EVALUATION BY THE ENGINEERED ALTERNATIVES  
MULTIDISCIPLINARY PANEL (EAMP)**

**WASTE FORM  
MODIFICATION ALTERNATIVES**

Compact Waste  
Incinerate and Cement  
Incinerate and Vitrify  
Shred and Bituminize  
Shred and Compact  
Shred and Cement  
Shred and Polymer Encapsulation  
Shred, Add Salt, and Compact  
Plasma Processing  
Melt Metals  
Shred and Add Bentonite  
Acid Digestion  
Add Gas Getters  
Decontaminate Metals  
Alter Corrosion Environment in WIPP  
Vitrify Sludges  
Cementation of Sludges

**BACKFILL ALTERNATIVES**

Salt Only  
Salt Plus Gas Getters  
Compact Backfill  
Salt Plus Brine Sorbents  
Grout Backfill  
Bitumen Backfill

**WASTE MANAGEMENT ALTERNATIVES**

Minimize Space Around Waste Stack  
Segregate Waste In WIPP

**FACILITY DESIGN ALTERNATIVES**

Ventilate Facility  
Change Mined Extraction Ratio  
Change Room Configuration  
Seal Individual Rooms  
Two Level Repository

**PASSIVE MARKER ALTERNATIVES**

Monument Forest Over Repository  
Monument Covering the Entire Repository  
Buried Steel Plate Over Repository  
Add Marker Dye To Strata

**WASTE CONTAINER ALTERNATIVES**

Change Waste Container Shape  
Change Waste Container Material

effect on a parameter (i.e., it worsened the situation instead of mitigating it), then the alternative was given a score of zero and eliminated from further consideration for that particular parameter. The difference between the "adverse effect" case and the "no effect" case is explained later in Section 2.2.3.

### 2.2.2 Evaluation of Feasibility

The feasibility was evaluated in terms of the three criteria originally defined as "must" criteria, and mentioned earlier in Section 2.1. These criteria were now used as weighted components of the overall feasibility criterion and formed the basis for ranking the relative feasibility of the alternatives that were still under consideration. The alternatives were scored on a scale of 1 to 10 based on their relative ease or difficulty in satisfying these criteria as judged by the EAMP. It should be noted that unlike the evaluation of effectiveness, the term "adverse effect" does not apply in this case because the feasibility of an alternative was assumed to be independent of the parameter being considered.

### 2.2.3 Overall Scoring Process for Alternatives

The overall scores for an alternative for mitigating the effects of a parameter were calculated by combining its effectiveness and feasibility scores using a weighted summation approach. The EAMP judged that effectiveness and feasibility were of almost equal importance with effectiveness being marginally more important than feasibility. Therefore on a weighing scale of 10, effectiveness was assigned a weight of 5.1 and feasibility was assigned a weight of 4.9. However, since the feasibility was evaluated in terms of the three criteria originally used as "must" criteria, the weight of 4.9 was further subdivided among the three criteria depending on their relative importance. It was decided that for feasibility considerations, the most important of these three criteria was Regulatory Compliance and Permitting, followed by Availability of Technology, and then Schedule of Implementation. This relative order of importance for the feasibility criteria was appropriately reflected in the weights assigned to these criteria. The relative weights assigned to the different evaluation criteria were as follows:

• Effectiveness	5.1
• Feasibility	
- Regulatory Compliance and Permitting	2.4
- Availability of Technology	1.5
- Schedule of Implementation	1.0
	<u>10.0</u>

The effectiveness and feasibility scores developed by the EAMP in each of the three subcategories (all on a scale of 1 to 10) were multiplied by the appropriate weights listed above and then added together to get the overall score for each alternative for a given performance parameter. The feasibility of an alternative was assumed to be independent of the performance parameter, and therefore remained the same irrespective of the parameter being considered. Figures A-2 and A-3 depict this evaluation process.

As an example, if an alternative received an effectiveness score of 9 for mitigating radiolytic gas generation, 5 for regulatory compliance and permitting, 6 for availability of technology, and 7 for schedule of implementation, then its overall score would be calculated as follows:

$$\begin{array}{rcl}
 9 \times 5.1 & + & (5 \times 2.4 + 6 \times 1.5 + 7 \times 1.0) \\
 \text{Effectiveness} & & \text{Feasibility} \\
 & = & 73.9 \\
 & & \text{Total}
 \end{array}$$

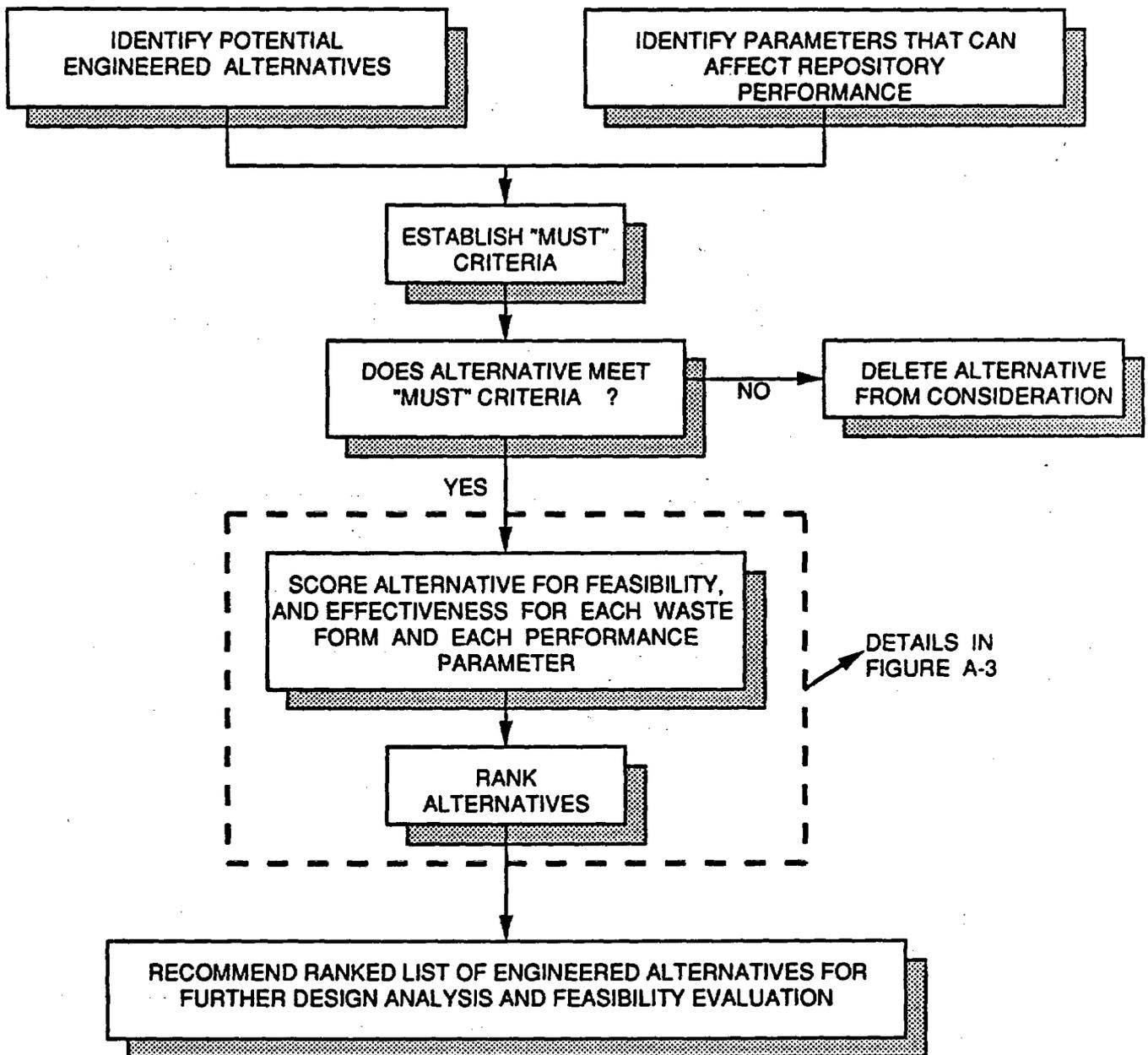


Figure A-2. Identification and Ranking of Potentially Feasible Engineering Alternatives

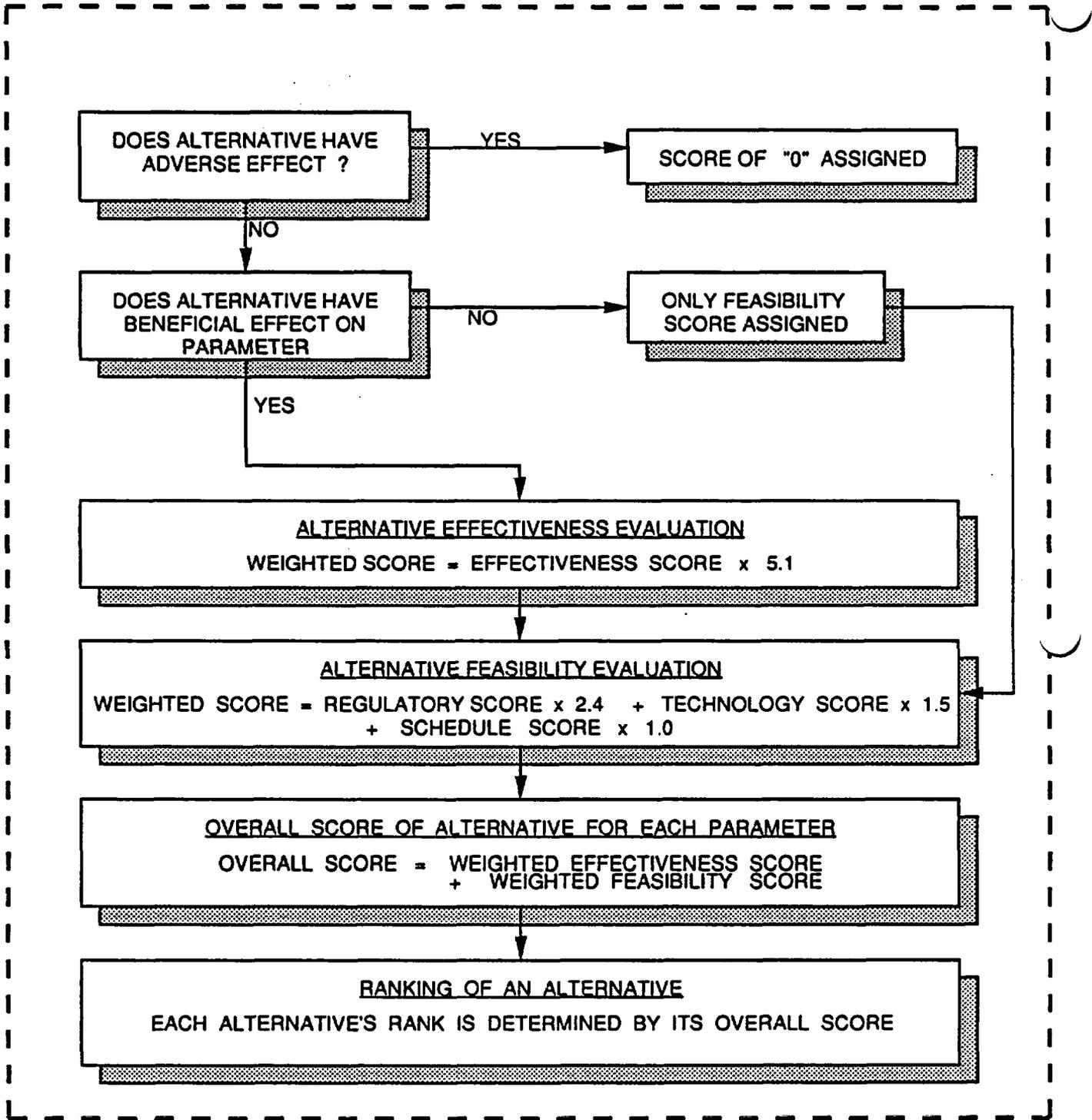


Figure A-3. Ranking of Alternatives for each Parameter

There were two exceptions to the weighted summation approach for calculating overall scores. If an alternative was judged to have an adverse effect on a performance parameter, (i.e., it was assigned a score of zero), then its overall score was also a zero irrespective of its feasibility score. On the other hand, if an alternative was judged to have no effect at all (positive or negative), then its overall score was simply equal to its feasibility score.

### **2.3 EVALUATION INCORPORATING HETEROGENEITY OF TRU WASTE**

After the preliminary evaluations were completed, the EAMP addressed the heterogeneity of the TRU waste recognizing that each major waste form may require different treatment. The composition of TRU waste comprising the potential WIPP inventory was provided to the EAMP by the EATF and is presented in Table A-4.

The EAMP addressed those waste forms that represent the largest quantities. These waste forms are:

- Sludges
- Solid Organics (combustibles)
- Solid Inorganics (glass and metals).

From Table A-4, these three waste forms comprise 89 percent of the total inventory volume and 83 percent of the total inventory weight. The EAMP believed that the remaining waste forms could be treated using the alternatives identified for the majority of the waste. Since all waste form modification alternatives are not applicable to all the major waste forms (e.g., compaction does not apply to sludges), the EAMP first identified those alternatives that could be applied to each of the three major waste forms (Table A-5).

The scoring methodology used was similar to the one described in Sections 2.2.1 - 2.2.3 with a few minor exceptions:

- Since the feasibility of an alternative is independent of the type of waste form being treated, the feasibilities were assumed to remain the same and were therefore not recorded.
- Only five performance parameters were considered instead of ten (as explained in Section 2.0).

**TABLE A-4**  
**COMPOSITION OF TRANSURANIC (TRU) WASTE\***

WASTE FORMS	VOLUME %	WEIGHT %
Sludges	15.3	37
Solid Organics (combustibles)	39.8	14
Filters	4.5	2
Asphalt/Dirt	2.1	5
Solid Inorganics (glass and metals)	34.3	32
Others (Salts, etc.)	4.0	10

\* Calculated from DOE, 1988b.

**TABLE A-5**  
**WASTE FORM MODIFICATIONS APPLICABLE  
TO THE THREE MAJOR WASTE FORMS**

SLUDGES	SOLID ORGANICS	SOLID INORGANICS
Alter Environment	Alter Environment	Alter Environment
Cementation	Add Gas Getters	Add Gas Getters
Plasma Processing	Plasma Processing	Plasma Processing
Vitrification	Compact	Compact
	Shred, Add Bentonite	Shred, Add Bentonite
	Shred and Bituminize	Shred and Bituminize
	Shred and Cement	Shred and Cement
	Shred and Compact	Shred and Compact
	Shred and Encapsulate	Shred and Encapsulate
	Acid Digestion	Melt Metals
	Incinerate and Cement	Decontaminate Metals
	Incinerate and Vitrify	Shred, Add Salt, and Compact
	Shred, Add Salt, and Compact	

### 3.0 RESULTS OF THE EAMP DELIBERATIONS

The results of the EAMP deliberations represent the relative effectiveness and feasibility of the listed alternatives and should not be considered in absolute terms. When specific problems associated with regulatory compliance have been identified, the results of the EAMP, supplemented by the results of design analysis studies, will determine which alternatives should be recommended to DOE for inclusion in WIPP performance assessment. At that time, alternatives that were not ranked highest for effectiveness and/or feasibility may, nevertheless, be found to be adequate to resolve the problem(s), if any, associated with regulatory compliance.

#### 3.1 EFFECTIVENESS OF ALTERNATIVES

The results of the preliminary evaluation are provided in Attachment C. The EAMP deliberations resulted in the scoring of alternatives for waste form modification, waste management, backfills, facility design, passive markers, waste container, and miscellaneous concepts for each of the ten parameters. The overall scores, combining effectiveness and feasibility, are also provided in Attachment C.

The final results of the scoring process for the alternatives which were evaluated on the basis of the heterogeneity of the TRU waste are shown in Table A-6. As mentioned in Section 2.3, the feasibility scores developed during the preliminary evaluations were not changed, and are reflected in Table A-6. The columns grouped under "Alternative Overall Score" show the total scores (effectiveness plus feasibility) for each parameter calculated according to the methodology described earlier in Section 2.0. These scores form the basis for ranking the relative merit of each engineered alternative in mitigating the effects of each performance parameter.

##### 3.1.1 Waste Form Modification Alternatives

The rationale behind the effectiveness scores assigned to various alternatives listed in Table A-6 for each one of the five major parameters is discussed in this section.

The alternatives "adding gas getters", "altering the (corrosion) environment", and "cementation", were also considered effective pH buffers. Therefore the term "pH-buffers" has often been used in the subsequent sections to refer to these three alternatives as well.

##### 3.1.1.1 Radiolytic Gas Generation

###### Sludges

Since the EAMP considered only the inorganic sludges which are a vast majority, the alternatives were rated primarily on their ability to remove the water present in the sludges, and to lower brine access to the waste (e.g., by lowering permeability). Plasma processing of the sludges was considered the best treatment for this waste form because it can remove all the water present as well as eliminating the most porosity. In comparison, vitrification, by more conventional means, was considered nearly as effective as plasma processing, but it may not remove as much residual porosity. The two other alternatives, cementation and altering

TABLE A-6  
SUMMARY OF OVERALL SCORES FOR ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS (Wt.=5.1)						FEASIBILITY (Wt.=4.9)				ALTERNATIVE OVERALL SCORE					
	SCORE						SCORE			SUM REG + TECH SCH	EFFECTIVENESS + FEASIBILITY					
	RAD GAS	BIO GAS	CORR GAS	PERM SOLUB	HUMAN INTRUS	-	REG (2.4)	TECH (1.5)	SCH (1.0)		RAD GAS	BIO GAS	CORR GAS	PERM SOLUB	HUMAN INTRUS	-
<b>WASTE FORM MODIFICATION ALTERNATIVES</b>																
<b>SLUDGES</b>																
Vitrification	9.0	8.0	9.0	9.0	0.0	-	4.0	7.0	6.0	26.1	72.0	66.9	72.0	72.0	26.1	26.1
Plasma Processing	10.0	10.0	10.0	10.0	0.0	-	3.0	4.0	1.0	14.2	65.2	65.2	65.2	65.2	14.2	14.2
Cementation	4.0	1.0	7.0	3.0	10.0	-	9.0	10.0	9.0	45.6	66.0	50.7	81.3	60.9	96.6	45.6
Alter Environment	4.0	2.0	7.0	2.0	10.0	-	6.0	7.0	6.0	30.9	51.3	41.1	66.6	41.1	81.9	30.9
<b>SOLID ORGANICS</b>																
Compact Waste	1.0	2.0	3.0	3.0	-	-	9.0	10.0	7.0	43.6	48.7	53.8	58.9	58.9	43.6	43.6
Shred and Compact Waste	1.0	3.0	4.0	3.0	-	-	9.0	10.0	7.0	43.6	48.7	58.9	64.0	58.9	43.6	43.6
Shred & Cement Waste	0.0	4.0	6.0	6.0	8.0	-	9.0	10.0	9.0	45.6	0.0	66.0	76.2	76.2	86.4	45.6
Shred & Polymer Encapsulate	0.0	0.0	5.0	8.0	0.0	-	9.0	5.0	6.0	35.1	0.0	0.0	60.6	75.9	35.1	35.1
Shred, Add Salt, Compact	1.0	3.0	5.0	7.0	-	-	9.0	10.0	7.0	43.6	48.7	58.9	69.1	79.3	43.6	43.6
Shred & Bituminize	0.0	0.0	5.0	8.0	0.0	-	3.0	10.0	5.0	27.2	0.0	0.0	52.7	68.0	27.2	27.2
Plasma Processing	10.0	10.0	10.0	10.0	6.0	-	3.0	4.0	1.0	14.2	65.2	65.2	65.2	65.2	44.8	14.2
Shred & Add Bentonite	0.0	1.0	6.0	6.0	-	-	9.0	10.0	9.0	45.6	0.0	50.7	76.2	76.2	45.6	45.6
Acid Digestion	9.0	9.0	10.0	9.0	6.0	-	3.0	4.0	2.0	15.2	61.1	61.1	66.2	61.1	45.8	15.2
Add Gas Getters	1.0	2.0	-	2.0	8.0	-	5.0	9.0	5.0	30.5	35.6	40.7	30.5	40.7	71.3	30.5
Incinerate & Cement	5.0	9.0	8.0	6.0	10.0	-	2.0	7.0	2.0	17.3	42.8	63.2	58.1	47.9	68.3	17.3
Incinerate & Vitrify	9.0	9.0	10.0	9.0	6.0	-	2.0	7.0	2.0	17.3	63.2	63.2	68.3	63.2	47.9	17.3
Alter Environment	1.0	2.0	7.0	2.0	8.0	-	6.0	7.0	6.0	30.9	36.0	41.1	66.6	41.1	71.7	30.9
<b>SOLID INORGANICS</b>																
Compact Waste	0.0	-	2.0	1.0	-	-	9.0	10.0	7.0	43.6	0.0	43.6	53.8	48.7	43.6	43.6
Shred & Compact Waste	0.0	2.0	2.0	3.0	-	-	9.0	10.0	7.0	43.6	0.0	53.8	53.8	58.9	43.6	43.6
Shred & Cement Waste	0.0	3.0	3.0	6.0	10.0	-	9.0	10.0	9.0	45.6	0.0	60.9	60.9	76.2	96.6	45.6
Shred & Polymer Encapsulate	0.0	0.0	3.0	7.0	0.0	-	9.0	5.0	6.0	35.1	0.0	0.0	50.4	70.8	35.1	35.1
Shred, Add Salt, Compact	-	2.0	-	5.0	-	-	9.0	10.0	7.0	43.6	43.6	53.8	43.6	69.1	43.6	43.6
Shred & Bituminize	0.0	0.0	5.0	7.0	0.0	-	3.0	10.0	5.0	27.2	0.0	0.0	52.7	62.9	27.2	27.2
Plasma Processing	10.0	10.0	8.0	10.0	8.0	-	3.0	4.0	1.0	14.2	65.2	65.2	55.0	65.2	55.0	14.2
Melt Metals	4.0	4.0	5.0	8.0	10.0	-	3.0	7.0	3.0	20.7	41.1	41.1	46.2	61.5	71.7	20.7
Shred & Add Bentonite	0.0	1.0	1.0	7.0	-	-	9.0	10.0	9.0	45.6	0.0	50.7	50.7	81.3	45.6	45.6
Decontaminate Metals	6.0	6.0	10.0	6.0	10.0	-	7.0	9.0	7.0	37.3	67.9	67.9	88.3	67.9	88.3	37.3
Add Gas Getters	1.0	2.0	NA	2.0	10.0	-	5.0	9.0	5.0	30.5	35.6	40.7	NA	40.7	81.5	30.5
Alter Environment	1.0	2.0	7.0	2.0	10.0	-	6.0	7.0	6.0	30.9	36.0	41.1	66.6	41.1	81.9	30.9

RAD = Radiolytical; BIO = Biological; CORR = Corrosion; PERM = Permeability of the Waste Stack; NA = Not Applicable  
SOLUB = Radionuclide Solubility in Brine; REG = Regulatory; TECH = Technological; SCH = Schedule; HUMAN INTRUS = Human Intrusion

TABLE A-6  
(contd.)  
SUMMARY OF OVERALL SCORES FOR ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS (Wt.=5.1)						FEASIBILITY (Wt=4.9)				ALTERNATIVE OVERALL SCORE					
	SCORE						SCORE			SUM REG + TECH SCH	EFFECTIVENESS + FEASIBILITY					
	RAD GAS	BIO GAS	CORR GAS	PERM SOLUB	HUMAN INTRUS		REG (2.4)	TECH (1.5)	SCH (1.0)		RAD GAS	BIO GAS	CORR GAS	PERM SOLUB	HUMAN INTRUS	
<b>WASTE CONTAINER ALTERNATIVES</b>																
Change Waste Cont. Shape	1.0	1.0	1.0	1.0	-	-	9.0	10.0	9.0	45.6	50.7	50.7	50.7	50.7	45.6	45.6
Change Waste Cont. Material	-	-	2.0	-	-	-	8.0	8.0	9.0	40.2	40.2	40.2	50.4	40.2	40.2	40.2
<b>WASTE MANAGEMENT ALTERNATIVES</b>																
Min. Space Around Waste Stack	1.0	2.0	1.0	1.0	-	-	10.0	10.0	10.0	49.0	54.1	59.2	54.1	54.1	49.0	49.0
Segregate Waste In WIPP	-	5.0	0.0	-	-	-	8.0	10.0	8.0	42.2	42.2	67.7	0.0	42.2	42.2	42.2
<b>BACKFILL ALTERNATIVES</b>																
Salt Only	4.0	2.0	2.0	2.0	-	-	8.0	7.0	9.0	38.7	59.1	48.9	48.9	48.9	38.7	38.7
Salt + Alkali	5.0	8.0	9.0	2.0	10.0	-	8.0	7.0	9.0	38.7	64.2	79.5	84.6	48.9	89.7	38.7
Compact Backfill	6.0	3.0	3.0	2.0	-	-	4.0	3.0	6.0	20.1	50.7	35.4	35.4	30.3	20.1	20.1
Salt + Brine Sorbents	8.0	5.0	5.0	2.0	-	-	8.0	7.0	7.0	36.7	77.5	62.2	62.2	46.9	36.7	36.7
Grout Backfill	10.0	10.0	10.0	7.0	10.0	-	8.0	8.0	9.0	40.2	91.2	91.2	91.2	75.9	91.2	40.2
Bitumin Backfill	0.0	0.0	5.0	10.0	0.0	-	3.0	5.0	5.0	19.7	0.0	0.0	45.2	70.7	0.0	19.7
<b>FACILITY DESIGN ALTERNATIVES</b>																
Ventilate Facility	4.0	5.0	4.0	-	-	-	4.0	4.0	4.0	19.6	40.0	45.1	40.0	19.6	19.6	19.6
Change Extraction Ratio	1.0	2.0	1.0	1.0	-	-	8.0	7.0	9.0	38.7	43.8	48.9	43.8	43.8	38.7	38.7
Change Room Configuration	-	-	-	-	-	3.0	7.0	10.0	7.0	38.8	38.8	38.8	38.8	38.8	38.8	54.1
Seal Individual Rooms	-	-	-	8.0	-	-	9.0	8.0	9.0	42.6	42.6	42.6	42.6	83.4	42.6	42.6
Two Level Repository	-	-	-	-	-	5.0	1.0	8.0	1.0	15.4	15.4	15.4	15.4	15.4	15.4	40.9
<b>PASSIVE MARKER ALTERNATIVES</b>																
Monument "Forest"	-	-	-	-	-	6.0	9.0	10.0	10.0	46.6	46.6	46.6	46.6	46.6	46.6	77.2
Monument Covering Repository	-	-	-	-	-	10.0	8.0	10.0	10.0	44.2	44.2	44.2	44.2	44.2	44.2	95.2
Buried Steel Plate Over Rep.	-	-	-	-	-	5.0	7.0	10.0	10.0	41.8	41.8	41.8	41.8	41.8	41.8	67.3
Add Marker Due To Strata	-	-	-	-	-	1.0	4.0	1.0	10.0	21.1	21.1	21.1	21.1	21.1	21.1	26.2

OVERALL SCORE CALCULATION

$$\text{OVERALL SCORE} = 5.1 \times \text{EFFECTIVENESS SCORE} + 2.4 \times (\text{REGULATORY FEASIBILITY SCORE}) + 1.5 \times (\text{TECHNOLOGICAL FEASIBILITY SCORE}) + 1.0 \times (\text{SCHEDULING FEASIBILITY SCORE})$$

RAD = Radiolytical; BIO = Biological; CORR = Corrosion; PERM = Permeability of the Waste Stack; NA = Not Applicable  
SOLUB = Radionuclide Solubility in Brine; REG = Regulatory; TECH = Technological; SCH = Schedule; HUMAN INTRUS = Human Intrusion

the environment were judged less effective. These alternatives eliminate free water but would only reduce the radiolytic gas generation rates instead of eliminating the potential.

### Solid Organics

The primary contributors to radiolytic gas generation in this waste form are the organic materials such as cellulose. Therefore, the scores were based primarily on the ability of the alternative to destroy organics.

Plasma processing was judged to be the most effective alternative because it is able to break down all the bonds in plastics and thus destroy the organics. Assuming that plasma would operate at much higher temperatures than normal incineration temperatures, incineration followed by vitrification was considered almost as effective as plasma processing for destroying organics. Acid digestion which was defined by the EAMP as acid digestion followed by calcination and vitrification, was considered as effective as incineration plus vitrification. However, some porosity may remain by using this process. Incineration and cementation was scored considerably lower. Although solid organics are incinerated, cementation leads to addition of water which increases the potential for radiolytic gas generation. Compaction will not have any positive effect on radiolytic gas generation except for reducing the permeability which in turn will lower the access to brine. The same is also true for the other forms of compaction like shredding followed by compaction, and shredding followed by addition of salt and compaction. Therefore, these three alternatives were given a lower score. Since the majority of the radiolytic gas generated is hydrogen, and there are no known effective, long-term gas getters for hydrogen, the gas getter alternative was given a low score. Altering the environment (e.g., adding large amounts of pH buffers) will not have much of an effect in mitigating radiolytic gas generation, except that it could reduce some brine inflow if large enough quantities of the buffer substantially reduced void volumes. All the other alternatives shredding and bituminizing, shredding and encapsulating, shredding and adding bentonite, and shredding with the addition of cement were considered adverse alternatives since they do not eliminate organics and in some cases would aggravate the problem of radiolytic gas generation by either increasing organics or increasing water content.

### Solid Inorganics

Although glass and metals themselves will not contribute substantially to radiolytic gas generation, the main concern of the EAMP was the plastic liners and plastic bags in the drums.

If the need for an alternative that destroys these plastics is identified, the EAMP assumed that the old waste has liners but the newly generated waste would not be stored in liners. Under these assumptions, it was hypothesized that for the old waste, plasma would destroy all the liner material and therefore is the best alternative. Decontaminating metals or melting metals would separate the liners from the metals and make the liners a part of the combustible waste. This would be a case of an alternative having no effect because the problem of gas generation from the liners is neither eliminated nor reduced but instead transferred to another waste form category. Assuming that the newly generated waste contains no liner, plasma and melting metals would get the same ranking because in both cases permeability, and therefore brine transport, would be reduced substantially. However, decontaminating metals will rank higher in comparison to both plasma and melting metals because only the residue would remain, which could be in a vitrified form.

Gas getters and altering the environment were both assigned a low score for the same reasons explained earlier under the combustibles category. Two of the three methods of compaction were assigned an adverse score because of the potential for increasing the radionuclide concentration by compaction, thereby potentially increasing radiolytic gas generation. The panel reasoned that this adverse effect outweighs the benefits of reducing the permeability through compaction since compacted metals are still quite permeable. Adding salt before compaction was considered to have no net effect because the potential for increased concentration of radionuclides would be offset by the increase in total volume due to the added salt. The other alternatives, shredding and cementing, shredding and bituminizing, and shredding and adding bentonite, were all assigned adverse scores for the same reasons explained earlier under the combustibles category.

### 3.1.1.2 Biological Gas Generation

#### Sludges

The primary basis for scoring these waste form modification alternatives was the ability of the alternative to eliminate the nitrates present in sludges. Plasma processing will destroy the nitrates by decomposition into nitrogen oxides. Although there is a possibility of nitrogen combining with some of the metal to form metal nitrides, plasma processing still appeared to be the best alternative relative to other alternatives. Vitrification by microwave melting would not reach as high a temperature as plasma, and therefore was given a lower score because it may not destroy all the nitrates. Cementation would add sulfates which might be detrimental. However, it would increase strength, decrease particulates, and help reduce permeability, thereby partially isolating the nitrates from the rest of the waste. Therefore, the panel agreed that cementation might have a small positive effect. Altering the environment, which refers to raising the pH, was considered somewhat better than cement because  $\text{Ca}(\text{OH})_2$  will absorb some carbon dioxide, and unlike cementation, no sulfates are added.

#### Solid Organics

Plasma processing was considered the best alternative because the processed product would have the lowest carbon content among the alternatives. Incineration plus vitrification or cementation, and acid digestion were not considered quite as effective as plasma processing for destroying organics and were scored slightly lower.

Some of the remaining alternatives would have an indirect positive effect by reducing generation rates, reducing permeability, or reducing the access to brine. Shredding and cementing would raise the pH and thereby decrease gas generation rates, but it would add some sulfates. The only benefits provided by any form of compaction would be to reduce permeability and limit brine access. Shredding will improve compaction, so this alternative was considered slightly better than compaction alone. Addition of salt is marginally beneficial for reducing voids in compacted combustibles and therefore shredding, adding salt and then compacting was given the same score as shredding and compaction. Shredding with the addition of bentonite may reduce free brine, but still provides moisture for gas generation when the bentonite absorbs brine. Both gas getters and altering the environment would be effective in absorbing some of the carbon dioxide generated. Shredding with the subsequent addition

of bitumen or polymer encapsulation were both expected to have adverse effects by adding food sources for the bacteria.

### Solid Inorganics

The main concern in this category is the plastic liner and bags in the drums. Therefore, the alternatives were ranked for their effectiveness in treating these plastics. The scoring for plasma processing, decontaminating metals, and melting metals was the same as for the radiolytic gas generation parameter. Since metals cannot be compacted to the degree needed to effectively reduce permeability, compaction was not considered an effective alternative. Shredding and cementing as well as shredding and compacting would not be quite as effective for glass and metals as they would be for combustibles, and were therefore scored lower than combustibles. The alternatives involving bitumen and polymer encapsulation were considered adverse alternatives for the same reasons mentioned for combustible waste. Shredding and adding bentonite would only reduce brine access somewhat, and was given a low score. The benefits of shredding, adding salt and then compacting are the same as for combustibles. However, for glass and metals the product will have more porosity and hence this alternative received a slightly lower score than it received for treating combustibles. Gas getters and altering the environment are beneficial in the near term. However, there is some doubt about their long term effectiveness, since bacteria may be able to adapt to this environment.

#### 3.1.1.3 Corrosion Gas Generation

### Sludges

The scoring of alternatives was based on their ability to reduce permeability and moisture, with the additional objectives of reducing brine inflow and/or raising the pH of the waste disposal areas.

Plasma processing was given the highest score for its ability to reduce porosity, resulting in maximum void volume reduction. Since vitrification may not eliminate quite as much porosity as plasma processing, it was given a somewhat lower score. Cementation would tend to raise pH and reduce free water thus lowering gas generation rates. However, it has some potential for long-term release of water. Altering the environment will reduce moisture and increase pH, but is not expected to reduce voids completely.

### Solid Organics

The panel considered any alternative favorably which could substantially reduce void volume and thereby reduce brine inflow. Therefore, plasma processing, incineration and vitrification, and acid digestion were given high scores because these waste treatments reduce void volume better than other alternatives. Incineration plus cementation will result in higher porosity than the aforementioned alternatives. Shredding with the addition of bentonite may produce void reduction properties similar to those of shredding and cementation. Altering the environment will help absorb some brine, raise the pH, and fill void volumes if large enough quantities of material are added. Shredding and adding bitumen produces a low permeability with small porosity and results in a plastic medium. Polymer encapsulation will have properties similar to bitumen. Compaction by itself is considered a marginal alternative. However, it has the positive effect of reducing permeability and consequently limiting brine inflow. Shredding before compaction enhances the reduction of voids, and was therefore scored

slightly higher than compaction alone. Adding salt to the shredded waste before compaction, is somewhat better than shredding and compacting alone for reducing permeability. Gas getters were judged to have no effect since the EAMP could not identify any effective long term getters for hydrogen gas.

### Solid Inorganics

This is the most important category for corrosion gas generation due to the large weight percent of corrodible metal in the waste inventory. For the undisturbed scenario, the panel assumed that the limited amount of brine inflow is insufficient to corrode the entire metal inventory. The EAMP also assumed that engineered alternatives to reduce permeability of the waste would be implemented if corrosion gas is recognized as a major problem. Reducing the permeability would limit the total corrosion gas potential from metal corrosion, if human intrusion causes large quantities of brine to enter the repository.

Based on the above assumptions, decontaminating metals received the highest score because metals would not be brought to WIPP for disposal. Plasma processing was given a somewhat lower score because, even though metal corrosion would be limited by reduced surface area and physical passivation, metal would still be brought to WIPP for disposal. Melting metals and plasma processing could result in preferential migration of the actinides into the resulting slag, thereby having a similar effect as decontamination of metals. However, the panel decided that there is not enough evidence available to justify scoring the alternatives on that basis. Therefore, melting metals was given a lower score than decontamination of metals. Altering the environment has the same effectiveness as explained in the previous section under combustibles. Gas getters were not given a score because they are not applicable in this case. Compaction would not decrease metal surface area sufficiently, though it will reduce overall volume, and room re-pressurization will occur more quickly. Shredding before compaction was not expected to enhance the end results appreciably. Shredding followed by polymer encapsulation, and shredding followed by cementation were considered good near-term waste treatments and will limit the rate of corrosion. However, both materials (polymer and cement) may crack providing brine access to the metals. By comparison, shredding and then adding bitumen was considered more effective because, unlike the preceding alternatives, bitumen would not be expected to crack, thus preventing the brine from reaching the metal. Shredding and subsequently adding bentonite puts the absorbed brine in close contact with the metal. However, it does prevent contact with free brine.

#### 3.1.1.4 Permeability of the Waste Stack

The permeability parameter refers to the permeability of the waste stack itself. The panel decided that backfill permeability would be considered separately. Since the EAMP could not, during the time available, determine the long term effectiveness of waste form treatments for reduction of permeability, it was decided to evaluate the alternatives based on their initial permeability to brine.

### Sludges

Plasma processing was considered most effective because it would almost completely eliminate interconnected porosity and thus reduce permeability to the greatest extent. Vitrification is

expected to leave slightly more porosity compared to plasma and so was scored somewhat lower.

Cement was considered a good alternative for lowering permeability in the near term. However, because of the presence of nitrates in the sludges, its longevity is questionable. The addition of calcium oxide or activated alumina will have a small effect on permeability by filling some voids.

### Solid Organics

Plasma processing was judged to produce the lowest waste permeability. Both incineration followed by vitrification, and acid digestion were considered to be of equal merit but not quite as good in densifying the waste as plasma. Compaction will reduce voids, but interconnections between pores will remain. Shredding before compaction will result in further reduction of volume. Cementation preceded by either shredding or incineration were considered reasonably effective because both alternatives will reduce voids and decrease interconnected pores. The two types of encapsulation, with either a polymer or bitumen, were both considered very effective because they will result in a low initial permeability, but may not decrease voids to the extent achieved by plasma or vitrification. Shredding followed by the addition of bentonite was considered virtually as effective as cemented waste forms, based on the assumption that bentonite will swell upon contact with the high magnesium brine encountered at WIPP. The addition of gas getters or altering the environment was not considered effective except for increasing the pH and filling some voids. Adding salt after shredding and then compacting would be an improvement for reducing voids, compared to shredding with the addition of bentonite, but it would not be as effective as encapsulation.

### Solid Inorganics

Plasma processing will result in the maximum reduction of permeability and so was given the highest score. Melting metals was scored somewhat lower because the residue from this process has a somewhat higher porosity than that resulting from plasma processing, and depends on the process used to solidify the residue. The panel came to the conclusion that the relative scores of many of the remaining alternatives would not change from those presented for combustibles. However, since metals cannot be volumetrically reduced as much as solid organics, some of the scores for glass and metals were slightly lower than for solid organics. Decontaminating metals does not result in permeability reduction per se, but does eliminate a highly permeable waste form. The EAMP assumed that the residue after decontamination would be cemented or vitrified. Compaction of glass and metals to a low permeability is difficult and therefore received a low score. Shredding before compaction was considered to be helpful in reducing the permeability to a level lower than by compaction only. Adding salt before compaction improves upon the preceding option. The addition of gas getters or altering the environment provide a marginal reduction of voids.

#### 3.1.1.5 Radionuclide Solubility in Brine

The term solubility refers to the solubility of radionuclides or hazardous chemical wastes in brine and is defined as the maximum amount of the solute that can dissolve in brine under given conditions of brine composition, pH and temperature. Since the temperature under repository conditions is not expected to vary substantially, solubility can be controlled by adjusting pH. In contrast, leachability deals with a rate process and is defined as the rate at

which a solute dissolves in a solvent to attain the maximum concentration possible under the given conditions. Whereas solubility can be reduced by increasing the pH and reducing the amount of organics present, leachability can be controlled by adjusting a number of factors. The desirable factors for having a low leaching rate are high pH, low surface area, low permeability, low level of organics, dense forms, and reduction of brine volumes. A reduction in solubility will also decrease the concentration gradient for mass transfer and thus decrease leachability.

### Sludges

Cementation or altering the environment were considered the best alternatives because they increase the pH through the addition of cement and lime respectively, leading to low solubilities and providing a stable environment for the precipitated hydroxide form of the nuclides.

The prime concern about plasma processing or vitrification was that these high temperature treatments will destroy the hydroxide form and the pH will be dominated by the pH of brine, which is around 5 to 6. At this low pH, oxides are more soluble, which would have an adverse effect if these alternatives are used. Although this problem can be eliminated if either lime or cement are added after high temperature processing to provide a pH buffer, these alternatives were scored as having adverse effects.

### Solid Organics

The effect of combustibles on the solubility parameter results mainly from the presence of organics which potentially provide complexing agents. Therefore, the panel decided that any alternative is attractive if it destroys organics. If an alternative could not destroy organics but did increase the pH sufficiently through the addition of cement, lime, or similar alkaline material, this could be even more beneficial than destroying organics. Finally, if an alternative could accomplish both the destruction of organics and provide the pH buffer, it would be considered the most effective alternative.

Based on the above considerations, incineration followed by cementation was the only alternative that both destroyed organics and provided a pH buffer. Cementation with prior shredding, altering the environment, and gas getters all satisfied the pH buffering criterion. Plasma processing, acid digestion, and incineration followed by vitrification would all destroy organics, but fail to satisfy the pH consideration. However, these waste treatments are expected to produce waste forms with lower leachability. The two forms of encapsulation, either with polymers or bitumen, were considered adverse alternatives because they add organics which would have an adverse effect on solubility. The different forms of compaction would have no effect on solubility because they do not change the status of organics or modify the pH. Shredding with the addition of bentonite was also judged to have no net effect, based on the assumption that nuclide adsorption on bentonite in a high-magnesium saturated brine is low, leaving the nuclides available for dissolution.

### Solid Inorganics

For glass and metals, the destruction of organics is of second order importance. Therefore, alternatives that provide sufficient pH buffer were considered the most effective for treating the glass and metal waste form.

Based on this consideration, altering the environment, gas getters, and cementation with prior shredding were all given top scores. Decontaminating metals and melting metals were also scored high based on the assumption that the residue, in both cases, could be cemented. Plasma processing would destroy organics, but it does not provide a pH buffer. Both forms of encapsulation were considered adverse alternatives because they would add organics. The remaining alternatives, which included the three forms of compaction and shredding with the addition of bentonite, were all judged to have little or no effect for the same reasons given during discussion of combustible wastes.

### Leachability Considerations

After evaluating the alternatives on the basis of solubility, the panel considered the effects on leachability to check if any of the scores might change. It was found that some of the alternatives would indeed rank higher if leachability was considered.

All the alternatives resulting in permeability reduction (e.g., plasma processing, vitrification, acid digestion, and encapsulation) would result in a lower effective leachability, since less brine will come in contact with the waste. Therefore, the panel noted that the rankings for these alternatives could be higher if leachability, rather than solubility as the bounding characteristic, is considered the controlling parameter.

### 3.1.2 Waste Management Alternatives

The EAMP considered two of the five potential waste management alternatives - Minimize Space Around the Waste Stack, and Segregate Waste in WIPP. The remainder were considered in conjunction with other alternatives or were not feasible.

#### Minimize Space Around the Waste Stack

It was assumed that implementation of this alternative would eliminate the need for backfill, and that space around the waste stack is needed only as long as waste operations are taking place in the storage panel to prevent the walls and back (ceiling) from contacting the waste. This alternative would actually take the place of backfill, but interstitial voids between waste containers and between the waste and waste disposal room walls would still exist, unless the waste container shape is modified. Therefore this alternative was scored lower than most of the backfill alternatives.

#### Segregate Waste in WIPP

This concept attempts to segregate the potential challenges associated with the different waste forms coming to WIPP. It was assumed that waste would be segregated by waste disposal panel, and operations in more than one panel at a time would be necessary. On the basis of these assumptions the EAMP recognized that the WIPP ventilation system would probably have to be redesigned to allow operations in more than one panel at a time. Since each operational panel would have to remain open longer than currently planned, premature creep closure was a concern. If all the sludges were stored together, a relatively high corrosion gas inventory could build up in those waste disposal rooms. The most promising result of waste segregation would be separation of nutrients ( $\text{NO}_x$ ) from biological substrate (cellulosics), and

potentially lower biological gas generation. The EAMP concluded that this was the only potential benefit of this alternative.

### 3.1.3 Backfill Alternatives

The backfill alternatives were considered during the preliminary evaluation of the alternatives. The EAMP decided to re-evaluate the backfill alternatives based on the five remaining performance parameters, and certain associated assumptions. For the sake of brevity the alternatives "Compact Backfill" and "Preformed Compacted Backfill," were combined into a single alternative, designated "Compacted Backfill." Thus, the following six backfill alternatives were reevaluated with respect to their mitigating effect on the five parameters:

- Salt Only
- Salt and pH Buffers
- Compacted Backfill
- Salt and Brine Sorbents
- Grout
- Bitumen.

The evaluation of backfills for the five parameters was based on the following assumptions:

- All organics are potential candidates for biodegradation.
- Bentonite and salt will reduce the voids to approximately the same extent, but salt will reconsolidate.
- Positive effects of backfill are reduction of initial void volume, minimization of brine flow through waste, and an increase in the pH to minimize corrosion and biological gas generation, and solubility of radionuclides.
- Backfilling takes place in a 13' x 33' x 300' room.
- Retrievability, after a disposal decision has been made, is not a consideration.
- All waste forms have been treated to minimize permeability.
- The backfill material needs to be reasonably free-flowing to effectively backfill between drums, or some engineering or operational changes may be necessary.
- Backfill around waste stack is independent of waste form.
- Backfills are not considered highly effective for mitigating the effects of gas generation parameters, compared to waste form alternatives, although backfills can absorb brine, raise pH, absorb carbon dioxide, and facilitate closure. Backfills affect gas generation rates rather than total gas potential.
- If solubility is found to be the only problem, then the backfill that adequately raises the pH may be the only solution needed.

### **3.1.3.1 Radiolytic Gas Generation**

Grout was given the highest score because it was considered the best backfill to reduce brine inflow and thereby mitigate radiolytic gas generation from that source. The positive effects identified were the filling of most voids, quicker room reconsolidation, keeping brine out, and having reasonable structural integrity. Salt with brine sorbents would not be as effective as grout in filling voids. It was assumed that absorption of brine will cause bentonite to swell against lithostatic pressure and moisture would not be squeezed out. Compacted salt backfill will not easily fill the interstitial voids between drums, which will maintain a higher permeability than could be achieved if these voids were filled. As a backfill, salt by itself does not have any notable chemical effects that would reduce or aggravate radiolytic gas generation. However, it is expected to reconsolidate quickly, achieving a relatively low permeability to brine in its reconsolidated state. The addition of pH buffers to crushed salt will enhance moisture absorbing capability compared to salt alone. Bitumen would keep moisture out, but would have the adverse effect of adding organics.

### **3.1.3.2 Biological Gas Generation**

The most effective alternative was judged to be grout because, in addition to keeping brine out, it would also increase the pH, both of which will decrease biological gas generation rates. Salt with the addition of pH buffers was also considered effective because it would have a pH buffering effect to partially compensate for the additional brine inflow. The addition of salt alone does not have a chemical effect on biological gas generation. However, since the transport of nutrients occurs in liquid media, the addition of salt will reduce the pathways for nutrient transport. Compacted backfills would be slightly better than salt alone because there are less initial voids. Salt with brine sorbents will be a better deterrent than salt alone to initially reduce brine inflow. Since bitumen adds organics, it was considered an adverse alternative. The safety concerns associated with emplacing hot bitumen underground was also considered by the EAMP.

### **3.1.3.3 Corrosion Gas Generation**

Grout was judged to be the most effective alternative because of its pH buffering capability. Salt plus pH buffers would keep brine out as well as raise pH but its initial permeability would not be as low as grout. Salt plus sorbents would absorb moisture and slow the gas generation rates. Bitumen does not provide pH control, but would restrict brine inflow. However, the emplacement challenges discussed earlier need to be considered. Salt alone and compacted salt backfill will reduce voids and thus reduce brine inflow, thereby possibly reducing the rate of corrosion gas generation.

### **3.1.3.4 Permeability of the Waste Stack**

Since this parameter is not concerned with pH control or the presence of organics, bitumen would be the best backfill if emplacement challenges could be overcome. Compared to bitumen, grout would have a higher porosity. The remaining backfill alternatives were judged approximately equivalent because none of them would be able to easily fill the interstitial voids between drums, since they are not as free flowing as bitumen or grout.

### 3.1.3.5 Radionuclide Solubility in Brine

For this parameter, the backfills were scored on the basis of their pH buffering capacity and the addition of organics. Grout and salt with pH buffers were judged to be the most effective in their ability to raise pH. Bitumen was considered an adverse alternative because the addition of organics has the adverse effect of increasing radionuclide solubility. The remaining alternatives would have no effect on pH, and therefore were judged to have no effect on solubility.

### 3.1.4 Facility Design Alternatives

The EAMP evaluated 12 facility design alternatives and concluded that six were considered in conjunction with other alternatives or were not feasible.

#### Gas Expansion Volume

The intent of this concept was to prevent overpressurization by waste generated gases, if this poses a potential but inconclusive threat to facility integrity. The alternative was to be considered only if gas generation is a marginal problem, requiring a relatively small expansion volume. The EAMP decided that the effectiveness of this alternative could not be determined. The addition of free volume could increase the time required for reconsolidation of the waste disposal rooms, thereby actually increasing the potential for brine inflow and gas generation. The added volume would probably not be able to accommodate the additional gas generated.

#### Ventilate Facility

The EPA Standards permit active institutional control by the implementing agency (DOE) for up to 100 years. This alternative would take advantage of this time period by continuing active ventilation of the waste disposal rooms, thereby evaporating inflowing brine until rooms had achieved closure. After that time, the reconsolidated room would resist the inflow of brine. The EAMP was concerned about this alternative due to several factors. There is no assurance that the ventilation spaces will remain uniformly open. The partial or total cessation of ventilation would allow brine to accumulate. There was also concern about safety problems associated with potentially breached waste containers, and sealing the waste disposal panels under these circumstances. Nevertheless, this alternative was given mid-range scores for mitigating the effects of brine inflow since there is no need to develop basic technologies, and engineering solutions may be available to overcome the alternative's shortcomings.

#### Change Extraction Ratio

The mined extraction ratio at WIPP is very small compared to what conventional mining techniques would suggest. If the ratio of mined volume to unmined pillar volume were increased, the waste disposal room creep closure would be expected to accelerate, thereby achieving room reconsolidation faster. This in turn would reduce the total brine inflow from the Salado Formation. This alternative was not given a high score because of the concern that the disturbed zone volume surrounding the waste disposal rooms and panels would increase, allowing a greater accumulation of brine during the pre-closure period.

### Change Room Configuration

This alternative, as described in Attachment B, has several options. The EAMP considered only the option of a taller room to reduce the overall footprint of the repository. The remaining options were considered part of other alternative evaluations. This alternative was considered potentially effective for mitigating the human intrusion probability parameter only. A low score was assigned because of the need for roof bolting throughout the mined areas, the question whether such a design could be validated, and in a broader context of human intrusion, the potentially higher consequences resulting from penetration of more waste containers during the intrusion event.

### Seal Individual Rooms

This alternative was considered for mitigating the effects of the two-borehole scenario, and to a limited extent, the single borehole drilled into the Castile brine. The EAMP modified this alternative by suggesting that floor to ceiling salt seals could be installed at each end of the waste disposal rooms, as well as at appropriate locations within the rooms. This would decrease the effective permeability of each waste disposal panel, and prevent hydraulic communication between the two boreholes. If this alternative is implemented, it would appear to effectively eliminate the effects of the two-borehole scenario. The score reflects the limited application of this alternative, and questions remained regarding how ventilation would be affected during installation of the seals.

### Two-Level Repository

The concept of a two level repository would effectively halve the footprint of the repository and reduce the probability of human intrusion by a like amount. However, in a broader context, the probability of penetrating twice the number of waste containers is a distinct possibility. Therefore, this alternative was not given a high score.

### 3.1.5 Passive Marker Alternatives

These alternatives apply only to the human intrusion probability parameter. Therefore they were evaluated relative to each other within this narrow context, and their scores should not be compared to the scores of alternatives outside the passive marker category. Four of the five potential alternatives were evaluated. The fifth alternative, "Artificial Surface Layer," was eliminated because a feasible concept could not be identified.

### Monument "Forest" over Repository

This concept received the second highest score among the passive marker alternatives. Although the individual markers, or pylons, would be deeply anchored, their longevity was somewhat questionable because they could be removed more easily than a single large monument.

### Monument Covering the Entire Repository

This alternative, possibly in the form of a truncated pyramid, would cover the entire footprint of the underground waste disposal area. Although this concept entails a very large

construction effort, it received the highest passive marker score because of its anticipated longevity and visibility.

#### Buried Steel Plate Over Repository

Although the concept of a steel plate buried some distance below the surface, above the entire repository footprint, received a mid-range score for effectiveness, the EAMP recognized that many questions remain unanswered regarding the plate's longevity.

#### Add Marker Dye to Waste or Strata Above the Repository

The EAMP could not identify any long lasting marker dyes during its deliberations. It is also conceivable that the dye would be indistinguishable in drilling mud. Nevertheless, since the concept had some small merit, it was given the lowest score possible.

### 3.1.6 Miscellaneous Alternatives

Three potential alternatives were initially identified - Draining the Castile (Brine) Reservoir which may be located below the repository, Grouting Culebra Formation Above Repository, and Increasing Land Withdrawal Area to Regulatory Boundary. The latter was not considered to be an engineered alternative, and the remainder were considered not technically feasible.

### 3.1.7 Waste Container Alternatives

The TRU waste is currently stored in steel containers which will generate corrosion gas after disposal in the repository. The EAMP therefore considered modifying the existing polyethylene liner so that it could be used in place of a metal drum, or the use of concrete containers. The alternative did not receive a high score because, by itself, it is only marginally effective. Total metal corrosion is a function of the amount of brine in the waste storage rooms. It is anticipated that there will not be enough brine to corrode either all the steel waste containers or all the metal waste. Since the total corrosion gas is limited by brine availability, elimination of the steel waste containers does not change the total amount of gas that can be generated. If metal wastes are processed or eliminated, together with the elimination of steel waste containers, then this combined alternative would score very high.

The EATF has convened a panel of knowledgeable persons (the Waste Container Materials Panel) in the areas of metals, ceramics, concrete, fabrication, etc., to evaluate alternative waste container materials that would not generate gas in the WIPP environment.

The EAMP also discussed the role that the waste container shape can play for reducing waste stack permeability. If the shape can be modified so that the interstitial voids between the existing drums can be minimized, then the effective waste stack permeability would be reduced. By itself, this alternative was considered only marginally effective.

## 3.2 FEASIBILITY OF ALTERNATIVES

Of the 64 alternatives evaluated by the EAMP, 14 were considered not feasible. This section provides a brief discussion concerning the overall feasibility scores assigned to each alternative. The relative feasibilities of the alternatives were considered in a broad sense,

assigning the best alternative the highest score, while other alternatives received scores relative to this "best" alternative. As discussed in Section 2.2.3, the feasibility of each alternative was determined by considerations of regulatory requirements and concerns, state of technology, and schedular factors.

### 3.2.1 Waste Form Modification Alternatives

#### Compact Waste

This alternative represents an existing full-scale technology for processing radioactive wastes, and implementation is not expected to pose any major regulatory concerns. However, compactors would require preparation of National Environmental Policy Act (NEPA) documentation. It was given the highest score for the state of technology, but a somewhat lower score for regulatory requirements and schedular considerations.

#### Incinerate and Cement

The technologies of incineration, and cementation, are well established. However, the EAMP recognized that some existing incinerator systems for nuclear waste treatment are not operating because of current regulatory challenges. Therefore, the feasibility score for this alternative is low because of the current regulatory climate and public opinion, and the effect this has on schedule.

#### Incinerate and Vitrify

The feasibility of this alternative is similar to "Incinerate and Cement", for the same reasons given above.

#### Wet Oxidation

The EAMP concluded that this technology has not been adequately demonstrated for other than liquid wastes. Therefore it was deleted from further consideration.

#### Shred and Bituminize

Shredding is a well established technology. Bituminization is being used abroad but has not been applied to long-term waste disposal in the United States. The EAMP was concerned that the application of hot bitumen in an alpha waste facility could give rise to regulatory and safety challenges since flammable, volatile organic compounds are involved. A bitumen plant would need to be permitted and require the preparation of NEPA documentation. Based on experience abroad, the alternative was scored higher than incineration alternatives.

#### Shred and Compact

Shredding and compacting are well established technologies and are not expected to present any major regulatory problems. However, NEPA documentation would be required. This alternative was scored the same as the compaction alternative.

**Shred and Cement**

This alternative received essentially the same score as "Shred and Compact", except that the possibility of starting waste treatment at the Process Experimental Pilot Plant (PREPP) gave this alternative a slightly higher score for the schedule criterion. An on-surface cementing plant would need to be permitted and require preparation of NEPA documentation.

**Shred and Polymer Encapsulate**

The EAMP could not identify any major regulatory concerns for implementing this alternative, except for NEPA documentation. This technology was developed for the commercial nuclear power industry, but was not used. Since this technology is not as well developed for application to TRU waste disposal and the disposal environment, the technology criterion and consequently the schedule criterion received lower scores than some of the more conventional alternatives.

**Shred, Add Salt, and Compact**

This alternative did not appear to present any major technological or regulatory difficulties and therefore received the same scores as those for the compaction alternative. Preparation of NEPA documentation would be required.

**Plasma Processing**

This alternative is in the demonstration phase and has not yet been applied to radioactive materials. The regulatory concerns may be similar to those involving incineration. Therefore, this alternative received the lowest overall feasibility score.

**Melt Metals**

The technology for melting metals under adverse circumstances is reasonably well established. However, because this is a thermal process, it may encounter regulatory difficulties, possibly similar to those of "Plasma Processing" and was therefore given a relatively low overall feasibility score.

**Add Salt Backfill**

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subjected to separate evaluation.

**Add Other Sorbents**

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subjected to separate evaluation.

**Add Gas Suppressants**

This alternative is inherent in other alternatives considered by the EAMP and therefore was not subjected to separate evaluation.

### Shred and Add Bentonite

This alternative received the same score as "Shred and Cement" because the process is relatively simple, basic technology development is not required, there should be few if any regulatory difficulties, and the process can be implemented in a relatively short time. The process will, however, require NEPA documentation.

### Acid Digestion

The EAMP believed that regulatory concerns regarding this alternative would be similar to those encountered for thermal processes. The technology was only developed to the pilot stage, and the implementation schedule was considered marginal for newly generated waste.

### Sterilize

The EAMP did not believe that the waste, and waste disposal rooms at WIPP, could be effectively sterilized in a manner that would permanently eliminate microbes and the consequent biological gas generation. Therefore, this alternative was deleted from further consideration.

### Add Copper Sulfate

This alternative was deleted because of the possibility that deposited copper may act as a galvanic couple, thereby increasing gas production rates to undesirable levels.

### Add Gas Getters

The regulatory process for this alternative is not expected to be complex. However, the possibility of additional worker exposure, while adding gas getters to existing waste containers, may complicate the process. This concern is reflected in the regulatory score. Preparation of additional NEPA documentation may be required. There is no basic technology development required, and the implementation schedule is expected to comply with the newly generated waste processing requirements.

### Add Fillers

This alternative is inherent in other alternatives considered by the EAMP, and therefore was not subject to separate evaluation.

### Segregate Waste Forms

This alternative is inherent in, or can be combined with, virtually any other alternative. Therefore, the EAMP did not evaluate this concept as a stand-alone alternative.

### Decontaminate Metals

Various technologies currently exist for decontaminating metals, such as those currently used in the commercial nuclear industry. While decontamination of hazardous constituents could be advantageous from a RCRA standpoint, this alternative would probably require a new

facility, preceded by NEPA documentation, permitting, and other regulatory considerations. To maximize the effectiveness of the alternative, the waste container material would have to be changed from steel to a non-corroding material. This may also entail additional regulatory activities. On this basis, technology was given a high score, while the regulatory and schedule scores were reduced to reflect the uncertainties.

#### Change Waste Generating Process

The EAMP considered this to be a worthwhile alternative for future study. However, the subject is too broad to be evaluated qualitatively and therefore did not receive further consideration.

#### Add Anti-Bacterial Matrix

It was concluded that this technology has not been demonstrated for use in a repository environment and therefore this alternative was deleted from consideration.

#### Accelerate the Waste Digestion Process

It was concluded that this technology has not been demonstrated for this application and therefore the alternative was deleted from further consideration.

#### Alter Corrosion Environment in WIPP

The EAMP considered such options as activated alumina, lime, and cement as means for altering the corrosion environment in WIPP. Although no major regulatory or technological challenges were identified concerning this alternative, uncertainties about selection of material(s) and processes lowered the scores for this alternative.

#### Alter Bacterial Environment in WIPP

This alternative was considered during evaluation of the alternative "Add Anti-Bacterial Matrix" and was not considered feasible because the technology has not been demonstrated in a repository environment.

#### Transmutation of Radionuclides

This technology has not been demonstrated to the degree needed to process large quantities of waste containing low concentrations of TRU isotopes. The EAMP felt that this alternative could not be implemented in a timely fashion.

#### Vitrify Sludges

The vitrification of sludges by microwave or Joule melting is in the demonstration phase. The regulatory difficulties of this alternative were considered to be somewhat less than for incineration (of combustibles), so the score given this alternative is somewhat higher than for incineration. Since the process still needs to be fully demonstrated, the scores for technology and schedule were lower than those for more fully developed systems.

### 3.2.2 Waste Management Alternatives

#### Minimize Space Around Waste Stack

The EAMP did not identify any regulatory, technological or schedular challenges for this alternative that would hinder its implementation, so the highest scores were assigned for these criteria.

#### Segregate Waste in WIPP

The EAMP did not identify any technological challenges that would hinder the implementation of this alternative. Some administrative control of transportation and waste emplacement management will be required, potentially having a small effect on the regulatory requirements.

#### Decrease the Amount of Waste Per Room

This alternative was considered together with some of the backfill alternatives, and hence not evaluated separately.

#### Emplace Waste and Backfill Simultaneously

This alternative was considered together with the "Preformed Compacted Backfill" alternative, and therefore not evaluated separately.

#### Selective Vegetative Uptake

This alternative has not been demonstrated for TRU waste. Therefore, the alternative was deleted from further consideration.

### 3.2.3 Backfill Alternatives

#### Salt Only

Crushed salt resulting from mining of the underground storage facility is the basic backfill material currently being considered to reduce void volume and hasten room closure. The EAMP did not identify any major impediments to using this material for backfill. There was some question whether the backfill emplacement methods are sufficiently developed to effectively fill the void spaces between waste containers. Therefore, the technology score was reduced somewhat to reflect this uncertainty.

#### Salt Plus Gas Getters

The EAMP considered only the addition of dry cement or lime as a getter for carbon dioxide, and judged the feasibility of this alternative the same as for the "Salt Only" alternative. No effective getters could be identified for hydrogen, nitrogen, or methane.

#### Compact Backfill

Compacting salt backfill in place has not been specifically demonstrated, but the EAMP felt that such a process could be developed and does not present extraordinary challenges.

However, there were concerns about the additional worker exposure and also the potential for additional regulatory concerns that might accrue from this process. Therefore, all scores were significantly lower than for the "Salt Only" alternative.

#### Salt Plus Sorbents

This alternative's regulatory and technological feasibility was judged to be about the same as salt backfill only. However, since the effectiveness of specific sorbents may need to be confirmed, scheduler feasibility was downgraded somewhat to allow time for experimentation.

#### Preformed Compacted Backfill

The EAMP considered only salt as a preformed compacted backfill. The feasibility of this alternative was judged somewhat higher than compacting backfill in place, but additional worker exposure during emplacement was still a concern.

#### Grout Backfill

The preparation and emplacement of grout in various industrial circumstances is a well established practice. Tailored, free-flowing grouts have been designed for numerous applications. Therefore, this backfill alternative was judged to have the highest feasibility since it can be efficiently emplaced, is expected to flow between waste packages, and worker exposure should be no more than encountered during emplacement of salt only backfill. The technology score is higher than for the "Salt Only" alternative to reflect the possibility of more easily filling the voids between the waste containers.

#### Bitumen Backfill

The use of bitumen as a backfill was judged to have the lowest feasibility because of potential fire hazards, worker exposure to volatile organic compounds, the difficulty of emplacement, and the required NEPA documentation. Although this alternative was considered to be feasible, recommendations for not using the alternative were voiced during the EAMP meetings.

#### Gas Suppressants

This alternative was considered together with the "Salt Plus Gas Getters" alternative, and therefore was not subject to separate evaluation.

### 3.2.4 Facility Design Alternatives

#### Brine Isolating Dikes

This alternative was considered to be similar to the "Seal Individual Rooms" alternative, and therefore was not subjected to separate evaluation.

#### Raise Waste Above Floor

This alternative was considered to be part of the "Salt Plus Sorbents" backfill alternative, and therefore did not undergo separate evaluation.

### Brine Sumps and Drains

This alternative was deleted because the EAMP believed that the flow paths leading to the sumps would not remain open long enough to allow substantial amounts of brine to be isolated from the waste.

### Gas Expansion Volume

The technology of mining and preparing these expansion volumes contiguous with the WIPP waste storage areas is currently available. Therefore, the alternative received the highest score for technology. Some concern was voiced by a few EAMP members about the accumulation of potentially hazardous gases in such unrestricted volumes, which prompted lower scores for the regulatory and scheduler criteria.

### Seal Disposal Room Walls

This alternative was deleted because sealing technology for this application has not been demonstrated. The EAMP judged that such technology could not be developed in a timely fashion.

### Vent Facility

This alternative was deleted. Venting the facility after active institutional control has been relinquished would not meet regulatory requirements.

### Ventilate the Facility

The EAMP voiced several concerns about ventilating the facility for up to 100 years (the active institutional control period). These included regulatory concerns about maintaining active facility control for such a long period, the difficulty of assuring continuous ventilation in all spaces, and the potential for rupturing waste containers during the ventilation period. The difficulty of safely sealing the rooms and panels of the facility, after so many years of creep closure has taken place, was also considered. Also, ventilation might violate the RCRA "no migration" variance proposed for WIPP. Based on these considerations, low feasibility scores were assigned to this alternative.

### Add Floor of Brine Sorbent Material

This alternative was considered together with the "Salt Plus Sorbents" backfill alternative, and therefore not evaluated separately.

### Change Mine Extraction Ratio

The ratio of mined to unmined volumes in the WIPP underground is considerably lower than normally found in extractive mining industry practice. This large safety factor makes it feasible to increase the ratio so that closure and reconsolidation take place faster. On this basis, the alternative was assigned reasonably high scores.

### Change Room Configuration

The EAMP limited this alternative to increasing the height of the waste disposal rooms. Such a design change could affect regulatory documentation and agreements with the State of New Mexico. Although some potential complications of intersecting additional clay seams or marker beds were recognized, the EAMP considered the technology well established. Therefore, the alternative received the highest score for technology and reduced scores for the regulatory and scheduler criteria.

### Seal Individual Rooms

The concept of sealing individual rooms or portions of rooms, using thick salt "dikes" which isolate smaller volumes of waste from each other, was considered the most feasible facility design alternative. While judging the feasibility of this alternative, the EAMP considered the potential for increased waste emplacement durations and a small increase in worker radiation exposure.

### Two-Level Repository

Existing technology can be used to construct a two-level repository, and so this alternative received a relatively high technology score. However, the EAMP recognized that a previous two level design for WIPP was intended to accommodate both transuranic waste and spent fuel. If a proposal was made to change the WIPP design to a two-level format, considerable public debate could take place, creating a difficult regulatory challenge and causing scheduler delays. Preparation of NEPA documentation would be required for the revised facility design. The very low regulatory and schedule scores reflect these concerns.

### 3.2.5 Passive Marker Alternatives

The scheduler feasibility criterion, as established by the EAMP, irrelevant for the construction of passive surface markers since they can be constructed during the waste emplacement period, or even after closure of WIPP but before active institutional control ends. Therefore these alternatives were given the highest schedule feasibility scores available.

### Monument "Forest" Over Repository

The EAMP could not identify any major impediments to implementation of this alternative. Preparation of NEPA documentation would be required. The possibility that regulatory concerns might be voiced, since the surface would not be returned entirely to its original condition, was reflected in the scores. However, the EATF has later realized that returning the surface to its original condition will not be a regulatory issue (DOE, 1980). Therefore, if this was incorporated in the EAMP deliberations, then this alternative would have scored higher.

### Monument Covering the Entire Repository

The feasibility of this alternative is similar to the previous alternative except that potential regulatory concerns may be somewhat greater. Preparation of NEPA documentation would be required. By covering the entire surface footprint of the repository with a single (or multiple

contiguous) monument, that portion of the land surface cannot be returned to its original condition, and the regulatory score reflects this concern. This alternative would also have scored higher for the same reasons mentioned above.

#### Buried Steel Plate Over Repository

While the technology for implementing this alternative exists, the need for corrosion control of the plate may raise regulatory challenges. Since NEPA documentation would probably be required, this alternative was scored somewhat lower for regulatory feasibility.

#### Artificial Surface Layer Over Repository

No feasible concept could be identified, and therefore this alternative was deleted.

#### Add Marker Dye to Waste or Strata Above Repository

The EAMP considered marker dye only in the strata above the repository. The technology required to implement this alternative is not well developed, so a very low score was assigned to the technology criterion. The EAMP was not in a position to identify specific dyes that would be effective over a long period. Additionally, regulatory problems may make this alternative unfeasible if only toxic dyes are available for effective use as markers, which is reflected in the regulatory score.

### 3.2.6 Miscellaneous Alternatives

#### Drain Castile Reservoir

This alternative was not considered to be feasible because of the relatively sparse information about the nature of the Castile reservoir and concern over potential subsidence of the repository itself if the reservoir is drained. Such questions as the amount of fluid in the reservoir, potential for recharge, and the time needed to pump the reservoir made the feasibility of this alternative indeterminate.

#### Grout Culebra Formation Above Repository

The EAMP questioned the ability to effectively grout the Culebra Formation, considering the extent of the formation and the longevity requirements. It was concluded that this alternative was not feasible.

#### Increase Land Withdrawal Area to the Regulatory Boundary

The EAMP did not consider this to be an engineered alternative, and therefore it was not evaluated further.

### 3.2.7 Waste Container Alternatives

#### Change Waste Container Shape

The EAMP could not identify any major regulatory or technological challenges associated with this alternative. Some DOE sites are already using boxes (instead of drums) for storage and

disposal of their wastes. However, if implementation of this alternative introduces the need to redesign the Transuranic Package Transporter-II (TRUPACT-II), then additional regulatory activities may need to be considered.

#### Change Waste Container Material

No major regulatory or technological challenges were identified concerning this alternative. The EAMP considered only existing technology, which can be implemented quickly if needed, and so the alternative received a high score for schedule considerations. However, since the existing (stored) waste would have to be repackaged, the scores for technology and regulatory considerations were somewhat lower. Newly generated waste could be packaged directly into the new waste containers. Discussion of alternate waste container materials is provided in Appendix H, Report of the Waste Container Materials Panel.

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## 4.0 CONCLUSIONS

The EAMP concluded that numerous potential engineered alternatives are available, if needed, to demonstrate compliance with the EPA Standard 40 CFR Part 191 (EPA, 1985). However, the qualitative evaluation process which ranked the relative effectiveness and feasibility of the alternatives precluded the recommendation of any particular alternative or a group of alternatives. The evaluations provide a basis for quantitative analysis of selected alternatives using design analysis models. If the performance assessment studies identify one or more parameters that impede the demonstration of compliance with EPA Standard 40 CFR Part 191, then the results from design analysis will provide one or more engineered alternative(s) to mitigate the problem.

The EAMP screening process eliminated all but 35 of the original 64 potential engineered alternatives originally suggested by the EATF. The EAMP added one alternative during the deliberations (cementation of sludges) making a total of 36 feasible alternatives belonging to the following categories:

Waste Form Modification Alternatives	17
Backfill Alternatives	6
Waste Management Alternatives	2
Facility Design Alternatives	5
Passive Marker Alternatives	4
Waste Container Alternatives	2

The EATF has used the results of the EAMP, and classified the waste form modification alternatives into seven generalized categories based on the similar final waste forms resulting from these treatments. These categories and the alternatives grouped into each category are:

- Vitrification of waste
  - Microwave melting (sludges only)
  - Plasma processing
  - Incinerate and vitrify (solid organics only)
  - Acid digest, calcine, and vitrify (solid organics only)
- Cementation of waste
  - Cementation of sludges into monoliths
  - Shred and cement (solid organics and inorganics)
  - Incinerate and cement (solid organics only)
- Compaction of waste (does not apply to sludges)
  - Compact
  - Shred and compact
  - Shred, add salt, then compact
- Encapsulation of waste (does not apply to sludges)
  - Shred and encapsulate with polymer
  - Shred and encapsulate with bitumen

- Preparation of ingots from melted metal waste (applicable only to solid inorganics)
- Shredding of waste followed by addition of bentonite
- pH buffering of waste
  - Buffering by lime
  - Buffering by cement
  - Buffering by alumina

In addition, the EATF has included one more category in the above list which is not a waste form modification, but considered by the EATF to be an equally important group of alternatives. This new category is:

- Changing of waste container material.

Based on Table A-6, and in conjunction with the deliberations of the EAMP, the EATF has noted that in Table A-6 there are some groups of alternatives which consistently received high scores for effectiveness, primarily because of their ability to eliminate the potential problem associated with a performance parameter. For example, all the different vitrification options (i.e., plasma processing, acid digestion, etc.) received consistently high effectiveness scores for the parameters associated with radiolytic gas generation, because they would (for all practical considerations) eliminate the potential associated with radiolytic gas generation. On the other hand, there are groups of alternatives in Table A-6 which have been assigned low to moderate scores for effectiveness because they can only slow down the rate processes associated with the parameter (instead of eliminating the potential). For example, any form of compaction of the waste was assigned low to moderate scores by the EAMP for corrosion gas generation, because these alternatives would only reduce the rate of corrosion gas generation but not eliminate it. Therefore, in order to develop a generalized set of recommendations for future design analysis, and for the WIPP Experimental Test Program, the EATF has divided the alternatives into two categories for each performance parameter:

- Alternatives which essentially eliminate the potential associated with a performance parameter.
- Alternatives which only reduce or control the rate processes.

Alternatives belonging to both of the above categories were identified for the three gas generation parameters. The remaining parameters (permeability of waste stack and radionuclide solubility in brine) did not have any applicable alternatives belonging to the first category. In other words, the EAMP concluded that permeability and solubility can only be reduced or controlled but never completely eliminated.

Since the objectives of the WIPP Experimental Test Program and the design analysis modeling are primarily related to the effectiveness of an alternative, the EATF has summarized the panel deliberations on the basis of the effectiveness scores in Table A-6 and the two categories of alternatives mentioned above. It should be noted, however, that the feasibility of the alternatives is also being studied in detail as part of the overall EATF objectives.

Table A-7 presents the set of alternatives which were consistently assigned high scores by the EAMP in Table A-6 for their effectiveness for eliminating the potential associated with a

performance parameter. Table A-8 presents similar information extracted from Table A-6 for alternatives which were assigned low to moderate scores for effectiveness because they can only reduce the rate process associated with a parameter, and cannot eliminate the potential.

Since the extent to which the rate can be reduced or controlled is different for each alternative, the alternatives are listed in descending order of merit for each performance parameter.

It should be noted that since the properties of the final waste forms resulting from a lot of the alternatives in Table A-6 are very similar, for the sake of brevity, alternatives in Tables A-7 and A-8 have been grouped into one of the seven generalized categories described earlier. For example, all the different forms of compacting the waste have been grouped together as "compaction" in Table A-8.

The EATF will perform design analyses of appropriate combinations of engineered alternatives from Tables A-7 and A-8 to quantify the improvements in repository performance using alternative waste forms. An example of such a combination for reducing the potential of radiolytic gas generation would be to cement the sludges, shredding and cementing the solid organics, and decontaminate the metals. Either grout or salt could be added in the repository as a backfill material. Similarly, decontamination of all corroding metals from the waste inventory, and changing the waste container material could be used to eliminate the potential of corrosion generation.

The EAMP considered ranking a set of combined alternatives based on their effectiveness and feasibility. However, it was decided that since the evaluation process was primarily qualitative, ranking the combinations merely on the basis of summation of their individual scores would not be meaningful and therefore not advisable.

The results of the EAMP's evaluations will be used to:

1. Recommend waste form alternatives that should be included in the WIPP Experimental Test Program.
2. Provide a basis for identification of combinations of alternatives that should be quantitatively analyzed for relative effectiveness.
3. Provide a basis for evaluation of the relative cost and schedule ramifications for implementing the most effective and feasible alternatives.

The final choice of alternative(s), and whether any alternatives are needed, will be decided in conjunction with the performance assessment studies when the extent of mitigation required is finally determined after these studies are completed.

**TABLE A-7**  
**WASTE FORM MODIFICATIONS FOR ELIMINATING POTENTIAL**

PARAMETER	WASTE FORM		
	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
<b>Radolytic Gas Generation</b>	Vitrification	Plasma processing Incinerate and Vitrify Acid digest and Vitrify	Vitrification
<b>Biological Gas Generation</b>	Vitrification	Plasma processing Incinerate and Cement Incinerate and Vitrify Acid digest and Vitrify	Category does not pose biological gas generation problem
<b>Corrosion Gas Generation</b>	Vitrification	Category does not pose corrosion gas generation problem	Decontamination of corroding metals Changing existing waste container materials
<b>Permeability of the Waste Stack</b>	None	None	None
<b>Radionuclide Solubility In Brine</b>	None	None	None

**TABLE A-8**  
**WASTE FORM MODIFICATIONS**  
**FOR REDUCING/CONTROLLING POTENTIAL**

PARAMETER	WASTE FORM		
	SLUDGES	SOLID ORGANICS	SOLID INORGANICS
<b>Radiolytic Gas Generation</b>	Cementation* pH Buffers	Inclinerate and cement Compaction pH Buffers	Decontamination Melted metals pH Buffers
<b>Biological Gas Generation</b>	Cementation* pH Buffers	Shred and cement Compaction pH Buffers Shred, add bentonite	Category does not pose biological generation problem
<b>Corrosion Gas Generation</b>	Cementation* pH Buffers	Category does not pose corrosion gas generation problem	Vitrification pH Buffers Encapsulation Melted metals Shred and cement Compaction
<b>Permeability of the Waste Stack</b>	Vitrification Cementation pH Buffers	Vitrification Encapsulation Cementation Shred, add bentonite Compaction pH Buffers	Vitrification Melted metals Shred, add bentonite Encapsulation Shred and cement Decontaminate metals Compaction pH Buffers
<b>Radionuclide Solubility In Brine</b>	Cementation pH Buffers	Cementation pH Buffers Vitrification	Decontaminate metals pH Buffers Shred and cement Melted metals

\*Cementation into monoliths.

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## ATTACHMENT A

### EAMP REQUIREMENTS AND QUALIFICATIONS OF MEMBERS

#### REQUIREMENTS

The Engineered Alternatives Task Force identified the disciplines needed for the Panel and established the requirements for Panel members based on its knowledge of the WIPP project and the challenge of demonstrating compliance with the EPA Standards.

**CHAIRMAN** - Broad understanding of the nuclear industry and the defense transuranic waste program, including the WIPP project, and a general knowledge of the disciplines denoted below. Undergraduate degree with 20 or more years of experience.

**DOE/INSTITUTIONAL** - Familiar with DOE programmatic sensitivities and requirements. Knowledgeable about institutional issues and the ability to project past challenges to future conditions. Ability to understand complex technical issues and to recognize potential solutions. Undergraduate degree with ten or more years of experience.

**GENERATOR WASTE PROCESSING** - Broad understanding of transuranic waste generation and waste processing at DOE facilities. Experience should provide the ability to form judgments regarding the impact of various waste form alternatives on the basic waste generation processes. Undergraduate degree with five or more years experience at DOE weapons production facilities.

**GEOCHEMISTRY** - Geology or geochemistry background, preferably in the hazardous or radioactive waste disposal areas. Capable of making judgments regarding processes occurring in the WIPP repository if engineered alternatives are applied. Familiarity with WIPP geology and/or geochemistry of the region. Graduate degree with ten or more years experience.

**METALLURGY/CORROSION** - Extensive experience solving corrosion problems and an in-depth understanding of corrosion mechanisms and products of corrosion. Understanding of corrosion inhibition and the effects of near saturated brines on corrosion of metals. Graduate degree with ten or more years experience.

**MICROBIOLOGY** - Experienced microbiologist with considerable background in bacterial degradation of hazardous, mixed waste, and nuclear waste forms. Understanding of bacterial energetics and reactions of halotolerant and halophilic organisms and the effect of salt environments on bacterial communities. Graduate degree with ten or more years experience.

**PERFORMANCE ASSESSMENT** - Familiarity with the EPA Standards 40 CFR Part 191 and the requirements to conduct performance assessment of deep geologic repositories. Generally knowledgeable about current performance assessment activities and challenges. Undergraduate degree with five or more years of experience.

**REGULATORY** - Background involving regulatory compliance activities, familiarity with 40 CFR Part 191, RCRA and states' permitting requirements. Sufficient experience in regulatory matters to understand the probability of permitting of new technologies by state and federal

agencies. Technical or legal background preferred. Graduate degree with five or more years experience.

**REPOSITORY OPERATIONS** - Operation and/or engineering experience on the WIPP project, including familiarity with mining, surface and underground facility design, and waste handling. Undergraduate degree (or equivalent) with five or more years of experience.

**ROCK MECHANICS** - Experience with mechanical deformation of rock, understanding of repository sealing technology and requirements and underground design experience. Overall familiarity with deep geologic repository underground design. Graduate degree with ten or more years of experience.

**WASTE TREATMENT** - Broad experience in nuclear and hazardous waste treatment technologies. Background should include development, design, and operation of waste treatment systems and facilities. Undergraduate degree with ten or more years of experience.

### **QUALIFICATIONS OF PANEL MEMBERS**

#### **CHAIRMAN**

**Mr. Hans Kresny** (Chairman and Facilitator)

Mr. Kresny is the President of Solmont Corporation, and a consultant to IT Corporation, with over 33 years of multidisciplinary technical and managerial experience in the nuclear industry. His background includes engineering and project management involving major nuclear facilities and programs, institutional issues resolution between the WIPP project and 23 States, shielding and radiation analysis, and nuclear space systems and power plant design. Education: Bachelor of Marine Engineering.

#### **PRIMARY PANEL MEMBERS**

**Mr. Mike McFadden** (DOE/Institutional)

Mr. McFadden has 14 years of experience, the major portion of which includes management positions with the Department of Energy. His background includes engineering and management of such projects as geothermal and laser facilities, management of the DOE Transuranic Waste Program, the WIPP transportation system, transporter development programs, and integration of WIPP and transuranic waste generator activities. Education: B.S., Civil Engineering.

**Mr. Vernon Daub** (DOE/Institutional)

Mr. Daub has 15 years of management and engineering experience. He has held the positions of mechanical engineer, test engineer, Chief of Test Engineering within the Department of Defense, and Research and Development Engineer, and Transportation Manager within the Department of Energy. He has extensive experience and has had significant responsibilities in a wide range of areas on the WIPP Project. Education: B.S., Mechanical Engineering; M.S., Industrial Engineering.

**Mr. Jeff Paynter (Generator Waste Processing)**

Mr. Paynter has six years of experience at the DOE Rocky Flats Plant, including criticality safety engineering; waste processing; operations; and package design, analysis, and testing. Education: B.S., General Engineering, Nuclear Option.

**Mr. Kyle Peter (Generator Waste Processing)**

Mr. Peter has nine years experience at the DOE Rocky Flats Plant, including responsibility for design, start-up, operation, and maintenance of waste processing treatment facilities. He is familiar with RCRA permitting, treatment, and storage regulations. Education: B.S., Chemical Engineering; M.S., Business Administration.

**Dr. Jonathan Myers (Geochemistry and Performance Assessment)**

Dr. Myers is a Technical Associate at IT Corporation with over ten years of geologic and geochemical experience solving technical problems in the field of hazardous and nuclear waste management. He has been actively involved in the WIPP and Yucca Mountain nuclear waste disposal projects, as well as the Swedish and Canadian waste disposal programs. He has also been an active participant in the WIPP Performance Assessment program. Education: B.S. and M.S., Geology; Ph.D., Geochemistry.

**Dr. Arun Agrawal (Metallurgy/Corrosion)**

Dr. Agrawal is a Senior Research Scientist at Battelle Memorial Institute and has been active in the corrosion and electrochemical fields for more than 15 years. He has extensive experience conducting research in these fields for various nuclear and nonnuclear organizations including the Electric Power Research Institute, Gas Research Institute, Department of Energy, Nuclear Regulatory Commission, and the National Science Foundation. Education: B.Sc. and M.S., Chemical Engineering; Ph.D., Chemical Engineering.

**Mr. Barry King (Microbiology)**

Mr. King is a Technical Associate and environmental biologist at IT Corporation with more than 23 years of experience including projects related to biodegradation of mixed hazardous wastes; long-term effects of geologic disposal; and various aspects of biological treatment, bioremediation, and technology development. Education: B.S., Microbiology; M.S., Environmental Biology.

**Mr. Roger Hansen (Regulatory Compliance and Permitting)**

Mr. Hansen is an environmental attorney and project director at IT Corporation with 27 years of legal experience. He has a multidisciplinary background in environmental law, land use and environmental planning, and communications. He is currently responsible for environmental regulatory analysis, permitting, documentation preparation, and providing technical and legal support for permitting and operation of hazardous, radioactive, and mixed waste management facilities. He is a registered Colorado attorney and a member of the American Bar Association. Education: B.S., Journalism; J.D.

**Mr. Bill White (Repository Operations)**

Mr. White has over 14 years of experience involved with operation of nuclear submarine and land-based nuclear power plants. He has held positions as Waste Handling Operations Manager and Start-up Engineer at the WIPP, was a Chief Operator at the Fast Flux Test Facility, and was a leading Petty Officer and Staff Instructor for nuclear plant operations in the U.S. Navy. Education: University of Texas at El Paso, plus various Navy nuclear power and engineering schools.

**Mr. Rodney Palanca (Repository Operations)**

Mr. Palanca has 27 years of experience with operation of nuclear submarine and land based nuclear plants. He attained the rank of Lieutenant Commander in the U.S. Navy and has supervisory and technical experience in nuclear reactor operation and testing, nuclear instrumentation and controls, nuclear chemistry and radiological controls, training curriculum planning and scheduling. He is currently an operations engineer in the WIPP Operations Support Group. Education: B.S., Chemical Engineering, plus numerous Navy nuclear training programs.

**Dr. Joe Tillerson (Rock Mechanics)**

Dr. Tillerson is Supervisor of the WIPP Sealing and Rock Mechanics Programs at Sandia National Laboratory. He has 15 years of experience including underground design, rock mechanics analysis, sealing programs, site characterization, rock mechanics measurement, code development and modeling of salt creep, and geotechnical analysis of oil storage caverns in salt. Education: B.S. and M.S., Aero Engineering; Ph.D., Aero Engineering.

**Mr. Milo Larsen (Waste Treatment)**

Mr. Larsen is President and General Manager of Haz Answers, Inc. He has over 20 years of experience in the nuclear industry including reactor operations, waste engineering development, waste treatment process development, and waste reduction operations. Mr. Larsen has extensive knowledge of the status of nuclear waste treatment technologies. Education: B.S., Physics.

**ALTERNATE PANEL MEMBERS**

Alternate Panel members were occasionally required to substitute for the primary members due to schedular conflicts.

**Dr. Murthy Devarakonda (Geochemistry)**

Dr. Devarakonda is a project engineer at IT Corporation with six years of experience in solvent recovery, waste water treatment, interactions among waste components in WIPP and the fate of mixed hazardous waste in WIPP over prolonged periods of time. Education: Bachelor of Technology, Chemical Engineering; Ph.D., Environmental Engineering.

**Dr. Paul Drez (Geochemistry)**

Dr. Drez is a Senior Technical Associate at IT Corporation with 20 years of experience. He is currently the Technical Director for the Engineered Alternatives Task Force effort. He has a broad background as a research geochemist for geologic exploration programs, and has been a key participant for evaluating the characteristics of TRU wastes destined for disposal at WIPP. He has also been actively involved in the WIPP performance assessment process, Supplemental Environmental Impact Statement, No-Migration Variance Petition, R&D Test Plan, and licensing of the TRUPACT-II and RH transportation systems. Education: B.S., Chemistry; Ph.D., Geochemistry.

**Ms. Barbara Deshler (Performance Assessment)**

Ms. Deshler is a geologist at IT Corporation with four years of experience including co-authorship of the WIPP No-Migration Variance Petition. As a result of her key involvement in preparing the WIPP Plan for Performance Assessment and Operations Demonstration, she has become very familiar with the performance assessment process. Her experience also includes the acquisition and start-up of a gas chromatograph/mass spectrometer laboratory at the WIPP site, environmental monitoring instrumentation, and technical input to environmental regulatory permit applications. Education: B.S., Geology; M.S., Geology (In progress).

**Ms. Karen Knudtsen (Regulatory)**

Ms. Knudtsen is a Project Scientist at Benchmark Environmental, Inc. with ten years experience in solid and hazardous waste management and environmental assessment. Her experience includes evaluation of hazardous and radioactive mixed waste characteristics and mechanisms of contaminant transport in the environment, preparation of regulatory summaries, development of technical positions regarding RCRA and CERCLA regulatory compliance, and permitting assistance for hazardous waste facilities. Education: B.S., Soil Science; M.S., Soil Chemistry.

**Mr. Clinton Kelley (Repository Operations)**

Mr. Kelley is a Senior Engineer for Westinghouse on the WIPP project with 15 years of experience in the nuclear industry. His principal duties currently involve planning, implementation and supervision of waste handling operations at the WIPP facility. His experience includes reactor operations for advance reactor systems, operations training, supervision of waste handling technicians, and preparation of operations procedures. Education: Science and math courses at several universities as well as numerous in-house technical and management courses.

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## ATTACHMENT B

DESCRIPTION OF ENGINEERED ALTERNATIVES

Engineered alternatives being considered for reducing the consequences of potential WIPP waste release scenarios are described in this Attachment as they were presented to the Panel for consideration. Assumptions made by the Panel which supplement the description of some of the alternatives are also included.

WASTE FORM MODIFICATION ALTERNATIVES**COMPACT WASTE**

Stored and newly generated waste is loosely packed in steel drums and boxes. Compacting the waste to much lower porosity and permeability, using state-of-the-art compactors, can reduce the ability of brine to either permeate the waste or flow through the waste matrix, thereby carrying some of the waste to the accessible environment or beyond the unit boundary.

Panel Assumption: It was assumed that compaction applies to all waste form categories except sludges. The Panel recognized but did not take into account the possibility of increased gas generation due to compaction, as discussed in Kroth and Lammertz (1988). The Panel also recognized that compacting the waste reduces initial void volume allows repressurization of waste rooms to occur sooner.

**INCINERATE AND CEMENT**

Incineration of combustible waste and cementation of the ash into an ash/cement matrix reduces the void volume and permeability of the waste. This alternative destroys essentially all organics and therefore is expected to eliminate microbial gas generation.

Panel Assumptions: Cemented form can be maintained until salt creep effectively encapsulates the waste. The Process Experimental Pilot Plant (PREPP) technology (rotary kiln incinerator) was assumed. Although there were plans for implementation of the PREPP process at the time the EAMP convened, the reader should note that the project has since been discontinued and not expected to be operational. The Panel also recognized that incineration may have the advantage of meeting the treatment standard for some types of organics restricted from land disposal under 40 CFR Part 268.

**INCINERATE AND VITRIFY**

This alternative is similar to "Incinerate and Cement" except that the residue is fused into a glass rather than a cement matrix and is likely to have a lower permeability and remain stable for a longer period of time.

**WET OXIDATION**

Wet oxidation involves the accelerated oxidation of waste in the presence of heated water vapor or steam, with the intent to chemical degradation of the waste prior to emplacement in WIPP. This technique has not been demonstrated for application to solid wastes.

#### **SHRED AND BITUMINIZE**

This alternative involves filling the voids of shredded waste with a bituminous compound. This has the effect of reducing waste permeability but may enhance microbial and radiolytic gas generation. All waste forms except sludges can be bituminized.

#### **SHRED AND COMPACT**

Compaction alone is limited by the available compaction forces (i.e., state-of-the-art equipment) and the stress strain characteristics of the waste form. Some advantage may be gained by first shredding the waste thereby compacting the waste to a more impermeable form. All waste forms except sludges can be compacted.

#### **SHRED AND CEMENT**

This alternative involves shredding the waste prior to cementation and repackaging. The intent is to reduce the permeability of the waste form. This alternative does not apply to the sludges.

Panel Assumption: The Panel assumed that the Process Experimental Pilot Plant (PREPP) shredding technology will be used.

#### **SHRED AND POLYMER ENCAPSULATION**

This alternative is similar to the shred and cement alternative except that the shredded waste would be encapsulated in a polymer. The use of polymers may increase microbial and radiolytic gas generation potential. All waste forms except the sludges can be encapsulated.

#### **SHRED, ADD SALT, AND COMPACT**

The purpose of this alternative is to reduce the permeability and initial void volume of shredded and compacted waste by mixing crushed salt into the shredded waste before compacting. The intent is to fill the voids that normally remain after compaction with crushed salt. The alternative can be applied to glass, metals, and combustibles. Corrosion and gas generation may be accelerated unless this alternative effectively excludes brine.

#### **PLASMA PROCESSING**

This alternative uses a high temperature plasma furnace to essentially eliminate organics and melt metals and sludges into a solid form. The products of this process are a vitrified glass form and solid metal.

Panel Assumptions: This alternative is in the demonstration phase. Therefore regulatory challenges may be similar to those concerning incineration.

#### **MELT METALS**

Since compacting metal wastes to a low permeability even after shredding may be difficult, an alternative is to melt the metals into ingots of a weight that is transportable. Some metals may require size reduction depending on furnace size. By definition, this alternative does not apply to sludges or combustibles.

**Panel Assumptions:** Depending on the process, the slag resulting from melting may contain most of the transuranic elements, substantially reducing metal waste volume while the ingots may qualify as low level waste. The slag resulting from melting may need to be solidified in cement or another medium.

#### **ADD SALT BACKFILL**

Adding crushed or pulverized salt into the larger void spaces around the waste in each waste container has the advantage of reducing the permeability of the waste but may induce accelerated corrosion and gas evolution.

#### **ADD OTHER SORBENTS**

Evaluation of sorbents in addition to or other than bentonite may lead to improved waste characteristics of permeability and porosity. These sorbents are intended to sorb brine and radionuclides.

#### **ADD GAS SUPPRESSANTS**

Adding materials to the waste that could reduce gas generation rates, such as materials that raise the pH of brine that comes in contact with the waste, could prove beneficial in reducing gas pressure buildup in the waste disposal rooms.

#### **SHRED AND ADD BENTONITE**

This alternative considers the addition of bentonite, a swelling, absorptive and colloidal clay, to shredded waste to reduce waste permeability, absorb brine that might otherwise come in contact with the waste, and sorb radionuclides to reduce their mobility. This alternative does not apply to sludges.

**Panel Assumptions:** Bentonite will absorb both brine and residual liquids in the waste.

#### **ACID DIGESTION**

This alternative would dissolve the waste in a strongly acidic solution that is subsequently neutralized and precipitated, resulting in a reduced volume sludge waste form, which is then solidified. In particular, the ability of organics and metals to generate gases is eliminated, and since the residue can be solidified, waste permeability and mobility are reduced.

**Panel Assumptions:** Waste may have to be segregated and shredded, with different process lines for metals and organics. The process may not be able to digest all plastics and may increase the nitrate inventory of the waste. The residue from this alternative will have to be combined with a solidification process such as calcining, cementation or vitrification. This alternative applies only to combustibles.

#### **STERILIZE**

Prior to emplacement of the waste in WIPP, sterilize the contents of each waste package to eliminate or reduce microbial gas generation. To be sufficiently effective, this alternative would probably have to be used in conjunction with sterilization of the entire underground waste disposal area, which is not considered a credible alternative at this time.

#### **ADD COPPER SULFATE**

The addition of copper sulfate to the waste is expected to reduce the generation of gases resulting from anoxic corrosion of iron based metals. The copper sulfate reacts with iron, forming ferrous sulfate and preventing the production of free hydrogen gas.

#### **ADD GAS GETTERS**

Several gases will constitute the major volumes generated over time in the waste disposal area of WIPP. If generation of gases cannot be prevented, gas getters added to the waste may eliminate significant gas volumes and prove to be a solution to the potentially negative effect that large gas volumes may have on repository performance. Carbon dioxide may be removed by the addition of gas getters that will react with the gas to produce a solid phase.

Panel Assumptions: The getters assumed were either lime or hydrated lime added to waste to reduce the carbon dioxide gas inventory. These were the only getters considered and assumes that enough getter material can be added to the waste to be effective.

#### **ADD FILLERS**

Adding filler materials to the waste in order to reduce initial void volume will reduce the waste's permeability and can reduce brine inflow during room reconsolidation.

#### **SEGREGATE WASTE FORMS**

This alternative refers to isolating each major waste form (i.e., sludges, combustibles, etc.) from one another. By segregating the various waste forms that are now intermingled within waste packages, several engineered alternatives could be applied to smaller waste quantities, thereby possibly reducing costs and overall schedule.

Panel Assumptions: It was assumed that this alternative would require that new waste be segregated as it is generated while stored waste would have to be sorted.

#### **DECONTAMINATE METALS**

The disposal of metals in WIPP is expected to generate hydrogen from anoxic corrosion. These metals may also be difficult to compact to a sufficiently low permeability. An alternative solution may be to decontaminate the metals and dispose of them as low-level or nonradioactive wastes. The residue from this process would be handled in a manner similar to that resulting from the "Acid Digestion" alternative. This alternative is not applicable for sludges or combustibles.

Panel Assumptions: To be completely effective, this alternative would have to be combined with "Change Waste Container Material", since a large part of the metal inventory consists of steel drums and boxes. The residue resulting from the decontamination process will have to be solidified by vitrification, cementation, or other means.

#### **CHANGE WASTE GENERATING PROCESS**

Since two-thirds of the waste that will ultimately be emplaced in WIPP has not yet been generated, an opportunity exists to change the processes that generate the remaining waste to minimize waste porosity, permeability, and gas generation. Some progress

has already been made in reducing waste generation volumes, and compaction of waste at generator sites is an example of a process that reduces porosity and permeability.

#### **CHANGE WASTE CONTAINER SHAPE**

A major goal of the Engineered Alternatives program is to evaluate reduction of void volumes in waste packages and in the repository in general. A square cornered or hexagonal waste package configuration could essentially eliminate void volumes between emplaced waste packages in the disposal areas. Other configurations may also provide similar results, such as interlocking waste packages that fit together tightly when emplaced in WIPP. This alternative will only reduce the interstitial spaces between waste packages disposed of in WIPP. Stored waste needs to be repackaged. Space around the waste stack is not affected.

#### **CHANGE WASTE CONTAINER MATERIAL**

The corrosion of steel drums or boxes that are currently used to package waste may add considerably to the gas generated by anoxic corrosion after waste emplacement. The use of alternate materials may reduce the amount of gas generated from this process. For instance, copper or ceramic materials may be candidates that could reduce or eliminate metal corrosion induced gas generation.

Panel Assumptions: The Panel assumed that the polyethylene drum and box liners could be made sufficiently strong to act as waste containers.

#### **ADD ANTIBACTERIAL MATERIAL**

The addition of an antibacterial material to the waste could alleviate some gas production if such a material does not pose a greater challenge than the gas itself. The material must have an estimated effective lifetime sufficient to prevent those microbes already present in the repository from eventually overtaking its effectiveness.

#### **ACCELERATE THE WASTE DIGESTION PROCESS**

This alternative suggests that the gas generation process might be accelerated so that gas generation is minimized after decommissioning of the repository. This requires the addition of appropriate bacterial agents to hasten waste digestion, which would have to be essentially complete before decommissioning.

#### **ALTER CORROSION ENVIRONMENT IN WIPP**

The use of copper sulfate has already been identified as an engineered alternative that might modify the corrosion process to generate less gas. Other alternatives may alter the chemical environment of the waste storage rooms, such as assuring dryness or maintaining a pH buffer, so that corrosion is minimized.

Panel Assumptions: Copper sulfate was not considered for reasons given under that alternative's description. The addition of activated alumina, calcium oxide or cement was considered. These additives may increase the total number of waste packages required but result in a drier environment.

#### **ALTER BACTERIAL ENVIRONMENT IN WIPP**

This alternative is analogous to "Alter Corrosion Environment in WIPP." By changing the chemistry of the waste, microbial gas generation rates may be reduced to acceptable levels.

#### **TRANSMUTATION**

This alternative considers transmutation of long-lived radionuclides to short-lived nuclides, eliminating the need for long-term disposal.

#### **VITRIFY SLUDGES**

Sludges have a high moisture content compared to other waste forms. Vitrifying the sludges using microwave or Joule melters will reduce waste volume, remove excess moisture, and possibly remove nitrates.

### **BACKFILL ALTERNATIVES**

#### **SALT ONLY**

This is the basic backfill material being considered to reduce void volume around the waste and to hasten room closure. The material results from mining the disposal rooms and drifts and can be processed by crushing or pulverizing to enhance backfilling operations. Unless this salt is preformed into compact shape(s), it has significant initial porosity and permeability, but will rapidly reconsolidate as a result of creep closure.

Panel Assumptions: Backfilling the void spaces around the waste will probably reduce the amount of brine entering the waste rooms. However, the void volume and permeability of the waste itself remains substantial and moisture in the waste (e.g., sludges) is not effected by this alternative.

#### **SALT PLUS GAS GETTERS/ALKALI/pH BUFFERS**

The addition of gas getters with the salt backfill may be advantageous for preventing buildup of unacceptable gas volumes. A potential disadvantage of applying getters in this manner is that salt reconsolidation takes place fairly quickly. If reconsolidation prevents interaction of gases with the getters in the salt matrix, it could prove ineffective. An added advantage of certain gas getters (e.g., CaO) is they will act as pH buffers thereby minimizing corrosion and radionuclide solubility in brine.

#### **COMPACT BACKFILL**

Compacting backfill in place could reduce its permeability sufficiently to prevent significant brine mobility. Such a procedure would probably require more storage space than currently planned to permit equipment access between and around the waste packages.

#### **SALT PLUS BRINE SORBENTS**

The presence of brine in the waste rooms is considered the primary medium for waste mobility to the accessible environment for certain scenarios. The brine source may be from a hypothesized brine reservoir or from migration of Salado brine from the surrounding salt into the waste disposal rooms. The expected volume of brine from the surrounding salt appears to be lower than previously anticipated. Therefore, sorbents such as bentonite added to the backfill may effectively preclude free brine in the

repository from this source. Sorbents may also be effective for reducing the mobility of radionuclides.

Panel Assumptions: The sorbents considered were bentonite, diatomaceous earth, and vermiculite. Approximately 30 percent sorbent in the backfill was considered enough to be effective. The effectiveness of backfill plus sorbents might be enhanced if installed below the waste as well.

#### **PREFORMED COMPACTED BACKFILL**

Preforming backfill into dense compacted modules, such as bricks or blocks, or shapes that can be inserted between waste packages, may reduce the overall permeability of the waste disposal rooms, thereby reducing the potential for brine contact with the waste. Compacted backfill reduces the time required for room closure and the amount of brine that can migrate into the room from the surrounding salt.

Panel Assumptions: Only salt was considered as a compacted backfill, and the precompact material was assumed to be nearly formfitting around waste packages.

#### **GROUT BACKFILL**

The use of a grout as backfill instead of salt has the operational advantage of handling a semi-liquid material that can flow relatively easily. However, the emplacement of grout between waste containers may still be a challenge. The relative impermeability of grout is an advantage, whereas its poor stability characteristics in a salt/brine environment are potentially disadvantageous unless room closure acts to mechanically stabilize the entire waste/grout monolith.

Panel Assumptions: Grout was assumed between waste packages, with concrete around the waste stack.

#### **BITUMEN BACKFILL**

Bitumen has been considered as a backfill medium, but the operational challenges of handling large quantities of hot bitumen underground, and the potential for this backfill acting as an additional source for microbial gas generation, probably precludes the material from consideration.

#### **ADD GAS SUPPRESSANTS**

This alternative is analogous to that described for the waste form (same name) but the suppressing material would be mixed with the backfill.

### **WASTE MANAGEMENT ALTERNATIVES**

#### **MINIMIZE SPACE AROUND WASTE STACK**

The waste disposal room dimensions were chosen so that retrieval after a five-year demonstration period would not be precluded by premature room closure. Therefore, space is available between the waste stack and the walls and ceiling which also acts as a ventilation flow path. Reduction or elimination of this space would result in the need for less backfill, quicker room closure, and less Salado brine migration into the room.

Panel Assumptions: Rooms will have to be mined to minimize space around the waste stack, consistent with remote-handled waste emplacement requirements. It was assumed that no backfill is required for this alternative.

#### **SEGREGATE WASTE IN WIPP**

The segregation of different waste forms in or among waste disposal rooms could prove beneficial. For instance, the segregation of permeable metal wastes in small amounts within more easily compacted or previously compacted waste could "encapsulate" the metals with other waste that is less permeable. The segregation of high gas-generation waste from more benign waste would focus the solution on a smaller area of WIPP. There may also be an advantage in segregating sludges that contain nitrates, from combustible wastes to prevent nitrate reducing bacteria from generating nitrogen gas.

Panel Assumptions: Administrative control of waste shipments is required. Segregation is by waste disposal panel. WIPP ventilation system redesign may be needed.

#### **DECREASE AMOUNT OF WASTE PER ROOM**

By leaving the room size the same as currently designed, but emplacing less waste volume per room, sufficient space may be gained around the waste stack to isolate the stack from the surrounding host salt. This would be accomplished by creating a waste stack that is as compact as practicable, surrounded by relatively "plastic" backfill containing sorbents and gas getters that would act as a secondary encapsulation medium. The host salt would, of course, remain the primary barrier.

#### **EMPLACE WASTE AND BACKFILL SIMULTANEOUSLY**

The intent of this alternative is to emplace backfill more efficiently so that its effect is maximized. This alternative would be used in conjunction with compacting in place or using precompactd (and preformed if necessary) backfill.

#### **SELECTIVE VEGETATIVE UPTAKE**

Using the vegetative uptake of certain plants to concentrate radionuclides has been proposed. Some work has been done demonstrating the vegetative concentration of heavy metals.

### **FACILITY DESIGN ALTERNATIVES**

#### **BRINE-ISOLATING DIKES**

Brine dikes can consist of partial or full-height walls of material that separate waste quantities to reduce the amount of waste accessed by inflowing brine or a driller's circulating mud.

#### **RAISE WASTE ABOVE FLOOR**

If it can be postulated that Salado brine will collect on the waste disposal room floor, then isolating the waste from the floor may be beneficial. If it can be further postulated that humidity generated by brine can be isolated from the waste, then this alternative may reduce the amount of corrosion-induced gas generation.

**Panel Assumptions:** The Panel assumed that crushed salt, bentonite or other absorbent material would be placed between the waste disposal room floor and the waste. On that basis, the Panel considered this alternative part of the "Add Floor of Brine Sorbent Material" alternative as defined by the Panel's assumptions for that alternative.

#### **BRINE SUMPS AND DRAINS**

By properly sloping the floor of waste disposal rooms toward collection sumps, it may be possible to isolate inflowing brine from the waste. Isolating the brine during room closure and designing the sumps so that they become "encapsulated" after closure, may result in reduced corrosion-induced gas generation.

#### **GAS EXPANSION VOLUMES**

This alternative refers to the mining of recesses within the repository to allow free expansion of the gases generated and thus reduce gas pressure.

**Panel Assumptions:** It was assumed that brine would not fill the void volumes. This alternative was considered only if gas generation is a marginal problem, requiring only small expansion volumes to prevent overpressurization.

#### **SEAL DISPOSAL ROOM WALLS**

This alternative refers to a flexible, impermeable seal applied to the walls of each room such that closure does not break the seal. The intent is to prevent contact between the waste stack and interstitial brine.

#### **VENT FACILITY**

If gas generation results in the potential for overpressurizing waste disposal rooms, providing a small engineered vent could alleviate this condition.

#### **VENTILATE THE FACILITY**

Continuous ventilation of the waste disposal rooms until complete closure has taken place would eliminate concern about brine from the surrounding Salado Formation collecting in the repository.

**Panel Assumptions:** Permanent panel seals and backfill would not be installed during the institutional control period.

#### **ADD FLOOR OF BRINE SORBENT MATERIAL**

The intent of this alternative is to prevent free brine from contacting the waste stack, thereby reducing the potential for corrosion induced gas generation.

**Panel Assumptions:** See "Raise Waste Above Floor."

#### **CHANGE MINED EXTRACTION RATIO**

By changing the mined extraction ratio (i.e., leaving less supporting salt around the mined waste disposal rooms), room closure can be affected more quickly, reducing brine inflow from surrounding Salado salt.

**Panel Assumptions:** An increase in the creep rate will result in faster closure, but the possibility of a larger disturbed zone may add to the brine inflow rate.

### **CHANGE ROOM CONFIGURATION**

This alternative involves several possibilities. Stacking the waste tightly against the walls would eliminate initial void volume and enhance closure time. Another option involves increasing room size, which would also increase the extraction ratio, making room for a buffer of sorbents and getters completely surrounding the waste stack. A third option involves increasing room height and stacking the waste higher to reduce the overall footprint of the repository.

Panel Assumptions: Since several of the stated options were considered under other alternatives, this alternative was considered only from the standpoint of stacking the waste higher than currently designed and reducing the overall footprint of the repository. Although the probability of a human intrusion event penetrating the waste stack is reduced, the consequences may be higher than for the current design.

### **SEAL INDIVIDUAL ROOMS**

If human intrusion were to take place, sealing off each room instead of sealing the panels may preclude brine from "sweeping" past enough waste to cause out-of-compliance releases of radionuclides. The effectiveness of this alternative depends on the mobility of the waste form, such as solubility of radionuclides in brine.

Panel Assumptions: The Panel considered this alternative for mitigating the effects of the single and two borehole scenarios only. The Panel assumed that there is a low probability of two boreholes penetrating the same waste storage room. Although waste permeability is unchanged, the individual room seals would decrease the overall effective "permeability" of the underground disposal area.

### **TWO-LEVEL REPOSITORY**

A two-level repository refers to decreasing the facility's surface footprint by placing half the waste disposal area above the other, creating a two-level facility. Although reduction of the facility footprint will reduce the probability of human intrusion into the underground disposal area, the consequences could double if the intrusion event penetrates both levels of the repository.

### **PASSIVE MARKER ALTERNATIVES**

#### **MONUMENT "FOREST" OVER REPOSITORY**

The use of closely spaced surface markers, consisting of long-lasting materials, can be used to alert potential intruders about the existence of the repository. These monuments could be mass produced and include pictorial and other designations describing the location and content of the disposal area. Each marker would be deeply anchored in bedrock.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

#### **MONUMENT COVERING THE ENTIRE REPOSITORY**

The waste disposal area of WIPP consists of approximately 100 acres. A monument 2,100 feet on a side, consisting of natural and/or man-made materials, could provide

adequate warning to potential intruders as well as adding to the difficulty of drilling into the repository. The alternative could consist of a single "pyramid" or multiple contiguous monuments.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

#### **BURIED STEEL PLATE OVER REPOSITORY**

The action of a drill bit makes it difficult to penetrate non-friable materials. Burying a relatively thick steel or other metal plate at some distance below the surface over the repository could alert an intruder that this is an unusual site. The plate would probably have to be sandwiched between corrosion inhibitors to assure longevity. Additionally, site exploration and evaluation prior to drilling would alert geologists that further exploration is needed.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

#### **ARTIFICIAL SURFACE LAYER OVER REPOSITORY**

Replacing the natural surface materials over the repository with a layer of artificial or sterile material to a reasonable depth is another way of alerting potential intruders to explore further before taking any action.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

#### **ADD MARKER DYE TO WASTE OR STRATA ABOVE REPOSITORY**

The use of a marker dye that is sufficiently strong to discolor the drillers mud pond may alert the intruder that some further evaluation is necessary.

Panel Assumptions: It was assumed that this alternative is applicable only for the reduction of human intrusion probability.

#### **MISCELLANEOUS ALTERNATIVES**

##### **DRAIN CASTILE RESERVOIR (Brine Pocket)**

This alternative refers to the draining of the Castile brine reservoir, and thus reducing the effect of human intrusion through the repository.

##### **GROUT CULEBRA FORMATION ABOVE REPOSITORY**

The Culebra is a potential conduit for releasing radionuclides to the accessible environment. Grouting the Culebra above the repository may reduce this pathway.

##### **INCREASE LAND WITHDRAWAL AREA TO THE REGULATORY BOUNDARY**

Currently planned land withdrawal boundaries do not extend to the regulatory boundaries of 40 CFR Part 191. Extending the land withdrawal boundaries to coincide with the permitted regulatory boundaries would provide longer nuclide transit times before reaching the boundaries used to calculate repository performance.

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## ATTACHMENT C

### PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

The results of the preliminary evaluation process are depicted in Attachment C. The alternatives shown comprise the total list of the 64 potential engineered alternatives considered by the EAMP. After eliminating the alternatives that did not satisfy the "must" criteria, the EAMP assigned each remaining alternative a preliminary score based on its effectiveness for mitigating each of the ten original performance parameters, and its feasibility of implementation. The scores were based on a scale of zero to ten, with ten being the highest score and zero denoting an "adverse effect." Some alternatives were judged to have "no effect" on a performance parameter, in which case no score was assigned (represented by a "-" in the scoring column).

The EAMP assumed all of the ten performance parameters to be mutually exclusive of one another, because it is not yet evident which parameter(s) will control the demonstration of compliance with EPA Standard 40 CFR Part 191. However, the feasibility of an alternative was assumed to remain the same irrespective of the performance parameter being considered for evaluation of effectiveness.

The overall scores for an alternative for mitigating the effects of a performance parameter were calculated by combining its effectiveness and feasibility scores using a weighted summation approach. This approach is described in Section 2.2.3.

The following equation represents this scoring process:

$$\begin{aligned} \text{Total score} &= 5.1 \times (\text{Effectiveness score}) \\ &+ 2.4 \times (\text{Regulatory score}) \\ &+ 1.5 \times (\text{Technology score}) \\ &+ 1.0 \times (\text{Schedule score}) \end{aligned}$$

There were two exceptions to the above equation. If an alternative was assigned an effectiveness score of zero for "adverse effect," then its total score would also be equal to zero. On the other hand, if an alternative was assigned a "-" for "no effect," then its total score was represented as follows:

$$\begin{aligned} \text{Total score} &= 2.4 \times (\text{Regulatory score}) \\ &+ 1.5 \times (\text{Technology score}) \\ &+ 1.0 \times (\text{Schedule score}). \end{aligned}$$

ATTACHMENT C

PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS SCORE										FEASIBILITY SCORE			TOTAL SCORE OF AN ALTERNATIVE												
	RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	INTRU	(2.4) REG	(1.5) TECH	(1.0) SCH	WEIGHTED FEASIBILITY SCORE WT. = 4.9	RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	INTRU		
<b>WASTE FORM MODIFICATION ALTERNATIVES</b>																										
COMPACT WASTE	-	2.0	2.0	4.0	4.0	8.0	6.0	1.0	5.0	-	9.0	10.0	7.0	43.6	43.6	53.8	53.8	64.0	64.0	84.4	74.2	48.7	69.1	43.6		
INCINERATE & CEMENT	5.0	8.0	3.0	1.0	1.0	3.0	5.0	3.0	2.0	-	2.0	7.0	2.0	17.3	42.8	58.1	32.6	22.4	22.4	32.6	42.8	32.6	27.5	17.3		
INCINERATE & VITRIFY	6.0	8.0	3.0	2.0	2.0	4.0	6.0	2.0	2.0	-	2.0	7.0	2.0	17.3	47.9	58.1	32.6	27.5	27.5	37.7	47.9	27.5	27.5	17.3		
WET OXIDATION	DELETED-TECHNOLOGY NOT DEMONSTRATED																									
SHRED & BITUMINIZE	-	0.0	2.0	5.0	5.0	3.0	6.0	-	5.0	-	3.0	10.0	5.0	27.2	27.2	0.0	37.4	52.7	52.7	42.5	57.8	27.2	52.7	27.2		
SHRED & COMPACT	-	2.0	2.0	5.0	5.0	8.0	4.0	1.0	6.0	-	9.0	10.0	7.0	43.6	43.6	53.8	53.8	69.1	69.1	84.4	64.0	48.7	74.2	43.6		
SHRED & CEMENT	2.0	4.0	3.0	4.0	4.0	5.0	5.0	3.0	4.0	-	9.0	10.0	9.0	45.6	55.8	66.0	60.9	66.0	66.0	71.1	71.1	60.9	66.0	45.6		
SHRED & POLYMER ENCAP	0.0	2.0	3.0	5.0	5.0	5.0	5.0	3.0	5.0	-	9.0	5.0	6.0	35.1	0.0	45.3	50.4	60.6	60.6	60.6	60.6	50.4	60.6	35.1		
SHRED, ADD SALT, COMPACT	-	2.0	-	7.0	7.0	8.0	5.0	1.0	7.0	-	9.0	10.0	7.0	43.6	43.6	53.8	43.6	79.3	79.3	84.4	69.1	48.7	79.3	43.6		
PLASMA PROCESSING	10.0	10.0	8.0	10.0	10.0	10.0	10.0	9.0	10.0	-	3.0	4.0	1.0	14.2	65.2	65.2	55.0	65.2	65.2	65.2	65.2	60.1	65.2	14.2		
MELT METALS	1.0	1.0	4.0	3.0	3.0	3.0	3.0	2.0	1.0	-	3.0	7.0	3.0	20.7	25.8	25.8	41.1	36.0	36.0	36.0	36.0	30.9	25.8	20.7		
ADD SALT BACKFILL	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																									
ADD OTHER SORBENTS	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																									
ADD GAS SUPPRESSANTS	CONSIDERED UNDER 'ADD GAS GETTERS'																									
SHRED & ADD BENTONITE	2.0	1.0	1.0	3.0	3.0	-	0.0	-	3.0	-	9.0	10.0	9.0	45.6	55.8	50.7	50.7	60.9	60.9	45.6	0.0	45.6	60.9	45.6		
ACID DIGESTION	5.0	6.0	2.0	4.0	4.0	5.0	6.0	3.0	5.0	-	3.0	4.0	2.0	15.2	40.7	45.8	25.4	35.6	35.6	40.7	45.8	30.5	40.7	15.2		
STERILIZE	DELETED-TECHNOLOGY NOT DEMONSTRATED																									
ADD COPPER SULFATE	POTENTIAL FOR H2 GENERATION IF DEPOSITED COPPER FORMS GALVANIC COUPLE																									
ADD GAS GETTERS	1.0	2.0	3.0	1.0	-	-	-	3.0	1.0	-	5.0	9.0	5.0	30.5	35.6	40.7	45.8	35.6	30.5	30.5	30.5	45.8	35.6	30.5		
ADD FILLERS	CONSIDERED UNDER OTHER TYPE OF ALTERNATIVES																									
SEGREGATE WASTE FORMS	ALTERNATIVE IS NOT A STAND ALONE PROCESS																									
DECONTAMINANT METALS	1.0	2.0	1.0	1.0	1.0	-	4.0	1.0	1.0	-	7.0	9.0	7.0	37.3	42.4	47.5	42.4	42.4	42.4	37.3	57.7	42.4	42.4	37.3		
CHANGE WASTE GEN. PROC.	TOO BROAD TO EVALUATE																									
ADD ANTI-BACTERIAL MATRIX	DELETED-TECHNOLOGY NOT DEMONSTRATED																									
ACCEL WASTE DIGESTION	DELETED-INEFFECTIVE ALTERNATIVE																									
ALTER CORROSION ENV. WIPP	5.0	7.0	8.0	2.0	2.0	-	-	-	8.0	-	6.0	7.0	6.0	30.9	56.4	66.6	71.7	41.1	41.1	30.9	30.9	30.9	71.7	30.9		
ALTER BACTERIAL ENV. WIPP	CONSIDERED IN EVALUATION OF OTHER ALTERNATIVES																									
TRANSMUTATION	TECHNOLOGY NOT DEMONSTRATED FOR SUCH LARGE AMOUNTS OF WASTE																									
VITRIFY SLUDGES	3.0	3.0	2.0	2.0	2.0	3.0	3.0	2.0	2.0	-	4.0	7.0	6.0	26.1	41.4	41.4	36.3	36.3	36.3	41.4	41.4	36.3	36.3	26.1		
<b>BACKFILL ALTERNATIVES</b>																										
SALT ONLY	-	1.0	-	1.0	1.0	-	-	-	1.0	-	8.0	7.0	9.0	38.7	38.7	43.8	38.7	43.8	43.8	38.7	38.7	38.7	43.8	38.7		
SALT + GAS GETTER	-	2.0	-	1.0	1.0	-	-	5.0	4.0	-	8.0	7.0	9.0	38.7	38.7	48.9	38.7	43.8	43.8	38.7	38.7	64.2	59.1	38.7		
COMPACT BACKFILL	-	1.0	-	1.0	1.0	-	-	-	2.0	-	4.0	3.0	6.0	20.1	20.1	25.2	20.1	25.2	25.2	20.1	20.1	20.1	30.3	20.1		
SALT + SORBENTS	3.0	3.0	4.0	1.0	1.0	-	-	2.0	6.0	-	8.0	7.0	7.0	36.7	52.0	52.0	57.1	41.8	41.8	36.7	36.7	46.9	67.3	36.7		
PREFORMED COMPACTED BACKFILL	1.0	2.0	1.0	1.0	1.0	-	-	-	2.0	-	6.0	5.0	7.0	28.9	34.0	39.1	34.0	34.0	34.0	28.9	28.9	28.9	39.1	28.9		
GROUT BACKFILL	1.0	2.0	3.0	1.0	1.0	-	-	3.0	2.0	-	8.0	8.0	9.0	40.2	45.3	50.4	55.5	45.3	45.3	40.2	40.2	55.5	50.4	40.2		
BITUMEN BACKFILL	1.0	0.0	5.0	1.0	1.0	-	-	-	4.0	1.0	3.0	5.0	5.0	19.7	24.8	0.0	45.2	24.8	24.8	19.7	19.7	19.7	40.1	24.8		
GAS SUPPRESSANTS	CONSIDERED UNDER GAS GETTERS IN BACKFILL																									

ATTACHMENT C  
(cont'd.)  
PRELIMINARY EVALUATION OF ENGINEERED ALTERNATIVES

ALTERNATIVE	EFFECTIVENESS SCORE										FEASIBILITY SCORE			WEIGHTED FEASIBILITY SCORE WT. = 4.9	TOTAL SCORE OF AN ALTERNATIVE										
	RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU	(2.4) REG	(1.5) TECH	(1.0) SCH		RAD GAS	BIO GAS	CORR GAS	PERM	POR	STREN	LEACH	SOLUB	BRINE	HUMAN INTRU	
	CONSIDERED UNDER 'SEAL INDIVIDUAL ROOMS NEEDS TO BE COMBINED WITH ADD SORBENTS TO BACKFILL DELETED-BRINE CAN'T FLOW DUE TO SALT RECONSOLIDATION										7.0	10.0	7.0		38.8	89.8	89.8	89.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8
<b>FACILITY DESIGN ALTERNATIVES</b>																									
BRINE ISOLATING DIKES	CONSIDERED UNDER 'SEAL INDIVIDUAL ROOMS																								
RAISE WASTE ABOVE FLOOR	NEEDS TO BE COMBINED WITH ADD SORBENTS TO BACKFILL																								
BRINE SUMPS AND DRAINS	DELETED-BRINE CAN'T FLOW DUE TO SALT RECONSOLIDATION																								
GAS EXPANSION VOLUME	10.0	10.0	10.0	-	-	-	-	-	-	-	7.0	10.0	7.0	38.8	89.8	89.8	89.8	38.8	38.8	38.8	38.8	38.8	38.8		
SEAL DISPOSAL ROOM WALLS	TECHNOLOGY HAS NOT BEEN LABORATORY DEMONSTRATED																								
VENT FACILITY	NOT REGULATORY FEASIBLE																								
VENTILATE FACILITY	4.0	5.0	4.0	-	-	-	-	-	-	9.0	4.0	4.0	4.0	19.6	40.0	45.1	40.0	19.6	19.6	19.6	19.6	19.6	65.5	19.6	
ADD FLOOR OF BRINE SORBENT	CONSIDERED UNDER BACKFILL + SORBENTS																								
CHANGE EXTRACTION RATIO	1.0	2.0	1.0	1.0	1.0	-	-	-	-	2.0	8.0	7.0	9.0	38.7	43.8	48.9	43.8	43.8	43.8	38.7	38.7	38.7	48.9	38.7	
CHANGE ROOM CONFIGURATION	-	-	-	-	-	-	-	-	-	3.0	7.0	10.0	7.0	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	38.8	54.1	
SEAL INDIVIDUAL ROOMS	-	-	-	8.0	-	-	-	-	-	-	9.0	8.0	9.0	42.6	42.6	42.6	42.6	83.4	42.6	42.6	42.6	42.6	42.6	42.6	
TWO LEVEL REPOSITORY	-	-	-	-	-	-	-	-	-	5.0	1.0	8.0	1.0	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	15.4	40.9	
<b>WASTE MANAGEMENT ALTERNATIVES</b>																									
MIN SPACE AROUND WASTE STACK	1.0	2.0	1.0	1.0	1.0	-	-	-	-	2.0	10.0	10.0	10.0	49.0	54.1	59.2	54.1	54.1	54.1	49.0	49.0	49.0	59.2	49.0	
SEGREGATE WASTE IN WIPP	-	5.0	0.0	-	-	-	-	-	-	-	8.0	10.0	8.0	42.2	42.2	67.7	0.0	42.2	42.2	42.2	42.2	42.2	42.2	42.2	
DECREASE AMT OF WASTE/ROOM	CONSIDERED UNDER ADD SORBENTS/GAS GETTERS TO BACKFILL																								
EMPLACE WASTE/BACKFILL SIMUL	CONSIDERED UNDER PREFORMED COMPACTED BACKFILL																								
SELECTIVE VEGETATIVE UPTAKE	NOT LAB DEMONSTRATED FOR TRU WASTE																								
<b>WASTE CONTAINER ALTERNATIVES</b>																									
CHANGE WASTE CONT. SHAPE	1.0	1.0	1.0	1.0	1.0	-	-	-	-	1.0	9.0	10.0	9.0	45.6	50.7	50.7	50.7	50.7	50.7	45.6	45.6	45.6	50.7	45.6	
CHANGE WASTE CONT. MATERIAL	-	-	2.0	-	-	-	-	-	-	-	8.0	8.0	9.0	40.2	40.2	40.2	50.4	40.2	40.2	40.2	40.2	40.2	40.2	40.2	
<b>PASSIVE MARKER ALTERNATIVES</b>																									
MONUMENT "FOREST"	-	-	-	-	-	-	-	-	-	6.0	9.0	10.0	10.0	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	46.6	77.2	
MONUMENT COVERING REPOSITORY	-	-	-	-	-	-	-	-	-	10.0	8.0	10.0	10.0	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	44.2	95.2	
BURIED STEEL PLATE OVER REP.	-	-	-	-	-	-	-	-	-	5.0	7.0	10.0	10.0	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	41.8	67.3	
ARTIFICIAL SURFACE LAYER	DELETED-UNABLE TO IDENTIFY A FEASIBLE CONCEPT																								
ADD MARKER DYE TO STRATA	-	-	-	-	-	-	-	-	-	1.0	4.0	1.0	10.0	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	26.2	
<b>MISCELLANEOUS ALTERNATIVES</b>																									
DRAIN CASTLE RESEVOIR	DELETED-NOT CONSIDERED FEASIBLE																								
GROUT CULEBRA	DELETED-NOT CONSIDERED FEASIBLE																								
INCR. LAND WITHDRAWAL AREA	NOT AN ENGINEERED ALTERNATIVE																								

TOTAL SCORE CALCULATIONS:

EFFECTIVENESS WEIGHTED SCORE = EFFECTIVENESS SCORE X (5.1)  
 FEASIBILITY WEIGHTED SCORE = REGULATORY SCORE X 2.4 + TECHNOLOGY SCORE X 1.5 + SCHEDULE SCORE X 1.0  
 TOTAL SCORE OF AN ALTERNATIVE = EFFECTIVENESS WEIGHTED SCORE + FEASIBILITY WEIGHTED SCORE

ABBREVIATIONS

RAD GAS = Radiolytic Gas Generation  
 BIO GAS = Biological Gas Generation  
 CORR GAS = Corrosion Gas Generation  
 PERM = Permeability of the Waste Stack  
 POR = Porosity of the Waste  
 STREN = Shear Strength of the Waste  
 LEACH = Leachability of the Waste  
 SOLUB = Radionuclide Solubility in Brine  
 BRINE = Brine Inflow  
 HUMAN INTRU = Human Intrusion  
 REG = Regulatory Score  
 TECH = Technology Score  
 SCH = Schedule Score

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**APPENDIX B**

**DEVELOPMENT OF THE ROOM-SCALE COMPONENT OF  
THE DESIGN ANALYSIS MODEL**

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## 1.0 DESIGN ANALYSIS MODEL PROGRAM LOGIC

### 1.1 PROGRAM LOGIC FOR GAS GENERATION

The ROOM-SCALE component of the Design Analysis Model is outlined in the flow diagram in Figures B-1 to B-3. The other component, the SHAFT-SEAL program is outlined in Appendix C. The Design Analysis Model instructions are written in a modular format such that the main program (ROOM-SCALE) is a driver routine which coordinates the functions performed by subroutines (Appendix B) used in modeling the processes considered (Section 2.0 in Volume I). Permeabilities of the shaft and panel seals are obtained by using the SHAFT-SEAL program (Appendix C) prior to use of the ROOM-SCALE program. This analysis provides data necessary in generating equations describing shaft-seal conductance over time. Calculations performed in the Design Analysis Model are dependent on data obtained from input files. Parameters which vary from one run to the next, such as brine inflow rate, creep closure rate, and waste form and backfill properties, are entered into the input file. The initial procedure of the program is to read this data file by calling a subroutine entitled READAT (Circle 1 in Figure B-1). After acquiring the variables from the data file, the program calls the next subroutine entitled INITIALIZE (Circle 2 in Figure B-1). The purpose of this subroutine is to perform the remaining calculations necessary to initialize the variables required by the model. These calculations provide information (which is evaluated using data from the input file) such as the initial void volume in a panel and the initial moles of each gas present in the panel. Following initialization, the actual simulation process begins. Time is set to start at zero and the entire set of calculations is performed and repeated as the time variable is incremented (for instance, by one year) until the termination conditions are satisfied.

After the initial void volume and ambient pressure in the panel are defined, the subroutine BRINFLOW (Circle 3 in Figure B-1) calculates the cumulative inflow of brine during the current time increment and determines the moles of  $H_2O$  contained in the brine. BRINFLOW (Circle 4 in Figure B-1) calculates the cumulative inflow of brine during the current time increment and determines the moles of  $H_2O$  available in the panel. COMPACTION (Circle 4 in Figure B-1) then computes the compaction stress due to the mechanical resistance to closure provided by the waste/backfill composite. The density of the solids within the panel is calculated based upon the current panel volume and the initial mass of the waste/backfill composite. The subroutine CREEP (Circle 5 in Figure B-1) calculates the extent of salt creep during the time increment and the height and width of a room-equivalent at the end of the time increment.

The program then calls the subroutine MASSGAS (Circle 6 in Figure B-1) to estimate the molar rates of gas generation due to the combination of radiolysis and microbial activity, and due to anoxic corrosion. MASSGAS also accounts for gas consumption and transport due to various mechanisms.

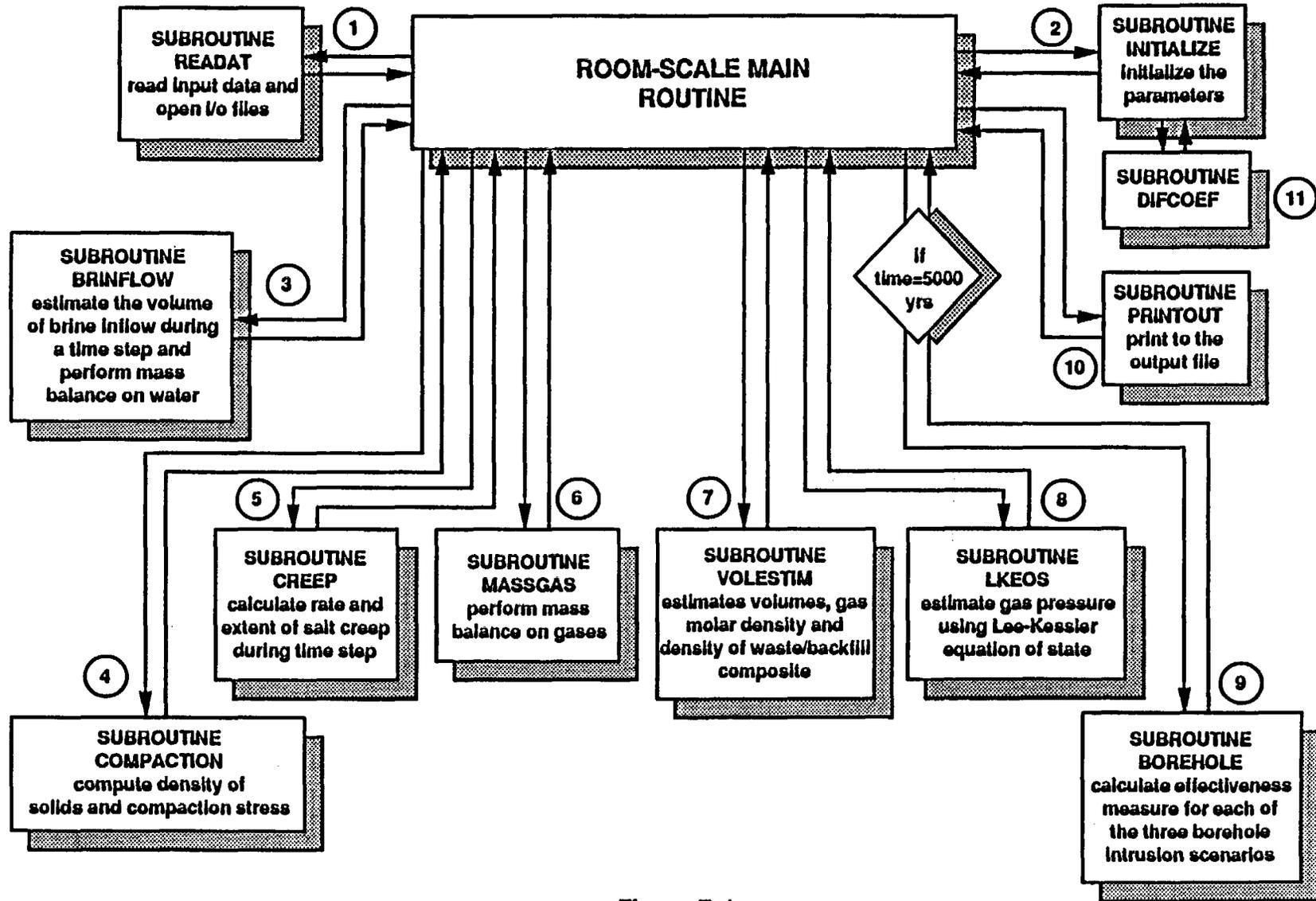


Figure B-1  
ROOM-SCALE Flow Diagram

During the mass balance calculations, MASSGAS uses a number of subroutines in the following order:

- **GASOLUB** (Circle 11 in Figure B-2) estimates the solubilities and Henry's Law Constants (in brine) of the various gases present in the panel.
- **ADVECTION** (Circle 1 in Figure B-2) estimates the rate of advection of gases into Marker Bed 139 and across the repository seals (Section 2.0 in Volume I). **ADVECTION** uses the following subroutines in evaluating the total molar advection rate at each point in time:
  - **VISCORR** (Circle 7 in Figure B-2) estimates the gas mixture viscosity using a correlation that is applicable to both low and high pressure conditions.
  - **MBFLOW** (Circle 8 in Figure B-2) estimates the void volume available for gas storage in the disturbed anhydrite beds at each point in time as brine is driven from the disturbed to the intact portions of the anhydrites.
  - **SHFTCOND** (Circle 9 in Figure B-2) evaluates the total conductance of the four shaft seals as a function of time.
- **DIFFUSION** (Circle 2 in Figure B-2) calls **DIFCOEF** (Circle 10 in Figure B-2) to determine the applicable diffusion coefficients and then calculates the molar rates of diffusion of gases out of the panel into the brine saturated host rock formation.
- **VAPLIQEQ** (Circle 4 in Figure B-2) evaluates the number of moles of each gas that will dissolve into the volume of brine available in the panel (Section 2.0). Subroutine **GASOLUB** is called to evaluate the Henry's Law Constants of the gases in brine.
- **BRINTERACT** (Circle 5 in Figure B-2) determines the amount of  $\text{CO}_2$  that can react with portlandite at the current panel pressure, the moles of portlandite consumed, and the water generated by the reaction. The moles of each gas in the panel are then updated in the **MASSGAS** to reflect the  $\text{CO}_2$  consumption.

The changes occurring in the **MASSGAS** subroutine are reflected in the number of moles of gases and liquids present in the panel.

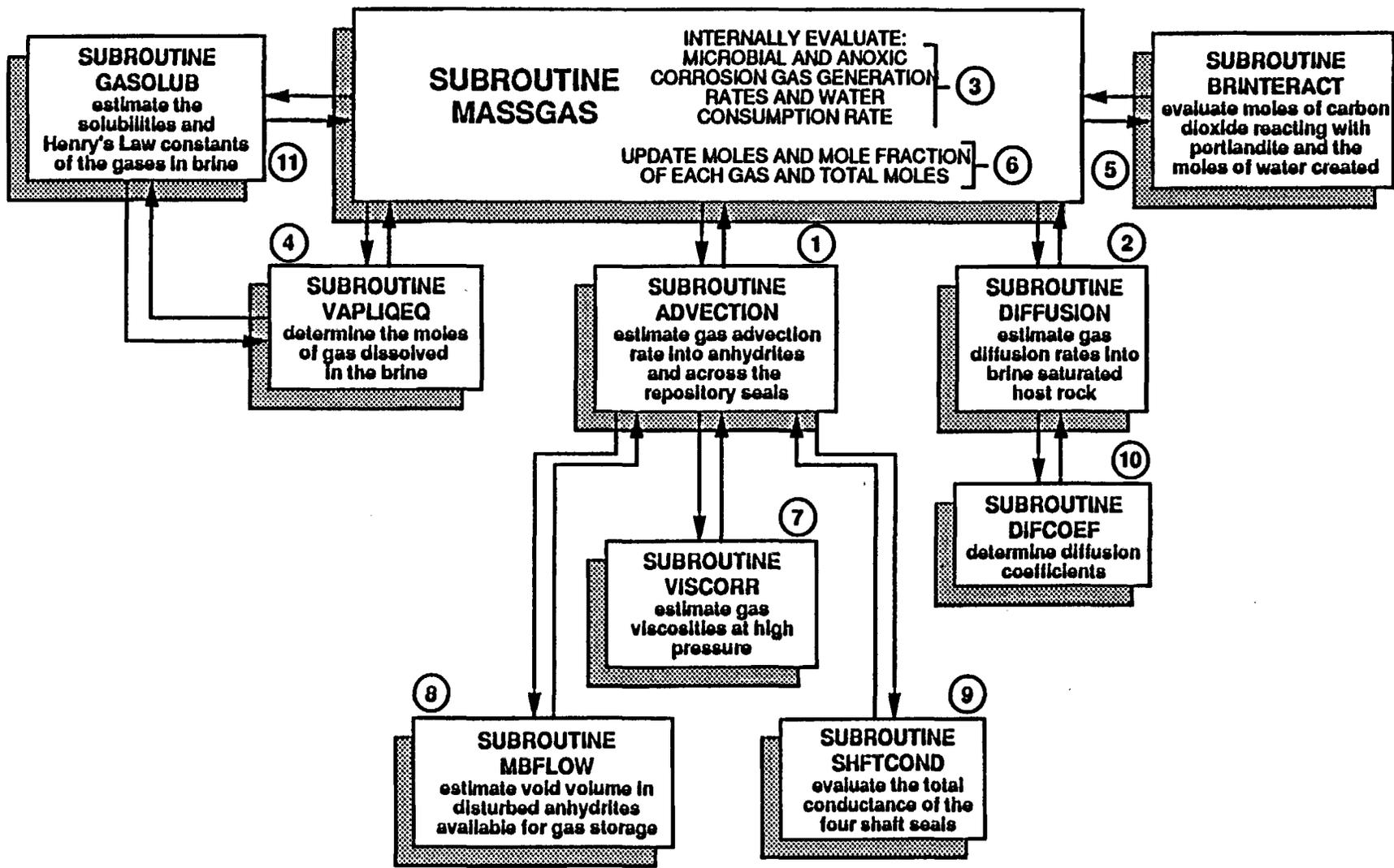


Figure B-2  
MASSGAS Flow Diagram

VOLESTIM (Circle 7 in Figure B-1) calculates the volume of the panel, and the volume of the air gap above waste/backfill composite (if no contact with the waste stack and the ceiling of the panel has occurred). These volumes are then used to calculate the void volume of the entire panel. In addition, the molar volume, molar density, and the density of the waste/backfill composite are evaluated. Prior to incrementing the time step, the subroutine LKEOS (Circle 8 in Figure B-1) evaluates the panel fluid pressure. This subroutine uses the Lee-Kessler Equation of State (Reid et al., 1987) taking into account the compressibility of the gases.

Consideration of the complex interactions that occur between the above processes enables the Design Analysis Model to predict the changes in fluid pressure, porosity, permeability and effective stress as a function of time for a typical storage room filled with waste and backfill.

## 1.2 PROGRAM LOGIC FOR HUMAN INTRUSION

The effects of human intrusion events may also be evaluated at any time. For consistency in the evaluation of alternatives, the intrusion is assumed to occur 5,000 years after decommissioning. At time equal to 5,000 years, the subroutine BOREHOLE (Circle 9 in Figure B-1) simulates the release of radionuclides resulting from three borehole intrusion scenarios (Section 2.0 in Volume I). All program values reflecting the conditions existing in the panel at the time of intrusion are sent to the BOREHOLE subroutine. The subroutine evaluates the permeability of the waste/backfill composite and the solubility of each radionuclide in brine. In addition, the volume of the cuttings removed from the repository by a drill bit and deposited on the surface is assessed for radionuclide content. For each of the three intrusion scenarios considered (Subroutines ISE1, ISE2, ISE1E2 in Figure B-3), the flow path through the panel contents is different (Marietta et al., 1989). The BOREHOLE subroutine makes use of the following subroutines:

- ESTHCKSS (Circle 1 of Figure B-3) estimates the hydraulic conductivity and the specific storage (volume of fluid released by a unit volume of aquifer under unit decline in hydraulic head) of the waste/backfill composite at the time of intrusion.
- RADACTIM (Circle 2 of Figure B-3) predicts the mass and activity of each radionuclide at the time of intrusion (5,000 years).
- CUTTINGS (Circle 3 of Figure B-3) estimates the release of radionuclides to the aboveground surface due to drill bit penetration of the repository. The erosion of the waste material immediately surrounding the bit is included and depends on the anticipated strength of the waste/backfill composite in the panel. In addition, the mass and activity of each radionuclide are evaluated on a panel basis.
- RADSOLUB (Circle 4 of Figure B-3) evaluates the solubility of each radionuclide in brine.

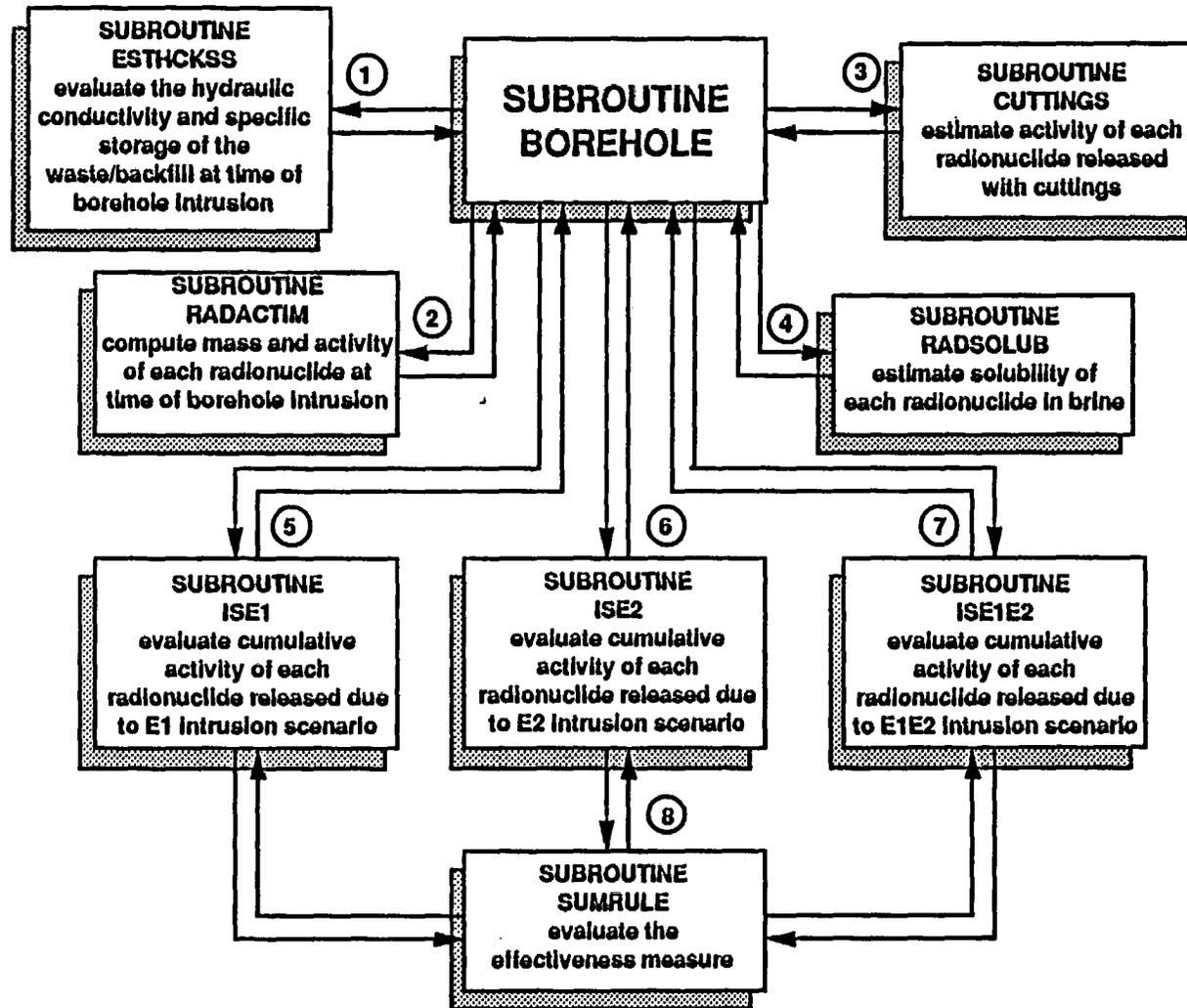


Figure B-3.  
BOREHOLE Flow Diagram

- Subroutines ISE1, ISE2, and ISE1E2 (Circles 5, 6, and 7 in Figure B-3) are used to estimate the resulting radionuclide releases during each of the three intrusion events simulated (Marietta et al., 1989). Separate evaluation schemes are necessary as the three scenarios vary significantly in flow path configuration (Section 2.0 in Volume I).
- SUMRULE (Circle 8 in Figure B-3) is used to calculate the Measure of Effectiveness of an engineered alternative for each one of the three intrusion scenarios (Section 2.0 in Volume I).

Following the BOREHOLE calculations, the program prints the resulting values to the output file and terminates. If intrusion is not being considered during the current run, the program continues to calculate the conditions existing in the panel until preset termination conditions are satisfied.

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## 2.0 PROCESSES AND EQUATIONS CONSIDERED IN THE DESIGN ANALYSIS MODEL

### 2.1 INPUT DATA AND PROGRAM INITIALIZATION (READAT AND INITIALIZE)

The input required by the Design Analysis Model for evaluating the effectiveness of each engineered alternative is obtained from the input data file in subroutine READAT. The data in the input file are specific to the alternative being evaluated (see Section 3.0 in Volume I for data development methodology). The parameters in the input file include:

- Initial room dimensions (height, width) and initial panel volume
- Time step size
- Stress exponent in the creep equations
- Print counters
- Horizontal and vertical creep rate constants for the creep equations
- Number of gas components
- Lithostatic pressure
- Brine inflow rate assuming one atmosphere pressure is maintained in the panel
- Initial porosity of the waste/backfill composite
- Width of the air gap clearance above the waste/backfill composite
- Temperature in the panel
- Microbial and radiolytic gas generation rates
- Maximum potential hydrogen gas generation from anoxic corrosion of iron (steel)
- Duration of microbial activity
- Initial density of the waste/backfill composite
- Stress-density and hydraulic conductivity-stress coefficients
- Void ratio-stress coefficients
- Element solubilities in brine
- Volume of waste/backfill versus stress coefficients for use in estimating the activity of radionuclides released to the surface with the cuttings of intrusion boreholes
- Radius factor (number of borehole radii removed with cuttings)
- Number of drum equivalents per panel
- Time of human intrusion
- Distance between boreholes in human intrusion scenario E1E2

- Brine pore pressure in intact anhydrite beds
- Permeability of the anhydrite beds.

The use of these parameters in the Design Analysis Model will be discussed in subsequent sections of this Appendix.

The subroutine INITIALIZE is called to initialize the variables which are used in the Design Analysis Model. The initial void volume in a panel is among the basic parameters required by the model. This requires that the volume of the air gap above the waste/backfill stack be evaluated as follows. Referring to Figure 2-1 (Vol. I), there are 7 storage rooms in a panel. Separating the rooms are 100 ft. (30.48 m) wide salt pillars. In the drift area along the ends of the salt pillars, there are a total of 12 sections, each with height and width equivalent to that of a room (as specified in the Input file), and each 100 ft. (30.48 m) long. As seen in Figure 2-1, there are 14 intersectional areas between rooms and access drifts which are square and have lateral dimensions equivalent to the width of a room. Thus, the volume of the air gap clearance is:

$$V_{\text{clme}} = 7h_{\text{clme}}w_{\text{room}}l_{\text{room}} + 12h_{\text{clme}}w_{\text{room}}w_{\text{pillar}} + 14h_{\text{clme}}w_{\text{room}}^2 \quad (2.1-1)$$

where,

- $V_{\text{clme}}$  = volume of air gap clearance ( $m^3$ )
- $h_{\text{clme}}$  = thickness of air gap clearance (m)
- $w_{\text{room}}$  = width of the room (m)
- $l_{\text{room}}$  = length of the room (91.44m)
- $w_{\text{pillar}}$  = width of the salt pillars between rooms (30.48m).

The following variables are then initialized:

- The initial gas pressure in the panel,  $P_0$ , is set to 0.101325 MPa (1 atm)
- The gas constant is initialized as 8.314 Nm/mol °K
- The moles of portlandite,  $\text{Ca(OH)}_2$ , in a panel is estimated as the product of 13.03 mol/drum and the number of unprocessed drum equivalents per panel.
- The brine density is initialized to 1220  $\text{kg/m}^3$ .
- The molecular weight of the WIPP brine is set to 20.49 g/mol.

- The molar density of the gas mixture in the panel (RHOM) is then evaluated as:

$$RHOM = \frac{P_0}{RT} \quad (2.1-2)$$

where,

$P_0$  = Initial fluid pressure in the panel (Pa)  
 $R$  = gas constant (8.314 Nm/mol °K)  
 $T$  = absolute temperature (300 °K)

- The initial void volume in a panel is then calculated as:

$$V_{void} = V_{atmc} + (V_{pnl} - V_{atmc}) n_{WB} \quad (2.1-3)$$

where,

$V_{void}$  = Initial void volume in the panel (m<sup>3</sup>)  
 $V_{atmc}$  = volume of the air gap clearance (m<sup>3</sup>)  
 $V_{pnl}$  = Initial panel volume (m<sup>3</sup>)  
 which is specified in the data input file  
 $n_{WB}$  = Initial waste-backfill porosity

- The total moles of gas present in the panel ( $N_{total}$ ) initially is estimated as:

$$N_{total} = RHOM V_{void} \quad (2.1-4)$$

- Air is assumed to be the only gas present in the panel initially. Thus the mole fractions of nitrogen and oxygen are initialized to 0.79 and 0.21 respectively.
- The initial moles of nitrogen and oxygen are evaluated by multiplying the initial total moles of gas ( $N_{total}$ ) by the mole fraction of each gas (i.e., 0.79 for N<sub>2</sub> and 0.21 for O<sub>2</sub>).
- It is assumed that no brine is present in the panel initially
- The gases are initially assumed to behave as ideal gases; thus, the compressibility factor is assigned as 1.0

- The porosity of the Intact Salado Formation is initialized as 0.001 (Marietta et al., 1989)
- The area available for diffusion of gases is assigned a value of 31756 m<sup>2</sup> based upon the areas of the floors, ceilings, and walls in the rooms and access drifts
- The molar rate of oxygen consumption is calculated by dividing the initial moles of oxygen present in a panel by 100 years, such that all the oxygen is consumed in the first 100 years
- The volume occupied by the waste and backfill less pores ( $V_{WB}$ ) is estimated as:

$$V_{WB} = (V_{pri} - V_{cld}) (1 - n_{WB}) \quad (2.1-5)$$

- The initial mass of the solids in the panel ( $m_{solids}$ ) is then calculated as:

$$m_{solids} = \rho_{initial} (V_{pri} - V_{cld}) \quad (2.1-6)$$

where,

$\rho_{initial}$  = *initial density of the waste/backfill which is specified in the data input file*

The final executable statement in the subroutine INITIALIZE is a call to the subroutine DIFCOEF. The DIFCOEF subroutine evaluates the diffusion coefficients of the various gases in brine, as described in the next section.

## 2.2 ESTIMATION OF GAS-BRINE DIFFUSION COEFFICIENTS (DIFCOEF)

The diffusion coefficient of a solute "A" (gas), in solvent "B" (brine), is estimated in subroutine DIFCOEF using the Wilke-Chang correlation (Reid et al., 1987) for each gas present in the panel.

The correlation takes the form:

$$D_{AB} = \frac{7.4 \times 10^{-12} (\phi M_B)^{0.5} T}{\mu_B V_A^{0.5}} \quad (2.2-1)$$

where,

$D_{AB}$  = mutual diffusion coefficient of solute A in brine B ( $m^2/s$ )

$M_B$  = molecular weight of brine (20.49 g/mol)

$T$  = absolute temperature (300°K)

$\mu_B$  = viscosity of brine (1.60 centipoise)

$V_A$  = molar volume of solute at its normal boiling temperature ( $cm^3/mol$ )  
the molar volumes of the various solutes are tabulated below:

$V_{Hydrogen} = 17.7 \text{ cm}^3/mol$

$V_{Oxygen} = 25.7 \text{ cm}^3/mol$

$V_{Carbon\ dioxide} = 33.3 \text{ cm}^3/mol$

$\phi$  = association factor of solvent  
(the value for brine is assumed to be the same as for water, i.e., 2.6)

### 2.3 ESTIMATION OF VOLUME OF BRINE AND WATER INFLOW (BRINFLOW)

The volumetric rate of brine inflow is assumed to be directly proportional to the difference between lithostatic pressure and the current fluid pressure in a panel. It is assumed that if the panel gas pressure equals or exceeds lithostatic pressure, brine inflow will cease. The volume of brine inflow during a time step is evaluated in the subroutine BRINFLOW as:

$$DELVB = Q_{Brine} P_B \quad (2.3-1)$$

where,

*DELVB* = volumetric brine inflow rate into a panel during the time interval (*t* to *t+dt*) ( $m^3/yr$ )

*Q<sub>Brine</sub>* = brine inflow rate assuming the pressure in a panel is maintained at 1 atm

*P<sub>B</sub>* = dimensionless pressure term defined as

$$= \frac{(P_F - P)}{(P_F - P_0)}$$

where,

*P<sub>F</sub>* = lithostatic or farfield pressure, 14.8 MPa (146.1 atm)

*P* = fluid pressure in panel at time, *t* = 0 (1 atm)

*P<sub>B</sub>* is 1.0 if gas pressure in the panel remains at 1.0 atm;

*P<sub>B</sub>* is 0.0 if the gas pressure equals or exceeds lithostatic pressure, *P<sub>F</sub>*.

The cumulative volume of brine, VBCUM, which has flowed into the panel during time, *t*, is:

$$VBCUM = \int_0^t DELVB dt \quad (2.3-2)$$

which may be expressed numerically as

$$VBCUM(t+dt) = VBCUM(t) + DELVB dt \quad (2.3-3)$$

where,

*dt* = time step size (yr).

The actual volume of brine remaining in the panel, VB, (i.e., brine which has not yet been consumed by anoxic corrosion) is also incremented by the same quantity, thus:

$$VB(t+dt) = VB(t) + DELVB dt \quad (2.3-4)$$

## 2.4 ESTIMATION OF ROOM CREEP CLOSURE (CREEP)

Chabannes (1982) has shown that the closure rate in a circular opening in a viscoplastic media at plane strain conditions with Norton's Law, is a power function of the difference between the far-field (lithostatic) and internal stresses. DOE (1988a) proposed an empirical equation for the creep closure in the rectangular rooms at WIPP. This empirical equation was based on the regression analyses of existing closure measurements at various locations at WIPP. Based on the above

two creep equations, and as first-order approximation, the creep equations for horizontal and vertical closure rate in the Design Analysis model then take the form:

$$\frac{dw}{dt} = - \epsilon_w \left[ \frac{(\sigma_w - \sigma)}{\sigma_o} \right]^v h^{1.085} w^{0.63} t^{-0.62} \text{ (horizontal)} \quad (2.4-1)$$

$$\frac{dh}{dt} = - \epsilon_h \left[ \frac{(\sigma_h - \sigma)}{\sigma_o} \right]^v h^{1.18} w^{1.039} t^{-0.24} \text{ (vertical)} \quad (2.4-2)$$

where,

- $w$  = width of panel (ft)
- $h$  = height of panel (ft)
- $dw/dt$  = horizontal creep rate (in/yr)
- $dh/dt$  = vertical creep rate (in/yr)
- $\sigma_o$  = constant ( $6.8975 \times 10^{-3}$  MPa)
- $\epsilon_w$  = horizontal creep constant ( $5.523 \times 10^{-18}$ )
- $\epsilon_h$  = vertical creep constant ( $1.464 \times 10^{-18}$ )
- $\sigma_w$  = lithostatic stress (14.8 MPa)
- $\sigma$  = internal stress in the panel which is the sum of the effective stress of the waste backfill composite (see Section 2.15) and the panel fluid pressure (MPa)
- $v$  = stress exponent (4.95)

The height and width of a panel room are evaluated at each time step by numerically integrating equations (2.4-1) and (2.4-2). This numerical integration is performed in the subroutine CREEP as:

$$h(t+dt) = h(t) + \frac{dh}{dt} dt \quad (2.4-3)$$

and

$$w(t+dt) = w(t) + \frac{dw}{dt} dt \quad (2.4-4)$$

where,

- $dt$  = time step size (yr)
- $t$  = time at previous time step (yr)
- $t+dt$  = current time (yr)

The derivatives  $dh/dt$  and  $dw/dt$  are evaluated using the values of internal stress in the panel from the previous time step.

The creep constants were evaluated using equations (2.4-1) and (2.4-2) assuming an internal stress level in the panel equal to 0.101325 MPa (1 atm). The resulting values of the creep constants,  $\epsilon_w$  and  $\epsilon_{tr}$ , respectively, calculated in this manner are  $5.523 \times 10^{-19}$  /yr and  $1.464 \times 10^{-19}$  /yr.

If the internal stress equals or exceeds lithostatic stress, creep is assumed to cease. In the vertical direction, only gas pressure is assumed to impede creep if a clearance exists above the waste stack. Once the clearance is eliminated by closure, both the panel gas pressure and the effective stress of waste compaction will retard the rate of creep closure. This neglects any effects of changing pore pressure on the creep constants.

## **2.5 MASS BALANCES ON GASES IN THE PANEL (MASSGAS)**

In the routine MASSGAS a mass balance on water and on each gas is performed considering the following processes:

- Advection into the intact host rock
- Advection up the four shaft seals
- Diffusion into brine saturated host rock
- Dissolution of gases in brine which is present in the panel
- Generation of gases by microbial and radiolytic mechanisms
- Hydrogen generation by anoxic corrosion of metals
- Consumption of water (brine) by anoxic corrosion of metals
- Removal of carbon dioxide by reaction with cement present in the waste.

The rates of gas advection into the intact host rock and up the shaft seals are evaluated in the subroutine ADVECTION (Sections 2.6 and 2.7).

Gases are assumed to diffuse into a fully brine saturated host rock. The rates of this mechanism of transport are evaluated in the subroutine DIFFUSION (Section 2.11).

The amount of each gas which can dissolve in the brine present in the panel is evaluated in the subroutine VAPLIQEQ (Section 2.9). Evaluation is based upon solubilities and Henry's Law constants computed in the subroutine GASOLUB (Section 2.10).

The consumption and generation of gases by microbial/radiolytic processes is modeled in the subroutine MASSGAS using assumptions described in Section 2.12.

Anoxic corrosion of metals present in the waste can potentially generate 1.7 moles of hydrogen per year for each drum present in a room (see Section 2.13). This rate will require  $5 \times 10^{-5}$  cubic meters of water per year, per unprocessed waste drum. If the water (in brine) availability is less than the required amount to sustain the maximum generation rate, the hydrogen generation rate is scaled down appropriately.

## **2.6 ADVECTION OF GASES INTO UNDISTURBED ANHYDRITE BEDS** **(ADVECTION AND MBFLOW)**

The advection of gases from the panel into the surrounding host rock is a potential mechanism by which generated gases may be dissipated. Several assumptions were made to simulate this process in the Design Analysis Model. The pores in the surrounding intact formation (outside the DRZ) are assumed to be saturated with brine. For gases to advect into the host rock, the pressure of the fluid in the panel must exceed the sum of the pressure in the brine plus the threshold pressure. The threshold pressure is defined as the capillary pressure corresponding to full saturation under draining conditions. This pressure (also referred to as the bubbling or breakthrough pressure) is the pressure required to overcome capillary forces at the gas-brine interface and create an incipient, interconnected, gas-filled pore network. A table of predicted threshold pressures (as a function of intrinsic permeability) was developed by Davies (1989). The permeability of the Intact Salado Formation is approximately  $10^{-21} \text{ m}^2$  (Laplin et al., 1989, Table 3-1) which corresponds to a threshold pressure of 10 MPa. Therefore, the fluid pressure in the panel would have to exceed 24.8 MPa [10 MPa (threshold pressure) + 14.8 MPa (lithostatic pressure)] for advection of gases into the Salado to occur.

The mechanism of advection into the surrounding Salado Formation is thus not considered due to the extreme panel pressures required to advect gases into the intact halite (10 MPa greater than lithostatic). However, the Intact Marker Bed 139 (MB 139) is made up of anhydrite, and may have a permeability as much as three orders of magnitude higher than that of the intact halite (Rechard et al., 1990, p. 171). Pressure tests of MB 139 indicate that the pore pressure is sub-lithostatic, resulting in a lower panel pressure being required to advect gases into the anhydrite beds. In modeling the advection of gases into the anhydrite beds, the anhydrites layers "a" and "b" overlying the repository are treated as a single bed and Marker Bed 139 underlying the repository is treated as another bed.

The baseline case analysis assumes that the anhydrite bed pore pressure is 70% of lithostatic (10.36 MPa), and the permeability is  $10^{-16} \text{ m}^2$ , with a corresponding 0.94 MPa threshold pressure (Davies, 1989). Thus advection into the undisturbed anhydrite bed may occur when the panel fluid pressure exceeds 11.3 MPa [10.36 MPa (pore pressure) + 0.94 MPa (threshold pressure)]. The model assumes that the anhydrites above and below the repository are disturbed (fractured due to the mine operations) and are represented by two disks of 400 m radius and thickness of 1 m for MB 139, and 0.27 m for the anhydrite "a" and "b" composite layer. These disturbed

anhydrite beds are assumed to be directly connected to the panels through fractures. Draining of the disturbed anhydrites above the repository due to gravity, has not been considered for this analysis. As a result, the anhydrites are assumed to be initially fully saturated with brine. Actual measurements have found both saturated and partially saturated conditions in these anhydrites.

A two-phase flow computer code was used to calculate quasi-steady state advection rates of gases across the intact-disturbed anhydrite interface as a function of:

- Panel fluid pressure
- MB 139 brine pore pressure
- MB 139 intrinsic permeability.

A description of this two-phase flow code comprises Appendix D. A parametric equation was developed using multi-parameter least squares regression (Box et al., 1978) from data obtained from a number of sensitivity runs varying panel fluid pressure and MB 139 brine pore pressure. The baseline case analysis assumed an anhydrite permeability of  $10^{-18}$  m<sup>2</sup> and a brine pore pressure of 10.36 MPa which is 70% of lithostatic. The parametric equation is used in subroutine ADVECTION, and takes the following form:

$$\begin{aligned} \dot{m}_{ANH} = & (1.27 - b_{ab} - b_{MB})\{-1.06966 \times 10^{-6} \\ & - 8.99901 \times 10^{-7} P_{ANH}^2 \\ & + 8.39754 \times 10^{-7} P^2 \\ & - 1.04066 \times 10^{-9} (P - P_{ANH}) \\ & + 8.68640 \times 10^{-7} (P - P_{ANH})^2\} \end{aligned} \quad (2.6-1)$$

where,

- $\dot{m}_{ANH}$  = molar advection rate of gases into intact anhydrite beds (mol/yr)  
 $P_{ANH}$  = brine pore pressure in MB 139 (MPa)  
 $P$  = panel fluid pressure  
 $b_{MB}$  = height of brine in the disturbed marker bed 139 (m)  
 $b_{ab}$  = height of brine in the disturbed anhydrite "a" and "b" composite layer (m).

The height of brine in the two anhydrite beds vary with time in the Design Analysis Model and are evaluated at each time step in the subroutine MBFLOW. The fluid pressure in the panel must exceed the brine pore pressure in the anhydrite before brine flows from the disturbed anhydrite into the intact anhydrite. If the fluid pressure in the panel exceeds the assumed brine pore pressure in the Salado (14.8 MPa), additional brine will flow from the disturbed anhydrite into the Salado above the anhydrite "a" and "b" composite layer and into the Salado below MB 139. A Salado permeability of  $3 \times 10^{-21}$  m<sup>2</sup> (Lappin et al., 1989) is used in the calculations. The volume of brine which flows out translates into an additional storage volume for panel gases. The flow into the intact marker bed is assumed to be one-dimensional. The intact marker bed is assumed to be saturated with brine at a pore pressure of  $P_{ANH}$  and is infinite in extent, with a permeability of  $10^{-18}$  m<sup>2</sup>. The transient one dimensional flow equation:

$$D \frac{\partial^2 h}{\partial x^2} = \frac{\partial h}{\partial t}$$

was solved subject to initial and boundary conditions:

- The hydraulic heads in the intact anhydrite and the intact Salado layers are initially  $h_{\text{ANH}}$  and  $h_{\text{SAL}}$ , respectively.
- At a distance far enough from the intact-disturbed interfaces, the hydraulic heads are  $h_{\text{ANH}}$  in the anhydrite and  $h_{\text{SAL}}$  in the Salado formation.
- The hydraulic head at the intact-disturbed marker bed interface,  $h_p$ , is equal to the pressure head in the panel.

Thus the solution is (Crank, 1975):

$$h(x,t) = h_i + (h_p - h_i) \operatorname{erfc} \frac{x}{2(D_i t_{R_i})^{0.5}} \quad (2.6-2)$$

where,

- $D$  = hydraulic diffusivity ( $m^2/yr$ )
- $t_R$  = time since the panel fluid pressure exceeded the marker bed brine pore pressure,  $P_{MB}$  (yr)
- $h_p = P/\rho g$  = hydraulic head at the disturbed-intact marker bed interface (m)
- $P$  = fluid pressure in panel (Pa)
- $\rho$  = brine density ( $1220 \text{ kg/m}^3$ )
- $g$  = gravitational acceleration ( $9.80665 \text{ m/s}^2$ )

•Subscript "i" refers to either anhydrite MB 139 (MB) or anhydrite "a" and "b" composite layer (ab), or Salado (SAL).

The volumetric flow rate of brine into the intact layer ( $Q_i$ ) is evaluated from Darcy's Law as:

$$Q_i = -K_i A_i \frac{\partial h}{\partial x} \Big|_{x=0} \quad (2.6-3)$$

where,

$Q_i$  = volumetric flow rate of brine from the disturbed anhydrite into the intact layer "I" ( $m^3/yr$ )

$K_i$  = hydraulic conductivity of the intact layer "I" relative to brine ( $m/yr$ )

$A_i$  = cross-sectional area over which flow is occurring ( $m^2$ )

$\frac{\partial h}{\partial x}|_{x=0}$  = partial derivative of hydraulic head with respect to distance from the intact-disturbed anhydrite interface.

Thus differentiating Equation (2.6-2) and evaluating the gradient at the interface ( $x = 0$ ):

$$Q_i = K_i A_i \frac{(h_p - h_i)}{(\pi D_i t_{R_i})^{0.5}} \quad (2.6-4)$$

The above solution has only been used for the flow during at time step such that time is not cumulative, and the pressure is updated at each time step.

For the anhydrite beds, a hydraulic conductivity of  $2.36 \times 10^{-4}$  m/yr was calculated and used in the model based on a brine density of  $1220 \text{ kg/m}^3$ , and a viscosity of  $0.0016 \text{ Pa}\cdot\text{s}$  (Lappen et al., 1989). The specific storage  $1.21 \times 10^{-5}$  was evaluated based on a marker bed compressibility of  $10^{-9} \text{ Pa}^{-1}$  (Freeze and Cherry, 1979), a brine compressibility of  $4.4 \times 10^{-10} \text{ Pa}^{-1}$  (Freeze and Cherry, 1979), and an assumed porosity,  $n$ , of 0.025. The hydraulic diffusivity was then calculated as the ratio of the hydraulic conductivity to that of the specific storage (Freeze and Cherry, 1979) and is equal to  $19.5 \text{ m}^2/\text{yr}$ . A hydraulic diffusivity of  $10.4 \text{ m}^2/\text{yr}$  was used for the Salado assuming a permeability of  $3 \times 10^{-21} \text{ m}^2$  (Lappen et al., 1989). The cross-sectional area over which flow is occurring is calculated as:

$$A_{MB} = 2\pi r_{dst} b_{MB} \quad (2.6-5a)$$

$$A_{ab} = 2\pi r_{dst}^2 b_{ab} \quad (2.6-5b)$$

$$A_{SAL} = \pi r_{dst}^2 = 502,655 \text{ m}^2 \quad (2.6-5c)$$

where,

$r_{dst}$  = radius of disturbed anhydrite beds (400 m).

To retain a balance of volume within the disturbed anhydrite beds, any volume of brine which flows out of the disturbed anhydrite is assumed to be replaced by gas from the room. This is realized as the gas occupying the top of the disturbed anhydrites provides some area for gas advection. This area is then subtracted from that available for brine to flow into the intact anhydrites.

Therefore, the cross-sectional areas vary with time, since  $b_{MB}$  and  $b_{ab}$  change with time, and are evaluated at each time step as:

$$b_{MB}(t+dt) = b_{MB}(t) - (Q_{SAL} + Q_{MB}) dt / (\pi r_{dst}^2 n) \quad (2.6-6a)$$

$$b_{ab}(t+dt) = b_{ab}(t) - (Q_{SAL} + Q_{ab}) dt / (\pi r_{dst}^2 n) \quad (2.6-6b)$$

The total cumulative void volume that is available for gas storage in the disturbed marker bed,  $V_{tot}$  is evaluated as:

$$V_{tot}(t+dt) = V_{MB}(t) + V_{ab}(t) + 0.109 (Q_{MB} + Q_{ab} + 2Q_{SAL}) dt \quad (2.6-7)$$

If the height of the brine for the next time step, in either the marker bed ( $b_{MB}$ ) or the anhydrite composite ( $b_{ab}$ ), evaluated through Equation (2.6-6) is negative, the height is set to zero and the cumulative void volume for the bed is then given by:

$$V_{MB} = 0.109 \pi r_{dst}^2 b_{MB}(0) n \quad (2.6-8a)$$

$$V_{ab} = 0.109 \pi r_{dst}^2 b_{ab}(0) n \quad (2.6-8b)$$

where,

$b_{MB}(0)$  = Initial height of brine in the disturbed marker bed (1.0m)

$b_{ab}(0)$  = Initial height of brine in the disturbed "a" and "b" composite layer (0.27m).

At each time step, an increase in available void volume is calculated on a per-panel basis, based upon the desaturation of the disturbed anhydrites. In order to obtain the cumulative void volume per panel, the factor 0.109 is used. This factor is the ratio of the panel floor area to that of the total storage floor area (8 panels and 2 equivalent panels) as listed in Table 4.7 of Lappin et al. (1989). This void volume is then added to the total voids available for pressurization by gases. The panel fluid pressure is then evaluated (see Section 2.16) using the total void volume.

## 2.7 ADVECTION OF GASES UP THE SHAFT SEALS (ADVECTION AND SHFTCOND)

The rock below the repository is assumed to be fractured such that all regions with void volumes are interconnected. However, the lateral fractures in the halite between the panels are not considered to be continuous, so that it is unlikely that there will be any actual flow between the rooms. Thus, the anhydrites are considered to have interconnected lateral porosity so that there might be equilibration of pressure, but no actual connection for gas flow between the panels and the shafts will occur until it is first established within the anhydrites. Therefore, the panel fluid pressure is the same as the pressure at the base of the shaft. Since the disturbed marker bed is assumed to be saturated with brine, advection up the shafts cannot occur until the panel fluid pressure exceeds the marker bed brine pore pressure (to open a pathway). The four shafts which are to be sealed in the current repository design are (DOE, 1990c):

- The Waste Shaft (diameter = 6.096 m)
- The Construction and Salt Handling (C&SH) Shaft (diameter = 3.607 m)
- The Air Intake Shaft (diameter = 6.172 m)
- The Exhaust Shaft (diameter = 4.572 m).

A pseudo steady-state approach was taken in modeling advection up the shafts. The steady state gas continuity equation was combined with Darcy's flow equation through porous media. According to an equation of state, the density of the gas is directly proportional to the fluid pressure. This is based on isothermal conditions, due to low decay heats.

The resulting differential equation which describes the steady state fluid pressure distribution as a function of distance is:

$$\frac{d^2 P^2}{dz^2} = 0 \quad (2.7-1)$$

where,

$P$  = fluid pressure in shaft (MPa)

$z$  = vertical distance through the shaft to the ground surface (m)

The applicable boundary conditions are:

$$P(z = 0, \text{ i.e., at the base of a shaft}) = P_p \quad (2.7-2a)$$

$$P(z = L, \text{ i.e., at the ground surface}) = P_{atm} \quad (2.7-2b)$$

where,

$$\begin{aligned} P_p &= \text{panel fluid pressure (evaluated at each time step)} \\ P_{atm} &= \text{atmospheric pressure of 0.101325 MPa.} \end{aligned}$$

The solution to equation (2.7-1) with the above boundary conditions is:

$$P = \left\{ (P_{atm}^2 - P_p^2) \frac{z}{L} + P_p^2 \right\}^{0.5} \quad (2.7-3)$$

The volumetric advection rate at the base of the shaft is evaluated as:

$$Q_{advection} = - \frac{kA}{\mu} \left. \frac{dP}{dz} \right|_{z=0} 31.5576 \times 10^6 \text{ s/yr} \quad (2.7-4)$$

Differentiation of (2.7-3) provides:

$$Q_{advection} = - \frac{A k (P_{atm}^2 - P_p^2)}{\mu 2 L P_p} 31.5576 \times 10^6 \text{ s/yr} \quad (2.7-5)$$

where,

$$\begin{aligned} Q_{advection} &= \text{volumetric advection rate up the shaft (m}^3\text{/yr)} \\ A &= \text{area of shaft (m}^2\text{)} \\ k &= \text{permeability of shaft (m}^2\text{)} \\ \mu &= \text{viscosity of gas mixture in panel (MPa}\cdot\text{s)}. \end{aligned}$$

The molar advection rate may be evaluated using an equation of state in the form:

$$\dot{m}_{shaft} = \frac{Q_{advection} P_p}{ZRT} \quad (2.7-6)$$

where,

$$\begin{aligned} \dot{m}_{shaft} &= \text{molar advection rate up the shaft at the shaft base (mol/yr)} \\ R &= \text{gas constant (8.314 Nm/mol }^\circ\text{K)} \\ Z &= \text{compressibility factor of the panel gas mixture} \\ T &= \text{absolute temperature (300 }^\circ\text{K)}. \end{aligned}$$

Combining equations (2.7-5) and (2.7-6) and defining  $AkL = C_{TOT}$  gives

$$\dot{m}_{shaft} = \frac{C_{TOT} (P_p^2 - P_{atm}^2)}{2 \mu Z R T} \quad (2.7-7)$$

where,

$C_{TOT}$  = total conductance of the four shaft seals.

The permeability and the length of each shaft is assumed to be the same, although the diameters are different. The conductance of the waste shaft seal was obtained as a function of time by using the shaft-seal component of the Design Analysis Model (Appendix C). The total conductance of the four shaft seals was evaluated by scaling the cross-sectional areas of the other shafts relative to the cross-sectional area of the waste shaft. It is assumed that the radius of the disturbed rock zone (DRZ) surrounding the shafts is 5 times the radius of the shaft itself. The equations which describe the variation of the total conductance,  $C_{TOT}$  in (mDarcy m), of the four shaft seals with time,  $t$ , are listed below and are coded in subroutine SHFTCOND as:

For  $0 < t \leq 35$  years

$$C_{TOT} = \exp(-6.306 - 4.7843 \times 10^{-2} t) \quad (2.7-8)$$

For  $35 \text{ years} < t \leq 95$  years

$$C_{TOT} = \exp(-6.7619 - 2.706 \times 10^{-3} t + 5.4411 \times 10^{-5} t^2 - 3.714 \times 10^{-7} t^3) \quad (2.7-9)$$

For  $95 \text{ years} < t \leq 125$  years

$$C_{TOT} = \exp(-1.429 - 5.5256 \times 10^{-2} t) \quad (2.7-10)$$

For  $125 \text{ years} < t \leq 775$  years

$$C_{TOT} = \exp(-8.1159 - 1.7525 \times 10^{-3} t) \quad (2.7-11)$$

For  $t > 775$  years

$$C_{TOT} = \exp(-9.3899 - 3.5659 \times 10^{-4} t) \quad (2.7-12)$$

## 2.8 ESTIMATION OF VISCOSITY OF GAS MIXTURE (VISCORR)

The viscosity of the gas mixture in a panel is evaluated in the subroutine VISCORR. The viscosity is used in equation (2.7-7) for estimating the gas advection rates through the shaft seals.

The Chung mixing rules (Reid et al., 1987, pp 413-414) are used to estimate the pseudocritical temperature,  $T_{cm}$ , and the pseudocritical volume,  $V_{cm}$ , of the mixture.

The critical mixture compressibility factor,  $Z_{cm}$  is evaluated using Kay's rule (Reid et al., 1987, pp 76-77) as:

$$Z_{cm} = \sum y_i Z_{ci} \quad (2.8-1)$$

where,

$$y_i = \text{mole fraction component, "i"}$$

$$Z_{ci} = \text{critical compressibility factor of component, "i"}$$

The critical mixture pressure,  $P_{cm}$  is evaluated using the Prausnitz and Gunn combination (Reid et al., 1987, p 77) as:

$$P_{cm} = R Z_{cm} \frac{T_{cm}}{V_{cm}} \quad (2.8-2)$$

where,

$$R = \text{gas constant (8.314 Nm/mol } ^\circ\text{K)}.$$

The Reichenberg method (Reid et al., 1987, pp 420-421) is used to estimate the viscosity of the gas mixture at high pressure. This method requires knowledge of the viscosity of the gas mixture at low (atmospheric) pressure. The low (atmospheric) pressure gas mixture viscosity is evaluated using the Wilke correlation (Reid et al., 1987, p 407). The viscosity of a gas mixture according to Wilke is:

$$\mu_o = \frac{\sum_{i=1}^{NC} \left[ \frac{y_i \mu_i}{\sum_{j=1}^{NC} y_j \phi_{ij}} \right]}{\sum_{j=1}^{NC} y_j \phi_{ij}} \quad (2.8-3)$$

where,

$$\phi_{ij} = \frac{[1 + (\mu_i/\mu_j)^{1/2}(M_j/M_i)^{1/4}]^2}{[8(1 + M_j/M_i)]^{1/2}} \quad (2.8-4)$$

and,

$\mu_0$  = viscosity of the gas mixture at low (atmospheric) pressure  
 $\mu_i$  = viscosity of pure component, "i"  
 $M_i$  = molecular weight of pure component, "i" (g/mol)  
 NC = number of components.

The viscosity ratio according to the Reichenberg method is given as (Perry et al., 1984):

$$\frac{\mu}{\mu_0} = 1 + \frac{Q A P_r^{3/2}}{B P_r + (1 + C P_r^D)^{-1}} \quad (2.8-5)$$

where,

$\mu$  = gas mixture viscosity at high pressure

$$A = \left(\frac{1.9824 \times 10^{-3}}{T_r}\right) \exp(5.2683 T_r^{-0.576}) \quad (2.8-6)$$

$$B = A(1.6552 T_r - 1.2760) \quad (2.8-7)$$

$$C = \left(\frac{0.1319}{T_r}\right) \exp(3.7035 T_r^{-79.8876}) \quad (2.8-8)$$

$$D = \left(\frac{2.9496}{T_r}\right) \exp(2.9190 T_r^{-18.8169}) \quad (2.8-9)$$

$$T_r = \frac{T}{T_{cm}} \quad (2.8-10)$$

$$P_r = \frac{P}{P_{cm}} \quad (2.8-11)$$

$$Q = (1 - 5.655DM_r) \quad (2.8-12)$$

$$DM_r = 52.46 DM_m^2 \frac{P_{cm}}{T_{cm}^2} \quad (2.8-13)$$

T = absolute temperature (°K)

P = pressure (MPa)

and the gas mixture dipole moment, ( $DM_m$ ), is evaluated as:

$$DM_m = \left[ \sigma_m^3 \sum_{j=1}^{NC} \sum_{i=1}^{NC} (y_i y_j \frac{DM_i^2 DM_j^2}{\sigma_{ij}^3}) \right]^{1/4} \quad (2.8-14)$$

$$\sigma_i = 0.809 V_i^{1/3} \quad (2.8-15)$$

$V_i$  = critical volume of pure component "i"

$$\sigma_{ij} = (\sigma_i \sigma_j)^{1/2} \quad (2.8-16)$$

$$\sigma_m^3 = \sum_{i=1}^{NC} \sum_{j=1}^{NC} y_i y_j \rho_{ij}^3 \quad (2.8-17)$$

$DM_i$  = dipole moment of component "i" (debye)

## 2.9 DISSOLUTION OF GASES IN BRINE (VAPLIQEQ)

The brine is assumed to contain considerable quantities of nitrogen and methane (DOE, 1983). Therefore, the dissolution and exsolution of these two gases is not considered in the Design Analysis Model. The amounts of other gases dissolved in the liquid phase at each time step are evaluated in the subroutine VAPLIQEQ. The final equation used in the subroutine was derived as follows.

A mass balance on gas "I" during a time step may be stated as:

moles of gas "I" which have dissolved in brine during the time step ( $l_i^{\Delta t}$ ) = moles of gas "I" in gas phase at time,  $t$  ( $g_i^t$ ) - moles of gas "I" in gas phase at time,  $t+dt$  ( $g_i^{t+\Delta t}$ )

or,

$$l_i^{\Delta t} = g_i^t - g_i^{t+\Delta t} \quad (2.9-1)$$

Assuming changes in both the compressibility factor,  $Z$ , and gas pressure,  $P$ , are negligible during a time step, then from the equation of state:

$$g_i^{t+\Delta t} = \frac{y_i^{t+\Delta t} PV}{ZRT} \quad (2.9-2)$$

where,

$y_i$  = mole fraction gas "I" in the gas phase  
 $P$  = fluid panel pressure  
 $V$  = void volume in panel ( $m^3$ )  
 $Z$  = gas mixture compressibility factor  
 $R$  = gas constant (8.314 Nm/mol °K)  
 $T$  = absolute temperature (300 °K)

Assuming the moles of gas dissolved in the liquid phase during a time step are negligible relative to the moles of liquid phase present at time,  $t$ , then:

$$x_i^{t+\Delta t} = \frac{l_i^{\Delta t} + l_i^t}{L^t} \quad (2.9-3)$$

where,

$x_i^{t+\Delta t}$  = mole fraction gas solute "I" in liquid phase at time,  $t+dt$   
 $l_i^{\Delta t}$  = moles of gas dissolved in liquid phase during a time step  
 $l_i^t$  = moles of gas solute "I" in liquid phase at the start of the time step, i.e., at time,  $t$   
 $L^t$  = total moles of liquid phase at time,  $t$

Substitution of equation (2.9-2) into equation (2.9-1) gives an equation with two unknowns,  $y_i^{std}$  and  $l_i^{std}$ .

A second equation relating  $y_i^{std}$  and  $l_i^{std}$  may be derived using Henry's Law (Reid et al., 1987) and equation (2.9-3).

Henry's Law states that:

$$y_i^{std} P = x_i^{std} H_{i,brine} \quad (2.9-4)$$

where,

$H_{i,brine}$  = Henry's Law constant for component "i" in brine (MPa)  
which is evaluated in routine GASOLUB.

Combining equations (2.9-3) and (2.9-4) yields:

$$y_i^{std} P = (l_i^{std} + l_i^h) \frac{H_{i,brine}}{L^i} \quad (2.9-5)$$

Substituting equation (2.9-5) into (2.9-2) and the resulting equation into equation (2.9-1) yields:

$$g_i^i = \left( \frac{(l_i^{std} + l_i^h) H_{i,brine}}{L^i} \right) \frac{V}{ZRT} + l_i^{std} \quad (2.9-6)$$

Solving for the moles of gas "i" dissolved in the liquid phase during a time step,  $I_i^{\Delta t}$ , in equation (2.9-6) provides the final equation which is coded in subroutine VAPLIQEQ.

$$I_i^{\Delta t} = \frac{g_i^i - \frac{I_i^i H_{i,brine} V}{L^i Z R T}}{1 + \frac{H_{i,brine} V}{L^i Z R T}} \quad (2.9-7)$$

Once the values of  $I_i^{\Delta t}$  have been evaluated for each gas using equation (2.9-7), the values of  $g$ ,  $I$ , and  $L^{i+\Delta t}$  are updated for the next time step as:

$$g_i^{i+\Delta t} = g_i^i - I_i^{\Delta t} \quad (2.9-8)$$

$$I_i^{i+\Delta t} = I_i^i + I_i^{\Delta t} \quad (2.9-9)$$

where,

$NC \equiv$  number of components

## 2.10 SOLUBILITIES AND HENRY'S LAW CONSTANTS OF GASES IN BRINE (GASOLUB)

The solubility of each gas in brine for use in diffusion calculations (see next section), and the Henry's Law constants for use in subroutine VAPLIQEQ (Section 2.9), are evaluated in subroutine GASOLUB at each time step. The brine is assumed to contain considerable quantities of nitrogen and methane so that neither dissolution nor diffusion of these gases into brine takes place (DOE, 1983).

For dilute solutions, Henry's law provides a good estimate of solubilities (Reid et al., 1987). Solubilities of various gases in water will be evaluated first and then corrected for dissolution in brine.

At equilibrium the following relations hold (Reid et al., 1987, pp 332 - 339):

$$f_i^L = f_i^V \quad (2.10-1)$$

$$H_{i,water} x_i = \phi_i y_i P \quad (2.10-2)$$

where,

- $f_i^L$  = fugacity of gas "I" in water (MPa)
- $f_i^V$  = fugacity of gas "I" in gas phase (MPa)
- $H_{i,\text{water}}$  = Henry's Law constant for gas "I" in water (MPa)
- $x_i$  = mole fraction gas "I" in water
- $\phi_i$  = vapor phase fugacity coefficient of gas "I"
- $y_i$  = mole fraction gas "I" in gas phase
- $P$  = fluid pressure (MPa).

The vapor phase fugacity coefficient of component "I",  $\phi_i$ , will be assumed to be 1, as it is for ideal gases.

The Henry's Law constant is corrected for pressure using (equation 8-11.3 of Reid et al., 1987, p 335) as:

$$\begin{aligned} \ln \left( \frac{y_i^P}{x_i} \right) &= \ln H_{i,\text{water}}^P \\ &= \ln H_{i,\text{water}}^{VP} + \frac{V_i^{\infty}(P - VP)}{(RT)} \end{aligned} \quad (2.10-3)$$

where,

- $H_{i,\text{water}}^{VP}$  = Henry's Law constant for solute gas "I" in the solvent (water) at the vapor pressure of the solvent (MPa)
- $H_{i,\text{water}}^P$  = Henry's Law constant for solute gas "I" in the solvent (water) at the gas pressure in the panel (MPa)
- $V_i^{\infty}$  = partial molar volume of solute gas "I" at infinite dilution in water ( $\text{cm}^3/\text{mol}$ )  
The volumes of the various gases are tabulated below and are extracted from (Reid et al., 1987, p. 336)
- VP = vapor pressure of solvent (water) at 300°K (0.03 atm)
- R = gas law constant (8.314 Nm/mol °K)
- T = absolute temperature (300°K).

Henry's Law constants for the gases in water are listed in Table B-1 (Atkins, 1982, p. 226).

TABLE B-1

## MOLAR VOLUMES AND HENRY'S LAW CONSTANTS FOR GASES IN WATER

GAS	$V_1^*$ (cm <sup>3</sup> /mol)	$H_{i,\text{water}}^{\text{vp}}$ (MPa)
Hydrogen	26	7,119
Oxygen	31	4,400
Carbon Dioxide	33	167

The Henry's Law constant for a gas "i" in brine will be estimated using the relation (Cramer, ND)

$$\log \left( \frac{H_{i,brine}^P}{H_{i,water}^P} \right) = k_s m_s \quad (2.10-4)$$

where,

$$\begin{aligned} H_{i,brine}^P &= \text{Henry's Law constant for gas "i" in brine at pressure } P \\ k_s &= \text{salting-out coefficient (kg/mol)} \\ M_s &= \text{molality of dissolved salts in the WIPP brine (8.80 mol/kg)}. \end{aligned}$$

The salting-out coefficients for methane, carbon dioxide and oxygen are listed in Table 13 of (Cramer, ND) at several temperatures. The salting-out coefficients at 27 °C (300 °K) were estimated by linear interpolation of the values for 20 °C and 40 °C. The coefficient for hydrogen was not available and was assumed to be equal to the average of the values for methane, carbon dioxide and oxygen. The salting-out coefficients are tabulated in Table B-2.

The mole fraction gas "i" in brine,  $x_i$ , may then be evaluated by rearranging equation (2.10-2), with  $\phi_i = 1$  as:

$$x_i = y_i \frac{P}{H_{i,brine}^P} \quad (2.10-5)$$

Once the mole fraction in brine has been evaluated, the solubility concentration may be estimated using the following conversions:

$$C_{si} = x_i \rho_{brine} \frac{(10^6 \text{ cm}^3/\text{m}^3)}{M_{brine}} \quad (2.10-6)$$

where,

$$\begin{aligned} C_{si} &= \text{solubility of gas "i" in brine (mol/m}^3\text{)} \\ M_{brine} &= \text{molecular weight of WIPP brine (20.49 g/mol)} \\ \rho_{brine} &= \text{density of WIPP brine (1.22 g/cm}^3\text{)}. \end{aligned}$$

**TABLE B-2**  
**SALTING-OUT COEFFICIENTS FOR EXPECTED GASES**

<b>GAS</b>	<b>SALTING-OUT COEFFICIENT <math>k_s</math> (kg/mol)</b>
Hydrogen	0.125*
Oxygen	0.135
Carbon Dioxide	0.104
Methane	0.136

\* The value of the salting-out coefficient for hydrogen was not available and is assumed to be the average of the values for oxygen, carbon dioxide and methane.

## 2.11 DIFFUSION OF GASES INTO BRINE SATURATED HOST ROCK (DIFFUSION)

The host rock is assumed to be an infinite medium whose pores are saturated with brine. A potential exists for gases to dissolve and then diffuse into the brine due to concentration gradients. The gas diffusion rates are estimated within the subroutine DIFFUSION. The solubility of gases in brine at the gas-brine interface will be continuously increasing as a function of time according to Henry's Law due to increasing partial pressure of the gases. The functional form for the increase is not known in advance due to the complex coupling of processes within the panel. For a constant concentration at the gas-brine interface, the concentration profile for one dimensional diffusion into an infinite medium may be described by the following relation (Crank, 1975, p. 122):

$$C_A/C_{sA} = \operatorname{erfc} \left\{ \frac{x}{2(D_{AB}t)^{0.5}} \right\} \quad (2.11-1)$$

where,

$D_{AB}$  = diffusion coefficient of gas "A" in brine "B" ( $m^2/yr$ )

The diffusion coefficients of gases are evaluated in the subroutine DIFCOEF of the Design Analysis Module (see Section 2.2)

$C_{sA}$  = solubility of gas "A" in brine "B" and is equal to the ( $mol/m^3$ )

concentration of "A" at the gas-brine saturated host rock interface. These concentrations are evaluated in routine VAPLIQEQ of the Design Analysis Module (see Section 2.9)

$C_A$  = concentration of gas "A" at a distance  $x$  from the gas-brine saturated host rock interface ( $mol/m^3$ )

$t$  = time since repository decommissioning (yr).

Fick's Law of Diffusion (Crank, 1975, p 2) is then used to evaluate the molar flowrate of gas "A" into brine at each time step, based upon an initial condition of zero within the brine, as:

$$\dot{m}_A = \varepsilon A D_{AB} \left. \frac{\partial C_A}{\partial x} \right|_{x=0} \quad (2.11-2)$$

where,

$\dot{m}_A$  = molar rate of diffusion of gas "A" into brine (molyr)  
 $\varepsilon$  = porosity of the brine filled host rock  
 $A$  = area available for diffusion (31756 m<sup>2</sup>).

Differentiating equation 2.11-1 with respect to distance, x and evaluating the derivative at the gas-brine saturated host rock interface yields:

$$m_A = \frac{\varepsilon A D_{AB} C_{s,A}}{(\pi D_{AB} t)^{0.5}} \quad (2.11-3)$$

## 2.12 MICROBIAL AND RADIOLYTIC GENERATION OF GASES (MASSGAS)

The rate and total potential amount of gas generated microbially and radiolytically are assumed to agree with Lappin et al. (1989). Since radiolysis and microbial activity utilize the same substrates (organics), the rate of 0.85 mole/drum/yr is assumed to represent both radiolysis and microbial activity. For gas generation due to anoxic corrosion, only brine (specifically the water in the brine) has been assumed to be the source of moisture. Water which is available from the waste is assumed to be consumed in microbial activities. Clarifying, the two competing reactions for water (corrosion and microbial activity) are assumed to partition the sources of water (water in brine and water in the waste). While this partitioning is artificial, it assures that the same component is not used in two different reactions. Estimates were made to determine if excess water available from the waste will exist to support the microbial activity.

An initial estimate of the amount of cellulose in the WIPP inventory is 6.07 x 10<sup>5</sup> lb (Lappin et al., 1989). Assuming a yield (mass of biomass produced per mass of substrate consumed) of 0.1 (typical yields are in the range of 0.3 to 0.8), degradation of the waste would result in the generation of 2.76 x 10<sup>5</sup> g of biomass. Assuming a water content of 80% for the biomass, the water requirement for microbial activity is 2.2 x 10<sup>5</sup> g, or 220000 liters. Assuming a total of 4 x 10<sup>5</sup> drums stored in the WIPP, the required free water requirement per drum is 0.55 liters.

In summary, the water required for anoxic corrosion is provided by, and is limited by the availability of brine. The water required for microbial gas generation is provided by the water in the waste, and is not considered to be limiting. These assumptions may be modified and updated when better estimates of the rates become available.

The ratio being used for gases expected to be generated in the WIPP repository is arbitrary and is based on the following assumptions:

- The gases being generated in any significant amounts due to microbial activity are  $N_2$ ,  $CO_2$ , and  $CH_4$
- Although anaerobic conditions are assumed for the repository, methane is not the predominant gas generated. Under ideal conditions in a digester, methane and  $CO_2$  are generated in the ratio 7:3 (Atlas, 1984). The methane generation is easily upset under non-ideal conditions. In the repository, the pH, carbon-to-phosphorus-to-nitrogen ratio, oxygen depletion, etc., are far from being ideal for methane generation. Radiolysis may generate pockets of oxygen (still under oxygen limiting conditions) which will favor  $CO_2$  generation. Hence  $CO_2$  has been assumed to be generated in larger quantities than methane.

Based on the previous discussion, these are the microbial gas generation parameters used in the modeling:

- During the first 100 years, oxygen is completely consumed with an equivalent molar rate of carbon dioxide production taking place. Accelerated microbial activity is assumed to set in only after this period. This is a reasonable assumption, since microbial activity at optimum rates requires availability of substrate, nutrients and water. This may be possible only after intimate mixing of the waste in the panel.
- Accelerated microbial activity is assumed to ensue after 100 years at the rate of 0.85 moles/drum/year with a gas production potential of 606 moles/drum (Lappin et al., 1989, p. 4-7).
- Therefore, the duration of microbial generation is 713 years, beginning 100 years after the start of the simulation. The gases which would be generated are methane, carbon dioxide, and nitrogen in the molar ratio 15:20:12.

### 2.13 HYDROGEN GENERATION BY ANOXIC CORROSION OF METALS (MASSGAS)

Anoxic corrosion of the metal drums is assumed to start at time = 0 and proceed until the gas production potential (894 moles of hydrogen/drum) has been generated (Lappin et al., 1989, p. 4-10). The maximum hydrogen generation rate is 1.70 moles/drum/year if  $5 \times 10^{-5} m^3$  of water are available, per year, per unprocessed waste drum. This is based on the assumption that amakanite is produced requiring 2 moles of water per mole of iron. If brine/water availability is less than the amount required for maximum hydrogen generation, the hydrogen generation rate

is scaled down based on the amount of available water contained in the brine present in the panel.

#### 2.14 REACTIONS OF CARBON DIOXIDE WITH BRINE AND CEMENT (BRINTERACT)

It was estimated that there are approximately 13.03 moles of portlandite [Ca(OH)<sub>2</sub>] per equivalent drum in a panel of 75,240 drums. Carbon dioxide, which may potentially be generated, will dissolve in brine and react with the portlandite to yield calcite and water by the following reaction (see Appendix E):



The geochemical modeling codes EQ3NR and EQ6 (Wolery, 1983; Wolery, 1984) were used to determine the fugacity of carbon dioxide in the brine, at equilibrium. This fugacity was calculated to be 0.08 atm. At equilibrium, the fugacity of a component in the liquid phase is the same as the fugacity in the gas phase. The fugacity of carbon dioxide in the gas phase is assumed to be equal to the partial pressure of the gas (true for ideal gases). The moles of carbon dioxide which are available for precipitation in brine are evaluated as:

$$\text{mole of CO}_2 \text{ available} = \text{mole of CO}_2 \text{ in gas phase} - \frac{0.08 \text{ atm} \times V_v}{ZRT} \quad (2.14-2)$$

where,

$$\begin{aligned} V_v &= \text{void volume in panel (m}^3\text{)} \\ Z &= \text{compressibility factor of panel gases} \\ R &= \text{gas law constant (8.206} \times 10^{-5} \text{ atm} \cdot \text{m}^3\text{/mol}^\circ\text{K)} \\ T &= \text{absolute temperature (300}^\circ\text{K)}. \end{aligned}$$

The number of moles of CO<sub>2</sub> available is scaled down by a factor which relates the amount of CO<sub>2</sub> which can react to form calcite to the amount of brine present in a panel. It is assumed that the reaction cannot proceed in the absence of brine.

This scale factor is evaluated through the following relation:

$$\text{SCALFACT} = 1 - \left[ \frac{V_v}{(V_v + V_b)} \right] \quad (2.14-3)$$

where,

$$V_b = \text{volume of brine in panel (m}^3\text{)}.$$

The actual moles of carbon dioxide which are removed from the gas phase is then:

$$\frac{\text{mole } CO_2}{\text{removed}} = \frac{\text{mole } CO_2}{\text{available}} \times SCALFACT$$

(2.14-4)

The moles of portlandite consumed is then equal to the moles of carbonate minerals precipitated. If there are less moles of portlandite present in the room than what can potentially be consumed, then the maximum consumed is equal to the moles present. The moles of calcite and water formed is equal to the moles of portlandite consumed. The moles of water and the moles comprising the liquid phase are updated based on the quantity of water generated. The total mass of the solids in the panel is also updated based upon the mass of calcite created and the mass of portlandite consumed.

## 2.15 ESTIMATION OF EFFECTIVE STRESS OF WASTE/BACKFILL COMPOSITE (COMPACTION)

As discussed in Section 2.4, the difference between the lithostatic stress and the sum of the gas pressure and the effective stress of the waste/backfill composite defines the rate at which rock creep (closure) occurs. Densities of the waste/backfill composite, as a function of applied stress level, have been evaluated for each engineered alternative (Section 3.0 in Volume I). The effective stress is the stress that is transferred between the solid particles of the waste/backfill composite. Regression equations relating effective stress as a function of density have been derived from the density-stress data. Coefficients of the regression polynomials are included in the input data file created for each alternative. The density of the waste/backfill composite is evaluated at each time step by dividing the mass of the solids by the difference of the panel volume and the volume of the air gap clearance in subroutine VOLESTIM (Section 2.17). The effective stress of the waste/backfill composite is then evaluated at each time step using the effective stress versus density regression equations in subroutine COMPACTION.

## 2.16 PRESSURE ESTIMATION USING THE LEE-KESSLER EQUATION OF STATE (LKEOS)

The pressure of the gas mixture in the panel is evaluated using the Lee-Kessler equation of state. This equation is a modification of the Benedict-Webb-Rubin equation of state (Reid et al., 1987). The Lee-Kessler equation is recommended by Reid et al. (1987), for generalized use in the computation of fluid pressure at expanded ranges of temperature and pressure. The equation is capable of accurately representing the liquid phase. In comparing the predicted compressibilities with experimental data, average errors were less than two percent for both the

vapor and liquid phases. A complete description of the equation is provided in Reid et al. (1987), pp. 47-49 and pp. 84-87.

The following is a summary of the methodology.

The pseudocritical properties of the gas mixture are computed as follows:

$$T_{cj} = (T_{ci} T_{cj})^{1/2} k_{ij} \quad (2.16-1)$$

$$V_{cj} = \frac{(V_{ci}^{1/3} + V_{cj}^{1/3})^3}{8} \quad (2.16-2)$$

$$T_{cm} = \frac{\sum_{j=1}^{NC} y_j V_{cj}^{1/4} T_{cj}}{V_{cm}^{1/4}} \quad (2.16-5)$$

$$P_{cm} = \frac{(0.2905 - 0.085\Omega_m) R T_{cm}}{V_{cm}} \quad (2.16-6)$$

where,

- $T_{ci}$  = critical temperature of component "i" (°K)
- $T_{cm}$  = pseudocritical mixture temperature (°K)
- $k_{ij}$  = binary interaction coefficient
- $V_{ci}$  = critical volume of component "i" (cm<sup>3</sup>/mol)
- $V_{cm}$  = pseudocritical mixture volume (cm<sup>3</sup>/mol)
- $y_i$  = mole fraction component "i"
- $\Omega_m$  = Pitzer acentric factor of mixture
- $R$  = gas constant (82.057 atm cm<sup>3</sup>/mol °K)
- $P_{cm}$  = pseudocritical mixture pressure (atm)
- $NC$  = number of components.

In practice, the compressibility factor of an actual fluid is evaluated from the properties of a "simple fluid" (one for which Pitzer's acentric factor is zero) and those of n-octane, which is the reference fluid for this method (Reid et al., 1987). Once the mixture pseudocritical properties are computed, the simple fluid compressibility factor,  $Z^{(0)}$  is evaluated as:

$$Z^{(0)} = \frac{1 + \frac{B}{V_r} + \frac{C}{V_r^2} + \frac{D}{V_r^3} + c_4 \left[ \beta + \frac{\tau}{V_r^2} \right] \exp\left(\frac{-\tau}{V_r^2}\right)}{T_r^3 V_r^2} \quad (2.16-7)$$

where,

$$T_r = \frac{T}{T_{cm}} \quad (2.16-8)$$

$$V_r = \frac{P_{cm} V}{R T_{cm}} \quad (2.16-9)$$

$$B = b_1 - b_2/T_r - b_3/T_r^2 - b_4/T_r^3 \quad (2.16-10)$$

$$C = c_1 - c_2/T_r + c_3/T_r^3 \quad (2.16-11)$$

$$D = d_1 + d_2/T_r \quad (2.16-12)$$

where the constants  $b_1, b_2, b_3, b_4, c_1, c_2, c_3, c_4, d_1, d_2, B$  and  $\tau$  are given in Table B-3 under the "Simple fluid" heading. Next, the compressibility factor for the reference fluid,  $Z^{(R)}$  is computed using equations (2.16-7) through (2.16-12), but using the constants  $b_1, b_2, b_3, b_4, c_1, c_2, c_3, c_4, d_1, d_2, B$  and  $\tau$  of the reference fluid from Table B-3.

The compressibility factor,  $Z$ , for the gas mixture is then calculated as:

$$Z = Z^{(0)} + \frac{\Omega_m}{0.3978} (Z^{(R)} - Z^{(0)}) \quad (2.16-13)$$

The pressure of the gas mixture is then:

$$P = \frac{Z R T}{V} \quad (2.16-14)$$

where,

$V$  = molar volume of gas mixture ( $\text{cm}^3/\text{mol}$ ).

**TABLE B-3**  
**LEE-KESSLER EQUATION OF STATE CONSTANTS**

CONSTANT	SIMPLE FLUID	REFERENCE FLUID
$b_1$	0.1181193	0.2026579
$b_2$	0.265728	0.331511
$b_3$	0.154790	0.027655
$b_4$	0.030323	0.203488
$c_1$	0.0236744	0.0313385
$c_2$	0.0186984	0.0503618
$c_3$	0.0	0.016901
$c_4$	0.042724	0.041577
$d_1 \times 10^4$	0.155488	0.48736
$d_2 \times 10^4$	0.623689	0.0740336
$\beta$	0.65392	1.226
$\tau$	0.060167	0.03754

Reid et al., 1987, p. 48

## 2.17 ESTIMATION OF VOLUMES IN PANEL (VOLESTIM)

Several volume related parameters are calculated in subroutine VOLESTIM and are described here.

Once the height,  $h$ , and width,  $w$ , of an equivalent room are evaluated in subroutine CREEP (Section 2.4) the volume of the panel ( $V_{pnl}$ ), at the end of a time step is evaluated as:

$$V_{pnl} = 7hw l_{room} + 12hww_{pillar} + 14hw^2 \quad (2.17-1)$$

where,

$$\begin{aligned} l_{room} &= \text{length of the room (91.44m)} \\ w_{pillar} &= \text{width of a salt pillar between rooms (30.48m)} \end{aligned}$$

The volume of the air gap clearance above the waste/backfill composite stack,  $V_{atmc}$  is then evaluated based on the discussion in (Section 2.1).

$$V_{atmc} = 7(h - h_{stack})wl_{room} + 12(h - h_{stack})ww_{pillar} + 14(h - h_{stack})w^2 \quad (2.17-2)$$

where,

$$h_{stack} = \text{height of the waste/backfill composite stack (3.3528m)}$$

The creep of the surrounding halite creates an additional void volume within a zone of enhanced porosity which the panel gases will occupy. The rate and extent of creep closure will govern the magnitude of this void volume. This void volume is calculated at each time step as the product of the porosity of the Intact Salado Formation (0.001) (Marietta et al., 1989, Table 3-9) and the difference between the initial panel volume and the panel volume at the current time step. It is assumed that the zone of enhanced porosity does not contain brine and that all pores are interconnected.

The void volume in the panel,  $V_v$  is then evaluated as:

$$V_v = V_{pnl} - V_{WB} - V_B + (V_{pnl}(0) - V_{pnl})n + V_{MB} \quad (2.17-3)$$

where,

- $V_{WB}$  = volume of the waste/backfill composite less pores ( $m^3$ )
- $V_B$  = volume of brine in the panel ( $m^3$ )
- $V_{pnl}(0)$  = initial panel volume ( $m^3$ )
- $V_{pnl}$  = panel volume at current time step ( $m^3$ )
- $n$  = porosity of the intact Salado Formation (0.001) (Marletta et al., 1989)
- $V_{MB}$  = cumulative void volume that is available for gas storage in the disturbed marker Bed 139 underlying the repository ( $m^3$ ) (Section 2.6).

The molar volume [for use in pressure estimation (Section 2.18)] is calculated by dividing the void volume in the panel by the total number of moles of gas present in the panel.

Finally, the density of the solids in the panel is calculated as:

$$\rho_{solid} = \frac{m_{solid}}{V_{pnl} - V_{cme}} \quad (2.17-4)$$

where,

- $\rho_{solid}$  = density of the waste/backfill composite ( $kg/m^3$ )
- $m_{solid}$  = mass of solids in the panel (kg).

## 2.18 SIMULATION OF BOREHOLE INTRUSION CONSEQUENCES (BOREHOLE)

The consequences of three borehole intrusion scenarios designated as E1, E2 and E1E2 (Marletta et al., 1989) were evaluated as part of the EATF modeling effort. The effectiveness and relative effectiveness measures of engineered alternatives are defined in Section 2.25. For consistency in evaluating the relative effectiveness measures of engineered alternatives, the intrusion is assumed to occur 5000 years into the simulation, for all cases. This results in a 5000 year time span for the release of contaminated brine, which is herein defined as the "release time."

The driver subroutine in the Design Analysis Model which coordinates the intrusion scenario simulations is called BOREHOLE. This subroutine calls other subroutines to calculate the effectiveness measure for the three scenarios, for each alternative studied. The sequence of calls to various subroutines is indicated by the order of the descriptions below. A detailed description of each subroutine follows in the subsections of this chapter.

Subroutine ESTHCKSS is called to evaluate the hydraulic conductivity and specific storage of the waste/backfill composite at the time of borehole intrusion.

Subroutine RADACTIM evaluates the mass and activity of each radionuclide in the total inventory at the time of borehole intrusion.

Subroutine CUTTINGS is called to evaluate the activity of each radionuclide released to the surface with the cuttings and eroded material resulting from the drilling extraction process. In addition the mass and activity of each radionuclide is also evaluated in this subroutine, on a panel basis.

Subroutine RADSOLUB evaluates the solubility of each radionuclide in brine.

Subroutine ISE1 evaluates the volume of contaminated brine reaching the Culebra as a result of intrusion scenario E1 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E1.

Subroutine ISE2 evaluates the volume of contaminated brine released to the Culebra as a result of intrusion scenario E2 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E2.

Subroutine ISE1E2 evaluates the volume of contaminated brine released to the Culebra as a result of intrusion scenario E1E2 (Marietta et al., 1989).

Subroutine SUMRULE is called to evaluate the effectiveness measure of an engineered alternative as a result of intrusion scenario E1E2.

## 2.19 ESTIMATION OF WASTE/BACKFILL COMPOSITE HYDRAULIC CONDUCTIVITY AND SPECIFIC STORAGE (ESTHCKSS)

During the development of physical and chemical properties resulting from the use of engineered alternatives, a table of hydraulic conductivity versus stress level was generated for each alternative. The methodology for hydraulic conductivity development is described in Section 3.0 in Volume I. The natural logarithm of the hydraulic conductivity is expressed as a ninth order polynomial function of the effective stress level of waste compaction. Therefore, from knowledge of the effective stress level of waste compaction at the time of borehole intrusion, the hydraulic conductivity is obtained from a regression equation.

The specific storage of a porous media such as the waste/backfill composite can be evaluated from the following equation (Freeze and Cherry, 1979, p. 59):

$$S_s = \rho g(\alpha + n\beta) \quad (2.19-1)$$

where,

- $S_s$  = specific storage (1/m)
- $\rho$  = density of brine (1220kg/m<sup>3</sup>)
- $\alpha$  = compressibility of the waste/backfill composite
- $n$  = porosity of the waste/backfill composite
- $\beta$  = compressibility of brine (4.4x10<sup>-10</sup>Pa<sup>-1</sup>) (Freeze and Cherry, 1979).

The compressibility of the waste-backfill matrix can be evaluated through the following relation (Freeze and Cherry, 1979, p. 338):

$$\alpha = \frac{-1}{(1+e_0)} \frac{de}{d\sigma} \quad (2.19-2)$$

where,

- $e$  = void ratio of the waste/backfill composite
- $e_0$  = void ratio of the waste/backfill composite at zero stress level
- $\sigma$  = effective stress level of waste compaction (MPa).

For each engineered alternative, a table of porosity at various stress levels was developed (Section 3.0 in Volume I). The void ratio corresponding to a porosity value,  $n$ , is calculated through the relation:

$$e = \frac{n}{(1-n)} \quad (2.19-3)$$

For each effective stress level of waste compaction, a corresponding void ratio is computed. A ninth order polynomial provides an adequate expression for the void ratio as a function of stress level. The derivative of the void ratio with respect to stress level ( $de/d\sigma$ ) is then obtained by differentiating the ninth order polynomial with respect to stress level:

$$\frac{de}{d\sigma} = c_2 + 2c_3\sigma + 3c_4\sigma^2 + 4c_5\sigma^3 + 5c_6\sigma^4 + 6c_7\sigma^5 + 7c_8\sigma^6 + 8c_9\sigma^7 + 9c_{10}\sigma^8 \quad (2.19-4)$$

where,

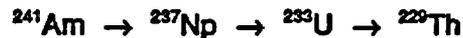
$c_2 \dots c_{10}$  = void ratio vs. stress level regression coefficients

and evaluating this derivative at the effective stress level corresponding to the time of borehole intrusion. The coefficients of this regression equation are included in the input data file created for each engineered alternative.

## 2.20 ESTIMATION OF THE INVENTORY RADIONUCLIDE ACTIVITIES (RADACTIM)

To evaluate the effectiveness measure of an engineered alternative, it is necessary to compute the activity and mass of each radionuclide in the inventory, as a function of time. The activity of each radionuclide can then be estimated for any assumed time of intrusion. The modified inventory and simplified radionuclide chains (Lappin et al., 1989, p. 4-25) were used in the calculations.

The simplified radionuclide chains are:



The following table (Table B-4) contains the differential equations describing the variation of the quantity of each radionuclide with time, the decay constants and the initial activity of each radionuclide.

where,

$n_i$  = atoms of radionuclide "i"

$\alpha$  = decay constant of radionuclide "i"

The decay constants were computed from the half-lives listed on pp. 4-25 of (Lappin et al., 1989) using the relation  $\alpha = \ln 2/\text{half-life}$ .

The differential equations listed in Table B-4 were solved analytically. The activity of each radionuclide at the time of intrusion was calculated as the product of the atoms of each nuclide and the decay constant of the nuclide. The evaluation of radionuclide activities and masses is performed in the subroutine RADACTIM of the Design Analysis Program.

## 2.21 ESTIMATION OF ELEMENT SOLUBILITIES (RADSOLUB)

The solubilities specified in the input data file of the Design Analysis Model are given by individual element and are not isotope (radionuclide) specific. To provide estimates of specific radionuclide

**TABLE B-4**  
**ACTIVITY DIFFERENTIAL EQUATIONS, INITIAL ACTIVITIES**  
**AND DECAY CONSTANTS OF RADIONUCLIDES**

Radionuclide Constant	ID Index "I"	Activity Differential Equation	Initial Activity (curies)	Decay ( $\alpha$ ) ( $\text{yr}^{-1}$ )
$^{240}\text{Pu}$	1	$dn_1/dt = -\alpha_1 n_1$	$1.05 \times 10^5$	$1.060 \times 10^{-4}$
$^{238}\text{U}$	2	$dn_2/dt = \alpha_1 n_1 - \alpha_2 n_2$	0	$2.962 \times 10^{-8}$
$^{241}\text{Am}$	3	$dn_3/dt = -\alpha_3 n_3$	$7.75 \times 10^5$	$1.604 \times 10^{-3}$
$^{237}\text{Np}$	4	$dn_4/dt = \alpha_3 n_3 - \alpha_4 n_4$	8.02	$3.239 \times 10^{-7}$
$^{235}\text{U}$	5	$dn_5/dt = \alpha_4 n_4 - \alpha_5 n_5$	$7.72 \times 10^3$	$4.395 \times 10^{-8}$
$^{229}\text{Th}$	6	$dn_6/dt = \alpha_5 n_5 - \alpha_6 n_6$	0	$9.329 \times 10^{-5}$
$^{238}\text{Pu}$	7	$dn_7/dt = -\alpha_7 n_7$	$3.90 \times 10^8$	$7.904 \times 10^{-3}$
$^{234}\text{U}$	8	$dn_8/dt = \alpha_7 n_7 - \alpha_8 n_8$	0	$2.841 \times 10^{-8}$
$^{230}\text{Th}$	9	$dn_9/dt = \alpha_8 n_8 - \alpha_9 n_9$	0	$9.002 \times 10^{-8}$
$^{226}\text{Ra}$	10	$dn_{10}/dt = \alpha_9 n_9 - \alpha_{10} n_{10}$	0	$4.332 \times 10^{-4}$
$^{210}\text{Pb}$	11	$dn_{11}/dt = \alpha_{10} n_{10} - \alpha_{11} n_{11}$	0	$3.108 \times 10^{-2}$
$^{239}\text{Pu}$	12	$dn_{12}/dt = -\alpha_{12} n_{12}$	$4.25 \times 10^5$	$2.876 \times 10^{-5}$

[Lappin et al., 1989]

solubilities, the following dimensional analysis relation is assumed valid:

$$S_i = M_e AW_i mf_i 1000 \text{ l/m}^3 \quad (2.21-1)$$

where,

- $S_i$  = solubility of radionuclide "i" in brine (g "i"/m<sup>3</sup>)
- $M_e$  = solubility of element "e" in brine (mol "e"/l brine)
- $AW_i$  = atomic weight of radionuclide "i" (g "i"/mol i)
- $mf_i$  = mass fraction of radionuclide "i"
  - mass of radionuclide "i" in waste divided by the sum of masses of all isotopes (radionuclides in the waste of the element which includes isotope "i").

The mass fraction of <sup>210</sup>Pb is evaluated by dividing the mass of <sup>210</sup>Pb in the inventory at the time of intrusion by the total lead in the inventory. The mass of stable lead in the inventory used in the calculation was 513,000 kg (Drez and James-Lipponer, 1989).

The specific radionuclide solubilities are evaluated in the subroutine RADSOLUB of the Design Analysis Model program.

## 2.22 ESTIMATION OF RADIONUCLIDE RELEASES WITH CUTTINGS (CUTTINGS)

The activity of each radionuclide released to the surface (with the cuttings and eroded waste/backfill material) during the drilling process is evaluated in the subroutine CUTTINGS.

The radionuclides are assumed to be evenly distributed in the waste and in the backfill existing between the waste containers and on top of the waste [i.e., it is assumed no radionuclides exist in the backfill on the sides of the waste stack to be conservative since this maximizes the activity density (Section 3.0 in Volume I)]. For each alternative, this effective waste volume (denoted by the variable VOLWST) is expressed by a ninth order polynomial equation. This equation was obtained by regressing the effective waste volume versus the effective stress-level of waste compaction data. The regression coefficients from this analysis are included in the input data file created for each individual engineered alternative.

At the time of borehole intrusion, the effective waste volume is estimated using this regression equation (from knowledge of the effective stress-level of waste compaction). The most recent estimate of the number of drum equivalents in the repository is  $5.56 \times 10^6$  (Lappin et al., 1989, p. 5-9). The activity of each radionuclide in the total repository at the time of borehole intrusion is evaluated in subroutine RADACTIM (Section 2.19). The activity of each radionuclide for each drum equivalent is then established. The number of drum equivalents per panel is specified in the input data file. The activity of a radionuclide per panel is then evaluated as the product of the

activity of that radionuclide per equivalent drum and the number of equivalent drums per panel. The activity density (curies of a radionuclide per cubic meter of waste and backfill on top) is then the ratio of the activity of that radionuclide per panel to the value of VOLWST.

The activity of each radionuclide released to the surface with the cuttings and eroded material resulting from the drilling of a single borehole (assumed to have a cylindrical shape) is evaluated in the subroutine CUTTINGS as:

$$A_{cut,i} = \frac{\pi (rf r_{bor})^2 h_{room} A_{rep,i}}{5.56 \times 10^5 \text{ drum equivalents/repository}} \times \frac{NDE}{VOLWST} \quad (2.22-1)$$

where,

- $A_{cut,i}$  = activity of radionuclide "i" released to the surface with the cuttings and eroded material from a single borehole (curie)
- $rf$  = radius factor (see below for description)
- $r_{bor}$  = radius of the intrusion borehole (m)
- $h_{room}$  = height of room (m)
- $A_{rep,i}$  = activity of radionuclide "i" in the entire repository (curie)
- $VOLWST$  = effective waste volume (m<sup>3</sup>)
- $NDE$  = number of drum equivalents per panel.

The radius factor will vary with the waste form to reflect the anticipated amount of erosion. For waste forms which are cemented and vitrified, one borehole radius was assumed (i.e.,  $rf = 1$ ). For all other waste forms a radius factor ( $rf$ ) of 2 was assumed, except for supercompacted waste forms for which a radius factor of 1.5 was assumed.

The mass and activity of each radionuclide are then evaluated as:

$$M_{panel,i} = \frac{M_{rep,i} NDE}{5.56 \times 10^5 \text{ drum equivalents/repository}} - \frac{A_{cut,i}}{SA_i} \quad (2.22-2)$$

and

$$A_{panel,i} = \frac{A_{rep,i} NDE}{5.56 \times 10^5 \text{ drum equivalents/repository}} - A_{cut,i} \quad (2.22-3)$$

where,

- $A_{panel,i}$  = activity of radionuclide "I" in a panel after removal  
of activity with cuttings (curie)  
 $M_{panel,i}$  = mass of radionuclide "I" in panel at the time of borehole intrusion (g)  
 $M_{rep,i}$  = mass of radionuclide "I" in entire repository  
at the time of borehole intrusion (g)  
 $SA_i$  = specific activity of radionuclide I (curie/g).

## 2.23 CONTAMINATED BRINE VOLUME RELEASED DUE TO E1 INTRUSION SCENARIO (ISE1)

Intrusion scenario E1 is modeled as a single borehole penetrating a waste-filled area located at the intersection of a room and drift (Marietta et al., 1989). The borehole passes through the repository and continues penetrating until a pressurized brine pocket in the Castile Formation is struck. This scenario was modeled as a two-dimensional problem using the SWIFT-III flow code. The hydraulic conductivity of the waste/backfill is assumed to be homogeneous and isotropic, with impermeable boundaries at the room edges. The borehole is also assumed to be homogeneous and isotropic, with a conductivity of  $1 \times 10^{-3}$  m/s. In addition, the borehole is assumed to have fixed pressures at the top and bottom of the repository. These pressures were evaluated by hydrostatic interpolation assuming  $0.92 \times 10^6$  Pa in the Culebra (located 440 m above repository) and  $16.0 \times 10^6$  Pa in the Castile formation (located 270 m below repository) (Marietta et al., 1989). Preliminary sensitivity runs indicated that steady state conditions are attained in a short time span relative to the release time.

Multi-parameter least-squares regression (Box et al., 1978) was used to derive parametric equations for the steady state flowrate ( $Q_w$ ) of Castile brine through the waste/backfill composite. These equations were based on data obtained from a series of SWIFT-III runs varying the hydraulic conductivity (K) of the composite and the intrusion borehole radius (r). The developed equations are given below:

For  $K < 1 \times 10^{-8}$  m/s

$$Q_w \times 10^5 = 0.2752 - 0.4831r + 92.675r^2 - 0.0276(-\log K) \quad (2.23-1)$$

For  $1 \times 10^{-8}$  m/s  $\leq K \leq 1 \times 10^{-6}$  m/s

$$Q_w \times 10^5 = 131.4734 + 6.5171r + 81.2264r^2 - 34.78(-\log K) - 2.2282 (-\log K)^2 \quad (2.23-2)$$

For  $K > 1 \times 10^{-8}$  m/s

$$Q_w \times 10^4 = 1608.0937 + 25.7528r - 847.4249(-\log K) + 149.0608(-\log K)^2 - 8.7619(-\log K)^3 \quad (2.23-3)$$

The volume of waste through which brine flows is termed the "wash-through volume". This volume is computed as an ellipsoid whose semi-axes are half the room height, an effective radius, and the effective width. The effective radius,  $r_{eff}$  is defined as the maximum distance from the borehole where the fluid velocity is  $10^{-12}$  m/s. The effective radius is computed through a regression equation developed from SWIFT-III computer code runs using various waste/backfill hydraulic conductivities (K in units of m/s). This parametric equation takes the form:

$$r_{eff} = 41.8976 - 3.84383(-\log K) + 0.0640027(-\log K)^2 \quad (2.23-4)$$

If the effective radius is less than half the room width the effective width is equal to the effective radius; otherwise it is set to half the room width (this is the maximum lateral axis radius possible). The fraction of radionuclides available for release (RLSFRAC, see Section 2.25) is defined as:

$$RLSFRAC = \frac{\text{wash-through volume} - \text{volume of cuttings}}{\text{total panel volume}} \quad (2.23-5)$$

The volume of brine which flows through the waste/backfill is the product of the flowrate through the waste/backfill and the release time.

## 2.24 CONTAMINATED BRINE VOLUME RELEASED DUE TO E2 INTRUSION SCENARIO (ISE2)

Intrusion scenario E2 is modeled as a single borehole penetrating the center of a waste-filled panel (Marletta et al., 1989). It is assumed that no additional sources of water or external pressurized brine pockets are intersected during the drilling process. An analytical solution is used to evaluate the cumulative volume of brine released during the release time. This equation is derived by solving the one-dimensional radial flow equation:

$$\frac{\partial \phi}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} rD \frac{\partial \phi}{\partial r} \quad (2.24-1)$$

where,

$$\phi = \text{dimensionless hydraulic head} = \frac{[h(r,0) - h(r,t)]}{h(r,0)}$$

$r$  = radial direction coordinate (m)  
 $D$  = hydraulic diffusivity ( $m^2/yr$ ).

with the following initial and boundary conditions:

$$\phi(r, t = 0) = 0 \quad (2.24-2a)$$

$$\phi(r = a, t) = \phi_a \quad [\text{fixed pressure head of brine in the borehole based on the distance to the culebra}] \quad (2.24-2b)$$

$$\frac{\partial \phi}{\partial r} \Big|_{(r = b, t)} = 0 \quad [\text{no flow at the edge of the panel}] \quad (2.24-2c)$$

where,

$a$  = radius of borehole (m)  
 $b$  = equivalent radius of panel  
 $= [(91.44m \times 7w + 30.48m \times 12w + 14w^2)/\pi]^{1/2}$  (m).

The initial hydraulic head in the panel,  $h(r,0)$  is evaluated as:

$$h(r,0) = \frac{P(r,0)}{\rho g} \quad (2.24-3)$$

where,

$h(r,t)$  = hydraulic head at radius,  $r$  (m)  
 $P(r,0)$  = gas pressure in panel at the time of intrusion (Pa)  
 $\rho$  = density of brine ( $1220kg/m^3$ )  
 $g$  = gravitational acceleration ( $9.80665m/s^2$ ).

The solution to equation (2.24-1) subject to the initial and boundary conditions (2.24-2a,b,c) is given by (Crank, 1975, p. 86)

$$\phi = \phi_s \left[ 1 - \pi \sum_{n=0}^{\infty} e^{(-\alpha_n^2 t)} J_1^2(b\alpha_n) \frac{J_0(r\alpha_n) Y_0(a\alpha_n) - J_0(a\alpha_n) Y_0(r\alpha_n)}{J_1^2(b\alpha_n) - J_0^2(a\alpha_n)} \right] \quad (2.24-4)$$

where  $\alpha_n$  are the roots of the equation

$$\alpha_n [J_1(b\alpha_n) Y_0(a\alpha_n) - J_0(a\alpha_n) Y_1(b\alpha_n)] = 0 \quad (2.24-5)$$

where the J's and Y's are the Bessel functions of the first and second type respectively.

The flowrate, Q out of the panel and into the borehole is then from (Freeze and Cherry, 1979, p. 16)

$$Q = Av = -AK \frac{\partial h}{\partial r} \Big|_{r=s} = -2\pi aHK \frac{\partial h}{\partial r} \Big|_{r=s} \quad (2.24-6)$$

where,

- $Q$  = volumetric flowrate ( $m^3/yr$ )
- $A$  = area of flow ( $m^2$ )
- $v$  = specific discharge ( $m/yr$ )
- $K$  = hydraulic conductivity ( $m/yr$ )
- $w$  = width of room in panel ( $m$ )
- $H$  = height of room ( $m$ ).

The flowrate to the borehole as a function of time is evaluated from equation (2.24-6) as:

$$Q(t) = 2\phi_s \pi^2 aHK h(r,0) \sum_{n=1}^{\infty} \exp(-D\alpha_n^2 t) f(\alpha_n, a, b) \quad (2.24-7)$$

where,

$$f(\alpha_n, a, b) = \frac{\alpha_n J_1^2(b\alpha_n) \{ Y_1(a\alpha_n) J_0(a\alpha_n) - J_1(a\alpha_n) Y_0(a\alpha_n) \}}{J_1^2(b\alpha_n) - J_0^2(a\alpha_n)} \quad (2.24-8)$$

The total volume of fluid released from the panel during release time,  $t_r$ , is evaluated by integrating equation (2.24-7) with respect to time which gives:

$$V_{\text{fluid}}(t_r) = 2\phi_r \pi^2 a H K h(r, 0) \sum_{n=1}^{\infty} f(\alpha_n, a, b) \left[ \frac{1 - e^{(-D\alpha_n^2 t_r)}}{D\alpha_n^2} \right] \quad (2.24-9)$$

The panel is assumed to be saturated with a homogeneous fluid with the properties of WIPP brine. Since the majority of the released fluid consists of generated gases, the actual volume of brine released is evaluated as:

$$V(t_r) = \frac{V_{\text{fluid}}(t_r) V_{\text{brine}}}{(V_{\text{void}} + V_{\text{brine}})} \quad (2.24-10)$$

where,

- $V(t_r)$  = volume of brine released to Culebra over the release time ( $m^3$ )
- $V_{\text{fluid}}(t_r)$  = total fluid (brine + panel gases) released to Culebra during the release time,  $t_r$ , evaluated in equation (2.24-9) ( $m^3$ )
- $V_{\text{void}}$  = void volume in panel at intrusion time ( $m^3$ )
- $V_{\text{brine}}$  = volume of brine in panel at intrusion time ( $m^3$ ).

The maximum quantity of brine available for release is the total volume of brine present in the panel at the intrusion time. This approach neglects the effects of the gas expansion up the borehole.

## 2.25 CONTAMINATED BRINE VOLUME RELEASED DUE TO E1E2 INTRUSION SCENARIO (ISE1E2)

Intrusion scenario E1E2 is modeled as two boreholes which fully penetrate opposite ends of a room filled with waste/backfill (Marietta et al., 1989). One borehole penetrates the pressurized brine in the Castile Formation and is assumed to be plugged between the repository and the Culebra. The second borehole penetrates the same panel but does not penetrate the Castile Formation and is plugged above the Culebra. A pathway is then established for the flow of brine from the Castile Formation through the waste and up into the Culebra. The boreholes are assumed to remain at fixed hydraulic heads neglecting slight changes in elevation from the

bottom to the top of the panel. The volume of brine which flows through the waste is evaluated from the solution to the one-dimensional flow equation:

$$\frac{\partial h}{\partial t} = D \frac{\partial^2 h}{\partial x^2} \quad (2.25-1)$$

with the following initial and boundary conditions:

$$h(x,0) = h_0 = h_1 \quad (2.25-2a)$$

The hydraulic head initially in panel is equal to the hydraulic head in the borehole penetrating the Castile Formation.

$$h(0,t) = h_1 = 1337.3 \text{ m} \quad (2.25-2b)$$

The hydraulic head of the second borehole is due to the pressure in the Culebra plus the elevation.

$$h(l,t) = h_2 = 787.9 \text{ m} \quad (2.25-2c)$$

where,

- $h$  = hydraulic head (m)
- $x$  = distance from the borehole penetrating the Castile along the line connecting the two boreholes
- $l$  = separation of the two boreholes (one room length is arbitrarily chosen as the distance separating the two boreholes, i.e., 91.44 m)
- $D$  = hydraulic diffusivity ( $\text{m}^2/\text{s}$ ).

The solution to equation (2.25-1) subject to initial and boundary conditions (2.25-2a,b,c) is given by (Carslaw and Jaeger, 1959, pp. 99-100) as:

$$\begin{aligned} h(x,t) = & h_1 + (h_2 - h_1) \frac{x}{l} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(h_2 \cos n\pi - h_1)}{n} \sin\left(\frac{n\pi x}{l}\right) \exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right) \\ & + \frac{2}{l} \sum_{n=1}^{\infty} \sin\left(\frac{n\pi x}{l}\right) \exp\left(-\frac{Dn^2\pi^2 t}{l^2}\right) \frac{h_2 (1 - \cos(n\pi))}{n\pi} \end{aligned} \quad (2.25-3)$$

The volumetric flowrate of brine leaving the repository and flowing into the Culebra may be expressed as:

$$Q = -KA \left. \frac{\partial h}{\partial x} \right|_{x=l} \quad (2.25-4)$$

where,

- $Q$  = volumetric flux of brine into the Culebra at time,  $t$  ( $m^3/yr$ )
- $K$  = hydraulic conductivity of the waste/backfill composite ( $m/yr$ )
- $A$  = cross-sectional area of the borehole connecting the waste with the Culebra ( $m^2$ )

The total volume of fluid released to the Culebra during the release time,  $t_r$ , is computed by integrating equation (2.25-4) with respect to time.

The cumulative volume of brine released to the Culebra during the release time,  $t_r$ , is thus:

$$V(t) = -KA \frac{(h_2 - h_1)t_r}{l} - \frac{2l}{D\pi^2} \sum_{n=1}^{\infty} \frac{(h_2 \cos(n\pi) - h_1) \cos(n\pi)}{n^2} \left[ \exp\left(\frac{-Dn^2\pi^2 t_r}{l^2}\right) - 1 \right] - \frac{2h_0 l}{D\pi^2} \sum_{n=1}^{\infty} \frac{(1 - \cos(n\pi)) \cos(n\pi)}{n^2} \left[ \exp\left(\frac{-Dn^2\pi^2 t_r}{l^2}\right) - 1 \right] \quad (2.25-5)$$

The quantity of radionuclides which can potentially be released is limited to the quantity present in the volume between the two boreholes. This fraction (RLSFRAC, see Section 2.26) of the total radionuclides in the panel is evaluated as:

$$\begin{aligned} \text{RLSFRAC} = & \text{room width at time of borehole intrusion} \\ & \times \text{room height at time of borehole intrusion} \\ & \times \text{room length / panel volume at time of intrusion.} \end{aligned} \quad (2.25-6)$$

## 2.26 EVALUATION OF MEASURES OF RELATIVE EFFECTIVENESS (SUMRULE)

The measure of effectiveness of an engineered alternative is evaluated for each alternative and for each of the intrusion scenarios in the subroutine SUMRULE of the Design Analysis Model. The measure of effectiveness is the sum (over all isotopes) of the ratios of the cumulative activity release of isotope "i" into the Culebra to that of the allowed activity release of isotope "i". The total activity of the WIPP radionuclide inventory was estimated by summing the activities of each radionuclide in Table 4-2 of Lappin et al. (1989). This sum is equal to 5.21 MCi. The allowed release for each radionuclide based on the CH-TRU waste inventory for the WIPP is obtained by multiplying the values in Table 1 of 40 CFR Part 191 by the factor 5.21 since the release limits

(allowed releases) are based per MCI. The allowed releases of the radionuclides are shown in Table B-5.

The release limits of radionuclides are stored in array RL in the subroutine SUMRULE. A call is made to SUMRULE after the cumulative volume of brine released to the Culebra,  $V(t_R)$ , and the fraction of radionuclides in the panel available for release (RLSFRAC) is evaluated for intrusion scenarios E1 and E2. The entire panel radionuclide inventory is available for release in Scenario E2; thus, the value of RLSFRAC for this scenario is equal to 1.

If the summed release is being evaluated for intrusion scenarios E1 or E1E2, then the mass of each radionuclide which can potentially be released is scaled down as:

$$M_{avail,i} = M_{panel,i} RLSFRAC \quad (2.26-1)$$

where,

$$\begin{aligned} M_{avail,i} &= \text{mass of radionuclide "i" available for release (g)} \\ M_{panel,i} &= \text{mass of radionuclide "i" in a panel at the time} \\ &\quad \text{of borehole intrusion (g)} \\ RLSFRAC &= \text{ratio of the wash-through volume} \\ &\quad \text{to the total panel volume (Sections 2.23 and 2.25).} \end{aligned}$$

The dissolution of radionuclides in brine is assumed to be an instantaneous process. The solubility of each radionuclide in brine is evaluated in routine RADSOLUB (Section 2.21).

The released volume,  $V(t_R)$ , is multiplied by the radionuclide solubilities,  $S_i$ , to evaluate the maximum mass of radionuclides which could dissolve in the released brine. If the available mass,  $M_{avail,i}$  is less than what could potentially dissolve in the brine, the mass released is inventory limited. The activity of radionuclide "i" released to the Culebra with brine,  $A_{brine,i}$  is calculated by multiplying the mass released by the specific activity of the radionuclide.

The activity of each radionuclide released with the cuttings from a single borehole,  $A_{cut,i}$  is evaluated in subroutine CUTTINGS (Section 2.22). If the summed normalized release is being computed for intrusion scenario E1E2, then the activity released with the cuttings is twice what it is for a single borehole.

The measure of effectiveness (SUMRAD) of an engineered alternative with respect to an intrusion scenario is evaluated as:

where,

$$SUMRAD = \frac{\sum_{i=1}^{12} (A_{cut,i} + A_{brine,i})}{RL_i} \quad (2.26-2)$$

where,

$$\begin{aligned} SUMRAD &= \text{effectiveness measure} \\ RL_i &= \text{activity release limit (allowed release) of radionuclide "i"}. \end{aligned}$$

**TABLE B-5**  
**ACTIVITY RELEASE LIMITS OF WIPP INVENTORY RADIONUCLIDES**

<b>RADIONUCLIDE</b>	<b>ACTIVITY RELEASE LIMIT (Ci)</b>
<sup>240</sup> Pu	521
<sup>238</sup> U	521
<sup>241</sup> Am	521
<sup>237</sup> Np	521
<sup>233</sup> U	521
<sup>229</sup> Th	521
<sup>235</sup> Pu	521
<sup>234</sup> U	521
<sup>230</sup> Th	52
<sup>226</sup> Ra	521
<sup>210</sup> Pb	521
<sup>239</sup> Pu	521

The value of SUMRAD for an engineered alternative being studied is divided by the value of SUMRAD evaluated for the baseline case design to obtain a measure of effectiveness for the particular engineered alternative. These numbers cannot be used to show or disprove compliance with EPA 40 CFR Part 191 for the following reasons:

- Probabilities associated with intrusion events have not been factored into the calculations made in these analyses.
- In these evaluations, EPA Summed Normalized Releases are evaluated at the Culebra and not at the unit boundary since far-field modeling of flow and transport in the Culebra Dolomite is not being performed as part of the EATF project.

**APPENDIX C**

**DEVELOPMENT OF THE SEAL-SYSTEM COMPONENT  
OF THE DESIGN ANALYSIS MODEL**

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## DEVELOPMENT OF THE SEAL SYSTEM COMPONENT OF THE DESIGN ANALYSIS MODEL

### Introduction

The basic goal of the sealing system is to limit fluid migration in, through, and out of the repository. A multiple component system allows individual seal components to serve different functions, to be effective over different time spans, and to exist in different locations and formations in order to ensure sufficient redundant barriers are in place at all times (Stormont, 1988). The seal system objectives are accomplished by a combination of short-term and long-term seals. The short-term seals are to function for approximately 100 years after emplacement, the time of institutional control over the facility and the approximate time required for long-term seals to become functional (DOE, 1990c).

The short-term seals in drifts consist of concrete plugs and possibly crushed salt. The current design indicates that short-term seals in the upper portions of the shafts consist of swelling clay material confined by concrete bulkheads. The disturbed rock zone (DRZ) around the seals represents a potential flow path for brine. Indirect evidence that the permeability of salt may increase in the vicinity to an excavation is obtained from laboratory tests which indicate that permeability is dependent on confining stress. Kelsall et al. (1984) presents a variation in permeability with radius from the excavation. Due to the surrounding salt creep closure, the stress is expected to build up rapidly on the concrete plug, which consequently reduces permeability of the DRZ and the plug-salt interface. The long-term seals are made of crushed salt (DOE, 1990c) which is chemically and mechanically compatible with the host formation. The creep closure of the surrounding intact salt will consolidate and densify the crushed salt to a condition comparable to intact salt. Recent studies (Stormont, 1988) show that when the porosity of the crushed salt decreases to 5 percent or less, its permeability approaches that of intact salt (Figure C-1). This information indicates that crushed salt provides a tight seal in the long term.

### Model Development

Two separate computer programs have been developed to model the short-term and long-term seals. The program TSEAL models the behavior of short-term seals, and the program SEAL simulates that of long-term seals. There are a number of assumptions and simplifications involved in this modeling effort:

- Analyses are for an idealized circular geometry and a homogenous media. Shafts are modeled more accurately because of geometry and the effects of stratigraphic layering on deformation. Therefore, these models should be cautiously applied to drift and panel seals.
- The backfill is emplaced to completely fill the opening.

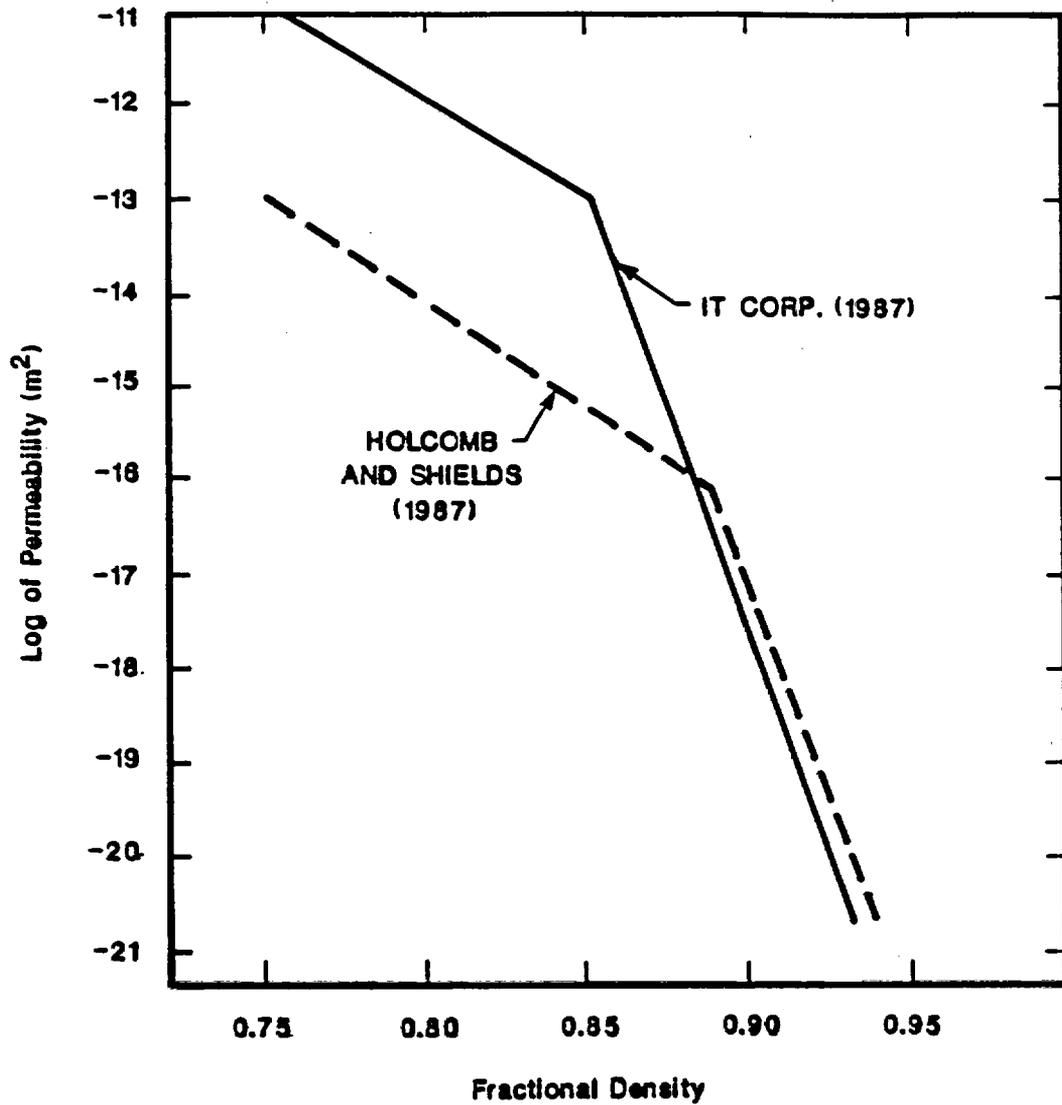


Figure C-1. Permeability Versus Fractional Density for Two Consolidation Tests on Wetted Crushed Salt (Stormont, 1988)

- The temperature at any given time is assumed to be uniform for both the intact salt and crushed salt backfill for all time.
- Thermoelastic stresses and their influence on consolidation and closure are neglected.
- Crushed salt backfill is assumed to consolidate homogeneously.
- Pore pressure will not develop as a result of wet crushed salt backfill consolidation. Furthermore, the result of the tests on wet crushed salt backfill material do not show a strong correlation between the consolidation rate and the moisture content (Sjaardema and Krieg, 1987).
- The stress field at each time step is the stationary, or steady-state stress field, which is a function of internal pressure and the far-field stress.

Intact salt, crushed salt, and concrete were modeled in the programs. The behavior of concrete has been assumed to be linear and elastic in the range of stresses expected in the repository. For the behavior of moist crushed salt, the proposed model by Sjaardema and Krieg (1987) for the hydrostatic loading of crushed salt has been used (crushed salt will not be subjected to deviatoric loading, since the cross-section of seals are assumed to be circular and the crushed salt is assumed to be consolidated homogeneously). Sjaardema and Krieg (1987) calculated the stress on crushed salt at the end of a time step,  $P_F$ , as follows:

$$P_F = \frac{-\ln}{B_1} \left\{ \frac{\hat{B} (1 + \alpha t)}{\alpha + \hat{K} + \hat{B}} + \left[ e^{-\alpha P_0} - \frac{\hat{B}}{\alpha + \hat{K} + \hat{B}} \right] \exp \{-t (\hat{K} + \hat{B})\} \right\} \quad (C-1)$$

where:

- $A, B_0, B_1, K_0, K_1$  are material constants
- $P_0$  = the pressure at the beginning of the time step
- $r$  = the volumetric strain rate during the time step
- $\hat{B} = B_0 B_1 K_0 e^{P_0(A+K_0)} / \rho_0$
- $\hat{K} = B_1 K_0 r e^{K_0 P_0}$
- $\alpha = (K_1 \rho_0 + A \rho_0 - 2)r$
- $\beta = K_1 \rho_0 r$
- $t$  = length of time step

And the following assumptions were used:

$$\alpha t, \beta t, \gamma t \begin{cases} < 0.5 \text{ for } < 10\% \text{ error} \\ < 0.1 \text{ for } < 1\% \text{ error} \end{cases}$$

Norton's law was used to model the creep behavior of the intact salt and has been expressed by Munson et al. (1989) in the following form:

$$\dot{\epsilon}_c = \dot{\epsilon}_{2M} \left( \frac{\sigma}{\mu} \right)^n \quad (\text{C-2})$$

where,

- $\dot{\epsilon}_c$  = steady-state strain rate
- $\dot{\epsilon}_{2M} = A_{2M} \exp(-Q/RT)$
- $A_{2M}$  = creep constant
- $\mu$  = salt shear modulus
- $Q$  = activation energy
- $R$  = universal gas constant
- $T$  = absolute temperature
- $n$  = stress exponent
- $\sigma$  = generalized stress

Chabannes (1982) proposed a closed-form solution for a thick-wall cylinder of salt in plane strain condition. Allowing the external radius to go to infinity, a solution is obtained for a circular opening in an infinite medium of salt. The solution accounts for the secondary creep of salt which was modeled by Norton's law. Chabannes calculated the radial displacement ( $u_r$ ) rate ( $w$ ) at any radius,  $r$ , as follows:

$$w = \frac{du_r}{dt} = -\dot{\epsilon}_{2M} \left[ \frac{\sqrt{3}}{2} \right]^{n+1} \left[ \frac{2a^{2n} (P_0 - P_i)}{\pi \mu \cdot r^{2/n}} \right]^n \cdot r \quad (\text{C-3})$$

where "a" is the radius of opening,  $P_0$  is the farfield stress, and  $P_i$  is the internal pressure.

The program TSEAL, which models the behavior of the temporary seal, uses Chabannes' solution to model the surrounding intact salt and assumes a linear elastic model for the behavior of concrete plugs. From the consistency of the rate of deformation between intact salt and a concrete plug, the rate of pressure change on the plug can be calculated in the form of a first-order nonlinear differential equation. This differential equation is then solved using a numerical integration scheme, and the pressure on the plug is calculated as a function of time. As a consequence of stress build-up on the concrete plug, the mean compressive stress in the DRZ will increase. Therefore, the porosity, and in turn the permeability of the DRZ, will decrease. The change in porosity at each point in time is calculated using the relaxed volumetric strain from the virgin state due to creep. The permeability of salt is then calculated using a relationship between porosity and permeability proposed by Lal (1971).

The behavior of long-term seals is modeled by the SEAL program which uses the Chabannes solution to model the surrounding intact salt. The proposed model of Sjaardema and Krieg (1987) is used to model the compaction of backfilled wet crushed salt. At each time step, the stress increase on the crushed salt due to its compaction is calculated using Equation (C-1) through an iterative procedure. The effect of stress build-up in crushed salt on the rate of creep closure is considered by modifying the internal stress in Equation (C-3) at each time step. Permeability of crushed salt at the end of each time step is obtained using a relationship between salt permeability and its fractional density (Figure C-1). The change in permeability of the DRZ is calculated as in the TSEAL program, and as explained in the previous paragraph.

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**APPENDIX D**

**MODELING OF GAS ADVECTION INTO ANHYDRITE BEDS**

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## MODELING OF GAS ADVECTION INTO ANHYDRITE BEDS

### Introduction

To examine the potential gas pressurization in the WIPP repository, all potential gas sources and sinks must be evaluated. One potential sink is the migration of the gases into the anhydrite layers which lie above and below the repository. The lower layer, known as Marker Bed 139 (MB 139), is located approximately 1 meter below the repository (Figure D-1). The upper layers, anhydrite beds "a" and "b," are located approximately 4 meters and 2 meters, respectively, above the repository. These anhydrite beds are considered to be made up of a disturbed zone and an intact zone. The disturbed zone is made up of fractured anhydrite caused by the repository excavation, and will exist above and below the entire repository. The intact zone is the undisturbed anhydrite, and exists beyond the area stressed by the mine operations. The anhydrite beds "a" and "b" overlying the repository are treated as a single composite layer for modeling advection. The program logic described below for MB 139 has also been used for the "a" and "b" composite bed.

Once the gas pressure in the repository has exceeded the pressure in an anhydrite bed, the gas will begin to migrate through the disturbed halite above and below the rooms and drifts into the disturbed zone of MB 139. The gas pressure will then drive the brine located in the disturbed zone (Figure D-2) into the intact marker bed, due to the pressure gradient developed by increasing gas pressure in the room. The brine is easily displaced, as the saturated capillary or threshold pressure in the disturbed marker bed is relatively small due to its enhanced permeability. However, as the brine reaches the undisturbed zone of Marker Bed 139, there is a large increase in the threshold pressure resulting from the lower permeability of this region. This threshold pressure must be exceeded in addition to the MB 139 pore pressure in order for gas to flow from the disturbed marker bed into the intact anhydrite (Figure D-3). The lower permeability does not allow the gas to displace the brine in the intact marker bed as freely as it does in the disturbed marker bed.

### Assumptions

To model the gas advection from the repository through the disturbed anhydrite beds into the undisturbed anhydrite beds, the following assumptions were made:

- Each room in the repository is directly connected with the disturbed anhydrite beds above and below it (this implies that the rooms are a linked network and that the network is equalized with respect to pressure).
- The gas displaces some brine in the disturbed anhydrite beds before the gas can migrate into the undisturbed zone
- The intact anhydrite beds are initially saturated
- The gas has the properties of hydrogen

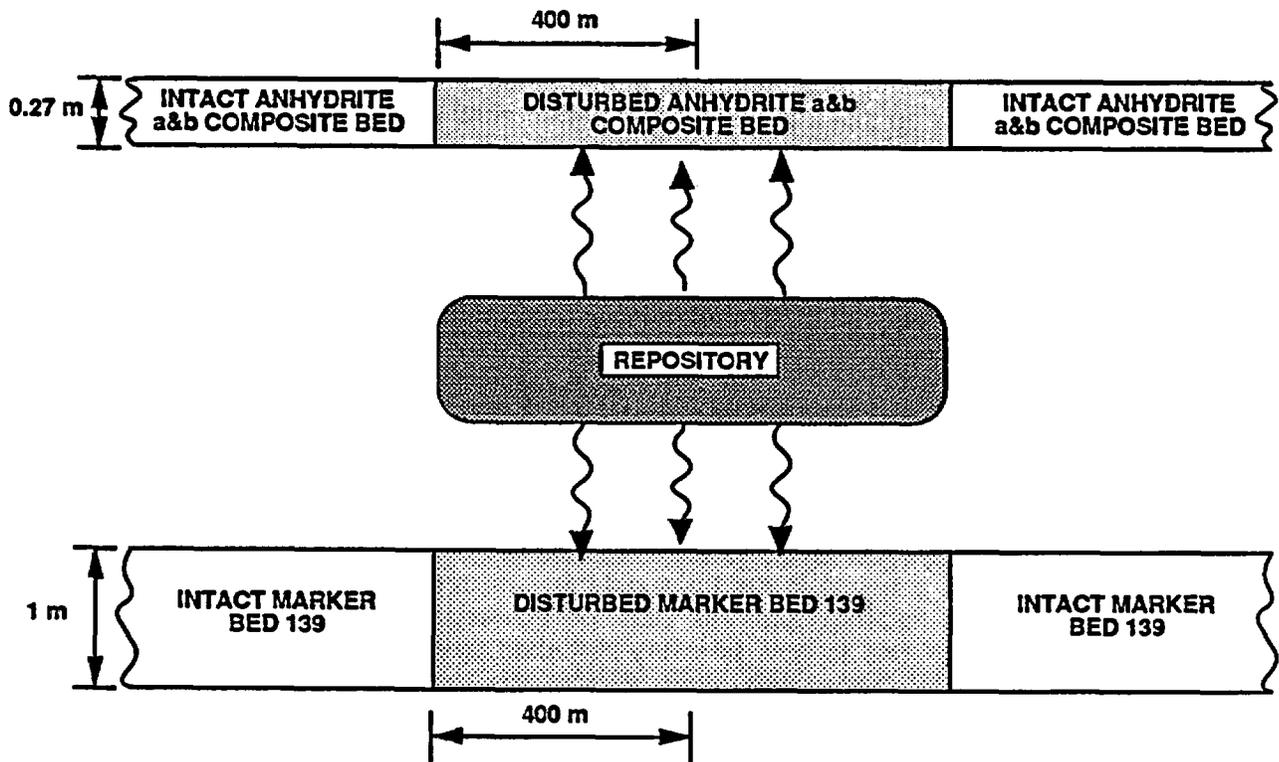


Figure D-1. Conceptual Model of Anhydrite Beds

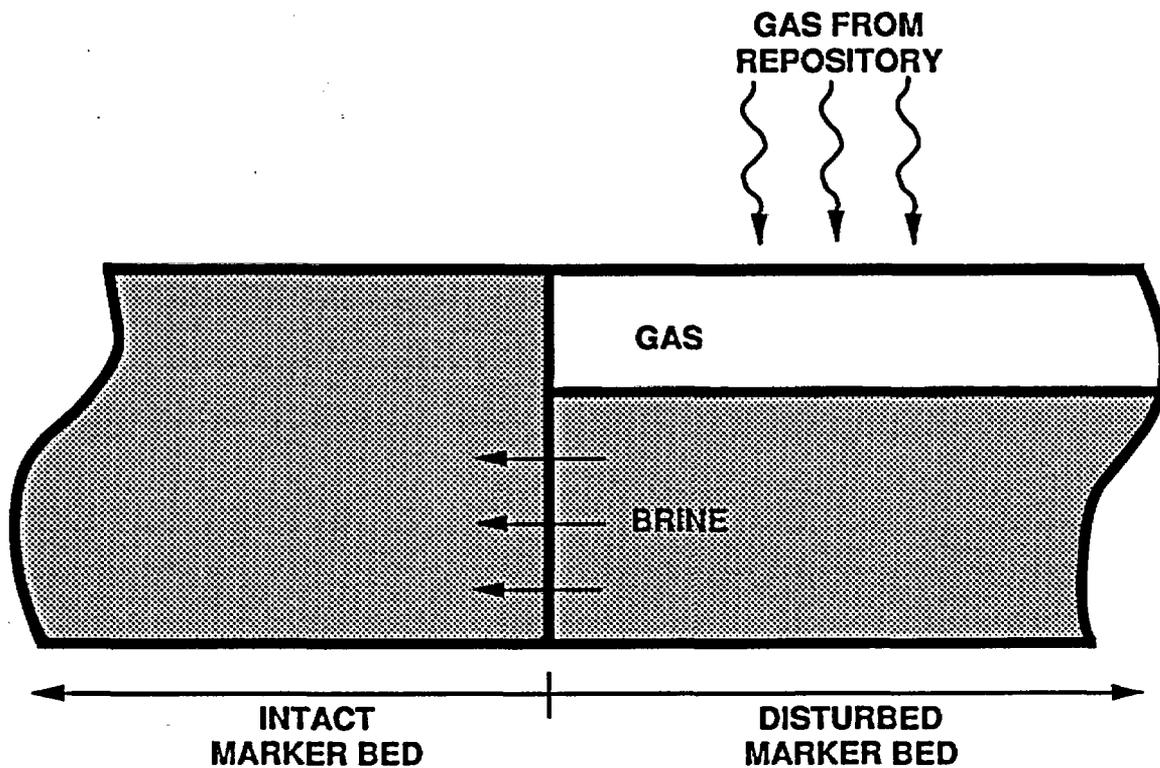


Figure D-2 . Brine Migration After Panel Pressure Exceeds MB 139 Pore Pressure

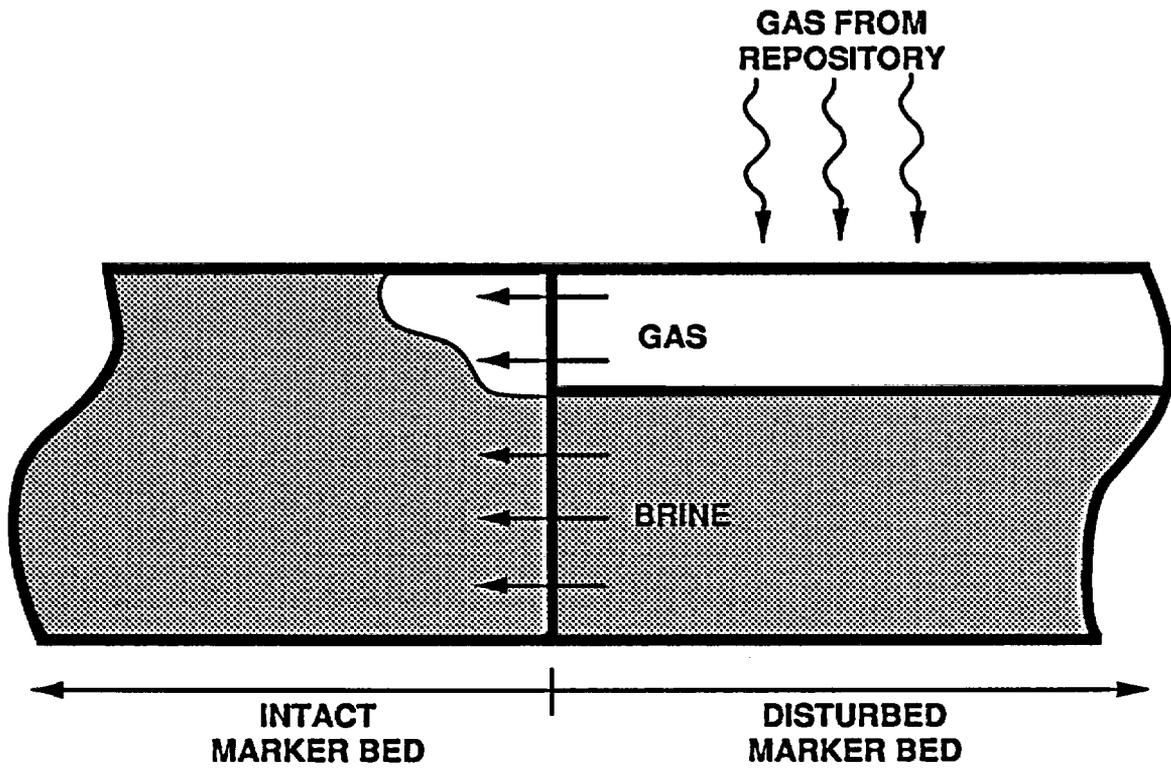


Figure D-3. Brine and Gas Migration After Panel Pressure Exceeds MB 139 Pore Pressure and Threshold Pressure

- The capillary pressure of the undisturbed anhydrite beds is always equal to the threshold pressure (saturated capillary pressure)
- The disturbed anhydrite beds are a cylinder, with a 400-meter radius
- The flow is radial
- The anhydrite beds have a constant thickness of 1 meter and 0.27 meters
- The anhydrite beds are homogeneous and isotropic
- The relative permeability curves for the intact anhydrite beds are the same as for the intact halite
- The pressure in the room remains constant
- The far-field pressure in the intact anhydrite beds remains constant
- There is no localized depressurization of the host rock.

Assuming that the gas has the physical properties of hydrogen, permits the maximum flow rates of gas into the intact anhydrite beds.

#### Program Description

A two-phase computer model was developed to simulate the gas advection into the intact anhydrite bed. The program developed is a versatile two-phase finite difference program which calculates the flow rate of gases in cubic meters per second, mass per second, and moles per second. The program uses the IMPES (Implicit Pressure Explicit Saturation) method for solving two-phase partial differential equations. This program is based upon a radial two-phase flow equation, a detailed description of which can be found in PRRC (1990).

The program allows the user to vary the important parameters such as the size of the disturbed zone, permeability of the intact anhydrite, capillary pressures, fluid properties, gas properties, boundary pressures, relative permeability curve, and the thickness of the marker bed. This flexibility facilitates the performance of sensitivity analyses on the listed parameters. This capability is particularly useful to determine the dependence of the gas advection on the different hydrologic parameters of the system.

The program was used to develop parametric equations for the gas advection rate (in moles per second) dependent on the permeability of the anhydrite beds, the far field pressure of the anhydrites, and the pressure of the room. These equations were used in the Design Analysis Model to compute the gas advection rate.

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**APPENDIX E**

**DEVELOPMENT OF BRINE/CO<sub>2</sub> INTERACTION PARAMETERS**

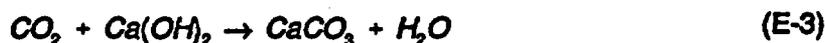
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## DEVELOPMENT OF BRINE/CO<sub>2</sub> INTERACTION PARAMETERS

The subroutine BRINTERACT was written to address the possible role of brine as a 'sink' for the gas carbon dioxide (CO<sub>2</sub>). Carbon dioxide will be produced by microbial activity in the waste panel rooms. If brine is available and in contact with cemented waste forms, the soluble masses of carbon dioxide and portlandite, Ca(OH)<sub>2</sub>, are available to react and produce calcite (CaCO<sub>3</sub>) and water (H<sub>2</sub>O) according to the reactions:



Combining these two reactions yields the overall reaction for the consumption process as:



The overall reaction progress (i.e., moles of produced CaCO<sub>3</sub> and H<sub>2</sub>O) is limited by the availability of carbon dioxide, portlandite and brine. If any one of these components is exhausted or unavailable, the reaction progress will terminate.

The subroutine BRINTERACT begins by establishing the molar volumes of portlandite, calcite and water, and then determines if the carbon dioxide produced from microorganism respiration is greater than the equilibrium fugacity of carbon dioxide in the brine. The fugacity of carbon dioxide in the brine (0.08 atm) has been calculated with the EQ3NR/EQ6 (Wolery, 1983; Wolery, 1984) speciation/reaction-path program by equilibrating the brine with excess carbon dioxide, portlandite and calcite. A mass balance is also carried out on portlandite and water to determine if these components are present in excess and, therefore, available to react with the carbon dioxide. If all of the above conditions are met, the subroutine will continue. However, if the carbon dioxide produced by the microorganisms is less than the fugacity of carbon dioxide in the brine, or there is insufficient portlandite or water, the subroutine will terminate at this point (i.e., the reaction cannot take place). Assuming the above conditions are met, the subroutine will continue by calculating a scale factor, which relates the amount of carbon dioxide that can react to the amount of brine present. The scale factor is multiplied by the carbon dioxide present in excess of the fugacity equilibrium value to determine the number of moles available to react. It accounts for the relative proportions of void volume in the waste and brine volumes to estimate the fraction of waste that would be contacted by the brine (i.e., the fraction of cemented waste available to react). The scale factor (SCALFACT) has the form:

$$SF = 1 - [V_v / (V_v + V_b)] \quad (E-4)$$

where  $V_v$  is the void volume and  $V_b$  is the volume of brine. Therefore, if the void volume is very large relative to the volume of brine, the term in brackets approaches one and the scale factor approaches zero (i.e., the reaction will consume very little carbon dioxide if brine is limited). If the volume of brine is very large relative to the void volume, then the term in the brackets approaches zero and the scale factor approaches one. A scale factor of one would allow complete reaction of all available carbon dioxide, if not limited by portlandite.

After the number of moles of carbon dioxide available for reaction have been determined, the subroutine reacts these moles with portlandite to produce calcite and water (reaction E-2). Mass balance calculations are then performed to determine the number of moles of carbon dioxide and portlandite remaining and the number of moles of calcite and water produced. The mass of portlandite consumed is subtracted, and that of calcite added, to the total mass of solids in the panel. Water produced from the reaction is added to the total mass of liquid in the panel.

Changes in the void volume are also calculated. Void volume will decrease as this reaction progresses because water is produced and added to the volume of brine, and because the molar volume of calcite (a reaction product) is slightly greater than that of portlandite (a reactant).

After completing the mass and volume balances, the subroutine passes the moles of remaining carbon dioxide, water, portlandite, liquid and total mass of solids, void volume, and volume of brine back to the MASSGAS subroutine. This terminates the subroutine BRINTERACT. It should be noted that the reaction of carbon dioxide with cementitious materials is insignificant as a mechanism for gas dissipation. Therefore, the removal of the BRINTERACT subroutine would not have any major effect on the results. This subroutine was included for the sake of completeness.

**APPENDIX F**  
**DESIGN ANALYSIS MODEL PROGRAM VERIFICATION**

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## DESIGN ANALYSIS MODEL PROGRAM VERIFICATION

The EATF modeling objectives have been performed in accordance with the Quality Assurance (QA) program used by International Technology Corporation (IT Corporation). The title of the document governing this program is the "Quality Assurance Procedure for Software Development And Use At The International Technology Corporation Albuquerque Modeling Center". The purpose of this appendix is to explain how the QA program used by the EATF was applied to program verification and validation for the Design Analysis Model. Verification is the process by which the output (numerical results) of a computer program are determined to be "correct". Verification implies that the program solves the numerical problem as intended by the EATF program author. Validation implies that the theory and assumptions used in constructing the program logic constitute a correct representation of the process or system being simulated by the program ROOM-SCALE, the main component of the Design Analysis Model, as it was developed by the EATF. The software QA procedure requires that such programs be verified using one, or some combination, of the following methods, depending on the intended use of the program:

- Independent manual calculations have been performed to verify all of the program algorithms. Manual calculations were documented and verified according to Sections 6.2.1 and 6.3.1 (included below) of the International Technology Corporation, Environmental Projects Group, Engineering Operations Quality Assurance Manual, Revision 1, July, 1987 (referred to as the ITEO QA Manual).
- The subroutine ISE2.FOR was compared to the results of an "independently developed" program which performs the same calculation. The term "independent development" can mean a program developed outside IT or by an independent internal working group. If avoidable, a program should not be verified against another program developed within the originating group unless the methodology and approach are entirely different. The input to both the program being verified and the program used for verification was independently checked.
- The program results can be compared to analyses published in textbooks and journals or to the results of applicable experiments. A complete reference for such material should be provided. This method includes verification with closed-form analytical solutions.

In addition, verification procedures used by the EATF are completely documented. This documentation includes, as appropriate:

- Description of verification method used
- Identification of the specific options verified
- Set of verification comparison materials (e.g., checked manual calculations)
- Verification runs, (i.e., checked copy of the computer output)
- Results.

Validation documentation, as necessary, consists of published conclusions comparing model predictions with data from laboratory experiments, field experiments, natural analogues, and published conclusions made by external review groups. Information regarding the conditions for which the model is valid were documented.

The following are Sections 6.2.1 and 6.3.1 of the ITO QA Manual which pertain to calculations. The relevant procedures listed in those subsections were applied to the EATF project.

### Calculations

For many projects, calculations represent the most important source of information when the work is completed. They shall be legible and in a form suitable for reproduction, filing, and retrieval. Documentation shall be sufficient to permit a technically qualified individual to review and understand the calculations and verify the results.

Calculations shall be performed on IT standard calculation paper whenever possible. Exceptions to this are items such as computer output and graphs drawn on oversized paper. All calculation pages shall be individually identified with the exception of large computer output. IT calculation paper provides spaces for the originator's name and date of work, the checker's name and date, calculation subject, project number, and page number. All of this information shall be completed for each page in a uniform manner. For extra pages, such as large graphs, this information shall also be included.

Calculations should, as appropriate, include:

- Statement of calculation intent
- Discussion of modeling requirements
- Description of methodology used
- Assumptions and their justification
- Input data and equation references
- Numerical calculations, including units
- Results.

Referencing input data, particularly input data obtained externally, is extremely important as it provides the basis for calculation checking. If initial parameters are supplied by an external source, the source shall be documented. Data that are provided by telephone shall be documented using an IT telephone record sheet. A request shall be made for formal written confirmation of critical data to serve as the final documentation. Input data may provide:

- Design program or regulatory requirements
- Performance and operational requirements under various conditions

- Data previously generated for a specific site or region (e.g., geological, hydrogeological, geochemical, geotechnical, meteorological, seismological, and man-made facilities and practices)
- Data previously generated for specific materials or chemical compounds (e.g., physical, chemical, geochemical, mechanical, thermomechanical, and toxicological)
- Loadings
- Results of field and laboratory testing or other calculations
- Other information obtained from the client or literature/information surveys.

Computer printouts that become an integral part of the calculations shall be referenced in the calculations by the run number or other unique means of identification. Short computer runs and spreadsheets can be directly incorporated into the calculations by affixing the output to IT paper or directly including output of standard sheet size (8-1/2 x 11 inches).

At the end of a calculation, the results should be summarized, if this will provide clarity. Also, all pages shall be consecutively numbered. On IT calculation pages, the page numbers of individual calculations shall be completed with the indexing of sheet \_\_\_ of \_\_\_. For the compilation of a set of calculations, the combined set should be consecutively numbered in the circles in the upper right corner of the calculation pages.

Calculations which are preliminary in nature (i.e., those not contributing to final project information) shall be marked "preliminary". If "preliminary" calculations are retained for future reference, each page shall be clearly marked "preliminary". Quality control requirements with final calculations, such as checking, are not applicable to "preliminary" work. Calculations which are superseded or replaced shall be marked "void" or destroyed. If "void" calculations are retained for future reference, each page shall be clearly marked "void" and the calculations should include, as necessary, an explanatory note as to why they are "void". The explanatory note shall be signed by the originator.

For calculations, the standard IT checking process is outlined as follows.

Assignments for checking shall be made or approved by the Project Manager. Verifications shall be performed by an individual(s) other than the person who performed the original work or specified the method or input parameters to be used. The individual(s) selected shall have the technical expertise in the calculation subject necessary to verify, as appropriate, that:

- Applicable design program, regulatory, and technical requirements have been properly identified and referenced and that these requirements have been met.
- Appropriate modeling and calculational methodology have been used

- Assumptions have been adequately described and, when necessary, justified
- Input parameters have been correctly selected and incorporated into the calculation
- Information and equations from external sources have been referenced
- Numerical calculations are correct and have been completely documented
- Results are reasonable considering the input.

It is emphasized that a numerical check is not sufficient. The checker is responsible for every item on every sheet -- including the completion of the title block and page numbers. The importance of a complete and thorough review cannot be overemphasized.

To properly check calculations:

- The originator supplies the designated checker with a machine copy of the calculations. Originals should not leave the originator's possession until they are ready for final checker signing.
- The checker marks the calculation copy with a yellow marker for all items he approves.
- If the checker disagrees, for any reason, the checker crosses through the item with a red marker and writes the recommended correction or comment above it.
- The checker signs and dates all pages of the checkprints.
- The checker returns the checkprints to the originator who, in turn, reviews all recommended changes. Agreed-to corrections may be marked with a check of a third color. If a disagreement still exists, the originator adds comments to the checkprints using the third color, initials and dates the checkprints, and then confers with the checker until all differences are resolved.
- The originator corrects, or "scrubs", the calculation originals so they agree with the checkprints. A one-to-one correspondence between the originals and checkprints must exist.

- The originator gives the originals and checkprints to the checker who compares them to verify all agreed-to corrections have been made.
- When the checker is satisfied, the checker signs and dates the originals.

Checkprints shall be maintained as a part of the project file, of equal importance as the originals.

Under no circumstances shall calculations be altered after final signature by the checker. If it becomes necessary for calculations to be revised, the new pages shall be formally checked as described above.

#### Verification of the Design Analysis Model

The room/panel behavior simulation portion of the Design Analysis Model is comprised of a number of subroutines which are called by a main program. The shaft-seal portion of the Design Analysis Model is comprised of two programs. Each subroutine of the ROOM-SCALE model was checked individually according to one of the three methods described above, as summarized in Tables F-1 and F-2. Each of the two shaft-seal programs were verified through independent hand calculations.

#### Validation of the Design Analysis Model

To date, the WIPP Performance Assessment models have not been coupled to the same degree as the Design Analysis Model. Consequently, code validation requires that modules of the Design Analysis Model be validated against codes used by SNL to predict individual processes that influence repository performance. Examples include comparison of predictions of room-closure and brine-inflow rates, predicted advection of gases along undisturbed anhydrite beds and up shaft seals, and simulation of borehole intrusion consequences.

Preliminary steps have been taken to validate the Design Analysis Model against the WIPP Performance Assessment models currently under development by SNL. Closure rates predicted by the Design Analysis Model, and by SNL's adaptation of the SANCHO code, are quite similar until the repository reaches lithostatic pressure. At that point, the SANCHO code predicts reinflation of the room in response to continued gas generation, while the Design Analysis Model assumes some advection of gas along anhydrite beds but room pressures in excess of lithostatic.

Validation of other components of the Design Analysis Model are more time consuming, and will not be performed unless results from the WIPP Performance Assessment models yield relative results substantially different from those predicted by the EATF. Performance Assessment is modeling the performance of three waste types: untreated wastes, Level II treated wastes, and Level III treated wastes. If relative performance between the three waste types are similar to those predicted by the Design Analysis Model, then the model will be

validated for its intended purpose, which is to compare the effectiveness in improving repository performance using the various engineered alternatives. The Design Analysis Model cannot predict absolute performance, as that was never the objective of the model. Consequently, the Design Analysis mode cannot be validated against the suite of Performance Assessment models.

Additional Quality Assurance for This Report

An independent review group was formed to review this report. The group consisted of an engineering and management consultant, and two professors in the fields of chemical engineering and geology. The modeling procedures were reviewed by the group for consistency, and termed by them to be a technically correct representation of the process in the repository, given the limitations involved.

TABLE F-1

ROOM-SCALE COMPONENTS OF THE DESIGN ANALYSIS MODEL

SUBROUTINE	METHOD OF VERIFICATION
ROOMSCAL	Independent hand calculation
READAT	Independent hand calculation
INITIALIZE	Independent hand calculation
DIFCOEF	Independent hand calculation
BRINFLOW	Independent hand calculation
COMPACTION	Independent hand calculation
CREEP	Independent hand calculation
MASSGAS	Independent hand calculation
DIFFUSION	Independent hand calculation
ADVECTION	Independent hand calculation
VISCORR	Independent hand calculation
SHFTSEAL	Independent hand calculation
MBFLOW	Independent hand calculation
BRINTERACT	Independent hand calculation
VOLESTIM	Independent hand calculation
LKEOS	Independent hand calculation
BOREHOLE	Independent hand calculation
RADACTIM	Independent hand calculation
RADSOLUB	Independent hand calculation
ESTHCKSS	Independent hand calculation
CUTTINGS	Independent hand calculation
ISE1	Independent hand calculation
ISE2	Independently developed program
ISE1E2	Independent hand calculation
SUMRULE	Independent hand calculation
PRINTOUT	Independent hand calculation
TIMEDATE	Not Applicable

**TABLE F-2**

**SHAFT-SEAL COMPONENTS OF THE DESIGN ANALYSIS MODEL**

<b>SUBROUTINE</b>	<b>METHOD OF VERIFICATION</b>
<b>SEAL</b>	Independent hand calculation
<b>TSEAL</b>	Independent hand calculation

**APPENDIX G**

**REPORT OF THE  
EXPERT PANEL ON APPLICATIONS OF CEMENT MATERIALS  
FOR USE AT THE WIPP**

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## PREFACE

The Expert Panel On Applications Of Cement Materials for use at the WIPP was convened by the EATF from May 15-17, 1990 and was composed of individuals representing many disciplines and organizations. The participants included:

### CHAIRMAN AND FACILITATOR

Jonathan Myers, IT Corporation

### PANEL MEMBERS

D. R. (Rip) Anderson  
Ned E. Bibler  
John Boa  
Barry M. Butcher  
Mark Gardiner  
Hamlin Jennings  
Lawrence Johnson  
Chris Langton  
Ken E. Philipose  
Lillian Wakeley

### ORGANIZATION

Sandia National Laboratories  
Westinghouse Savannah River Company  
U. S. Army Corps of Engineers  
Sandia National Laboratories  
IT Corporation  
Northwestern University  
AECL Research/Whiteshell  
Westinghouse Savannah River Company  
AECL Research/Chalk River  
US Army Corps of Engineers

### OBSERVERS

Don Blackstone  
Tod Burrington  
Andrew Peterson  
John Valdez

U.S. Department of Energy/WIPP Project  
Office  
Westinghouse Electric Corporation/Waste  
Isolation Division  
Sandia National Laboratories  
IT Corporation

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## EXECUTIVE SUMMARY

An expert panel was convened as part of the Engineered Alternatives Task Force, to determine whether cementitious materials should be considered further for use at the WIPP to improve long-term performance and reduce uncertainties in key performance parameters. The panel included eleven members from organizations including the Army Corps of Engineers (2), Savannah River (2), Atomic Energy of Canada Ltd. (2), Sandia National Laboratories (2), Northwestern University (1), and IT Corporation (2). Observers were also present from Westinghouse and the DOE WIPP Project Office.

Specific applications of cement-based materials considered are for use as backfill, waste forms, and container material. The panel was confident that a methodology can be developed to evaluate long-term performance of cementitious material formulations for use at the WIPP, and agreed that properly formulated cement-based materials are likely to meet long-term performance criteria including permeability and shear strength. The panel also cautioned that the development of proper formulations for these applications should consider the specific environment and must take into account waste and repository characteristics.

In the case of backfill, the panel recommended the use of a concrete with a high percentage of salt aggregate to provide deformability and maintain low permeability. Several reactive components were suggested for evaluation for use as a binder, including reactive alkalis such as CaO or MgO, hygroscopic glass, Portland cement, zeolite, expansive clays, and aluminate cements. It is anticipated that such a formulation will have plastic properties that will self-seal and maintain acceptably low permeabilities under the conditions of 2,000 psi confining stress in the repository environment.

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## 1.0 INTRODUCTION

### 1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes. TRU wastes are generated from defense-related activities of the U.S. Department of Energy (DOE). The underground storage area of the WIPP repository is located 2,155 feet below the surface in the Salado Formation, composed of a bedded salt (halite) of Permian (250 million year) age. After emplacement of the waste in the WIPP storage rooms, closure of the repository occurs by the creep (plastic flow) of the surrounding salt formation. This creep is in response to the pressure gradient that exists between the far-field pressure away from the repository (referred to as the lithostatic pressure, or the pressure at the depth of the repository due to the overlying rock) and the pressure in the repository which is initially at atmospheric conditions. In a freshly excavated room, this creep rate is of the order of a few inches per year. Under ideal conditions, creep results in complete closure of the repository, and the waste is permanently encapsulated in salt and isolated from the surrounding environment.

The waste to be disposed of consists of materials such as laboratory hardware, inorganic sludges, protective clothing, plastics, rubber, resins, and tools that have become contaminated with transuranic elements, mostly plutonium, with minor amounts of americium, uranium, neptunium, and thorium. The specific isotopes of these elements that are present in WIPP waste are generally alpha emitters with long half-lives and minimal heat production, although a small volume (less than 3 percent) of the inventory is categorized as "remote-handled" waste which has moderate heat production from short-lived fission products. The majority of waste to be disposed of is presently stored in 55-gallon steel drums and a lesser number of steel boxes, at major DOE waste generation and storage sites across the country.

### 1.2 ENVIRONMENTAL CONDITIONS WITHIN THE REPOSITORY

The anticipated environmental conditions in the WIPP repository are summarized as follows:

- Temperature - The temperature in the repository is expected to remain constant at approximately 26°C. The average decay heat generation from the waste is less than 0.1 watt per drum which does not significantly raise the temperature above ambient. Remote-handled TRU (RH-TRU) waste has greater heat generation, however the volume of RH-TRU is less than 3 percent of the total inventory.
- Humidity - Limited volumes of brine have been observed to flow into the repository (Deal and Case, 1987). After the facility is sealed, the humidity of the room will be controlled by the thermodynamic activity of H<sub>2</sub>O in the brine. Assuming there is a small volume of saturated brine in the sealed repository with gas above the brine, then the relative humidity in the repository will be buffered at approximately 70 percent.

- **Oxygen** - Although the repository will initially have an oxic environment, this oxygen is expected to be consumed in the process of microbial degradation of organic materials present in the waste, thereby eventually leading to an anoxic environment. Some oxygen is also expected to be consumed by corrosion of the mild steel drums. However, some oxygen could also be generated within the repository from the radiolytic decomposition of brine. Overall, the rate of generation of oxygen by radiolysis is expected to be less than the rate of consumption of oxygen by microbial degradation and corrosion, therefore an anoxic environment is expected to be eventually established within the repository.
- **Stresses** - The creep closure of salt surrounding the waste will eventually result in isostatic (nondirected) stress equal to the lithostatic pressure of about 2000 psi (15 MPa). However, since the storage rooms are 33 feet in width and only 13 feet in height, the closure rate in the ceiling-to-floor direction is greater than the closure rate in the horizontal direction. This will result in some directed stress until complete closure has taken place. Once the room has completely repressurized, isostatic conditions are expected to return.
- **Brine Composition** - The major elements present in the brine include Cl<sup>-</sup> (~200,000 mg/l), Na<sup>+</sup> (~85,000 mg/l), Mg<sup>+2</sup> (~18,000 mg/l), K<sup>+</sup> (~18,000 mg/l), and SO<sub>4</sub><sup>-2</sup> (~17,000 mg/l). Br and B are also present at concentration above 1,300 mg/l. The pH is 6.1, and the total dissolved solids equal ~350,000 mg/l. The brine is saturated with respect to the minerals halite (NaCl) and anhydrite (CaSO<sub>4</sub>).

### 1.3 REGULATORY CONSIDERATIONS

The geologic disposal of TRU waste is governed by U.S. Environmental Protection Agency (EPA) Standard 40 CFR Part 191 (EPA, 1985). This regulation sets limits on the cumulative allowable releases of radioactivity to the accessible environment over a 10,000-year period, based on predictive modeling analyses referred to as performance assessment (PA). Both undisturbed performance, as well as the consequences of inadvertent human intrusion in the form of future exploratory drilling through the storage rooms, must be considered, as mandated by the EPA Standard. In addition, the Standard requires that the uncertainties in the predicted 10,000-year cumulative release be developed by propagating uncertainties in input parameters through the calculations.

The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL), and is expected to be completed by 1994 (DOE, 1990d). Work currently in progress at SNL has suggested that there might be potential problems with the current waste forms and/or repository design and that some modifications may be necessary to demonstrate compliance with the EPA Standard. In response to this concern, and based on the recommendations of the National Academy of Sciences (NAS), the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989. The charter of the EATF was to evaluate the effectiveness and feasibility of various modifications to the WIPP facility design and waste forms that would improve the long-term isolation capability of the repository and/or reduce uncertainties in key performance parameters (Hunt, 1990). Preliminary assessments of the long-term performance of the disposal system have

Identified three key parameters that affect disposal system performance: (1) gas generation, (2) waste form and backfill permeability, and (3) waste element solubility. The importance of these parameters is discussed in the following sections.

#### **1.4 GAS GENERATION**

Preliminary assessments of the long-term performance of the disposal system have identified gas generation as one of the key parameters that might affect performance of the disposal system (DOE, 1990a). Lappin et al. (1989) discusses the possibility that up to 1,500 moles of gas can be generated per drum (or drum equivalent) of waste from anoxic corrosion, microbial degradation, and radiolysis, at rates that may be as high as 2.55 moles/drum/year. Although processes exist to dissipate excess gas pressure, these processes are currently believed to be slow relative to the current estimates of gas generation rates, resulting in gas pressures in storage rooms that may temporarily exceed lithostatic pressure. The consequences of exceeding lithostatic pressure are currently being evaluated by SNL (Lappin et al., 1989). Unless these evaluations conclusively demonstrate that either excess pressures will not occur or that excess pressures will not degrade the performance of the disposal system, some type of facility or waste form modification may be required to either eliminate or reduce the rate of gas generation.

The three main mechanisms for the generation and consumption of gases in the underground environment are: (1) corrosion of metals, (2) microbial activity, and (3) radiolysis. The potential for these mechanisms to generate gases is discussed below.

**Corrosion of Metals** - The primary metals that are of concern with respect to gas generation are ferrous alloys (iron and steel) and aluminum. These metals are present in the inventory as metallic waste, as well as the 55-gallon steel drums and steel boxes that contain waste. There are two general mechanisms for corrosion of metals that may operate in the underground WIPP environment. Oxidic corrosion occurs when iron reacts with oxygen to form corrosion products, usually iron oxides. Anoxic corrosion occurs when iron reacts with brine or water vapor to form iron oxides or oxyhydroxides plus hydrogen. The net effect of oxidic corrosion is the consumption of oxygen, and the net effect of anoxic corrosion is the production of hydrogen. Water in either a liquid or vapor state is required for anoxic corrosion and is consumed in the process, suggesting that the availability of moisture may be the rate-limiting step in this process. Cement containers can be used to replace the steel drums and boxes, thus eliminating a major source of metal in the inventory. The use of cement waste forms and/or cement backfill will raise the pH of any brine in the storage room to values which tend to reduce the corrosion rates of iron-based alloys. The use of low permeability waste forms and backfill will limit the availability of brine for corrosion.

**Microbial Activity** - Microbial activity can potentially break down organic materials such as paper, plastic, and wood, consuming oxygen and generating carbon dioxide and methane in the process. Sulfate reducing bacteria, if present, can generate hydrogen sulfide from sulfate present in natural brine, and nitrate reducing bacteria, if present, can generate nitrogen from nitrate salts present in the waste. The large mass of organic materials in the WIPP inventory, plus the presence of sulfate and nitrate suggest that there is a potential to eventually generate

large amounts of gases. However, the rate at which these gases are generated is a key factor in predicting pressurization of the waste storage rooms. The use of a cement waste form and/or a cement backfill may raise the pH of any moisture present in the storage room to a range where the rates of microbial activity are reduced.

**Radiolysis** - Radiolysis has the potential to generate hydrogen and oxygen from the decomposition of water, and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials. Oxygen that is generated by the decomposition of water will probably be consumed by microbial or chemical reactions, but the accumulation of hydrogen, methane, and carbon dioxide is of potential concern. The dominant form of radiation present in TRU waste is the emission of alpha particles which have a very limited range. A "matrix depletion effect" is commonly noted in alpha radiolysis experiments, where the gas generation rate decreases with time as the material that is in close proximity to the alpha source becomes depleted in volatile components. However, the matrix depletion effect has not been observed in situations where the alpha emitters are dissolved or are otherwise in intimate contact with aqueous solutions. The potential for the generation of radiolytic gases from unprocessed or incinerated waste immobilized in cement needs to be evaluated.

## 1.5 PERMEABILITY

A second potential problem with demonstrating regulatory compliance relates to the consequences predicted from future inadvertent human intrusion events. Some of the preliminary evaluations of compliance with the containment requirement of 40 CFR Part 191 (EPA, 1985) performed by SNL suggest that some of the current waste forms (under current interpretations of human intrusion provisions) may eventually be found to be unacceptable for disposal at the WIPP (Marietta et al., 1989). This may be due to uncertainties in key performance parameters of the waste forms. Key parameters that control the release of radionuclides during human intrusion scenarios are permeability of the waste and backfill in the storage rooms and radionuclide solubilities.

The consequences of release scenarios involving the inadvertent exploratory drilling by future generations are critically dependent on the permeability of the waste storage rooms. Panel member B. Butcher (SNL) estimated that the average permeability of the materials in the room needs to be within five orders of magnitude of the intact host rock to demonstrate compliance. However, sensitivity analyses performed subsequent to the panel meeting suggest that five orders of magnitude is in fact too high. Currently, a reduction in permeability to  $10^{-18}$  m<sup>2</sup> for the backfill is recommended, and a value of  $10^{-19}$  m<sup>2</sup>, if possible, is preferred. Both crushed salt and crushed salt with bentonite are predicted to reach  $10^{-19}$  m<sup>2</sup> within 100 years. Some proposed alternative designs that lower the permeability of the waste and backfill involve the use of cemented waste forms and/or cement backfill. A key question here is whether a low permeability cement can be relied upon to maintain an adequately low permeability in the repository environment over the 10,000-year regulatory period.

## 1.6 WASTE ELEMENT SOLUBILITIES

The solubilities of waste elements in the repository environment have been identified as a critical performance parameter in SNL preliminary performance assessment analyses (Marietta et al., 1989). Solubility, in this case, is defined as the maximum amount of a waste element that can be dissolved in brine that may contact the waste. Most release scenarios involve the transport of contaminated brine from the waste storage rooms to the environment. Two critical parameters that determine the consequences of such scenarios are the volume of brine available for transport and the solubility of waste elements in that volume of brine. The radionuclide releases predicted from design analysis and performance assessment models are linearly dependent upon the values chosen for waste element solubilities. Increasing the assumed solubility of a waste element by a factor of two, for example, will increase the predicted release of that element by roughly the same factor. Thus, the uncertainty in release estimates are directly proportional to the uncertainty in solubility assumptions.

Existing data on actinide element solubilities are available for dilute ground waters, but data appropriate for the brine environment at the WIPP are not available, nor is there a valid method of extrapolating solubility data obtained from dilute systems to high-strength brine environments. The current performance assessment calculations performed by SNL use a range of actinide solubilities from  $10^{-3}$  to  $10^{-6}$  moles/liter (Rechard et al., 1990).

Some engineered alternatives under active consideration involve the use of cemented waste forms, the use of grout backfill, and the addition of lime (CaO) to the waste drums. Advantages of cemented waste, grout, and lime is that any brine that comes in contact with these materials will undergo an increase in pH from the ambient value of approximately 6.0 up to a value of approximately 11.5. It is known that, in general, the solubilities of actinide elements are several orders of magnitude lower at pH values above 9 than at neutral pH conditions, however, the exact decrease in solubilities over this pH range in WIPP brines is unknown. The relative merits of these types of alternatives can only be fully evaluated by obtaining estimates of waste element solubilities both at the anticipated pH conditions and at the elevated pH conditions offered by these alternatives.

It should be noted, however, that the pH of the room environment can only be controlled by the use of a buffer if there is no significant movement of fluid through the repository. Such movement would eventually dissolve and remove the buffer material, limiting its effectiveness. No such migration of fluid through the repository is anticipated under undisturbed conditions. However, human intrusion scenarios that involve the connection of a storage room with an underlying brine reservoir in the Castile Formation may provide sufficient migration of brine through the room to eventually remove the buffer. In this case, the pH of the room environment would be dominated by the pH of the Castile brine.

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## 2.0 EVALUATION OF CEMENT-BASED MATERIALS

The mission of the Cement Materials Expert Panel was to determine whether cementitious materials should be considered further for use at the WIPP to improve long-term performance and reduce uncertainties in key performance parameters, including gas generation and permeability of the waste/backfill composite.

Specific applications considered for cementitious materials are for use as backfill to lower the permeability of the storage rooms, waste forms to immobilize waste elements in a low permeability medium, and for use as a container material to eliminate hydrogen generation from anoxic corrosion of the steel drums.

There is little doubt that cementitious materials will, at least initially, perform adequately in these roles as backfill, container, and waste forms. The critical issue is one of longevity. Values for critical parameters such as permeability of the cement must remain within an acceptable range for the 10,000-year regulatory period. The EPA standard recognizes the difficulty in quantifying the performance of a disposal system over a long period of time and allows the use of "expert judgment" in estimating performance.

A working assumption that the Panel used in evaluating candidate materials is that the more closely the materials resemble the host rock, the more they reduce chemical potential gradients, thereby minimizing any driving force for degradation of the material. Risk or uncertainty can be reduced by minimizing the use of unlike materials. It was also assumed that in the case of backfill and waste forms, rigid materials are not necessarily the best choice, since a plastic material will have self-healing properties under confined conditions.

The Panel also cautioned against using conventional construction thinking when considering the longevity of cement-based materials in the WIPP environment. The major processes that affect the physical stability of these materials in a surface environment are changes in temperature and humidity, cyclical wetting/drying and freeze/thaw, directed stresses, exposure to wind, and exposure to flowing water, which can selectively remove leachable phases in the cement. However, these processes that can promote physical degradation do not occur in the WIPP repository environment. The constant temperature and humidity, isostatic (nondirected) stress and low permeability of the host rock (which precludes flowing ground water) offer an environment that will tend to maintain the physical properties of cement-based materials. In this environment, chemical durability is the main issue. The dehydration of cement phases or the reaction of cement phases with  $\text{CO}_2$  are processes that lead to a decrease in volume of solids. In rigid materials, these processes may lead to increases in porosity and permeability over time. However, if the material is plastic under the applied isostatic stress, then any chemical reactions that lead to a volume reduction will not necessarily result in a corresponding increase in porosity.

The following sections summarize the recommendations of the Cement Panel with respect to use of cement-based materials as a backfill, waste form, and waste container.

## **2.1 BACKFILL CONSIDERATIONS**

A backfill material will be emplaced between and around the waste containers and will be required to eventually consolidate under lithostatic stress to a low permeability and porosity, thereby encapsulating the waste. The requirements of the backfill are as follows:

- **Maintain permeability within three orders of magnitude of the intact host rock. This range of permeability will reduce the release of radionuclides in response to human intrusion events.**
- **Fill voids as completely as possible. This will lead to rapid reconsolidation and will minimize the accumulation of brine in the storage rooms.**
- **Maintain acceptable shear strength. This will reduce the volume of waste that may be brought to the surface if the storage room is breached by an exploratory drill hole.**
- **Minimize residual free water. This will reduce the volume of contaminated fluid that may be available for transport away from the storage room environment.**

The current reference backfill is crushed salt, which has many favorable properties and may prove to be acceptable. One potential drawback however, is that crushed salt has an initially high porosity and will require a certain length of time, ranging from approximately 50 to 150 years, to reconsolidate and achieve acceptably low permeability and porosity. If performance assessment studies indicate that it is necessary to maintain low permeability and porosity during this early postclosure period, then an alternate material may need to be selected.

The recommendations of the Panel for such an alternate material is as follows:

- **Use cement with a high percentage of salt aggregate. This will provide deformability, will be self-sealing, and will maintain low permeability under the anticipated 2,000-psi isostatic confining stress. Concretes with aggregate contents as high as 95 percent have been used in underground applications at the Nevada Test Site, although concretes with high salt content have not been produced to date.**
- **Use a WIPP brine composition as the makeup water. This will minimize concentration gradients between the backfill and the host rock.**
- **Use the minimum volume of brine necessary to form an emplaceable grout. This will minimize the volume of residual brine. Water/cement mass ratios of less than 0.3 have been achieved, although not with brine.**
- **Add the minimum amount of reactive component necessary to absorb most of the added brine when set. This will ensure that the backfill will have mechanical properties similar to that of consolidated salt. The Panel agreed that low modulus**

(50 - 100 psi), self-sealing concretes have been prepared before for other applications.

Reactive components that should be considered for evaluation include: reactive alkalis such as CaO or MgO, hygroscopic glass (silica fume), hemihydrate (partially hydrated gypsum), Portland cement, zeolites, expansive clays, and aluminate cements. The Panel advised that simpler systems, such as aluminate cements are less complex than Portland-type formulations and therefore have more predictable behavior. Experiments will be required to select the reactive component and optimize the proportions of salt, brine, and reactive components. The objectives of these experiments may include the following:

- Determination of hydration capacity
- Characterization of hydrated phases
- Development of optimal emplacement techniques
- Determination of residual free brine volume
- Measurement of permeability under confining stress
- Evaluation of set time
- Determination of shear strength
- Optimization of dry mix grain size
- Measurement of initial viscosity.

The following points were made by the Panel on the anticipated performance of the recommended backfill formulation:

- Cement-based grouts can be formulated to have plastic properties that will self-seal and maintain acceptably low permeabilities under a 2,000-psi confining stress.
- Permeability and creep properties of this formulation will be similar to salt.
- No mechanism that may degrade permeability could be identified under the anticipated repository environmental conditions of constant temperature and humidity, lithostatic confining stress. Also, no ground water flow is anticipated that may dissolve and remove backfill material, with the possible exception of a human intrusion event that provides a connection with the room and a Castile brine reservoir.

## **2.2 WASTE FORM CONSIDERATIONS**

The WIPP waste inventory can be divided into three main categories: sludges; organics (paper, plastic, wood, rubber, etc.); and inorganics (glass, metals, ceramics, etc.). If it is determined through the Performance Assessment process that the gas generation rates, permeability, shear strength, or waste element solubilities for some or all of the three waste categories are unacceptable, then some form of waste processing may be necessary to produce alternate waste forms with acceptable properties. The use of cemented waste forms provides the following potential advantages:

- Low permeability and porosity, especially if a high salt aggregate formulation of the type proposed for use as backfill is used (see Section 2.1).
- High shear strength, which will minimize release of waste in response to inadvertent exploratory drilling through the repository by future generations.
- Establishment of a more favorable chemical environment. Portland-type cement will buffer the pH of any brine that comes in contact with the waste to values in the range of approximately 12. These conditions will reduce the anoxic corrosion rate of ferrous alloys, reduce the rate of microbial degradation, and lower waste element solubilities.

Potential applications of cement-based waste forms are discussed below.

Shredding and Cementing of Organic Waste - This waste form will have a lower initial permeability and porosity than unprocessed organic waste forms, and the pH buffer effect will reduce microbial degradation rates and lower waste element solubilities.

Shredding and Cementing of Inorganic Waste - Glass, ceramic, and metallic waste forms can also be shredded or crushed and then cemented to produce a low permeability waste form. The elevated pH environment that this waste form creates will reduce the corrosion rate of ferrous-based metals, but can increase the anoxic corrosion rate of metallic aluminum. If hydrogen generation from anoxic corrosion is determined to be a problem, then cementation of metallic aluminum should be avoided.

Cemented Incinerator Ash - If it is determined that microbial gas generation must be eliminated, then some type of thermal treatment may be required to destroy the organic component of the waste. The resultant ash will need to be incorporated into a matrix to eliminate any hazard from airborne alpha particles. Cementation of incinerator ash from medical waste and low-level radioactive waste incinerators is a well-established technology that can produce a low permeability, low porosity waste form with little or no gas generation potential. The pH buffering effect of portland-type cement will have the added benefit of reducing waste element solubilities.

Cementation of Sludges - Sludges consisting of chemically precipitated metal oxides and hydroxides comprise approximately 20 percent by volume of the total WIPP inventory [based on (DOE, 1988b)]. If it is determined that the permeability of these sludges is too high, then cementation of the sludges may be required to produce a waste form with a lower permeability. Cementation of newly generated sludges can easily be accomplished by modifying the waste streams. Stored drums of sludge will need to be opened, broken into chunks, cemented and repackaged.

One concern regarding cemented waste forms is that the intimate contact between the alpha emitters and free (unbound) water in the cement matrix may yield hydrogen and oxygen from the radiolytic decomposition of the water. The Panel recommends that the gas generation potential from this process be evaluated, and, if necessary, investigate methods to reduce radiolytic gas generation. These methods may include the following:

- The addition of nitrite salts to inhibit gas generation
- The use of heat to reduce the volume of unbound water
- The use of a self-desiccating formulation to minimize unbound water
- The application of mechanical force during the curing process to press excess water from the matrix.

The panel cautioned that the influx of brine into the waste storage rooms should be avoided since such influx may cause additional radiolytic gas generation.

The following is a summary of the recommendations of the Panel on the applications of cement materials for use as waste forms.

- Cemented waste forms will be effective in reducing the initial void volume of the storage rooms, thus leading to more rapid repressurization of the repository environment. Rapid repressurization will minimize the volume of brine that may seep into the storage rooms under a pressure gradient.
- Formulations similar to those suggested for backfill should be evaluated.
- Grouting of metallic aluminum waste may generate hydrogen.

The heterogeneous nature of the waste suggests that the chemical interactions between the various waste components as they age and degrade will probably be quite complex. For this reason, the longevity of cemented waste forms is less certain than longevity of the recommended backfill formulations. The Panel cautioned that the chemical interactions between the waste and the cement matrix needs to be clearly understood or there will be no assurance that a cemented waste form will maintain desirable properties such as low permeability for 10,000 years. The Panel also stated that they have no reason to believe that aging reactions will degrade the performance of cement waste forms. However, lacking a quantitative basis for long-term waste form permeability, greater reliance should be placed on the recommended backfill formulations, rather than on cement waste forms.

### **2.3 CONTAINER CONSIDERATIONS**

Waste containers are required for ease of handling and to contain the hazardous and radioactive materials, thus providing protection for workers and the environment. The current containers are standard 55-gallon drums, plus a lesser number of steel boxes. These

containers provide adequate protection. However, if hydrogen generation from anoxic corrosion of steel is determined to be a problem in long-term performance of the repository, then an alternate container may need to be employed.

The requirements of such an alternate container are as follows:

- The material should be easily fabricated into a container of the required shape. This can be a drum, rectangular box, or hexagonal cylinder.
- The containers should not degrade in any way that will significantly increase the permeability of the storage room environment.
- The cost of the alternate container should not be greater than a container fabricated from a noncorroding metal such as titanium.
- The container should be able to show compliance with the Department of Transportation (DOT) Type A Packaging Tests (DOT, 1989). Compliance is demonstrated by surviving a drop test and a puncture test with no loss of containment.
- The container material should either not generate gas or have an acceptably low gas generation rate in the repository environment.
- The container material should be chemically compatible with the backfill and waste forms.

The panel agreed that cement-based containers should be considered along with other materials for use as alternate containers. A wide range of properties is achievable with cement-based materials, including high flexural and compressive strength, low porosity, and low permeability.

The challenge in designing a cement-based container will be to utilize high-strength low-cost materials to minimize wall thickness and weight, as well as maximizing payload volume, while maintaining compliance with the DOT containment requirements. The Panel agreed that this goal is probably achievable through the use of reinforcement materials embedded in the cement to increase strength. This approach will allow a lighter design with thinner walls than would be possible with nonreinforced cement.

#### **2.4 COMPARTMENTALIZATION CONCEPT**

The Panel suggested that a compartmentalization concept should be considered where waste is emplaced in a series of compartments that are isolated from each other by some low permeability material. With this approach, the total volume of waste that can be released by any single event (such as intrusion by an exploratory drill hole) is limited to the volume of waste that is contained within the compartment that is breached. They further advised that the waste should be compartmentalized on several scales, including pieces of waste within

containers embedded in cement, waste containers embedded in backfill, waste compartments within rooms periodically separated by zones of thick backfill, and individual waste panels isolated by panel seals. This "fractal compartmentalization" will provide engineered upper bounds on releases resulting from a wide range of intrusion events.

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### 3.0 PANEL CONCLUSIONS

The Panel is confident that a methodology can be developed to evaluate the long-term performance of cementitious material formulations for use as backfill, waste forms, and containers at the WIPP. They also agree that properly formulated cement-based materials are likely to meet long-term performance criteria including low permeability and high shear strength required for backfill and waste forms, and high impact resistance required for waste containers.

In the case of backfill, the Panel provided guidance on the development and testing of a high salt aggregate formulation that will have plastic properties that will self-seal and maintain low permeabilities under a 2,000-psi confining stress.

For waste forms, the Panel recommended that shredded and cemented organic and inorganic wastes, cemented incinerator ash, and cemented sludges will produce superior waste forms if properly formulated. They did, however, caution that the development of effective formulations for waste forms must take into account the repository environment as well as the physical and chemical characteristics of the waste to be effective for the 10,000-year regulatory period.

For containers, the Panel agreed that cement-based containers should be considered along with other materials for use as alternate containers. A wide range of container properties is achievable with cement-based materials, including high flexural and compressive strength, low porosity, and low permeability, especially by incorporation of reinforcement techniques.

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**APPENDIX H**  
**REPORT OF THE**  
**WASTE CONTAINER MATERIALS**  
**PANEL**

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## PREFACE

The Waste Container Materials Panel, described in this report, was composed of individuals representing many disciplines and organizations. The participants included:

### CHAIRMAN AND FACILITATOR

Hans Kresny, President, Solmont Corporation

### PANEL MEMBERS

<u>NAME</u>	<u>AFFILIATION</u>	<u>DISCIPLINE</u>
Barry Butcher	Sandia National Laboratories	Performance Assessment
Noel C. Calkins	Calkins R&D Inc.	Ceramic Fabrication
Frank W. Clinard, Jr.	Los Alamos National Laboratory	Basic Ceramic Research
F. H. Froes	University of Idaho	Physical Metallurgy
Hamlin M. Jennings	Northwestern University	Cementitious Materials
Daniel C. Meess	West Valley Nuclear Services	Concrete Container Fabrication
Jonathan Myers	International Technology Corp.	Geochemistry
Rodney Palanca	Westinghouse Electric Corp. Waste Isolation Division	Waste Handling/Repository Operations
R. E. Westerman	Pacific Northwest Laboratories	Metallurgy/Corrosion

### OBSERVERS

<u>NAME</u>	<u>AFFILIATION</u>
Ravi Batra	Department of Energy (DOE) WIPP Project Office
Doree Donovan	Westinghouse Electric Corporation Waste Isolation Division
Sayan Chakraborti	International Technology Corporation

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## EXECUTIVE SUMMARY

The Waste Isolation Pilot Plant (WIPP) is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes generated from defense-related activities of the U. S. Department of Energy (DOE). The WIPP storage rooms are mined in a bedded salt (halite) formation and are located 2,155 feet below the surface. Once the waste is disposed in the storage rooms, complete closure of the repository occurs by the creep (plastic flow) of the salt formation, and the waste is permanently isolated from the surrounding environment.

The geologic disposal of TRU waste is governed by the U. S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985), which sets limits on the cumulative allowable releases of radioactive isotopes to the accessible environment over a period of 10,000 years. The study done to show compliance with this regulation is referred to as performance assessment. The performance assessment for the WIPP repository is being conducted by the Sandia National Laboratories (SNL), and is expected to be completed in 1994 (DOE, 1990d). Preliminary analyses performed at SNL indicate that the current waste forms may need some modifications in order to demonstrate compliance with the EPA Standard. In response to this concern and based on the recommendations of the National Academy of Sciences, the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989. The charter of the EATF was to evaluate the effectiveness and feasibility of various modifications to the current waste forms and/or WIPP facility design which would improve the long-term isolation capability of the repository (Hunt, 1990).

The ongoing performance assessment studies have identified gas generation as one of the three key parameters that might affect the performance of the disposal system (DOE, 1990a). The three mechanisms for the generation and consumption of gases in the underground repository are:

- Corrosion of metals
- Microbial activity
- Radiolysis.

The corrosion of metals could take place by two general mechanisms; oxic corrosion, when iron reacts with oxygen to form oxides or oxyhydroxides, and anoxic corrosion, where iron reacts with brine or water vapor to form oxides/oxyhydroxides and hydrogen. Microbial activity has the potential to attack organic materials such as paper, plastic, and wood present in the WIPP waste inventory, consuming oxygen and generating carbon dioxide and methane in the process. Radiolysis can potentially generate hydrogen and oxygen from the decomposition of water; and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials.

The gases produced by the above mentioned mechanisms may result in higher than acceptable pressure in the repository, because although the excess gas pressure can be dissipated by advection through the surrounding rock, the rate of advection is believed to be

slow relative to the current estimates of gas generation rates. The effect of any excess gas pressure on the performance of the repository has not yet been conclusively determined, and is presently being studied by SNL.

The carbon steel drums and boxes that are presently being used for the storage of TRU waste are expected to corrode if they come in contact with the brine in the repository, and generate hydrogen by the process of anoxic corrosion. Although the effect of excess gas pressure is still to be determined by SNL, the EATF is studying alternate waste container materials, so that if necessary, modifications to the existing container materials can be addressed in an effective manner.

The Waste Container Materials Panel (WCMP) was convened by the EATF from August 20-21, 1990, for the preliminary identification and evaluation of alternative materials for manufacturing waste containers that would not generate gas in the WIPP environment. The panel comprised a group of technical experts from the following disciplines:

- Basic Ceramic Research
- Ceramic Fabrication
- Cementitious Materials
- Concrete Container Fabrication
- Physical Metallurgy
- Metallurgy/Corrosion
- Geochemistry
- Performance Assessment
- Waste Handling and Repository Operations.

The specific objectives of the WCMP were to:

- Identify container materials that will not generate gas in the WIPP repository environment, or generate gas at substantially lower rates as compared to the existing container material, and can be fabricated to the requirements for containment, handling, and transportation of Contact-Handled Transuranic (CH-TRU) waste.
- Evaluate the identified materials with respect to various design requirements for a waste container such as fabricability, availability, mechanical properties, etc.

This report describes the methodology used by the WCMP to accomplish the above objectives, the evaluation of the different materials, and the conclusions reached by the WCMP regarding the possibility of using alternative waste container materials that would satisfy the gas generation requirements (if gas generation is determined to be a problem by the ongoing performance assessment studies).

## METHODOLOGY FOR WCMP EVALUATION

The panel members were briefed on the WIPP repository, the different constituents of TRU waste, the regulations governing the disposal of TRU waste, performance parameters such as gas generation, permeability, etc., and the possible outcomes of excess gas pressure in the storage rooms. The existing configuration for the handling and transportation of TRU waste, the U.S. Department of Transportation (DOT) Type A Packaging Tests (DOT, 1989), and the environmental conditions within the repository such as temperature, humidity, oxygen, stresses, and brine chemistry which are likely to be encountered by the waste container materials, were also explained to the panel members.

The WCMP defined the following criteria for evaluation of the alternative waste container materials:

- Fabricability - The ease with which the material can be fabricated into a container with a size and shape similar to the existing 55-gallon drums.
- Availability - The availability of material to manufacture the required number of containers per year.
- Fabrication Capacity - The existing capacity to fabricate waste containers from the given material.
- Status of Technology - The current state of technology for fabrication of the material.
- Cost - The overall cost for manufacturing a waste container including material and fabrication costs, but excluding any research and development costs that might be necessary for some materials.
- Mechanical Properties - The ability of a container made of an alternate material to survive the DOT Type A packaging tests.
- Gas Generation Potential - The total moles of gas that can be theoretically generated by thermodynamically favored reactions between the alternative material and all other species present in the repository environment.
- Gas Generation Rate - The rate at which gas might be expected to be generated from the material by either anoxic corrosion, microbial activity, or radiolysis. The panel members agreed that the rate of corrosion under anoxic conditions was a good indicator of the rate of gas generation.

Since the existing waste containers are made of mild steel, the WCMP established mild steel as the reference standard material, and evaluated each alternative material by comparing it to mild steel with respect to the criteria mentioned above.

Apart from the evaluation criteria mentioned above, the WCMP set forth the following general design requirements for waste containers to be built from alternative materials:

- Eliminate or minimize gas generation from container material for the regulatory period of 10,000 years.
- Maintain complete containment of the waste for a minimum of 25 years, (the duration of the operating life of the repository).
- Meet DOT Type A requirements.

The WCMP also made the following assumptions about the waste containers made from alternative materials:

- The alternative waste containers would be subject to the same regulations which apply to the existing containers.
- The alternative waste containers may be "free-standing" (similar to a 55-gallon drum or box), or it could be "formed" around the waste by isostatically pressing a container material such as cement around a monolithic block of processed waste.

The different classes of materials and their subcategories evaluated by the WCMP were as follows:

- Metals
  - Copper and alloys
  - Titanium and alloys
  - High-nickel alloys
  - Zirconium and alloys
  - Stainless steel
- Ceramics
  - Fired ceramics
  - Chemically bonded ceramics
  - Glass
- Cements
  - Nonreinforced cements
  - Discontinuous reinforcement
  - Continuous reinforcement

- Coatings
  - Corrosion retardation
  - Containment enhancement for monolithic waste forms
- Polymers
  - Polyethylene.

The WCMP assumed that all the brittle materials such as ceramics, cements, and glass, will be reinforced as required to provide whatever mechanical properties are deemed necessary to satisfy the DOT Type A packaging tests.

### RESULTS OF WCMP EVALUATION

The evaluation of five different groups of materials (listed above) indicate that there are quite a few candidate materials which are likely to satisfy the design requirements for alternative waste containers. The WCMP believed that subsequent to the preliminary evaluation, with respect to the criteria defined earlier, there are two important characteristics that need to be verified for each of the candidate materials through development programs; the degree to which the material can satisfy the "no gas generation" requirement, and whether it can be fabricated into a container satisfying the appropriate transportation and handling requirements. Therefore, apart from cost, the WCMP summarized its evaluations of alternative materials in terms of four other criteria closely related to the verification of the above characteristics:

- Time likely to be needed to establish the effectiveness of the material in meeting the "no gas generation" requirement.
- Time likely to be needed to develop fabrication technology, and make a full-scale fabricated container.
- Probability of success in terms of the WCMP's best judgement that the material will satisfy the "no gas generation" requirement.
- Probability of success in terms of the WCMP's best judgement that the material can be fabricated into a container satisfying DOT Type A requirements.
- Cost of container in comparison to mild steel.

It was noted by the panel members that if DOT Type A requirements are to be met, then containers made of metals and polymers would probably carry the maximum payload per container. The WCMP also came to the conclusion that any research involving microbial gas generation is likely to become a long-term project because of the uncertainty associated with microbes. Therefore, whenever possible, experimental schedules for establishing the

effectiveness of a material, and efforts to establish a full-scale product, should be planned in parallel to make the most efficient use of time.

The conclusions of the WCMP are presented in Table HES-1. It should be noted that the cost estimates do not include any developmental costs or the costs of building any new facilities that might be required for some materials. Also, the estimates of schedules do not include programmatic planning time likely to be associated with the planning of research strategies, approval of schedule and budget, etc.

The summary presented in Table HES-1 is based on preliminary evaluation of these materials, and therefore represents best estimates rather than precise values. The figures in Table HES-1 provide relative estimates of the probability of the materials in meeting the effectiveness and fabricability requirements for a container, as well as the time required to verify these probabilities. The WCMP decided that copper, titanium, high-nickel alloys, zirconium alloys, ceramics, glass, and cements are all viable materials which could possibly satisfy the design requirements for an alternative waste container. However, there are some concerns associated with each material that need to be resolved.

The WCMP noted that although ceramics and cements have excellent gas generation properties as compared to metallics, and are inexpensive, waste containers made from these brittle materials are likely to have smaller internal volumes due to the thicker container walls required to satisfy DOT Type A requirements. This will result in a smaller TRU waste payload per container. In addition, if the container weight is heavier than the existing drums, then fewer containers will make up the TRUPACT-II payload, leading to increased number of waste shipments from the storage sites to the WIPP site. These factors can have large impacts on the overall program cost beyond the low unit costs required to fabricate the containers. It should also be noted that with the possible exception of cements, there is no technology presently in place to fabricate large containers from the nonmetallic materials. Therefore, the fabrication of an acceptable nonmetallic container that would satisfy the DOT Type A requirements, is likely to require long-term research and development efforts.

Among the metallics evaluated by the WCMP, with the exception of copper, there are expensive metal alloys (titanium, high-nickel, and zirconium) that have relatively fewer uncertainties associated with them, especially with respect to fabricability, and payload volume per container. Once their low anticipated corrosion rates are validated under WIPP conditions, these alloys have the potential of immediately satisfying the design requirements. Whereas, the higher end high-nickel alloys (e.g., Hastelloy C-276), and the zirconium alloys would substantially escalate program costs (roughly by \$1 billion based on 600,000 mild steel drums at a cost of \$50 per mild steel drum), the WCMP felt that the lower cost titanium alloys would be adequate for the purpose. Besides, under the relatively mild temperatures expected in the repository environment (~ 30°C), there is not likely to be any notable differences in corrosion properties between the relatively inexpensive titanium alloys and the more expensive ones such as zirconium and higher end high-nickel alloys.

**TABLE HES-1  
SUMMARY OF RESULTS**

	<u>Time to Establish Effectiveness</u>	<u>Time to Establish Full-Scale Product</u>	<u>Cost Factor<sup>a</sup></u>	<u>Probability of Success in Establishing Effectiveness</u>	<u>Probability of Success in Meeting DOT Type-A Requirements</u>
Copper & Alloys <sup>b</sup>	1-2 yrs.	2 yrs.	5-8 x	90%	100%
Titanium & Alloys	1-2 yrs.	2 yrs.	10-20 x	95%	100%
High-Nickel Alloys	1-2 yrs.	2 yrs.	15-35 x	97%	100%
Zirconium Alloys	1-2 yrs.	2 yrs.	35 x	98%	100%
Stainless Steel <sup>b</sup>	1-2 yrs.	0-1 yrs.	5-8 x	50%	100%
Free Standing Ceramics <sup>c</sup>	0 yrs. (validate)	4-8 yrs.	25-30 x	99.9%	30%-90%
Chem. Bonded Ceramics <sup>c</sup>	0 yrs. (validate)	3-5 yrs.	1-10 x	99.9%	30%-85%
Glass <sup>c</sup>	0 yrs. (validate)	2-4 yrs.	1-10 x	99.9%	20%-90%
Cements <sup>c</sup>	1-2 yrs.	2-4 yrs.	2-8 x	99.9%	30%-85%
Polymers	5 yrs. <sup>d</sup>	0-1 yrs.	5-10 x	Indeterminate	100%

<sup>a</sup> Relative to a mild steel container.

<sup>b</sup> Uncertainty associated with effect of microbes - not considered in duration.

<sup>c</sup> Reinforced as required.

<sup>d</sup> Should be dropped from consideration if effectiveness cannot be proven within 5 years.

The results of the WCMP should be used to:

- Select a few promising alternative materials for detailed testing regarding their fabricability and corrosion/gas generation properties
- Evaluate, with the help of appropriate experiments, the effectiveness of the selected materials for meeting the "no gas generation" requirement
- Design and demonstrate the fabricability of the selected materials (reinforced as required) into a container satisfying all transportation and handling requirements
- Estimate the total cost per container, and its impact on overall program cost for the selected materials based on the annual fabrication requirements.

Thus, the right choice of material would have to be decided by tests on a few promising materials for effectiveness and feasibility, and would also be determined by applicable cost, schedule, and transportation constraints.

## 1.0 INTRODUCTION

### 1.1 BACKGROUND

The Waste Isolation Pilot Plant (WIPP) in southeastern New Mexico is an underground repository designed for the safe geologic disposal of transuranic (TRU) wastes. Transuranic wastes are generated from defense-related activities of the U.S. Department of Energy (DOE). The underground storage area of the WIPP repository is located 2,155 feet below the surface in a bedded salt (halite) formation. After disposal of the waste in the WIPP storage rooms, closure of the repository occurs by the creep of the surrounding salt formation. This creep is in response to the pressure gradient that exists between the far-field pressure away from the repository (referred to as the lithostatic pressure, or the pressure at the depth of the repository due to the overlying rock), and the pressure in the repository which is initially at atmospheric pressure. In a freshly excavated room, the creep is of the order of a few inches per year. Under ideal conditions, complete closure of the repository occurs due to creep, and the waste is permanently isolated from the surrounding environment.

The waste to be disposed at WIPP consists of materials such as laboratory hardware, inorganic sludges, protective clothing, plastics, rubber, resins, and tools that have become contaminated with transuranic elements, mostly plutonium with minor amounts of americium, uranium, neptunium, and thorium. The specific isotopes of these elements that are present in WIPP waste are generally alpha emitters with long half-lives and minimal heat production. The waste is presently stored in 55-gallon steel drums and a lesser number of steel boxes at ten major waste generation and storage sites across the country.

### 1.2 REGULATORY CONSIDERATIONS

The geologic disposal of TRU waste is governed by the U.S. Environmental Protection Agency (EPA) Standard - 40 CFR Part 191 (EPA, 1985). This regulation sets limits on the cumulative allowable releases of radioactive isotopes to the accessible environment over a period of 10,000 years. The study done to show compliance with this regulation is referred to as performance assessment. Both undisturbed performance as well as the consequences of inadvertent human intrusion in the form of future exploratory drilling must be considered, as required by the EPA Standard.

The performance assessment for the WIPP repository is being conducted by Sandia National Laboratories (SNL), and is expected to be completed by 1994 (DOE, 1990d). Work currently in progress at SNL has suggested that some modifications to the current waste forms may be necessary to demonstrate compliance with the EPA Standard (DOE, 1990a). In response to this concern, and based on recommendations of the National Academy of Sciences (NAS), the DOE WIPP Project Office established the Engineered Alternatives Task Force (EATF) in September 1989, to evaluate the effectiveness and feasibility of various modifications to the WIPP facility design and waste forms which would improve the long-term isolation capability of the repository (Hunt, 1990). Preliminary assessments of the long-term performance of the

disposal system have identified gas generation as one of the three key parameters that might affect performance of the disposal system (DOE, 1990a). The different gas generation mechanisms are discussed in the next section.

### 1.3 GAS GENERATION

The three main mechanisms for the generation and consumption of gases in the underground environment are:

- Corrosion of metals
- Microbial activity
- Radiolysis

Corrosion of Metals - There are two general mechanisms for corrosion that may occur in the underground WIPP environment. Oxidic corrosion occurs when iron reacts with oxygen to form corrosion products such as iron oxides or oxyhydroxides. Anoxic corrosion occurs when iron reacts with brine or water vapor to form iron oxides or oxyhydroxides and hydrogen. The net effect of oxidic corrosion is the consumption of oxygen, and the net effect of anoxic corrosion is the production of hydrogen. Water, in either a liquid or vapor state, is required for anoxic corrosion and is consumed in the process, suggesting that the availability of moisture may be the rate-limiting step in this process.

Microbial Activity - Microbial activity can potentially break down organic materials such as paper, plastic, and wood, consuming oxygen and generating carbon dioxide and methane in the process. Sulfate-reducing bacteria, if present, can potentially generate hydrogen sulfide from sulfate present in natural brine, and nitrate-reducing bacteria, if present, can potentially generate nitrogen from nitrate salts present in the waste. The large mass of organic materials in the WIPP waste inventory, together with the presence of sulfate and nitrate, suggest that there is a potential to eventually generate large amounts of gases.

Radiolysis - Radiolysis has the potential to generate hydrogen and oxygen from the decomposition of water; and carbon dioxide, carbon monoxide, hydrogen, and methane from the decomposition of organic materials. Oxygen that is generated by the decomposition of water will probably be consumed by microbial or chemical reactions, but the production of hydrogen, carbon dioxide, and methane is of potential concern. The form of radiation present in TRU waste is the emission of alpha particles which have a very limited range.

The carbon steel drums and boxes currently in use are expected to corrode if they come in contact with brine in the repository. The gases produced by anoxic corrosion and other mechanisms such as microbial activity and radiolysis, may result in higher than desired pressure in the repository, because although processes exist to dissipate excess gas pressure by advection through the host rock, these processes are believed to be slow relative to the current estimates of gas generation rates. The effect of excess gas pressure on the performance of the repository is presently being studied by SNL. Whether gas generation is a problem has not yet been conclusively determined. Nevertheless, alternate container

materials are being considered now by the EATF, so that if necessary, modifications can be made in a timely manner.

#### **1.4 THE WASTE CONTAINER MATERIALS PANEL AND ITS OBJECTIVES**

The Waste Container Materials Panel (WCMP) was convened by the EATF for the preliminary identification and evaluation of alternative materials for manufacturing waste containers that would not generate gas in the WIPP environment. The panel comprised a group of technical experts from different areas of materials science, and from certain areas associated with the WIPP repository and its environment. The following disciplines were represented on the panel:

- Basic Ceramic Research
- Ceramic Fabrication
- Cementitious Materials
- Concrete Container Fabrication
- Physical Metallurgy
- Metallurgy/Corrosion
- Geochemistry
- Performance Assessment
- Waste Handling and Repository Operations.

A description of the qualifications of the members of the WCMP is provided in Attachment A. The objectives of the WCMP were to:

- Identify container materials that will not generate gas in the WIPP repository environment, or will potentially generate gas at substantially lower rates as compared to the existing container material, and that can be fabricated to the requirements for containment, handling, and transportation of Contact-Handled Transuranic (CH-TRU) waste.
- Evaluate the identified materials with respect to various design requirements for a waste container such as fabricability, availability, gas generation, mechanical properties, etc.

This report describes the methodology used by the WCMP to accomplish the above objectives, the results of the WCMP deliberations, and the conclusions reached by the WCMP regarding the possibility of using alternative materials to manufacture waste containers that would meet design objectives.

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## 2.0 METHODOLOGY USED BY THE WASTE CONTAINER MATERIALS PANEL (WCMP)

The WCMP was convened from August 20-21, 1990. The panel members were briefed on the WIPP repository, the different constituents of TRU waste, the applicable regulations, performance parameters such as gas generation, permeability, etc., and the possible outcomes of excess gas pressure in the storage rooms. In addition, the existing configuration for the handling and transportation of TRU waste in the TRUPACT-II package (NuPac, 1989), and the U.S. Department of Transportation (DOT) 49 CFR Part 173.465 Type A Packaging Tests (DOT, 1989) were explained to the panel.

### 2.1 ENVIRONMENTAL CONDITIONS WITHIN THE REPOSITORY

The various environmental conditions in the WIPP repository which are most likely to be encountered by the waste container materials were outlined as follows:

- Temperature - The temperature in the repository is expected to remain constant around 26°C, which is the ambient rock temperature at the facility horizon. Radiogenic heat generation from the waste is minimal (less than 0.1 watt per drum). Remote-handled TRU (RH-TRU) waste generates a greater amount of radiogenic heat, however it constitutes only three percent of the waste inventory.
- Humidity - Limited amounts of brine have been observed to flow into the repository, and after the facility is sealed, the humidity of the room will be controlled by the evaporation of the brine. Assuming there is saturated brine in the sealed repository with air at atmospheric pressure above the brine, then the relative humidity in the repository will be approximately 70 percent.
- Oxygen - Although the repository will initially have an oxic environment, this oxygen is expected to be consumed in the process of microbial degradation of organics present in the waste, thereby eventually leading to an anoxic environment. Some oxygen is also expected to be consumed during the corrosion process of the mild steel drums. However, some oxygen could also be generated within the repository from the radiolysis of brine. Overall, since the rate of generation of oxygen by radiolysis is expected to be less than the rate of consumption of oxygen by microbial degradation and corrosion, an anoxic environment is expected within the repository after the depletion of the initial oxygen.
- Stresses - The reconsolidation of salt, which is plastic, will result in an isostatic stress equal to the lithostatic pressure of about 2000 psi (15 MPa). However, since the storage rooms are 33 feet in width and only 13 feet in height, the reconsolidation of salt in the ceiling-to-floor direction occurs much faster than the reconsolidation in a horizontal direction. This will result in some unidirectional

stress until complete closure has taken place. Once the salt has completely reconsolidated, the stress is expected to be isostatic throughout the repository, and equal to the lithostatic pressure.

- **Brine** - The major elements present in the brine include Cl (~200,000 mg/l), Na (~85,000 mg/l), Mg (~18,000 mg/l), K (~18,000 mg/l), and  $\text{SO}_4^{2-}$  (~17,000 mg/l). Br and B are also present at concentrations above 1,300 mg/l. The pH is 6.1, and total dissolved solids equal ~350,000 mg/l.

## 2.2 EVALUATION CRITERIA FOR MATERIALS

The WCMP defined the following criteria for evaluation of alternative waste container materials:

- **Fabricability** - The ease with which the material can be fabricated into a container with size and shape similar to a 55-gallon drum. Rectangular and hexagonal shapes were also considered.
- **Availability** - The availability of the raw material to manufacture the required number of containers per year (thousands of waste containers per year for several years).
- **Fabrication Capacity** - The existing capacity to fabricate waste containers from the given material (i.e., whether there are facilities available today which can accept a bulk order and start delivering waste containers within a reasonable time).
- **Status of Technology** - The current state of technology for fabrication of the material (i.e., whether the different techniques for fabrication are well understood for commercial-scale production purposes, or if the technology needs further research and development for implementation).
- **Cost** - The cost of a material was defined as the overall cost for manufacturing a waste container including both material and fabrication costs. Since the objective of this panel was primarily a preliminary evaluation of different prospective materials, the WCMP decided against subdividing the total cost into materials and fabrication because this would have complicated the process of evaluation to an extent well beyond the nature and scope of this panel. The WCMP also refrained from including developmental cost because of the difficulties in estimating the uncertainties associated with any research and development program. Any estimates of developmental cost at the onset could be significantly altered, if for example, there is an unexpected breakthrough in the research program. Therefore, developmental costs were not included as part of the overall cost.

- **Mechanical Properties** - These refer to the ability of a container made of an alternate material to survive the DOT Type A Packaging Tests (DOT, 1989). The WCMP decided to evaluate the materials in terms of certain mechanical properties (e.g., tensile strength, fracture toughness, etc.) which are required to satisfy the DOT Type A requirements. Although the WCMP could not evaluate whether meeting Type A would be a requirement or not in the future, it was decided that these requirements should be included in view of the existing WIPP Waste Acceptance Criteria (DOE, 1989b) which list the DOT Type A packaging tests as a requirement for waste containers. It was decided that any material judged to be at least equivalent to mild steel in overall mechanical properties would be rated as "adequate."
- **Gas Generation Potential** - This refers to the total moles of gases that can be theoretically generated by thermodynamically favored reactions between the alternative material, and all other species, given the repository environment (i.e., pressure, temperature, humidity, presence of brine, etc.). The WCMP agreed that given the potential complexity of the WIPP repository environment coupled with the regulatory period of 10,000 years, it is probably safer and conservative to assume that all reactions which are thermodynamically favored might eventually go to completion, unless adequate kinetic data is available to demonstrate that favored reactions will not occur.
- **Gas Generation Rate** - This is defined as the rate at which gas is expected to be generated from the material by either one of the three mechanisms discussed earlier in Section 1.3. Whereas the gas generation potential gives an indication of the total amount of gas that could be generated (provided all reactions go to completion), the gas generation rate provides a measure of how fast (or slow) this potential might be achieved. Thus, even if a given material has a high potential for gas generation, it cannot be ruled out from consideration. An alternative container material might have a rate of gas generation which is low enough that the rate of advection from the repository is adequate to prevent high gas pressures in the repository. The WCMP was not in a position to address how low the gas generation rates need to be relative to the advection rates. However, for quantitative comparisons, the WCMP agreed that the rate of corrosion of a material under anoxic conditions was a good indicator of the gas generation rate for that material.

Considering the broad spectrum of materials being evaluated (ranging from metals to ceramics to concrete), the WCMP established mild steel as the reference standard material to facilitate easy comparison between the materials. The selection of mild steel was based on two reasons:

- Since mild steel is being used for the existing waste containers, a comparison with mild steel provides an indication of the merits and disadvantages of each alternative material relative to the presently used container material.

- Since mild steel is a commonly used material for a wide variety of purposes, its properties are well documented and hence provide a firm basis for comparison.

Thus, the WCMP decided to compare all alternative materials to mild steel with respect to each evaluation criteria discussed earlier. As an example, while evaluating the fabricability of a material, the WCMP would judge whether its fabricability is easier, the same, or more difficult in comparison to mild steel.

### **2.3 DESIGN REQUIREMENTS FOR WASTE CONTAINERS**

Apart from the specific criteria defined above for evaluation of materials, the WCMP also agreed to some general design requirements for waste containers to be built from alternative materials. These requirements were outlined as:

- Minimize or eliminate gas generation from container material for the regulatory period of 10,000 years.
- Maintain complete containment of the waste for a minimum of 25 years, (the duration of the operating life of the WIPP repository).
- Meet DOT Type A requirements.
- The containers should not degrade in any way that will significantly increase the permeability of the storage room environment.

In addition, the WCMP also made the following assumptions regarding the waste containers:

- The waste containers fabricated from alternative materials will be subjected to the same regulations which apply to the existing containers.
- The container may be "free-standing" (i.e., similar to a 55-gallon drum or box), or it could be "formed" around the waste (i.e., by isostatically pressing a container material such as cement around a monolithic block of waste).

### **2.4 MATERIALS SELECTED FOR EVALUATION**

The WCMP initially selected five different classes of materials for evaluation. Each class of material was further subdivided into its own categories by appropriate classification schemes. Metals were classified by each metal and its alloys. Since ceramics are strongly bonded, they are all very stable materials from a gas generation standpoint, and therefore do not have any significant chemical properties to distinguish one from another. Therefore, ceramics were classified by their manufacturing method because there is a distinguishable difference between the processing techniques for different ceramics. In a similar manner, the WCMP decided to classify cements in terms of the reinforcements used in them because these lead to significant

differences in cost and properties. The different classes of materials and their subcategories evaluated by the WCMP were as follows:

- **Metals**
  - **Copper and alloys**
  - **Titanium and alloys**
  - **High-nickel alloys**
  - **Zirconium and alloys**
  - **Stainless steels**
- **Ceramics**
  - **Fired ceramics**
  - **Chemically bonded ceramics**
  - **Glass**
- **Cements**
  - **Non-reinforced**
  - **Discontinuous reinforcement**
  - **Continuous reinforcement**
- **Coatings**
  - **Corrosion retardation**
  - **Containment enhancement for monolithic waste forms**
- **Polymers**
  - **Polyethylene.**

Each of the above materials were evaluated with respect to the criteria described earlier in Section 2.2. The results of the evaluation are described in the next section.

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### 3.0 RESULTS OF THE WCMP EVALUATION OF ALTERNATIVE MATERIALS

The WCMP evaluated all the materials by comparing them to mild steel (as explained in Section 2.2), for each of the evaluation criteria described earlier. It should be noted that these evaluations were to a large extent judgmental, and are preliminary in nature. If performance assessment studies identify gas generation as an impediment to demonstrating compliance with the regulatory standard described in Section 1.2, then the evaluations of the WCMP could be used as a basis for any detailed future studies on alternative container materials.

The WCMP also established rough estimates for the cost of mild steel to set up a baseline for cost comparison of alternative materials. It was agreed by the WCMP that based on a material cost of 27 to 37 cents per pound of mild steel sheet, and a total cost of approximately \$50 for a 60-lb. drum, a fabrication cost of 50 cents per pound was a reasonable assumption based on fabricating a 60-lb. drum. Thus, for cost comparisons, all materials were compared with the baseline of 77 to 87 cents per pound of finished mild steel product.

#### 3.1 COPPER AND ALLOYS

- Fabricability - Copper is a little harder to weld than mild steel because of its high thermal conductivity, and therefore joining and handling of copper might be more difficult than mild steel. However, bearing in mind that the technology was well established, the WCMP rated the overall fabricability of copper to be about the same as that of mild steel.
- Availability - Assuming that any drums fabricated would use sheet metal as the starting material, the availability of copper and alloys was deemed to be plentiful, and equivalent to the availability of mild steel.
- Fabrication Capacity - Although the technology for fabricating copper is well established, the WCMP did not think that there are facilities available today which could start manufacturing copper drums at a short notice. Therefore the fabrication capacity of copper and alloys was judged to be "limited" in comparison to mild steel.
- Status of Technology - Since the metallurgy and fabrication of copper are quite well understood, the status of technology was deemed adequate and equivalent to mild steel.
- Cost - The cost would depend on the type of copper or its alloys being used. The cost of electrolytic copper is about \$1.50/lb. Assuming the fabrication cost to be close to \$50 for a 60 lb. drum, the WCMP estimated the total cost of a

copper drum to be roughly \$150. This works out to be approximately 3 times that of mild steel. The WCMP also consulted the report on container materials for high level waste (Braithwaite and Molecke, 1980) where cost per unit weight of a manufactured copper container was 8.2 times that of mild steel. However, the dimensions of the container cited in this report were much larger than a 55-gallon drum, and the WCMP decided that for a smaller container the increase in cost is more likely to be 5 times that of mild steel. Overall, the WCMP agreed that a conservative estimate of 5 to 8 times that of mild steel would be a reasonable estimate for the cost of copper. It should be noted that this figure is very likely to increase if copper is alloyed with other materials.

- Mechanical Properties - Cold rolled copper will have mechanical properties very similar to that of lightly cold rolled low carbon steel, and if alloyed with 10% nickel, the properties could be very similar to mild steel. Based on these assumptions, the mechanical properties of copper were rated to be equivalent to that of mild steel. However, the WCMP agreed that the mechanical properties of a copper drum need to be verified after fabrication to determine whether copper needs alloying to enhance the properties. The alloying materials suggested for improvement were Ni (10%) or Zn (15%).
- Gas Generation Potential and Rate - Copper or copper-alloys have been found to be stable and resistant to corrosion in deaerated neutral pH conditions even under prolonged (2 months) exposure to brine at high temperature (150°C). Therefore, under deaerated conditions, it is not a gas generator (Westerman, 1988). However, the presence of any oxygen, sulfates, nitrates, or carbon dioxide open up a wide range of possibilities. The WCMP expressed concerns at the possibility of sulfates being reduced to sulfides by sulfate-reducing bacteria, which could then react with copper, resulting in the formation of copper sulfide and hydrogen. Similarly, the nitrates present in the sludges could be reduced to ammonia which in turn could cause stress corrosion cracking in copper. There were other concerns expressed about the corrosion of copper in low pH (2.0) carbonic acid solutions which could potentially form from microbial activity. The study by Braithwaite and Molecke (1980) reported corrosion rates of copper to be 25 times less than mild steel. Therefore the WCMP rated the gas generation rate of copper to be low in comparison to mild steel. Limited experiments may be required to verify these low rates.

The above scenarios notwithstanding, the potential for gas generation from copper depends entirely on the presence of a few microbially or radiolytically generated components such as  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{NO}_3^-$ , etc. The WCMP acknowledged the fact that the simultaneous presence of these species can at best be termed uncertain, and therefore agreed to rate the gas generation potential for copper as low. The WCMP recommends, however, that the effect of these species on gas generation potentials be resolved by appropriate experiments if copper is chosen as an alternative material for waste containers.

### 3.2 TITANIUM AND ALLOYS

- Fabricability - Titanium is a difficult material to weld, forge, or join for a variety of reasons. It has a tendency to weld to the tool during machining, leading to chipping and premature tool failure. Its low heat conductivity could increase the temperature at the tool/workpiece interface, thereby adversely affecting tool life. Also, the surface of titanium alloys is easily damaged in machining operations, especially during grinding, resulting in lower fatigue strength (Kahles et al., 1985). The WCMP agreed that the fabricability of titanium is more difficult than mild steel.
- Availability - It was estimated that based on a requirement of 600,000 drums over a period of 25 years, and a weight of 60 lbs/drum, the material required would be approximately 1.44 million lbs/year. However, it should be noted that because of the excellent corrosion resistance of titanium and its alloys, the actual amount of material required could be less than the estimated figure of 1.44 million lbs/year. This is only about 2% of the current U.S. production capacity, and therefore availability of titanium was considered to be adequate for the purpose.
- Fabrication Capacity - Facilities are available at this time to manufacture titanium drums, and there are a few companies who have fabricated drums with TiCode-12 and Grade 2 titanium. However, these have been done only on a pilot-scale, and at present no such facility exists to start delivering thousands of drums per year at a short notice. A considerable amount of scale-up effort may be required, and so the current fabrication capacity can at best be termed "limited."
- Status of Technology - Since titanium can be fabricated, and has been demonstrated for drum fabrication on a pilot-scale, the WCMP rated the technological status to be equivalent to that of mild steel.
- Cost - The report by Braithwaite and Molecke (1980) quoted the cost of a titanium container to be approximately 13 times that of mild steel. On this basis, the WCMP agreed that a cost of 10 to 20 times that of mild steel would be a reasonable assumption for titanium containers. The WCMP also noted that any alloying will increase the cost.
- Mechanical Properties - Titanium has yield stress and ultimate stress values of approximately 40% higher than those of mild steel. However, the term "mechanical properties" as defined by the WCMP also included other properties like resistance to tear (for surviving a drop test). Therefore the WCMP agreed that considering all the variables involved, the mechanical properties of titanium and its alloys are not substantially better than mild steel and rated them to be equivalent to mild steel.

- **Gas Generation Potential and Rate** - Titanium is susceptible to crevice corrosion under low pH conditions and temperatures ranging from 80°C to 150°C (Westerman and Telander, 1986). The product of crevice corrosion is titanium dioxide, but under anoxic conditions hydrogen will be released on the outside of the crevice. At the relatively low temperatures in the repository (around 26°C), the possibility of crevice corrosion is extremely low, especially if an alloy like TiCode-12 is used which is more resistant to crevice corrosion than the pure metal. However, it cannot be guaranteed that crevice corrosion would not occur for 10,000 years. Also, considering the definition of gas generation potential, the WCMP decided that titanium could have a relatively high gas generation potential.

Braithwaite and Molecke (1980) reported that the rate of uniform corrosion of titanium was 70 times less than copper which in turn was 25 times less than mild steel. On this basis, the rate of corrosion (and therefore gas generation) from titanium and alloys was rated low compared to mild steel.

### 3.3 HIGH-NICKEL ALLOYS

These alloys, which are often called "superalloys" typically contain 40 to 75% nickel, 12 to 20% chromium, 3 to 12% molybdenum, 1 to 45% iron, and minor quantities of other metals as required for enhancing appropriate properties.

- **Fabricability** - Although joining or welding of these alloys is not considered to be a significant problem, they present major problems during cutting, sawing, or lathe-turning operations. The WCMP readily agreed that the fabricability of high-nickel alloys is more difficult than titanium, and definitely much more difficult than mild steel.
- **Availability** - The required amount is roughly equal to 2% of the existing capacity to produce these alloys. Also, since numerous facilities for producing these alloys exist in the U.S., the WCMP considered the availability of high-nickel alloys to be adequate.
- **Fabrication Capacity** - The fabrication technology of these alloys are well understood, but the alloys are primarily used for other purposes which have more stringent requirements (such as steam generators, etc.) There has been no need, so far, for drums made of these expensive superalloys, and therefore there is no existing fabrication capacity for superalloy drums. Although no major problems were anticipated by the WCMP, the implementation of high-nickel alloys as waste container material will definitely require the establishment of fabrication capacity.
- **Status of Technology** - The WCMP agreed that the metallurgical and fabrication technology for these alloys is well established, and the feasibility of scale-up to thousands of drums is not in doubt. However, fabrication technology may have

to be tailored to the production of containers depending on the chosen alloy. Since it is merely a question of time before proper facilities are constructed leading to scale-up, the status of technology for high-nickel alloys was rated to be adequate, and equivalent to mild steel.

- **Cost** - These alloys are very expensive and their costs exhibit a wide range of variation, depending upon the chosen alloy. Inconel-825, which is probably the cheapest of the group, is roughly 12 times more expensive than mild steel, whereas Hastelloy C-276 costs about 34 times more than mild steel. Thus, a cost of 15 to 35 times that of mild steel was considered to be a reasonable estimate by the WCMP. However, the WCMP noted that even the least expensive of these alloys might be adequate as a solution, if gas generation is determined to be a problem.
- **Mechanical Properties** - These alloys have excellent mechanical properties. Their tensile and yield stresses can range from 60-140 ksi and 30-140 ksi, respectively, depending on the alloy. Overall, the WCMP agreed that the mechanical properties were adequate for the purpose and better than mild steel.
- **Gas Generation Potential and Rate** - Compared to mild steel, the partial pressure of hydrogen in equilibrium with nickel is lower. If indeed the equilibrium partial pressure is low enough (2-3 atm.), then any corrosion reaction will stop at an early stage before any appreciable amount of hydrogen has been generated. However, the WCMP also recognized that apart from nickel there are chromium and iron present in these high-nickel alloys. Since both of these are much more susceptible to oxidation than nickel, the overall gas generation potential of superalloys was rated as moderate. The lower end superalloys have been shown to crevice corrode in sea water. If the lower alloys are used, they need to be investigated for pitting and crevice corrosion. Although the report by Braithwaite and Molecke (1980) cited that Inconel-825 (low end) had almost similar crevice corrosion rates as Hastelloy C-276 (high end) for an experimental period of 28 days, it did mention that the rates are dependent on the dimensions of the specimen, duration of experiment, etc. Since the lower alloys also had corrosion rates which were much lower in comparison with mild steel, the gas generation rate for all of these alloys was rated low by the WCMP.

### 3.4 ZIRCONIUM ALLOYS

- **Fabricability** - The fabricability of zirconium is very similar to titanium. It is a difficult material to machine, and was rated to be much more difficult than mild steel for the same reasons outlined earlier for titanium and alloys in Section 3.2.
- **Availability** - The WCMP agreed that there are plenty of facilities in operation for making zirconium sheet. However, the WCMP did not have any rough estimate of whether the production of thousands of drums would have any major impact

on the present supply of zirconium. Therefore, the availability of zirconium was assumed to be adequate, provided it does not make an impact on the present capacity.

- **Fabrication Capacity** - At present there is no existing capacity for making zirconium drums (i.e., there are no facilities fabricating drums made of zirconium at this time). However, since sheet metal technology for zirconium is well understood, the WCMP believes that the development of drum fabrication technology should be relatively straightforward.
- **Status of Technology** - The technological status for fabrication of zirconium drums was considered to be adequate by the WCMP.
- **Cost** - The Office of Civilian Radioactive Waste Management Investigations on containers for high-level waste (Russell, et al., 1983) estimated costs of a container made of zirconium alloy (Zircaloy-702) to be 35 times that of mild steel. The WCMP thought that this was a reasonable estimate, especially when compared to the cost estimates for titanium and high-nickel alloys discussed in Sections 3.2 and 3.3, respectively.
- **Mechanical Properties** - Since zirconium alloys are used for fuel cladding in nuclear reactors, the WCMP agreed that its mechanical properties were definitely adequate for the purpose of containment of TRU waste for 25 years as well as for meeting DOT Type A requirements.
- **Gas Generation Potential and Rate** - The WCMP used the thermodynamic arguments similar to the ones used for evaluating the gas generation potential of titanium to conclude that zirconium also has a high gas generation potential.

The corrosion rate of zirconium has been studied by Russell et al, (1983). These studies show that zirconium has exceptional corrosion resistance, and is predicted to be resistant to corrosion even at high temperatures for long periods of time. The extremely low rates of corrosion led the WCMP to conclude that zirconium will also have a very low rate of gas generation.

### **3.5 ALUMINUM AND ALLOYS**

In view of the very low corrosion resistance of aluminum in brine, the WCMP could not justify the possibility of using aluminum as an alternative waste container material. By a unanimous decision, the WCMP eliminated aluminum from further consideration.

### **3.6 STAINLESS STEELS**

The WCMP did express some doubts about considering stainless steels for evaluation, because of their known susceptibility to stress-corrosion cracking in solutions containing

chlorides. However, keeping in mind that the conditions at the WIPP are not going to be very extreme in nature, i.e., the temperature is expected to be below 30°C, and the fact that many stainless steels will probably adequately resist stress-corrosion cracking in the WIPP environment, the WCMP agreed to consider stainless steels for further evaluation. Also, on the basis of the study by Braithwaite and Molecke (1980) which reported that the corrosion rates of stainless steel at high temperatures in brine similar to WIPP brine is 100 times less than mild steel, the WCMP decided that the gas generation rates for stainless steel are low enough to justify its further evaluation.

- Fabricability - The fabricability of stainless steel is not much different from mild steel, and for the purposes being considered, was rated to be the same as mild steel.
- Availability - Stainless steels are widely available materials, and there is adequate supply for manufacturing thousands of drums per year.
- Fabrication Capacity - Stainless steel drums are presently produced (although not in large quantities), and Oak Ridge National Laboratory uses them on a regular basis. Although the installation of additional capacity might be needed, this is attainable, and therefore the WCMP considered fabrication capacity of stainless steel to be adequate.
- Status of Technology - The technology has been well demonstrated on a commercial scale, and is adequate for drum fabrication.
- Cost - The cost of stainless steel will depend upon the particular alloy chosen. Based on the study by Braithwaite and Molecke (1980) which quoted stainless steel to be 6 times more expensive than mild steel, the WCMP decided that considering the wide range of stainless steels available, a range of 5 to 8 times that of mild steel would be a reasonable estimate for the cost of 300 series stainless steel. It should be noted that the cost of 400 series stainless steel will be lower.
- Mechanical Properties - The WCMP decided that the mechanical properties of stainless steel were better than mild steel although not by a wide margin. Therefore, the properties were rated as "adequate."
- Gas Generation Potential and Rate - The WCMP agreed that the overall gas generation potential from stainless steel would not be much different from mild steel, and therefore rated the gas generation potential as high.

On the issue of rate of gas generation, the Braithwaite and Molecke (1980) study was quoted as having reported that the corrosion rates of stainless steel were 100 times lower than mild steel when exposed to high magnesium brine at 250°C for 28 hours. The WCMP was hesitant to extrapolate such short-term data to

the lower temperature conditions expected at the WIPP site, because it was noted that corrosion rates do not necessarily increase with higher temperatures. Therefore the WCMP questioned the applicability of the data from Braithwaite and Molecke (1980) under WIPP conditions, and decided that the gas generation rate of stainless steel should be judged as moderate compared to mild steel. Additional testing under the WIPP conditions may be appropriate to clarify the gas generation rates from stainless steel.

### **3.7 FIRED CERAMICS - FREE-STANDING CONTAINER**

The majority of the WCMP initially expressed doubts about the fabricability of ceramics into free-standing containers (similar to a drum). It was suggested that using ceramic materials might cause a total redesign of the container (i.e., a deviation from the standard concept of containers which are normally visualized as initially "empty" with the waste packed inside later). In contrast, ceramic containers would probably be much more attractive for a processed monolithic waste form where the container will actually gain in mechanical properties from the monolithic waste inside it. Some advantages of using alternative shapes were pointed out as well. As an example, the current cylindrical design of drums allows more void space when stacked in a storage room than a rectangular or hexagonal design. A reduction in void space using an appropriate shape (e.g., cubic) would decrease the required time for storage room reconsolidation, thereby reducing the time available for brine inflow into the repository.

Finally, the WCMP believed that given the rapid advances in the science of ceramics, there is a high probability that a fired ceramic could be formulated that can be fabricated into a free-standing container. In addition, all forms of ceramics, as well as glass and cements, could be reinforced as necessary to improve mechanical properties. On this basis, the panel members proceeded to evaluate a free-standing container made out of fired ceramics.

- **Fabricability** - The possibilities of firing large monolithic pieces using available microwave technology (especially for thick-walled vessels encountering temperature gradients) are becoming technologically manageable. However, although promising technologies exist, the fabrication of these materials into free-standing containers has not yet been demonstrated. Also, since these containers have to be sealed, joining the lids to the body of the containers may present considerable challenges. Therefore, the WCMP rated the fabricability of these materials to be much more difficult than mild steel.
- **Availability** - The basic material (i.e., fired ceramics) is widely available, and therefore its availability was judged to be adequate by the panel members.
- **Fabrication Capacity** - There is no current fabrication capacity for free-standing containers made out of fired ceramics. However, alternative container designs based on existing ceramics fabrication capabilities should be investigated, because there might be alternate designs which are more feasible to fabricate from ceramics than a 55-gallon drum.

- **Status of Technology** - The WCMP took note of the fact that although the fabricability of a 55-gallon drum has not been demonstrated, smaller pieces of alumina which have been extruded and then fired, have been obtained on a laboratory/bench-scale setup. However, it was also noted that a common rule of thumb for ceramics is that the larger the piece, the lower the quality of the ceramic. Nevertheless, the WCMP concluded that although a ceramic drum has not yet been fabricated (probably because of cost and lack of need for one), the technology does exist to make a free-standing container and appears to be adequate.
- **Cost** - There was not enough information available regarding developmental cost; therefore, the WCMP only considered raw materials. Since the cost of alumina is approximately \$10/lb and most other fired ceramics are more expensive, a figure of 25 to 30 times that of mild steel was deemed reasonable by the panel members.
- **Mechanical Properties** - The majority of the panel members felt that the mechanical properties of fired ceramics were much worse than mild steel, and expressed doubts over whether a container made of a fired ceramic would survive the DOT Type A requirements. In a ceramic the atomic bond between metal and nonmetal is so strong and directionally oriented that there is no mechanism for deformation. As a result, even though the material may be strong in tension, brittleness will most likely render a container vulnerable to damage from a 4-foot drop on an unyielding surface. Thus, the WCMP rated the mechanical properties of fired ceramics to be much worse than mild steel.
- **Gas Generation Potential and Rate** - The WCMP decided that since all these ceramic materials are oxides, there is no chance of their generating any gas, and for all practical purposes, the gas generation potential is zero. However, since there could be hypothetical scenarios of zirconium hydride present in the waste reacting vigorously with an oxide ceramic, the WCMP was conservative and labeled the potential as "near zero" instead of zero.

### 3.8 CHEMICALLY BONDED CERAMICS

In a fired ceramic, the high-temperature process of firing strengthens the ceramic by allowing diffusion and shrinkage to fill the gaps in the material. The process succeeds, but introduces cracks in the material (Birchall and Kelly, 1983). Unlike fired ceramics, chemically bonded ceramics are processed at low temperatures and use water as a solvent for ions and as a medium for their diffusion. The process is similar to that of hydraulic cements (e.g., Portland cement) where solids set and harden irreversibly in the presence of water.

Application of chemically bonded ceramics to form a container around the TRU waste would probably depend heavily on the waste form. If the waste is converted to a solid monolithic

form, it might be possible to compact specially prepared powders around the waste. If the waste remains in its present loose form, compacting powder around a mold instead of the waste, to create a free standing container, might be feasible. A container made of such reactive materials as tricalcium silicate, or a mixture of tricalcium silicate and a zeolite, will combine with free water, and will also react with carbon dioxide. These characteristics can be advantageous in the repository. Some panel members expressed concerns about the permeability of the material, and also about the possible cracking of the material due to the development of nonuniform stresses when the material solidifies in contact with moist air. However, since the material has been reported to be denser than concrete or cement paste, the WCMP decided that the permeability is sufficiently low and would not be a drawback. Also, based on the fact that inspection under a confocal microscope had failed to reveal any changes in a 1/4-inch thick ceramic disk before and after immersing in water, the WCMP was assured that the material was not prone to cracking during solidification.

The WCMP recognized that the application of this concept to the containment of TRU waste requires considerable research and development. Also, the installation of a filtered vent in each container (a transportation requirement) poses significant engineering challenges. Nevertheless, the WCMP evaluated chemically bonded ceramics as candidate materials.

- **Fabricability** - The fabricability of chemically bonded ceramics is not difficult on a laboratory-scale, but definitely needs scaling up for manufacturing a container similar to a 55-gallon drum. However, assuming that the ease of fabricability of the material under laboratory-scale could be duplicated on a commercial scale, the WCMP rated the fabricability of this material to be similar to that of mild steel.
- **Availability** - The basic materials used for making this type of ceramic are certain silicates and zeolites which are widely available, and therefore the availability of raw material is comparable to mild steel and adequate.
- **Fabrication Capacity** - The fabricability of chemically bonded ceramics has been limited to a laboratory-scale, and there are no existing facilities which fabricate containers from these materials.
- **Status of Technology** - The technology needs to be developed for successful scale-up from laboratory-scale fabrication of these materials. The WCMP felt that a lot of research and development needs to be done in this area, and at best, the status of technology for chemically bonded ceramics can be termed as being "under development."
- **Cost** - Since the material has been fabricated only on a laboratory-scale, it was difficult for the WCMP to establish a range of cost for its commercial fabrication. It was suggested that since the cost of the raw material is approximately 2 to 3 cents per pound, a total cost of 10 cents per pound might be reasonable, including the cost of the cold-isostatic pressing needed during fabrication.

However, there was strong disagreement among the panel members regarding the cost of cold-isostatic press, and according to some panel members this step could cost as high as 25 cents/pound. Finally, the WCMP agreed that based on a conservative estimate of 25 cents/pound for the cold-isostatic press, the total cost would be close to 30 cents/pound, which was still considerably lower than the cost of mild steel. Since the cross-sectional area required for this material to satisfy DOT Type A requirements is likely to be much more than mild steel, the WCMP decided that the lower unit cost of chemically bonded ceramics would be offset by the lower amount of material required for a mild steel drum. Therefore the overall cost was rated to be similar to mild steel. However, these cost estimates should be viewed in light of the uncertainties involved in the wall thickness and weight of any container made from this material.

- Mechanical Properties - The WCMP unanimously concluded that in general, the mechanical properties of this material would not be any better than that of fired ceramics, and therefore rated these to be "much worse" as compared to mild steel.
- Gas Generation Potential and Rate - The WCMP readily agreed that this material will be exceptional in satisfying the requirements for no gas generation, because it does not generate gas by itself, and in addition also absorbs carbon dioxide and, possibly, adsorbs hydrogen as well. Thus, both gas generation potential and gas generation rate were judged to be "near zero." The WCMP also noted that this material might be useful as an effective backfill in the repository.

### 3.9 GLASS

Glasses are more sensitive to radiation than ceramics, and this was a concern to some panel members. However, given the fact that the majority of the isotopes of the elements present in the waste inventory are mostly alpha emitters, the WCMP decided that at such relatively low levels of radiation, the sensitivity of glass to radiation should not pose a problem. Another concern of the panel members was the possible increase in the storage room permeability resulting from crushed glass rubble after the reconsolidation of waste storage rooms. If the small broken chunks of glass cannot be further compressed by lithostatic stress, then a tortuous, interconnected path may develop for flow of brine through the waste stack.

- Fabricability - The WCMP decided that glass containers were a well established technology, and the fabricability is equivalent to mild steel.
- Availability - The availability of glass was rated to be the same as that of mild steel.
- Fabrication Capacity - Products made of glass are being fabricated widely in the U.S., and therefore the fabrication capacity was considered to be the same as that of mild steel.

- **Status of Technology** - This was considered to be the same as that of mild steel because of the same reasons outlined above.
- **Cost** - The cost of a glass container was deemed to be similar to mild steel pending confirmation of exact cost figures.
- **Mechanical Properties** - The mechanical properties of glass are not likely to satisfy DOT Type A requirements because of the brittle nature of glass. However, the WCMP felt that if reinforced, glass might be able to withstand DOT Type A requirements.
- **Gas Generation Potential and Rate** - For reasons similar to those outlined under the ceramics discussed earlier, glass was also rated to have a gas generation potential or rate near or equal to zero.

### 3.10 **NONREINFORCED CEMENTS**

The WCMP decided to evaluate cements as a general category instead of considering different types of cements (e.g., Portland cement, alumina-based cements, etc.) separately, because the characteristics of all these cements related to the criteria for evaluation are quite similar.

- **Fabricability** - The fabricability of cements, in general, was rated by the panel members to be as easy as fabricating mild steel, perhaps even easier.
- **Availability** - All basic materials needed for manufacturing cement containers are widely available, and therefore availability was not considered to pose any problem.
- **Fabrication Capacity** - Cementitious materials are widely fabricated all over the U.S. Specific fabrication capability to produce TRU waste containers may need to be built depending on the final container design.
- **Status of Technology** - The technology is believed to be established well enough to rate the status of technology equivalent to mild steel.
- **Cost** - Assuming a thick-walled structure and a cost of material of 2 to 3 cents/pound, the total cost of a drum was not expected to be high in comparison to mild steel. Some panel members did express concern about the greater wall thickness likely to be required for a cement drum in order to satisfy DOT Type A requirements, resulting in increased total cost. However, it was pointed out that fabrication does not have to produce a free-standing container. Rather, the waste could presumably be suspended in a bag at the bottom of a large tube that acts as a mold, and then free-flowing liquid cement poured around it. If such a fabrication process is adopted, then it has to be ensured that the density

of waste in the bag is greater than the density of the liquid cement, otherwise there is the possibility of the waste floating up during container fabrication. The WCMP noted that this would be a good example of a "formed" container where the container will actually gain in strength, if the waste inside it is in monolithic form (e.g., shredded and cemented). This method would probably not require the extra wall thickness required by a "free-standing" cement container, and based on this assumption the panel members estimated the cost to be similar to that of mild steel.

- Mechanical Properties - The mechanical properties of nonreinforced cement would be very similar to the ceramics discussed earlier, i.e., brittle and unlikely to survive a DOT Type A drop test. Therefore, the WCMP rated nonreinforced cement to be much worse than mild steel with respect to its mechanical properties.
- Gas Generation Potential and Rate - Since cement is a porous material, it might absorb water leading to potential for gas generation by radiolysis if alpha-emitters are in close contact with the water. However, the WCMP assumed very little free water present, and rated nonreinforced cement to have low overall gas generation potential and rates. The WCMP noted that Portland or alumina-based cement will also result in higher pH values of any brine that may come in contact with the containers, thereby causing decreased microbial gas generation, a reduction in the corrosion rate of ferrous materials, and a decrease in the solubility of actinides. The one drawback of cements, noted by the WCMP, is a possible increase in the corrosion rate of any aluminum present in the waste caused by the increased pH.

### 3.11 REINFORCED CEMENTS

A nonreinforced cement container can probably be designed to meet the DOT requirements. However, the payload volume may be small and the container weight quite high. The primary objective of using reinforcements is to improve the mechanical properties so that thinner walls can be used to satisfy DOT requirements, thus increasing usable volume and decreasing container weight. Reinforcements that were considered were subdivided into two groups:

- Discontinuous reinforcement (e.g., particulates, transformation toughening, etc.)
- Continuous reinforcement (e.g., wire, mesh, cage, etc.).

#### 3.11.1 Discontinuous Reinforcement

The WCMP agreed that discontinuous reinforcement of cements would not change the fabricability, availability, fabrication capacity, or status of technology in comparison to the base material (i.e., nonreinforced cements). Therefore, the WCMP rated all of these properties to be similar to mild steel, and hence adequate.

- **Cost** - The cost will be a function of the cost of the material used for reinforcement. As an example, if rocks are used then cost will be relatively low, whereas, if the reinforcement material is carbon fibers, then cost will increase. The WCMP estimated that the cost using different reinforcement materials would range from 1 to 2 times that of mild steel.
- **Mechanical Properties** - The WCMP felt that the mechanical properties of reinforced cements would be adequate to meet DOT Type A requirements. However, the WCMP noted that there were a lot of uncertainties about shape, wall thickness of the container (which would probably be smaller due to reinforcement), and limitations on the maximum payload due to weight of container. All of these and their effects on the DOT Type A requirements need to be evaluated in detail.
- **Gas Generation Potential and Rate** - This will almost be the same as that of the base material (i.e., cement) being reinforced, with marginal variation according to the gas generation properties of the material used for reinforcement. However, due to the reinforcement, the amount of cement required per container might be less than that required for a nonreinforced container thereby decreasing the total potential for gas generation to an even lower value than nonreinforced cement.

### 3.11.2 Continuous Reinforcement

- **Fabricability** - The WCMP judged continuous reinforcement to be a more difficult and labor intensive process than discontinuous reinforcement. Automation of the reinforcing process (i.e., forming a cage/mesh, putting it in a mold, and then pouring concrete around it) is likely to be difficult, and so the WCMP rated the fabricability to range from "more difficult" to "much more difficult" in comparison with mild steel, depending on the technique used for reinforcing and the material used for reinforcement.
- **Availability** - There is no shortage of cements or reinforcing materials, and the availability of material was termed adequate by the panel members.
- **Fabrication Capacity** - Facilities are available for fabrication of reinforced concrete shapes. However, specific capabilities can be built only after a final container has been designed.
- **Status of Technology** - The WCMP had some doubts whether anything similar to a fiber-glass cage has ever been fabricated. However, they decided that this was more a question of engineering and set-up of fabrication facilities rather than technological development. Therefore, the status of technology was termed adequate.

- **Cost** - There are a wide variety of technologies available for continuous reinforcement of cements (e.g., injection molding), and therefore the cost could vary over a wide range - perhaps 2 to 3 times that of mild steel.
- **Gas Generation Potential and Rate** - This was rated to be low for the same reason as presented under the discussion on discontinuous reinforcements in Section 3.11.1. The WCMP also noted that using metallics as reinforcement materials should not be a cause for concern from the standpoint of corrosion, because a lot of the reinforcing material will be embedded in cement and may never come into contact with the environment. In addition, the cement is likely to raise the pH of any brine that might infiltrate through the container, and thus retard the corrosion rate.

### 3.12 COATINGS

Although coatings by themselves do not fall under the category of "waste container materials," the WCMP considered coatings from the standpoint of providing additional protection to the base material used for alternative waste containers. Coatings were subdivided under two categories depending on the purpose of the coating:

- Corrosion retardation for metals and alloys
- Containment enhancement for structurally weak containers (e.g., ceramics) or monolithic waste forms during waste handling and transportation.

After a brief discussion, the panel members agreed that coating metallics (especially mild steel) enhances their corrosion resistance. However, this only decreases the rate of gas generation, but has no effect on the gas generation potential. It was also pointed out by the WCMP that coatings are, at best, a temporary retardant on a time-scale of 10,000 years. Once the drums get crushed upon total reconsolidation of salt, it is very likely that part of the base metal will be exposed, and thereafter coatings would not be completely effective for stopping corrosion over a period of 10,000 years. In fact, it is extremely difficult to quantify or justify protection by coatings over such a long period of time. In view of these arguments the panel members eliminated coatings from any further evaluation, but noted that coatings that reduce corrosion rates could be a valuable approach if performance assessment studies can quantify the extent to which gas generation rates need to be reduced. The WCMP also noted that certain coatings could be used for enhancing the strength of cementitious or ceramic materials for fracture toughness. As an example, solidified monolithic waste forms inside a cementitious container, may be coated with various materials such as polymers, to assure containment during transportation and handling until the WIPP repository is decommissioned.

### 3.13 POLYMERS

A significant problem with polymers is proving their stability over a period of 10,000 years under the processes of microbial degradation as well as radiolysis. Obtaining the proof of

stability will require a substantial investment in research and development, and even then could not be guaranteed to be successful. Even if a polymer could be shown to withstand microbial attack in the short-term, the validity of such data is questionable over a 10,000 year period, because given the time, the microbes have the capability of adapting to new environments and attacking the organic materials present. Also, organic materials could break down by other mechanisms such as radiolysis, and then become susceptible to microbial attack. The WCMP took note of all these drawbacks of polymers, but decided that they have many desirable properties (no corrosion, toughness, etc.) to be discarded from consideration. Instead of generalizing for all polymers, the WCMP decided to evaluate polyethylene specifically, because many of its properties relevant to this evaluation were known.

Since status of technology for polymers is quite advanced, the WCMP did not have any doubts about the fabricability, availability, fabrication capacity, or the mechanical properties of polymeric containers. In fact, TRU waste stored in 55-gallon drums is actually contained in 90-mil polyethylene liners inside the drums. Although it was estimated that the cost of such a container would be 5 to 10 times that of mild steel, the WCMP expected these containers to pass DOT Type A requirements. The major concern about the use of polymeric materials, as mentioned before, was that the gas generation potential and rates were unknown to panel members. Although a lot of information is available about the radiolysis of polymers and a substantial research and development effort might not be needed in this area, the WCMP felt that these materials would require detailed investigation for microbial degradation before they can be used as a container material.

### 3.14 OTHER MATERIALS

Apart from the materials already discussed in Sections 3.1 to 3.13, the WCMP also examined a different material suggested by one of the panel members.

This material is based on a 10- to 20-year-old technology popularly known as "impregnation into metal." The existing 55-gallon drums are impregnated from both sides with a nonoxide ceramic containing no free oxygen (such as boron nitride) up to a thickness of 0.003 to 0.015 inch. Since radiation is not a prime concern for CH-TRU waste, there are a number of alternatives (e.g., manganese oxide, silicon oxide, etc.) that are cheaper. After impregnation, the metal surface can be coated with a polymer (polyvinylidene) for additional protection. The impregnation is done by ion-bonding the ceramic to the metal by a proprietary method. The purpose of the ion-bond is to convert the surface of the metal into a ceramic, thereby preventing corrosion.

The WCMP expressed a lot of concerns about this material, especially about its corrosion properties when crumpled during the reconsolidation of salt. Although the panel members agreed that impregnation could provide corrosion protection for the metal surface (if impregnated on both sides), they were very much concerned about the region of unimpregnated metal sandwiched between the inner and outer surfaces of the drum. The WCMP argued that after reconsolidation, the drums are most likely to rupture, leaving the unimpregnated metal at the center exposed to the corrosive environment in the repository.

Once unprotected metal is exposed the corrosion process will start, and although the rate of corrosion might be low, the impregnation techniques will be rendered ineffective in the long run. Another concern of the panel members was about the ductility of the impregnated layer. Most panel members questioned the ability of this material to withstand the bending stresses expected during room closure without developing cracks or exposing unimpregnated metal.

Overall, the panel members recognized that this could be a very promising material, especially for the purpose of reducing the rate of gas generation from corrosion, although it would not reduce the total potential of gas generation from mild steel drums. However, it appeared to the panel members that due to the proprietary nature of the technology, there was not enough information available about the material at this stage for a complete evaluation. Therefore, due to the lack of adequate information, the WCMP was unable to decide whether this technology merits further evaluation. If performance assessment studies determine that merely controlling the rate of gas generation would ensure that there is no gas generation problem, then this could be a very promising material.

A summary of the results for each material with respect to each evaluation criteria is presented in Table H-1.

TABLE H-1  
EVALUATION OF ALTERNATIVE MATERIALS

MATERIAL	CRITERIA FOR EVALUATION						GAS GENERATION	
	FABRICABILITY*	AVAILABILITY*	FABRICATION CAPACITY*	STATUS OF TECHNOLOGY*	COST*	MECHANICAL PROPERTIES*	POTENTIAL	RATE
Copper & Alloys	Same	Same	Limited	Same	5-8x	Same	Low	Low
Titanium & Alloys	Much more difficult	Same	Limited	Same	10-20x	Same	High	Low
High-Nickel Alloys	Much more difficult	Same	None	Same	15-35x	Same	Moderate	Low
Zirconium and Alloys	Much more difficult	Same	None	Same	35x	Same	High	Low
Stainless Steels	Same	Same	Same	Same	5-8x	Same	High	Moderate
Fired Ceramics	Much more difficult	Same	None	Appears to be same	25-30x	Much worse	Near zero	Near zero
Chem. Bonded Ceramics	Same	Same	None	Being developed	Same	Much worse	Near zero	Near zero
Glass	Same	Same	Same	Same	Same	Much worse	Near zero	Near zero
Nonreinforced Cements	Same	Same	Same	Same	Same	Much worse	Low	Low
Reinforced Cements Discontinuous	Same	Same	Same	Same	1-2x	Probably same	Low	Low
Continuous	Worse	Same	Same	Same	2-5x	Probably same	Low	Low
Polyethylene	Same	Same	Same	Same	5-10x	Same	Requires investigation	Requires investigation

\*In comparison with mild steel.

#### 4.0 CONCLUSION

The WCMP concluded that the evaluation of five different groups of materials showed that there are several candidate materials available which are capable of satisfying the design requirements for waste containers to varying degrees. In order to summarize the evaluation, the WCMP decided that there are two basic criteria that need to be addressed in detail for each one of the evaluated materials. One is the effectiveness of the material for meeting the "no gas generation" requirement; the other criterion is whether the material can be fabricated into a container satisfying the appropriate transportation and handling requirements.

The effectiveness and fabricability of different materials would have to be established through development programs of varying durations for the different materials. As an example, materials like ceramics which are brittle, are likely to take a lot more development time than a metal like copper, to establish their fabricability into an acceptable container. Therefore, the WCMP summarized its evaluations of alternative materials with respect to the following criteria:

- Time likely to be needed to establish the effectiveness of the material in meeting the "no gas generation" requirement.
- Time likely to be needed to develop fabrication technology and actually make a full-scale fabricated container.
- Probability of success in terms of the WCMP's best judgment that the material will satisfy the "no gas generation requirement."
- Probability of success in terms of the WCMP's best judgment that the material can be fabricated into a container satisfying DOT Type A requirements.
- Cost of container in comparison to mild steel.

The WCMP assumed that all the brittle materials such as ceramics, cements, and glass will be reinforced as required to provide whatever mechanical properties are deemed necessary to satisfy the DOT Type A requirements. Thus, all materials evaluated earlier under the "reinforced" prefix were not summarized separately, but rather assumed to be included in their respective base material groupings. It was noted by the panel members that if DOT Type A requirements are to be met, then containers made of metals and polymers would probably carry the maximum payload per container. The WCMP also came to the conclusion that any research involving microbial gas generation is likely to become a long-term project because of the uncertainty associated with microbes. Therefore, whenever possible, all experimental schedules for detailed evaluation of materials should be planned in parallel to make the most efficient use of time.

The conclusions of the WCMP are presented in Table H-2. It should be noted that the cost figures are taken directly from Table H-1, and do not include developmental costs, or costs

**TABLE H-2  
SUMMARY OF RESULTS**

	<u>Time to Establish Effectiveness</u>	<u>Time to Establish Full-Scale Product</u>	<u>Cost Factor<sup>a</sup></u>	<u>Probability of Success in Establishing Effectiveness</u>	<u>Probability of Success in Meeting DOT Type-A Requirements</u>
Copper & Alloys <sup>b</sup>	1-2 yrs.	2 yrs.	5-8 x	90%	100%
Titanium & Alloys	1-2 yrs.	2 yrs.	10-20 x	95%	100%
High-Nickel Alloys	1-2 yrs.	2 yrs.	15-35 x	97%	100%
Zirconium Alloys	1-2 yrs.	2 yrs.	35 x	98%	100%
Stainless Steel <sup>b</sup>	1-2 yrs.	0-1 yrs.	5-8 x	50%	100%
Free Standing Ceramics <sup>c</sup>	0 yrs. (validate)	4-8 yrs.	25-30 x	99.9%	30%-90%
Chem. Bonded Ceramics <sup>c</sup>	0 yrs. (validate)	3-5 yrs.	1-10 x	99.9%	30%-85%
Glass <sup>c</sup>	0 yrs. (validate)	2-4 yrs.	1-10 x	99.9%	20%-90%
Cements <sup>c</sup>	1-2 yrs.	2-4 yrs.	2-8 x	99.9%	30%-85%
Polymers	5 yrs. <sup>d</sup>	0-1 yrs.	5-10 x	Indeterminate	100%

<sup>a</sup> Relative to a mild steel container.

<sup>b</sup> Uncertainty associated with effect of microbes - not considered in duration.

<sup>c</sup> Reinforced as required.

<sup>d</sup> Should be dropped from consideration if effectiveness cannot be proven within 5 years.

of building any new facilities which might be required. Also, the estimates of schedules do not include programmatic planning time associated with planning of research strategy, approval of schedule and budget, etc. The conclusions of the WCMP for each material are discussed below.

#### Copper

It would not take a significant amount of time to evaluate the effectiveness of copper in order to reduce some of the uncertainties associated with its corrosion. Most experiments will take one to two years, depending on the extent of evaluation. However, as discussed earlier, copper could corrode if microbes reduce sulfates and nitrates in the repository. It should be noted that this uncertainty has not been included in the one to two year estimate of experimental duration. Full-scale production can probably be established in about two years, and might be done in parallel with effectiveness evaluation.

The WCMP rated the probability of success for meeting the "no gas generation" requirement using copper or its alloys to be about 90 percent. Since this figure was based purely on qualitative judgment, the WCMP decided to assign probabilities to all the materials, and then later compared them to each other in order to be assured that the relative percentages for probabilities between different materials were reasonable. The WCMP did not have any doubts about the ability of copper to satisfy DOT Type A requirements and rated the probability of success at 100 percent.

#### Titanium

The time to establish the effectiveness of titanium would be about one to two years. However, unlike copper, there is no microbial uncertainty with titanium. Some experiments are needed at high CO<sub>2</sub> overpressure in concentrated brine at the maximum temperature expected in the repository, and may be conducted at a higher temperature to accelerate data acquisition. The WCMP was confident that these experiments could be done in one to two years. The time to establish full-scale fabrication capability was estimated to be similar to that of copper, i.e., approximately two years.

The probability of success in meeting the "no gas generation" requirement for titanium was estimated to be 95 percent. Some panel members expressed concern at this high figure because of the high potential for gas generation from titanium. However, it was pointed out that the potential and probabilities are quite unrelated. As an example, even though diamond has a very high potential for oxidizing, the probability of this actually happening is very low. Also, titanium is known to be extremely corrosion resistant in a variety of environments because of a protective layer of titanium dioxide, which rapidly forms again if the surface is scratched. Although crevice corrosion can occur in brine this normally occurs at much higher temperatures than that expected in the repository. Like copper, titanium was not expected to face any problems in satisfying DOT Type A requirements and was rated to have a 100 percent probability of success.

### High-Nickel Alloys

As mentioned earlier, if these alloys are to be considered as candidate container materials, then pitting and crevice corrosion of these alloys needs to be investigated as well as data about the equilibrium partial pressure of hydrogen which will stop the corrosion reaction. These alloys are extremely corrosion resistant, so that any experiments to quantify their corrosion rates will take a long time. In addition, there is also the issue of finding the optimum alloy for the given conditions. The WCMP noted these issues, and decided that it would take one to two years to establish the effectiveness of high-nickel alloys. The time for full-scale fabrication and the probability of success in meeting DOT Type A requirements were judged to be equivalent to that of copper and titanium based materials, i.e., two years and 100 percent, respectively. Since the rates of corrosion of high-nickel alloys are slower than titanium, these were judged to have a slightly higher probability of success for gas generation requirements compared to titanium, and rated at 97 percent.

### Zirconium Alloys

These were considered to be similar to the high-nickel alloys, except that in recognition of their exceptional corrosion resistance, these materials were rated to have a higher probability of success (98 percent) for meeting gas generation requirements.

### Stainless Steels

The time for verifying the effectiveness of stainless steel should take no more than one to two years. However, like copper, uncertainties about microbial attack are also associated with stainless steels. These uncertainties are not included in the above estimates for experimental duration. The time for full-scale production would be less than any of the other metals discussed before, because drums are being produced now for commercial purposes. Since the present production capacity is not at a level required for manufacturing thousands of drums per year, the WCMP estimated a period of approximately one year for full-scale production of stainless steel drums. Like all metals, the probability for meeting DOT Type A was rated at 100 percent. The relatively higher corrosion rates of stainless steel in comparison to titanium, zirconium, etc., reduced the probability of success in meeting gas generation requirements to 50 percent.

### Free Standing (Fired) Ceramics

The WCMP felt that there was no need for any experimental studies to establish their effectiveness for meeting the "no gas generation" requirement. For all practical purposes these materials were considered to have a 99.9 percent probability of success in not generating gas. On the issue of time required for full-scale production, a broad range was noted because of a wide variety of material that can be used. As an example, a lower end material like low grade alumina could take a total of four years (two years to develop and another two years to scale-up), whereas a higher end material like toughened zirconia could take eight years. The same wide range would also apply to the probability of success in meeting DOT Type A requirements as well. The WCMP decided that the probability for low grade alumina would be about (30) percent whereas it would be considerably higher (90 percent) for a higher end material like toughened zirconia.

### Chemically Bonded Ceramics

The gas generation characteristics were deemed to be similar to fired ceramics, i.e., they also were rated to have a probability of success of 99.9 percent and would not require any experimental time for verification. For full-scale production, it is conceivable that some sort of isostatic pressing technology might be developed quickly (one to two years). Once the technology for fabrication has been developed, the scaling up could take two to three years. Therefore, full-scale production could take anywhere from three to five years. Since this type of ceramics is not as tough as fired ceramics, the WCMP rated their probability of success for meeting DOT Type A to be 30 to 85 percent.

### Glass

The WCMP considered the fabrication of glass to be a well-established technology, easier than any other ceramic evaluated. Full-scale production of glass containers should take one to two years. However, recognizing the fact that glass needs to be reinforced, and that design and evaluation of mechanical properties cannot be done in parallel, the WCMP estimated that two to four years is probably a more realistic figure for full-scale production. All other criteria (i.e., probability of success, etc.) were judged to be equivalent to fired ceramics for similar reasons.

### Cements

If cements are to be considered as candidate materials for alternative waste containers, then the chemistry of exposing cement to brine needs to be investigated in detail. This could take one to two years. There is also the need for verifying the stability of cement for 25 years. Using some kind of accelerated degradation process, the stability could probably be verified within two years. Therefore, the WCMP felt that two to four years would be a reasonably conservative estimate for the full-scale production of a cement container.

The probability of success for meeting gas generation requirements was rated at 99.9 percent provided that proper reinforcements (such as glass) are chosen which do not generate gas themselves. For meeting DOT Type A requirements, the WCMP felt that these can be met, although a lot will depend on a cost effective compromise between wall thickness, amount of reinforcement, and payload constraints.

### Polymers

The main problem with polymers is their possible degradation under microbial attack, and radiolysis. The WCMP recognized that a given polymer might be effective, and be able to withstand microbial attack for 10,000 years. The difficulty lies in the verification of their effectiveness, because short-term research data showing lack of microbial degradation does not guarantee that such degradation would not take place over 10,000 years. Since there is a lot of uncertainty involved, the WCMP decided that if the effectiveness cannot be established within a period of five years, polymers should be dropped from further consideration as an alternative waste container material. If they are selected, the polymers should not have any problem in meeting the DOT Type A requirements, and considering their well-established technology, it should not take more than one year for full-scale production of polymer containers.

### Coatings

The WCMP did not discuss coatings with respect to criteria used for summarizing other alternative materials, because coatings were considered to be a subcategory of other alternatives (a part of the process rather than a container material by themselves). It should be noted that these coatings are for surface containment of solid wastes to facilitate handling and transportation, and for retarding the corrosion rate of metallics. For example, in the case of chemically bonded ceramics there is a possibility of contaminating the powder during the process. So an option is to paint or coat the surface to isolate any contamination. Thus, coatings should be used when and wherever applicable if it indeed improves the characteristics of the container material.

It should be noted that the information presented in Table H-2 is based on preliminary evaluation of these materials, and represents educated estimates rather than precise values. The figures in Table H-2 provide relative estimates of probability of the materials in meeting the effectiveness and fabricability requirements for a container, as well as the time required to verify these probabilities. The WCMP decided that copper, titanium, high-nickel alloys, zirconium alloys, ceramics, glass, and cements were all viable materials which could possibly satisfy the design requirements for an alternative waste container. However, there are some concerns associated with each material that need to be resolved.

The WCMP noted that although ceramics and cements have excellent gas generation properties, and are inexpensive, waste containers made from these brittle materials are likely to have smaller internal volumes due to the thicker container walls required to satisfy DOT Type A requirements. This will result in a smaller TRU waste payload per container. In addition, if the container weight is heavier than the existing drums, then fewer containers will make up the TRUPACT-II payload, resulting in increased number of waste shipments from the storage sites to the WIPP site. These factors can have large impacts on the overall program costs beyond the low unit costs required to fabricate the containers. It should also be noted that with the possible exception of cements, there is no technology presently in place to fabricate large containers from the nonmetallic materials. Therefore, the fabrication of an acceptable nonmetallic container that would satisfy the DOT Type A requirements, will very likely require long-term research and development efforts.

In contrast to the nonmetallics, and with the exception of copper, there are expensive metal alloys (titanium, high-nickel, and zirconium) that have relatively fewer uncertainties associated with them, especially with respect to fabricability, and payload volume per container. Once their low anticipated corrosion rates are validated under WIPP conditions, these alloys have the potential of immediately satisfying the design requirements. Whereas, the higher end high-nickel alloys, and the zirconium alloys would substantially escalate program costs (roughly \$1 billion, based on 600,000 drums and a cost of \$50 for an existing mild steel drum), the WCMP felt that lower cost titanium alloys would be adequate for the purpose. Besides, under the relatively mild conditions at WIPP, there is not likely to be any notable differences in corrosion properties between the titanium alloys which are relatively inexpensive, and the more expensive ones such as zirconium and higher end high-nickel alloys.

These results of the WCMP should be used to:

- Select a few promising alternative materials for detailed testing regarding their fabricability and corrosion/gas generation properties
- Evaluate, with the help of appropriate experiments, the effectiveness of the selected materials for meeting the "no gas generation" requirement
- Design and demonstrate the fabricability of the selected materials (reinforced as required) into a container satisfying all transportation and handling requirements
- Estimate the total cost per container, and impact on overall program cost for the selected materials based on the annual fabrication requirements.

Thus, the right choice of material would have to be decided by tests on a few promising materials for both effectiveness and fabricability, and would also depend on applicable cost, schedule, and transportation constraints.

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**ATTACHMENT A****QUALIFICATIONS OF PANEL MEMBERS****CHAIRMAN****Mr. Hans Kresny (Chairman and Facilitator)**

Mr. Kresny is the President of Solmont Corporation, and a consultant to IT Corporation, with over 33 years of multidiscipline technical and managerial experience in the nuclear industry. His background includes engineering and project management involving major nuclear facilities and programs, institutional issues resolution between the WIPP project and 23 States, shielding and radiation analysis, and nuclear space systems and power plant design. He was also the chairman of the WIPP Engineered Alternatives Multidisciplinary Panel. Education: Bachelor of Marine Engineering.

**PANEL MEMBERS****Dr. Barry M. Butcher (Performance Assessment)**

Dr. Butcher is currently the Principal Investigator at Sandia National Laboratories (SNL) for WIPP programs related to the selection of backfill for the disposal rooms, development of a model for the mechanical and hydrological response of the disposal rooms, and investigation of engineered alternative concepts. He has over 30 years of experience in investigation of the dynamic behavior of materials, and is the author of over 30 publications on the subject. At SNL, he has held positions as Supervisor of the Stress Wave Research Division, and as Supervisor of the Geomechanics Division providing rock mechanics support to the WIPP and Yucca Mountain projects. Education: B.E., Civil Engineering; Ph.D., Engineering Materials (Materials Science).

**Mr. Noel Calkins (Ceramic Fabrication)**

Mr. Calkins has 33 years of experience as a mechanical engineer working in various areas of management, research and development, and production. The last 10 years of his experience have included working in Los Alamos National Laboratory. He has worked extensively in the area of fabrication of several materials including metals, ceramics, and composites. His process experience encompasses all traditional and non-traditional metal and ceramic removal systems, including water jet cutting, ultrasonic impact grinding, free abrasive machining (FAM), etc. He also holds patents in the areas of ceramic processing and ceramic armor. Education: B.S., Mechanical Engineering.

**Dr. Frank W. Clinard, Jr. (Basic Ceramic Research)**

Dr. Clinard is a Senior Laboratory Associate at Los Alamos National Laboratory (LANL) with over 25 years of technical and managerial experience in a variety of areas in materials science. His experience in LANL includes 17 years as a Project Leader for research in the area of ceramics for fusion reactor application, and as a Section Leader for irradiation effects, advanced materials, and physical ceramics. He has also been a consultant to various companies in the areas of physical properties of metals, ceramics, polymers, and ceramic

composites. Education: B.S., Mechanical Engineering; M.S., Metallurgical Engineering; Ph.D., Materials Science.

Dr. F. H. Froes (Physical Metallurgy)

Dr. Froes is the Director of the Institute for Materials and Advanced Processes at the University of Idaho, and has been active in the fields of physical metallurgy, powder metallurgy, metal matrix composites and intermetallics for over 23 years. Before assuming his position at the University of Idaho, he has held various positions supervising research in the areas of titanium, aluminum, and superalloys at the Air Force Materials Laboratory in Dayton, Ohio. He also holds in excess of 40 patents in Material Science and related fields. Education: B.S., M.S., and Ph.D., Physical Metallurgy.

Dr. Hamlin M. Jennings (Cementitious Materials)

Dr. Jennings is an Associate Professor in the Department of Civil Engineering and the Department of Materials Science and Engineering at Northwestern University. He has 15 years of teaching and research experience in the area of cementitious materials. His research has included the study of microchemistry and microstructure of various ceramics and cement-based materials using mathematical modeling and transmission electron microscopy. He has also been a member of the WIPP Cement/Grout Expert Panel which discussed the stability of cement-based materials in the WIPP environment for a period of 10,000 years. Education: B.S., Physics; Ph.D., Materials Science.

Mr. Daniel C. Meess (Concrete Container Fabrication)

Mr. Meess is currently the Design Manager of the Nuclear Waste Department, Illinois LLW Project for Westinghouse Electric Corporation. He has over 15 years of project leadership experience in goal-oriented development of advanced energy technologies, and the management of hazardous, low-level radioactive and mixed wastes with a focus on project management, developmental engineering, and technical operations. He was the Project Leader for the development, testing, and commercialization of the SUREPAK modules for the safe storage and disposal of low-level radioactive and hazardous wastes. Education: B.S., Mechanical Engineering, and Public Affairs; M.S., Mechanical Engineering.

Dr. Jonathan Myers (Geochemistry)

Dr. Myers is a Senior Technical Associate at IT Corporation with over ten years of geologic and geochemical experience solving technical problems in the field of hazardous and nuclear waste management. He has been actively involved in the WIPP and Yucca Mountain nuclear waste disposal projects, as well as the Swedish and Canadian waste disposal programs. He has also been a member of the WIPP Engineered Alternatives Multidisciplinary Panel, chairman of the WIPP Cement/Grout Expert Panel, and a participant in the WIPP Performance Assessment Program. Education: B.S. and M.S., Geology; Ph.D., Geochemistry.

Mr. Rodney Palanca (Waste Handling)

Mr. Palanca has 27 years of experience with the operation of nuclear submarine and land-based nuclear plants. He attained the rank of Lieutenant Commander in the U.S. Navy, and has supervisory and technical experience in nuclear reactor operation and testing, nuclear

instrumentation and controls, nuclear chemistry and radiological controls, training curriculum planning and scheduling. He was also a member of the WIPP Engineered Alternatives Multidisciplinary Panel. He is currently a senior engineer in the WIPP Engineered Alternatives Group. Education: B.S., Chemical Engineering, plus numerous U.S. Navy nuclear training programs.

**Dr. R. E. Westerman (Metallurgy/Corrosion)**

Dr. Westerman is a Senior Staff Scientist and Technical Leader of the Components Analysis Group at the Pacific Northwest Laboratories (PNL). He has 30 years of experience in the metallurgical and corrosion research of various materials, and has been involved in nuclear waste package development programs since 1977. At PNL, he has led a group involved in the selection and evaluation of metallic materials including nickel-, iron-, copper-, titanium-, and lead-based alloys, for application to engineered barrier systems for the long-term containment of nuclear waste. He has also acted in the capacity of Technical Leader of the chemical Metallurgy and Metallurgy Research Sections at PNL, either directing or contributing to a variety of programs, including the effect of hydrogen on the mechanical properties of titanium alloys and the manufacture and evaluation of alloy steel specimens made by various powder metallurgy techniques. Education: B.S., Metallurgical Engineering; Ph.D., Metallurgy.

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**APPENDIX I**

**COMPARATIVE RISK ASSESSMENT  
OF ENGINEERED ALTERNATIVES**

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## EXECUTIVE SUMMARY

The total risk associated with various waste treatments is an important component in the evaluation of the feasibility of alternatives conducted by the Engineered Alternatives Task Force (EATF). Treatment of the wastes, prompted by the desire to improve long-term performance of the WIPP repository, will lead to some increases and decreases in different contributions to the total risk of the WIPP. It is the purpose of this study to evaluate numerically the balance between the changes in the short-term risk components and compare them to the expected improvement in the long-term risks.

This study evaluates the total risks from treating, handling, transporting, and emplacing waste in the WIPP. It then compares the total risks associated with no waste treatment (baseline case) with those associated with the four selected waste treatments, carried out at four selected site combinations. The total risk of the WIPP operations, as envisaged in the Final Supplemental Environmental Impact Statement (FSEIS) (DOE, 1990a) and Final Safety Analysis Report (FSAR) (DOE, 1989a) results in the evaluation of 124 different contributions to the total risk or risk components. These components arise from the analysis of 60 scenarios (Appendix I, Section 4.3). The risk components are written in mathematical form and their properties for different levels of treatment activities are studied. According to these properties, all risk components are then scaled appropriately to the treatments selected. Thus total risks of the WIPP for 16 treatment and location options are calculated.

The comparison of these multi-component quantities is not a trivial operation. Only two numbers can be compared at one time, and only if they are measured for the same quantity, given in the same units. A novel procedure for comparing multi-component risks was developed for this purpose, using some of the tools of Multi-Attribute Utility Theory (Appendix I, Section 3). As a consequence of inserting only risk components as attributes into this theory, and due to some special characteristics common to all risk components, a special form of utility function is selected. Based on the properties of this function, two related quantities are then defined: the consequence reduction index and its inverse, the consequence augmentation index (Appendix I, Section 3.2.2). Both indices can be interpreted as the weighted geometric average of all contributions to the total risk, relative to the same contributions to the baseline risk. A reduction index larger than one indicates a decrease in overall risk; or, more precisely, in overall consequences, an index less than one, indicates an increase. Conversely, a consequence augmentation index larger than one is an indication for an increase in overall consequences, whereas an index less than one indicates a decrease in consequences.

These indices are single, dimensionless numbers that can be compared directly. They are composites of all the risk components, weighted with a societal valuation of each particular component. Thus, a fatality will be weighted differently from an injury or the risk of some monetary losses. In deriving these societal valuations, the future application of this analysis is taken into account. In Section 6.4 and 9.0 of the main report, it becomes an integral part of the

database required to decide between the feasibility of different treatment alternatives and the plant locations. This is, thus, a technical decision. Into this decision, the societal valuations of different risk components need to be embedded. In the limited scope of this investigation it is assumed that there is one decision maker who consults with some experts to help him establish his own set of weights (Appendix I, Section 5.1). The decision maker then uses these weights in the procedure outlined to rank the total risks of the 16 treatment/location options.

In most cases, a risk comparison is part of a larger evaluation that will make a decision on engineered alternatives based on a number of criteria, among them total risk. The decision maker in that process will need to inspect the weighting process and possibly influence it in such a manner that it reflects the needs of his own multi-criteria decision analysis. In this way he becomes one of the most important members of the circle of experts consulted by the decision maker for the risk comparison, decisively influencing the weighting used in the ranking of treatment/location options.

As an additional aid in making this ranking, the relevant standard errors of all parameters are followed throughout the calculation, using algebraic methods of error propagation. The result is a set of risk reduction and augmentation indices with standard errors. Two mathematical criteria are employed to establish significant and insignificant differences between indices. More important, however, are the groupings of alternatives and the trends within groups established in this analysis (Appendix I, Section 5.1).

The results of the decision maker's evaluation are shown in Figure I.ES-1, where the consequence augmentation indices are listed in a 4 x 4 array for all 16 treatment/location options. The four location options are listed horizontally in increasing decentralization; the four treatment options are listed vertically in increasing complexity of the treatment. The left column lists the consequence augmentation factors for a single treatment center at the WIPP. For treatment at the WIPP, transportation risks are thus unchanged from the baseline case, and the sharp increase of the indices for Level III treatments (Treatment Option 4) reflects the rising influence of the treatment risks. For Treatment Option 4, the location dependence reflects the rising influence of the transport risks, mostly the reduction in normal traffic accidents due to the reduction in the number of transports when wastes are treated prior to shipment. The cells with the highest augmentation indices (greatest increase in risk due to treatment) have the lightest pattern; those with the lowest indices (here given as inverse values, that is, as consequence reduction indices) have the darkest shadings.

For Level II Treatment Options 1 and 2, the consequence augmentation indices are found to be closely grouped with overlapping errors. This signals a near independence from location and a general increase in the composite risk augmentation index to 1.5, resulting in an even shading of all the cells.

		Location Option			
		1	2	3	4
Treatment Option	1	$1.40 \pm 0.02$	$1.51 \pm 0.04$	$1.41 \pm 0.05$	$1.37 \pm 0.05$
	2	$1.43 \pm 0.02$	$1.58 \pm 0.04$	$1.49 \pm 0.05$	$1.45 \pm 0.05$
	3	$1.62 \pm 0.02$	$1.41 \pm 0.09$	$1.23 \pm 0.11$	$1.19 \pm 0.11$
	4	$2.06 \pm 0.03$	$1.28 \pm 0.02$	$\frac{1}{1.14 \pm 0.03}$	$\frac{1}{1.21 \pm 0.04}$

 Group 1   
  Group 2   
  Group 3   
  Group 4

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Appendix I, Exec Summary

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FIGURE I.ES-1 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS

For both Level III treatments (Treatment Options 3 and 4), clear trends with location are evident. Level III treatments tend to significantly reduce the required number of TRUPACT-II transports relative to the baseline, untreated waste case. For Treatment Option 3, consequence augmentation indices of about 1.6 for treatment at the WIPP decrease to indices of 1.2 for decentralized treatment. An augmentation index of 1 means equivalence with the overall baseline risk. For Treatment Option 4, this trend is much stronger and the consequence augmentation indices range from the lowest to the highest value in the array. For this manpower intensive treatment, the increased treatment risk and the reduced transportation risk lead to an augmentation index of 2 for treatment at the WIPP, and to reductions with indices near 0.8 or 1/1.2 for treatment near the originators of the waste.

In this context, it is important to realize that, although an index larger than 1 indicates an increase in consequences, the relationship is nonlinear and does not indicate an increase by this amount over the baseline risks. In fact, by virtue of the method used here, no absolute risks can be calculated for the treatment/location options.

For an evaluation of the influence of each consequence component on the value of the index, the sensitivity study in Appendix I, Section G.4 lists the factors by which each component contributes to the result. These trends and their causes show that the radiological risks are among the smallest contributions to the total risk, both in the baseline risks given in the FSEIS (DOE, 1990a) and in the risk comparison here. This arises from the valuation of society, which discounts traffic fatalities and injuries strongly, discounts occupational fatalities somewhat less, but puts strong emphasis on radiation injuries resulting in cancer and other health effects. The small size and influence of radiation risks is a testimony to effective intervention by health physicists in this respect. Thus the low but generally much larger occupational and transportation accident risks are expected to dominate most of the discussion.

Thus, in summary, Level II treatments lead to an increase in consequences, which is not sensitive to the location of that treatment. Level III treatments, on the other hand, are sensitive to location varying from increases in total risk to moderate decreases. This general insight is felt to be insensitive to most of the biases encountered here; robust even with regard to the largest source of bias, the decision maker.

## 1.0 INTRODUCTION

A key component in evaluating the feasibility of alternatives identified by the Engineered Alternatives Task Force (EATF) is the assessment of risk associated with the various waste treatments. Waste treatment will increase or decrease some components of the total risk of managing and transporting transuranic (TRU) wastes and of operating the WIPP. Most notably, decreases in the long-term risk components such as those due to human intrusion scenarios, can only be achieved at the price of increasing some short-term risk components, such as cancer risks; other short-term components, such as transportation risks, are decreased by some of the treatments proposed. It is the objective of this investigation to evaluate the balance of the short-term risk components and to weigh them against the improvements in the long-term risk components.

This evaluation compares the total risks inherent in managing, transporting, and emplacing differently treated wastes in the repository relative to the baseline risks associated with the shipment and emplacement of "as received" wastes. It also uses current WIPP waste container and repository designs. From the many possible treatments of the wastes, a few options were chosen to represent the span of characteristics of treated wastes, with the various components of each compared against the "baseline" to arrive at a relative risk reduction factor. One of the primary tasks of this comparative risk assessment was to scale all components of the total baseline risks to the level of activity required by the different treatment options.

A relative risk assessment of the entire WIPP operation over its operating lifetime and the subsequent post-closure period includes risks for a variety of operations, incidents, and accidents. Most prominent among them are those connected with the transportation of the wastes, the corresponding handling operations, and the emplacement of the wastes underground. While these factors are addressed in the "baseline" risk, selection of any waste treatment leads to additional risks due to handling and transportation, in addition to the risks due to the treatment. Consequently, the relative risk assessment must consider all components of the total risk.

Factors addressed by the relative risk assessment include transportation and occupational accidents, exposure to radiation either due to direct external exposure or incorporation of radioisotopes by the inhalation or ingestion route, and exposure to toxic chemical agents in the wastes. With the exception of traffic and occupational accidents not involving the radioactivity or chemical toxicity of the wastes, the risk components are all small. Traffic and occupational accidents pose larger risks, but these are essentially on the same scale as accidents in industrial operations of similar scope. For all risk components, both routine exposures and exposures under accident conditions are addressed and the corresponding risks to the public and the work force are considered. These short-term risks are evaluated both during the operational phase and as carcinogenic risks in 5 to 20 years. Long-term risks are those associated with the hypothetical human intrusion event 5,000 years after decommissioning of the WIPP (see discussion of the

Design Analysis Model in Section 2.4 of the main body of this report). These include the risks to workers involved in human intrusion scenarios and to nearby residents that are exposed to radionuclides released as a result of the intrusion.

Increased handling due to waste treatment, and thus an increase in the work force, leads to an increase in the incidence of work-related accidents, resulting in both occupational injuries and fatalities. Among these accidents, forklift accidents are quite prominent because they contribute only 1 percent to the incidence of accidents but result in 10 percent of the injuries with workdays lost (U.S. Department of Labor, 1986). Also, some waste treatments will result in an increase in the number of TRUPACT-II shipments to the WIPP (because the treatment increases the weight of the waste form, which reduces the number of drums per transport), while others decrease the number of transports relative to the "baseline" case of no waste treatment. Of all risk components, transportation risks have the largest number of expected fatalities and injuries (DOE, 1990a), and even relatively small increases/decreases will result in significant changes of both the short-term and overall risks.

The transportation risk components consist of the risks of death or injuries in accidents involving TRUPACT-II transports, as well as the health effects due to direct exposures of the transport crew and of the public to penetrating radiations. The two components due to traffic accidents are the largest risk components projected for the entire WIPP activity (DOE, 1990a). In routine transportation, public and occupational radiation exposures are limited to persons on or near the highways traveled. In accident scenarios, however, the public at larger distances downwind or downstream may also be at risk. For these rare accidents, waste treatment may offer significant risk reductions if the fraction of wastes that are released as airborne particles is minimized.

The largest contributions to the relatively small radiation risks of the actual disposal operations in the WIPP arise from direct irradiations of the work crew. These risks are not expected to be strongly affected because the same amount of radioactivity must be handled and emplaced underground, regardless of whether the wastes are treated. In the incident and accident scenarios, however, these smaller risk components could be significantly reduced. For radiation exposures, the changing risk of cancer as well as of genetic damages is addressed. For chemical toxicants, the reduced risks of both cancer and non-cancer health effects due to the destruction of Volatile Organic Compounds (VOCs) are discussed. Both the risk to workers and those to the public are addressed.

All components of the overall risk that involve the actual treatment of the wastes will lead to a small increase in the number of injuries and fatalities. These risks arise here from routine treatment operations and from regular maintenance activities. Both the workers and the public are at risk, but it is mostly occupational risks that increase when wastes are treated. This is due to the deposition of airborne wastes in the interior of the plant, the filtration, and environmental dilution which are expected to reduce public exposures substantially.

Routine exposures can be assumed to be low due to the health and safety procedures instituted at the treatment facility. The requirements of the As Low As Reasonably Achievable (ALARA) concept (International Commission on Radiological Protection, 1959) are expected to be followed rigorously. Nevertheless, penetrating radiations will lead to a low-level radiation exposure in the workplace and, consequently, an occupational risk of cancer and of genetic damage is assumed to exist. Accidental events will lead to an increase of direct external and internal exposures but for a short duration only and with a relatively low probability.

Fugitive emissions of radioactive aerosols from the enclosures of the treatment devices during routine operations will lead to a potential incorporation of radioisotopes by inhalation and ingestion, resulting in relatively small risks of cancer and genetic effects. The potential for such exposures is somewhat greater during routine maintenance operations, although personal respiratory protection and the enforcement of strict health and safety rules are expected to keep these risks low as well.

The risk of exposure to volatile chemical toxicants, both carcinogenic and non-carcinogenic, in treatment activities is expected to be higher than in any other operation because all waste enclosures such as plastic bags are opened at one point or another during treatment, allowing the volatile organics to escape. Entraining the fumes in ventilating air streams will protect worker health, and adsorptive filters in the exhaust will protect the public. The fraction of gases that penetrate to the outside may lead to health effects according to the carcinogenic or non-carcinogenic action of the toxicants. Escapes of substantial amounts of VOCs during accidental events may lead to increases of these exposures, but again for a short duration only and with a low probability of occurrence.

The basic mathematical operation in evaluating different treatment options and the location of the corresponding facilities is a comparison of the total risks for two or more different treatment/location options. This comparison is made difficult by the fact that the total risk is a multicomponent quantity. Numerical comparisons, however, can only be carried out for two quantities of the same kind, measured in the same units. Consequently, only comparisons between the same components of two total risks are possible, falling short of the goal of comparing two total risks. For that purpose, it is useful to apply some of the tools of multicriteria decision analysis to risk comparison. Formerly a branch of economics, decision analysis has over the last few decades grown into an independent discipline, which offers the basic tools needed for an application to the comparison of multicomponent total risks.

The method chosen here is based on Multi-Attribute Utility Theory (MAUT; Keeney, 1978) but modified and adapted to reflect the facts that all attributes are components of a risk and thus of a similar nature, and that risks are uncertain quantities, a characteristic that needs attention in the process of comparison. In the application of some of the tools of MAUT developed here, unusual restrictions and special considerations are imposed on the evaluation, leading to a new method of comparing and quantitatively ranking multicomponent quantities such as risks.

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## 2.0 BASIS FOR EATF RISK COMPARISON

### 2.1 GENERAL CRITERIA FOR COMPARISONS

The EATF selected 14 combinations of alternatives for analysis, far too many to be subjected to a Comparative Risk Assessment. Four forms of waste treatments were selected for assessment of risk, primarily to span the range of treatment options. Similarly, multiple choices for the location of the Treatment Facilities (TF) are being considered. Four combinations of locations were chosen, again more to span the range of options than to represent four proposed or even feasible sitings. Since the risks of transporting the wastes are the largest contributions to the total risk of WIPP activities, it is important to study a wide range of possibilities in order to be able to make use of any significant risk reductions that may arise.

The scenarios studied comprise all those discussed in the FSEIS (DOE, 1990a) and in the RADTRAN III code (Madsen et al., 1986), except for the human intrusion scenarios that occur after the WIPP is decommissioned. These were treated using the Design Analysis Model (Section 2.0 of the main body of the report) plus simplifying assumptions for radionuclide transport to the accessible environment.

In this analysis, routine operations, maintenance operations, and accidents are considered whenever the treatment requires a change relative to the baseline case. Baseline risks are not calculated in this study, but instead are taken from the risks discussed in the FSEIS and in some cases from the FSAR (DOE, 1989a). Thus a risk comparison involves the detailed discussion of a particular event, once with waste "as received," and once with waste treated in accordance with one of the four options discussed. All other parameters that define the risk of the event are kept exactly the same and cancel when calculating the relative risk reduction.

The risk comparison, therefore, is based on the evaluation of the complete mathematical expression approximating the risk and a study of the treatment dependence of each parameter. From this discussion, the scaling properties of the risk can be deduced. These properties determine how the risk will change when these parameters are given the values characteristic of the treated wastes or the treatment of the wastes.

In the FSEIS, different phases of the overall WIPP activities are distinguished. This procedure is not followed here, because to do so would incur efforts outside the limited scope of this study. In particular, it is assumed here that the WIPP activities reach an equilibrium phase in which the total activity in the wastes produced during a year is the same as the activities of the wastes transported, treated, and emplaced in the repository during that year. All risks are, therefore, expressed in terms of risk per year of equilibrium operation.

## **2.2 ALTERNATIVES SELECTED FOR ANALYSIS**

Treatment and location alternatives are selected to span the range of options discussed in more detail in the main report.

### **2.2.1 Basic Considerations**

The baseline case and the treatment/location alternatives selected for evaluation are described here at the minimum level of detail necessary to perform a risk analysis.

#### **2.2.1.1 Baseline Repository and Waste ("As Received")**

The baseline case for this analysis is the "proposed action" of the FSEIS, and in some cases from the FSAR. For the risk assessment, the most important assumptions about the repository are:

- Each room in a panel is filled with 6,000 drums containing "as received" waste and backfilled with crushed salt.
- After repository closure, all panel and shaft seals are in place, with crushed salt backfill.

These assumptions do not change with the four treatments selected for evaluation. In all four cases the activity in 6,000 drums of treated wastes is assumed to be higher than that for untreated wastes, the relative difference being a function of the extent to which radionuclides are concentrated during treatment.

For the risk assessment, "as received" waste is defined as follows:

- Sludges have some cement added as solidifying agents in a 55-gallon (208 L) drum. However, this does not result in a concrete monolith.
- Solid organics, metals, and glasses are in their original form, wrapped in multiple layers of high-density polyethylene inside a 90-mil (2.3 mm) liner in a 55-gallon (208 L) steel drum.
- The average drum contains 12.9 PE-Ci (477 PE-GBq) alpha activity and the corresponding average activities for emission of beta, gamma, and neutron radiation.

### **2.2.1.2 Treatment Alternatives For Comparison**

In Section 3.0 of the main body of this report, 14 combinations of alternatives for waste treatment, waste container, backfill, and repository design are discussed. These combinations represent the range of alternatives that might improve the long-term performance of the WIPP with regard to gas generation (from anoxic corrosion of steel or microbial degradation of organics) or human intrusion. Depending on the aspect that turns out to be most critical, there is thus a set of alternatives representing different levels of effort to effect an improvement. The span of treatments is represented by the four combinations of alternatives included in this risk assessment.

In Table I.2-1 these four treatment options are summarized. The alternatives are arranged in increasing complexity and effort. Treatment Option 0 is the baseline case involving handling, transport, and emplacement of wastes as they are planned today. In Treatment Option 1, sludges are not treated at all, but combustibles, metals, and glass are shredded and cemented. Treatment Option 2 is basically the same, except that sludges are cemented as well. Treatment Options 1 and 2 are, therefore, Level II treatments, which result in a reduction in gas generation rates but no change in gas-generation potential.

Treatment Options 3 and 4, on the other hand, are Level III treatments involving the sorting of the waste and a reduction in gas-generation potential by elimination of organics through incineration and encapsulation of the ashes by cementation or vitrification. Treatment Option 3 cements the sludges, and after sorting, shreds and cements the metal/glass fraction, whereas the combustible fraction is incinerated and its ashes cemented. Treatment Option 4 is the most complex treatment considered. It vitrifies the sludges, incinerates combustibles and vitrifies their ash, and finally decontaminates the metals by melting them with frit, disposing of the metal as low-level waste, and sending only the slag enriched in radioactive isotopes to the repository.

In all of these treatments, the closure operations in the repository are assumed to be identical, i.e., the same backfill (crushed salt) is used, and the same seals for panels and the entire repository are put into place. In this form, Treatment Options 1 and 2 correspond to Alternatives 1 and 2 of the main report, whereas Treatment Option 3 corresponds to Alternative 4, and Option 4 to Alternative 8.

### **2.2.2 Process Descriptions for Treatment Alternatives Selected**

The process descriptions given here are generic, based on general information and on some details available from similar processes.

**TABLE I.2-1**  
**ACTIVITIES FOR THE FOUR TREATMENT OPTIONS**

<b>WASTE FORMS</b>	<b>BASELINE 0</b>	<b>OPTION 1</b>	<b>TREATMENT OPTION 2</b>	<b>OPTION 3</b>	<b>OPTION 4</b>
All	Retrieve/Select Waste				
All	Assay and Certify				
Sludges	--	--	Cement	Cement	Vitrify
Combustible Waste	--	Shred/Cement	Shred/Cement	Incinerate/ Cement Ash	Incinerate/ Vitrify Ash
Metal/Glass Waste	--	Shred/Cement	Shred/Cement	Shred/Cement	Decontaminate
All	Load in TRUPACT-II Transport				
All	Unload TRUPACT-II				
All	Emplace in WIPP				
All	Human Intrusion After 5,000 Years				

### **2.2.2.1 Shred and Cement Combustibles, Glass, and Metals**

Risks are calculated using the following approach to shredding and cementing as one approach to waste treatment. Waste will be removed from the drums, sorted if necessary, and gravity fed into a shredder. Shredded waste will then be loaded into a feed hopper. Shredded waste and Portland cement will be simultaneously loaded into 55-gallon (208 L) drums, and mixed with an in-drum mixer. This device consists of a motor and shaft attached to the drum in place of a lid. The shaft goes into the waste/cement mixture and rotates to form a homogenous waste form.

The mixer is removed and drum lid installed. The shredding process results in an increased waste loading of 20 percent, with the cement occupying the void space within the shredded waste. The average weight of a processed drum is approximately 950 lbs (430 kg). This final waste form can be described as shredded waste encapsulated in cement.

### **2.2.2.2 Cement Sludges**

Treatment risks assume the following approach to cementing sludges. The sludge is removed from the drums and pulverized into a granular form. The granular sludge is then mixed with cement either as an in-drum procedure or as a batch process. Cementing sludges will not result in a volume reduction. It is assumed that the volume of added cement is equivalent to the void spaces that exist in the sludge prior to reprocessing. The average weight of a processed drum is approximately 760 lbs (350 kg). The final waste form can be described as a concrete-like monolith with a homogeneous distribution of contamination. The material will be indistinguishable from cement within the monolith. For newly generated sludges this process is already in use. There may be a need for refining the process to meet particular specifications. For stored waste a new process would be required.

### **2.2.2.3 Incinerate and Cement Combustibles**

Risks are evaluated based upon the following procedure for incinerating and cementing combustibles. Waste is removed from the containers, sorted, and fed into a shredder. After shredding, the waste will be directly fed into the incinerator. Incinerator ash is collected and mixed with cement either as an in-drum process or as a batch process. This process results in an increased waste loading of three to one. The average weight of a processed drum is approximately 1,050 lbs (480 kg). The final waste form can be described as a concrete block with a homogeneous distribution of contamination. The ash will be indistinguishable in the cement block.

### **2.2.2.4 Vitrify Sludges**

Risks are less well defined for vitrifying sludges because the process is not fully demonstrated. For newly generated sludges it may be possible to add a melter to the end of the process that

generates the waste. For stored waste, the process is new. The sludge will be removed from the drums and pulverized into a granular form that can be fed into a microwave melter. Once processed, drums filled with melted sludge are removed from the microwave cavity and stored until cool. This process results in an increased waste loading of 9.1 to 1. The average drum of vitrified sludge weighs approximately 1,000 lbs (450 kg). The final waste form can be described as a borosilicate glass nugget. The sludge will be indistinguishable within the glass.

#### **2.2.2.5 Incinerate and Vitrify Combustibles**

Waste will be removed from the containers, sorted, and fed into a shredder. The shredding process will be the lead-in for the incinerator. After incineration, the ash will be collected and fed into the vitrification process. The vitrification process will consist of feeding ash into a microwave melter in a continuous or batch mode. Drums will then be removed from the microwave cavity and allowed to cool. This process results in an increased waste loading of 13 to 1. The average drum of processed waste is approximately 1,150 lbs (520 kg). The final waste form can be described as a borosilicate glass nugget. The incinerator ash would be an integral part of the glass.

#### **2.2.2.6 Decontaminate Metals and Glass by Melting**

The beginning of this process will involve removing all metallic components from the combustibles. This involves a sorting process in which drums will be emptied and all metallic components removed for decontamination. The remaining waste would be removed for incineration and vitrification (see Treatment Option 4). The contamination from the metal components would be homogeneously contained within a borosilicate glass nugget. This process involves melting metals and a preferential migration of the radionuclides into the slag material (borosilicate glass). The metallic waste is eliminated from the waste inventory with this process. The process results in an increased waste loading of 7.4 to 1. In the final product, the waste is in the form of a slag instead of a metal. The average weight of a drum containing slag is approximately 1,150 lbs (520 kg).

#### **2.2.3 Location of Treatment Plants Selected**

The risk assessment of the Engineered Alternatives considers the different numbers and locations of treatment plants to provide insights into the influence of these parameters on risk. According to the FSEIS, the transportation risk is the largest component of the total baseline risk. For each treatment option, the location options are varied from a single, centralized treatment facility located at the WIPP to a relatively decentralized option with local treatment facilities at all larger generator sites. The actual sites are chosen so as to best represent the multitude of possible site combinations for calculational purposes only. No other considerations were taken into account. If treatment should be required in the future, other influences and aspects would determine facility locations. The sites considered here are:

- Idaho National Engineering Laboratories (INEL)
- Rocky Flats Plant (RFP)
- Hanford Reservation (HAN)
- Savannah River Site (SRS)
- Los Alamos National Laboratories (LANL)
- Oak Ridge National Laboratories (ORNL)
- Nevada Test Site (NTS)
- Argonne National Laboratories - East (ANL)
- Lawrence Livermore National Laboratories (LLNL)
- Mound Laboratories (MOUND).

Four facility siting options are described in Table I.2-2. Only waste shipments from these ten originators will be considered in the risk assessment.

Location Option 1 (Figure I.2-1) has one treatment facility at the WIPP where all wastes are processed. For transportation, this option corresponds to the baseline case as every waste generator currently plans to send its waste to the WIPP in an untreated state. Location Option 2 (Figure I.2-2) has three regional treatment facilities located at the WIPP, RFP, and INEL. The INEL processes its own waste as well as the waste generated at HAN. The RFP processes only its own waste and the WIPP site processes all other wastes.

Location Option 3 (Figure I.2-3) has five treatment facilities. The WIPP processes waste from smaller generators such as LANL, LLNL, and NTS. The SRS acts as a regional treatment facility in the east and services ANL, MOUND, and ORNL facilities. The RFP, INEL, and HAN sites all treat their own waste before shipment to the WIPP.

Location Option 4 (Figure I.2-4) has seven treatment facilities, one at each of the major waste generators. Only smaller waste generators such as ANL, MOUND, NTS, and LLNL would ship their wastes directly to the WIPP for processing.

## **2.3 SCENARIOS SELECTED FOR RISK COMPARISONS**

Both routine and accident exposure scenarios are considered in the risk comparison. The following descriptions are either summarized from information in the FSEIS or used in the analysis of the new treatment risks. No credit is taken for recently improved operating procedures, such as the use of a vent hood during the unloading of the TRUPACT-II containers.

### **2.3.1 Routine Scenarios for Baseline Risks**

Routine scenarios, denoted here by the letter N, describe the day-to-day exposures to radiation and chemical toxicants.

**TABLE I.2-2**  
**LOCATION OF TREATMENT FACILITIES**

LOCATION OPTION	INEL	HAN	RFP	LANL	ORNL	SRS	WIPP
1	--	--	--	--	--	--	x
2	x	--	x	--	--	--	x
3	x	x	x	--	--	x	x
4	x	x	x	x	x	x	x

x - Denotes the presence of a treatment facility.

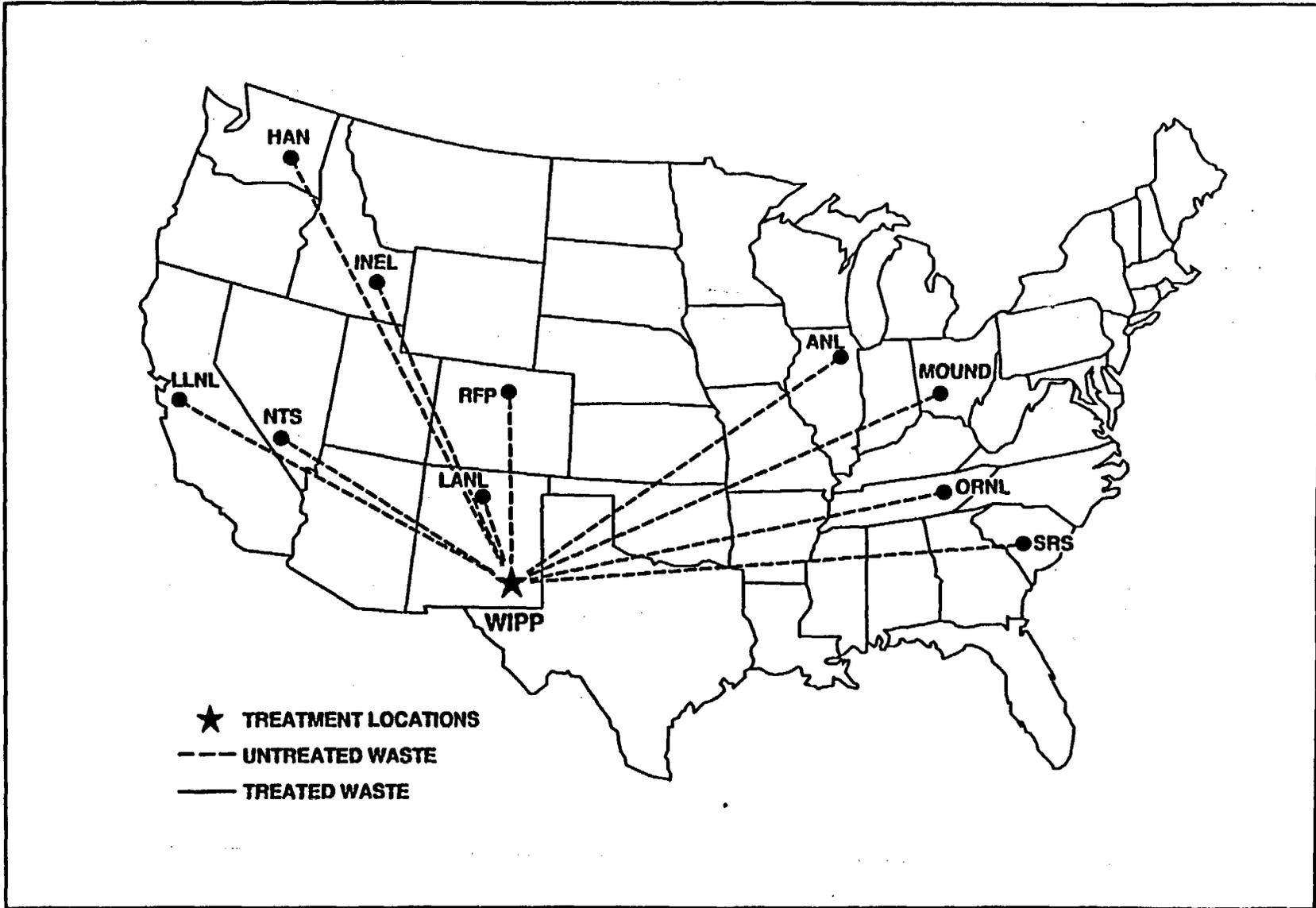


FIGURE I.2-1 TREATMENT PLANT LOCATIONS - OPTION 1

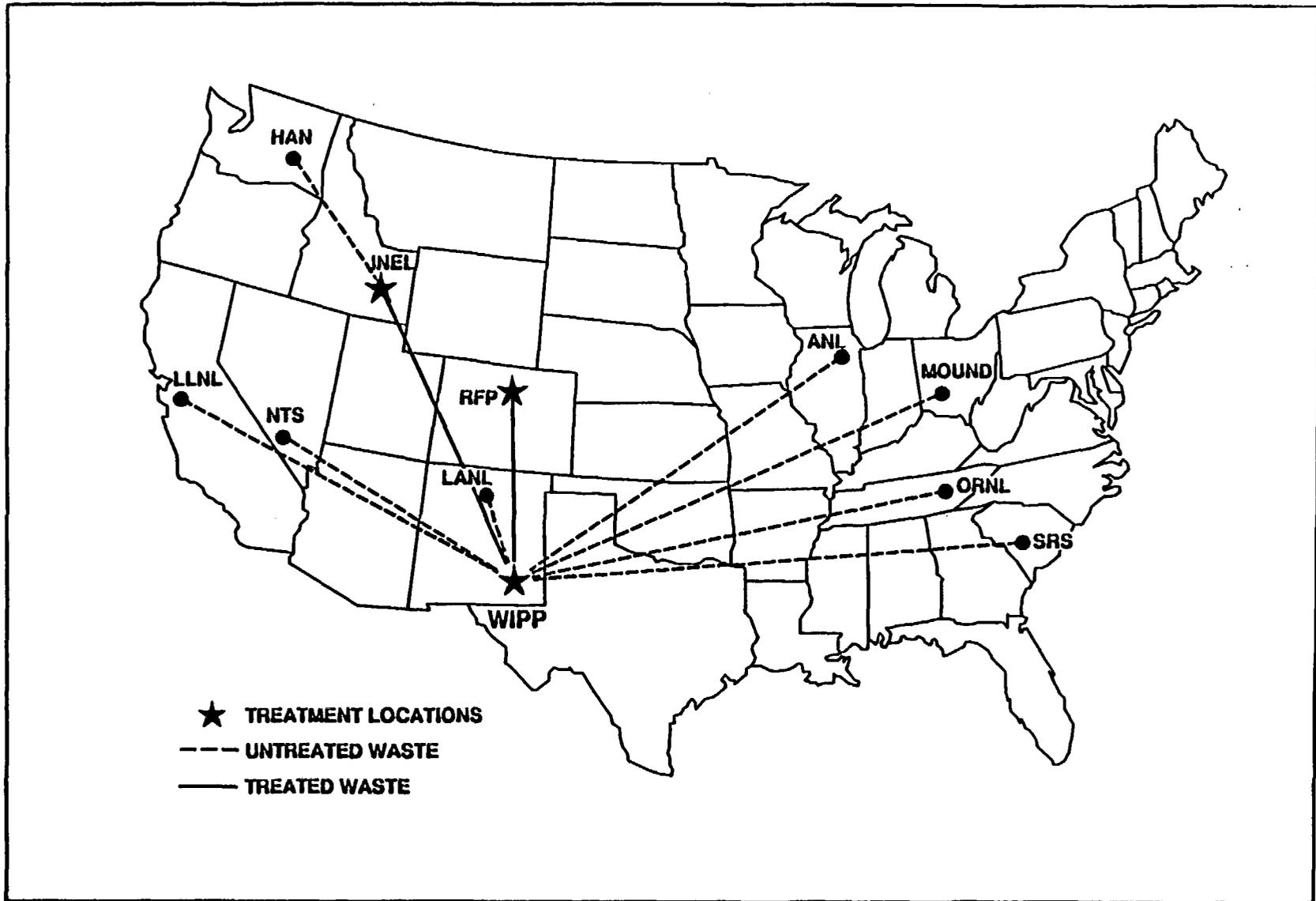


FIGURE I.2-2 TREATMENT PLANT LOCATIONS - OPTION 2

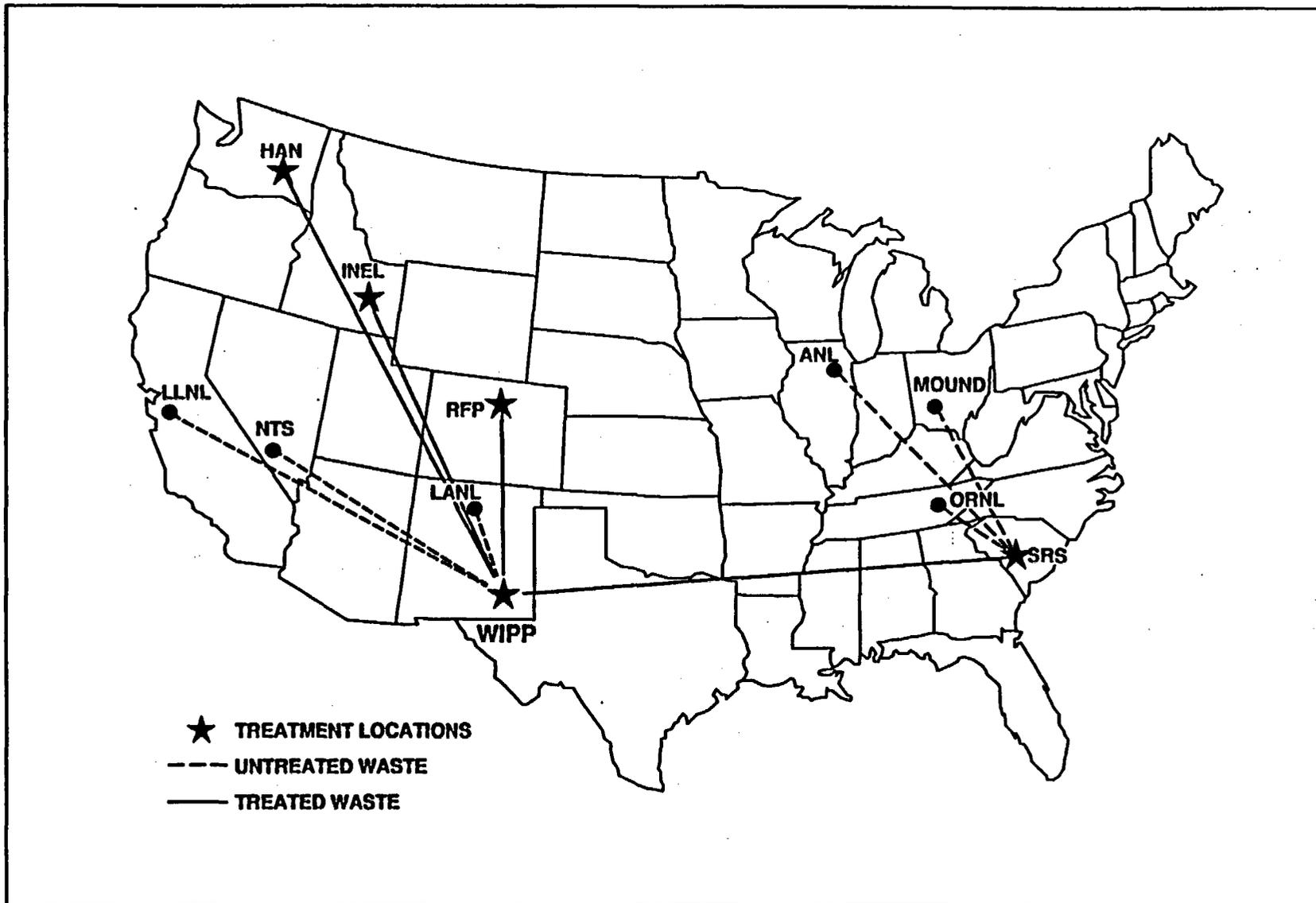


FIGURE I.2-3 TREATMENT PLANT LOCATIONS - OPTION 3

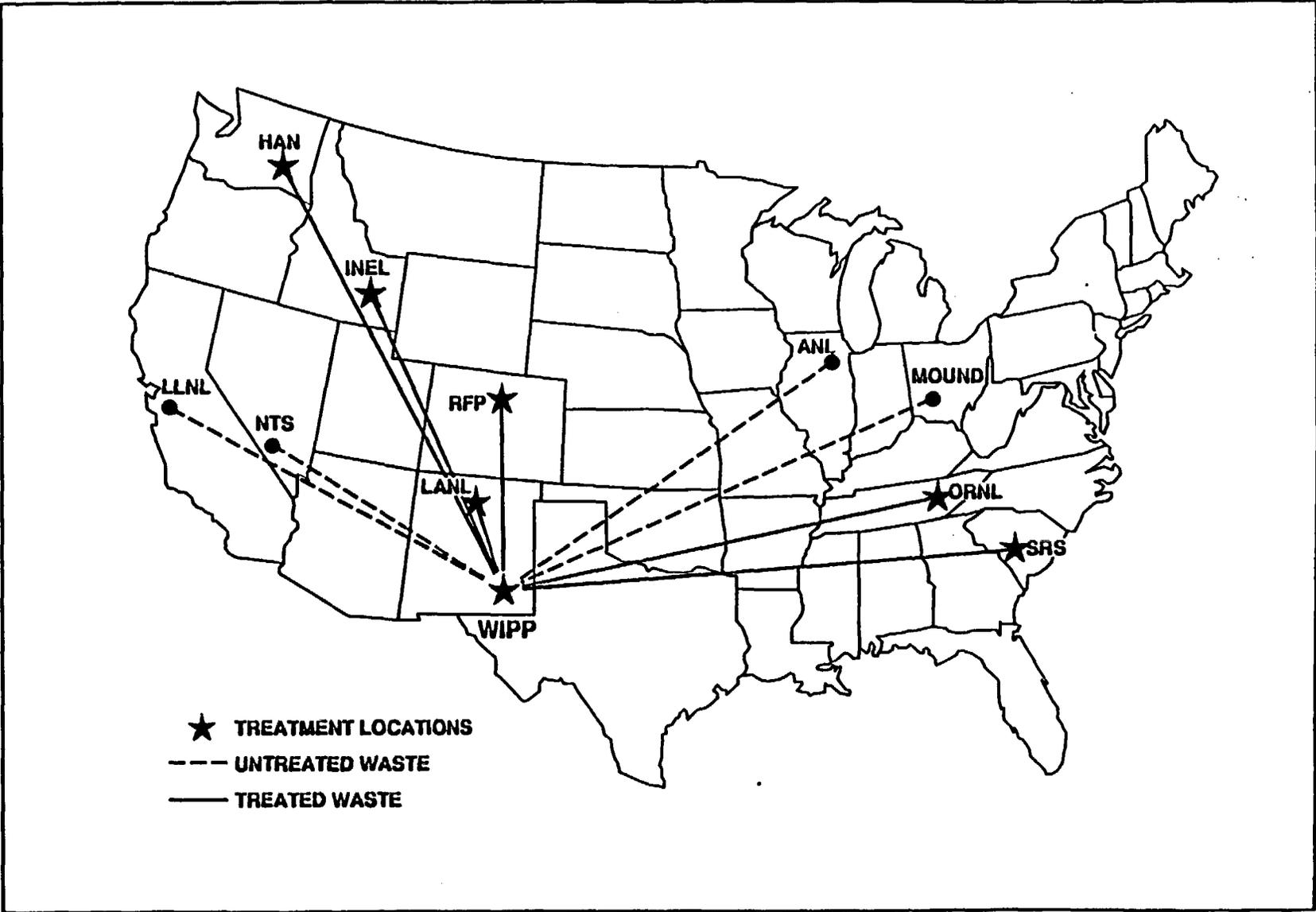


FIGURE I.2-4 TREATMENT PLANT LOCATIONS - OPTION 4

### **2.3.1.1 Routine Scenarios for Handling and Disposal at the WIPP**

For this assessment, routine exposures are those that occur without detection by the radiation monitoring devices such as the Continuous Air Monitors (CAMs). Routine inhalation exposures that occur during waste handling operations are considered to be a continuous, chronic exposure, and workers are assumed to be without respiratory protection.

#### **2.3.1.1.1 N1 Routine Exposure Scenario**

Drums may contain surface contamination at levels below those defined in the Waste Acceptance Criteria (DOE, 1989b). Through routine handling, some contamination can be mobilized and suspended in the air. Occupational exposure results from inhalation and deposition of the suspended particles in the lung. Public exposures result from suspended particles which penetrate the High Efficiency Particulate Air (HEPA) filters and escape to the outside environment.

#### **2.3.1.1.2 N2 Routine Exposure Scenario**

In this scenario, a drum is perforated before it reaches the Waste Handling Building (WHB). During handling, but before assay and certification, small amounts are released from the drum, resuspended in the air, and subsequently inhaled by the work crew, resulting in an occupational risk. Again the public may be exposed to the particulates that escape deposition in the HEPA filters resulting in the public risk component. There is no further risk after the drum has been assayed and certified, as it is assumed that any perforation is detected by these procedures and remediated by overpacking. Recent changes in procedures (vent hood) significantly reduce this small risk.

#### **2.3.1.1.3 N3 Routine Exposure Scenario**

This scenario is identical to N1 except that the routine exposure occurs underground and results in both occupational and public risk components.

#### **2.3.1.1.4 N4 Routine Exposure Scenario**

This scenario incorporates the risk from external radiation during the unloading, assay and certification, and transport procedures in the WHB. All other elements of the scenario are the same as for Scenario N1.

#### **2.3.1.1.5 N5 Routine Exposure Scenario**

This scenario is identical to N4 except that the routine external exposure occurs underground during the unloading, transport, and disposal operations.

### **2.3.1.2 Routine Scenarios for Waste Transport**

The routine exposure scenarios for the TRUPACT-II transports are those evaluated in the RADTRAN-III code (Madsen et al., 1986). They consist of a number of public and occupational exposure models designed to evaluate radiation exposures below regulatory limits for the general population. These models are used as baseline scenarios.

#### **2.3.1.2.1 Routine Public Exposures Near Road Taken by the TRUPACT-II Vehicle**

The public living or working in close proximity to the roads traveled by the TRUPACT-II transports are routinely exposed to the low-intensity penetrating radiations emitted by some of the radioisotopes in the wastes. Exposures depend on the distance from the road, the speed of the transport, and the population density along the road for rural, suburban, and urban sections of each route used.

#### **2.3.1.2.2 Routine Public Exposures During Stops**

During stops, due to regulation breaks or caused by road conditions, a small portion of the public will be in relatively close proximity of the TRUPACT-II transport, and will be exposed to the low-level penetrating part of the radioactivity in the wastes. These exposures can be of somewhat lengthy duration but are distributed among relatively few persons.

#### **2.3.1.2.3 Routine Exposures Due to Public Traveling in the Opposite Direction**

The public traveling in vehicles in a direction opposite to that of the TRUPACT-II transport is also exposed to the penetrating radiations from the wastes. These low-level exposures are of very short duration due to the high relative velocities of source and receptors, and take place at relatively large distances, depending on the type of road.

#### **2.3.1.2.4 Routine Exposure Due to Public Traveling in the Same Direction**

Again, an exposure of the public to the low-intensity penetrating gamma and neutron radiations of source radioisotopes in the wastes occurs. In this case, however, the exposure times may be considerably longer due to the low relative velocities and the proximity of the vehicles during passing.

#### **2.3.1.2.5 Routine Exposure of Crew During Transport**

During most of the time spent in transit, the crew is exposed continuously to the penetrating radiations emanating from the wastes in the TRUPACT-II containers. Although still relatively low, considerably below occupational exposure limits, theirs are among the highest individual occupational exposures.

### **2.3.1.2.6 Routine Exposures of Warehouse Personnel**

Warehouse personnel at both origination and destination points are exposed to the penetrating radiations of up to a full load of drums, however, without the shielding effect of the TRUPACT-II walls. This is mitigated by a larger distance and potentially some shielding required by health and safety regulations and ALARA concerns.

### **2.3.2 Accident Scenarios: Assumptions and Descriptions**

In this analysis, accidents are assumed to produce short exposures because extensive health and safety precautions are in place and assumed to be followed. Each accident scenario considered directly or indirectly by the risk assessment in the FSEIS will be described briefly here. Conservative assumptions are made with respect to the amount of radioactivity or chemical agent released per accident and the fraction available in respirable form. The assumptions made are uniformly on the conservative side leading to a bias in risk comparisons by overestimating the accident risks. No credit is taken for the measures planned for mitigation and control of the accident consequences. A dose calculation and a risk assessment are then made for each accident scenario postulated. Risks are calculated for both the public and occupationally exposed persons. Only accidents considered by the risk assessment in the FSEIS will be described, as others have been discounted because of extremely low probability of occurrence or because no release is postulated.

#### **2.3.2.1 Accidents During Handling and Disposal**

The accidents during handling and disposal are those denoted by the letter C in the FSEIS. The descriptions are given only in the detail required for a risk comparison.

##### **2.3.2.1.1 Drum Drop from a Forklift in the WHB (C2 Accident)**

With a certain frequency, a waste drum will be dropped from a forklift in the WHB. Waste drums are Type A packages and are designed to withstand a 4 foot drop without being damaged enough to release activity. However, it is conservatively assumed in the FSEIS that the drop results in the loss of the lid, the inner plastic liner tears, and part of the drum content is spilled. Of the wastes spilled, a fraction is suspended and available in inhalable form. The drum is assumed to contain the 12.9 PE-Ci (477 PE-GBq) cited as the average alpha radioactivity per drum. It is further assumed that the Waste Acceptance Criteria (WAC) limit of 5 percent of the total radioactivity in the drum is contained in the one weight-percent of particles with diameters less than 10  $\mu\text{m}$ . Particles greater than this size are not considered to be respirable. Resuspension is assumed to cancel the depletion of activity in the room air by sedimentation or plate-out, so the total amount of suspended radioactivity in the room air reaches an equilibrium value. Between the WHB and the outside, HEPA filters are on-line that would reduce the source term to the environment by a factor of about one million.

Worker doses are estimated assuming established operating procedures and facility design. It is also assumed that the workers in the immediate area will respond as trained and immediately evacuate the area. The contamination will spread slowly and the internal deposition is, therefore, not considered to be part of the exposure. Where applicable, these assumptions will be transferred to other scenarios.

#### **2.3.2.1.2 Two Drums Punctured by Forklift, One Drum Dropped in the WHB (C3 Accident)**

It is postulated that a forklift accidentally punctures two drums with its forks and the lid of a third drum falls off as it falls from the stack. Withdrawing the forks from the drums is not advisable but is assumed to happen. For the drum with lid loss, a C2 scenario is involved; for each of the punctured drums another fraction of the waste is spilled, but from then on the probability of suspending an inhalable fraction of the activity and other assumptions are the same.

#### **2.3.2.1.3 Transporter Hits a Pallet in the Underground Storage Area (C4 Accident)**

A transporter is assumed to hit a pallet of waste drums in the underground storage area, causing the drums to fall. As in the C2 scenario, it is conservatively assumed that the lid of one of the drums is knocked off and the inner liner tears. This accident is identical to the C2 scenario with the exception that it occurs underground. HEPA filters are not assumed to be on-line as they are assumed not to be activated by the radiation detection instruments. Workers downstream from the accident would receive an inhalation dose. This part of the assessment differs from a C2 accident above ground in that there is a higher rate of air flow within the repository and there is probably a longer distance between the point of release and the workers. It is assumed that the plume is homogeneously distributed in a volume equal to 4.0 by 3.5 by 6.1 cubic meters. Conservatively, the workers are assumed to not be wearing a respirator and to be in an area not normally occupied.

#### **2.3.2.1.4 Drum Drops from Forklift in the Underground Storage Area (C5 Accident)**

This accident and its ramifications are bounded by the previously described C4 scenario.

#### **2.3.2.1.5 Drums Punctured by Forklift, One Drum Drops in Underground Storage Area**

This scenario is identical to the C3 accident scenario except that it occurs underground and that the HEPA filters are assumed to be off-line. It is further assumed that a depletion of activity occurs by plate-out and sedimentation before release to the environment. The subsequent risk to the public can be calculated from this information. The occupational worker exposure is modeled after the C4 accident scenario.

#### **2.3.2.1.6 Fire Within a Drum Underground (C10 Accident)**

Spontaneous ignition within a drum is postulated to occur only in the Underground Storage Area, because the probability rate is very low and the residence time in the WHB is brief. It is not assumed that such an event would spread to adjacent waste drums. It has been estimated that the probability of spontaneous ignition within a drum is less than 1 per 1.8 million drum-years. The drum involved in this accident is assumed here to have an average radioactivity content, contrary to the FSEIS which assumes a total alpha activity, in excess of 1,000 PE-Ci (37 PE-TBq). The spontaneous ignition is postulated to suspend some of the radioactivity content into the air underground. The deposition rate is high due to the fact that the suspended particles are in a heated state and will react with the cooler surfaces within the facility. The release to the environment and thus the amount of activity available for public exposure is estimated, assuming no HEPA filtration. There is no occupational dose postulated for this event because the waste is emplaced and stored downstream from the workers.

#### **2.3.2.2 Accidents During Waste Transports**

The accidents described here are the scenarios given in the RADTRAN code used in the FSEIS for TRUPACT-II transports.

##### **2.3.2.2.1 Direct Consequences of Traffic Accidents**

Traffic accidents, involving a TRUPACT-II transport, its crew, and members of the public and their vehicles are the largest contribution to the total risk of WIPP operations (DOE, 1990a). The number of traffic fatalities and injuries is directly related to the number of transport-kilometers and is thus sensitive to the location of the Treatment Facilities. These are the consequences of typical traffic accidents, not modified in any way by the radioactivity or chemical toxicity of the cargo.

##### **2.3.2.2.2 Nondispersal Transportation Accidents**

Nondispersal accidents mainly constitute a source of penetrating radiation with a limited range of significant exposures due to the decrease of radiation dose rate, roughly with the inverse of the square of the distance. In rare cases, close-in exposures may be incurred that cause early and late health effects such as radiation sickness, cancer, other somatic, and genetic effects. Here, the averages for accident severity, taken over the entire waste transport system and given in the FSEIS, are assumed.

##### **2.3.2.2.3 Transportation Accident with Waste Dispersal**

In this scenario, an average over large parts of the transportation system is assumed for the typical severe accident with an atmospheric suspension and dispersion of a fraction of the wastes

(see DOE, 1990a). Dispersion will subject the public to inhalation exposures and to direct exposures due to airborne radioactivity and activity deposited on the ground.

### 2.3.3 Routine Scenarios for Treatment Options

The modular composition of the TF allows the relatively simple evaluation of the risks for routine operations and maintenance. The same standards for health and safety, as well as ALARA, used for WIPP operations are assumed here also. Similarly, exposures to volatile chemicals are limited by forced ventilation, filters, and chemicals traps.

#### 2.3.3.1 Occupational Accidents Typical of Industry

Risks of occupational fatalities and injuries are evaluated for the crew of the TF and the WHB. As no direct incidence data are available, information for similar industries are used. With forklift movements an integral part of the operations in handling the wastes, forklift accidents are given special attention.

#### 2.3.3.2 Routine Radiation Exposures During Normal Operations

For routine operations with each one of the treatment devices for different waste forms, exposures to penetrating radiations are incurred. Shielding designed to satisfy health and safety criteria reduces this exposure to ALARA levels, taking into account duration of treatment and time-motion studies for the device.

Despite airlocks, some low-level airborne activity is assumed to escape from the enclosure of the device and inhaled and ingested by unprotected workers outside the enclosure. Risks are evaluated by calculating Cumulative Effective Dose Equivalents (CEDEs). The activity levels in air are assumed to be minute because they are low enough not to be detected by any of the monitors. After passing through the HEPA filters, the residual airborne activity, further diluted by atmospheric dispersion, can lead to low exposures of the public. Similarly, fugitive emissions from the device enclosures are assumed to lead to occupational exposures. Residual concentrations of VOCs after passing through filters and traps are carried outside the plant and are attenuated further by atmospheric dispersion, leading to very small public exposures to chemical toxicants.

#### 2.3.3.3 Routine Exposures During Normal Maintenance

In routine maintenance, both external and internal exposures occur. External exposures arise from the surface contaminations of device and enclosure. Internal exposures occur by penetration or bypassing of the respirator and by ingestion. The CEDE is the quantity needed to evaluate the risk of cancer and genetic effects. Resuspended activity, after passing through HEPA filters and diluted by environmental dispersion, will lead to some public inhalation

exposures. The routine exposure to chemical agents during maintenance will be very low because treatment will reduce the presence of VOCs to negligible levels.

#### 2.3.4 Accident Scenarios for Treatment Options

Due to the limited scope of this study and the effort required for the accident risk assessment of the six treatment devices and the appropriate accident scenarios for each, accidents in the TF are not considered in this study. Routine exposures to radiations and chemicals, as well as non-radiation, non-chemical work accidents typical of this type of industry are the only contributions to the risks of treatment taken into account. Neglecting the accident risk will lead to an underestimate of the treatment risk, and will thus introduce a bias in favor of the treatment options over the baseline case. In this type of operations, the routine risks are normally larger than the accident risks, so that this bias is not considered severe enough to invalidate the basic conclusions.

#### 2.3.5 Human Intrusion Scenarios

The repository in an undisturbed state poses no direct risk of significance to man or environment (DOE, 1990a, 1990c). Human intrusion is needed to bring noticeable amounts of radioactivity or chemicals to the surface.

##### 2.3.5.1 General Considerations

Human intrusion scenarios are based on the assumptions discussed in Sections 2.0 and 4.0 of the main report. Most important for the risk comparison are the following characteristics:

- The intrusion occurs 5,000 years after decommissioning of the repository.
- The hydraulic conductivity of the waste/backfill composite is the weighted geometric mean of the waste forms and backfill properties.
- The borehole conductivity is  $1 \cdot 10^{-3}$  meters/second (clean sand/gravel) obtained from Table 2-2 in Freeze and Cherry (1979).
- Waste element solubilities have been assumed to be  $1 \cdot 10^{-6}$  mol/liter from Table 3-10 in Marietta et. al. (1989).

The three scenarios used here are described in detail elsewhere (Marietta et al., 1989). The details relevant for a risk assessment are given here.

### 2.3.5.2 The E1 Scenario

The E1 scenario, shown schematically in Figure I.2-5a, assumes a borehole penetration through a waste-filled panel and continuing into or through a pressurized brine pocket existing in the Castile Formation underlying the repository. Afterwards, the drillhole is assumed to be plugged near the surface and just above the Culebra aquifer. Risks to man arise from three sources: cuttings in the drilling mud from the repository exposing the drilling crew directly; wind erosion of the dried drilling mud leading to an inhalation exposure of the nearby public; and radioactive brine contaminating the Culebra aquifer and a stock well drilled into it. This results in contaminated beef and an ingestion exposure of the public.

The model for the drill cuttings is straightforward, as is the model for the wind erosion of the dried-up mud pool and the subsequent atmospheric dispersion. The relevant quantity in both cases is the activity contained in the cross-section of the borehole and the depth of the repository (3 drums). Pressurized brine flows through the borehole and through an ellipsoidal volume of the wastes, transporting additional activity to the surface (see Section 2.2 and Appendix B.18). The contamination of the Culebra aquifer is modeled using a parametric equation relating flow rate through the waste/backfill composite to the hydraulic conductivity of the composite. This equation was developed for Section 2.2 of the main report using data from a transport model (Reeves et al., 1986).

### 2.3.5.3 The E2 Scenario

Scenario E2, shown in Figure I.2-5b, assumes a borehole penetrating just into the repository, not passing through. After penetration the borehole is assumed to be plugged, once near the surface and once above the Culebra aquifer. The scenarios exposing the drilling crew to direct radiation from the drill cuttings in the mud, and the subsequent public exposures are essentially unchanged. The scenario leading to the contamination of the Culebra aquifer is modeled using an analytical solution for the radial flow equation through a porous medium, simulating the borehole and the panel as concentric circles (Walton, 1989). The model is discussed in more detail in Section 2.2 of the main report and in Appendix B.18. The same model as in the E1 scenario is used to estimate the contamination in the Culebra aquifer and the stock well.

### 2.3.5.4 The E1E2 Scenario

The E1E2 scenario, shown schematically in Figure I.2-5c, assumes a combination of the first two scenarios; two boreholes penetrate the repository in the same panel. One borehole provides a pathway for brine flow from the Castile Formation brine pocket directly into the panel. After drilling through the repository and the brine pocket, it is assumed to be plugged near the surface and between the repository and the Culebra. The other borehole provides a pathway for the contaminated brine to reach the Culebra aquifer, as it is plugged near the surface and above the aquifer. Both boreholes provide separate sources for the exposure of the drilling crew and

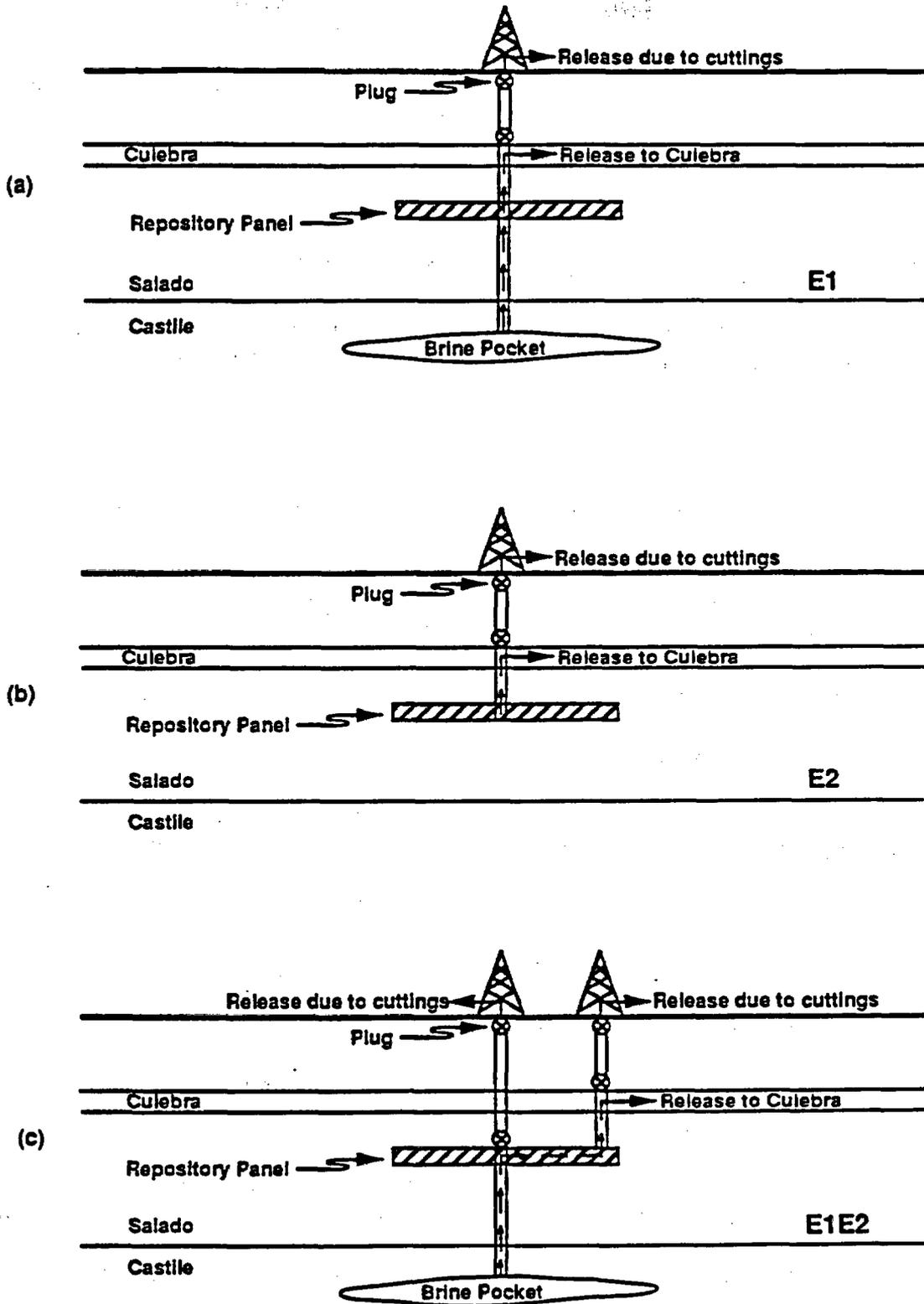


Figure I.2-5. Human Intrusion Scenarios

subsequently of the public by activities derived from drill cuttings. The contamination of the Culebra occurs by way of a flow path from the E1 borehole through the wastes to the E2 borehole and up to the Culebra. The model for the contamination of that aquifer and the stock well is the same as the one used in scenario E1.

## **2.4 ASSUMPTIONS FOR RISK ESTIMATES AND COMPARISONS**

The assumptions presented and discussed in this section are limited to those that apply to all risk models in this study. More detailed assumptions are made when the need arises.

### **2.4.1 General Assumptions**

Risk components may be dependent on several variables. These include treatment options, location options, routine scenarios, accident scenarios, and human intrusion or late effect scenarios. Variables such as routine and accident scenarios use the baseline cases as detailed in the FSEIS as a basis for comparison (DOE, 1990a). As stated before, the baseline cases for the human intrusion scenarios are those of the main body of this report. Treatment and location options vary the risk components but again the baseline case is used as a basis for comparison.

This study uses the same information given in the FSEIS when describing accidents, events, locations, severities, environmental conditions, and dose-effect relations. As in most of the FSEIS, risks are given as risks per year of operation, but they refer to the equilibrium phase.

The following assumptions are made for the purposes of the risk comparison mostly due to the limited scope of this study or due to lack of information on baseline risks.

- Only CH-TRU waste is considered; RH-TRU waste is not included.
- All CH-TRU waste is exclusively transported by truck.
- Risks are estimated for the equilibrium phase of operations only.
- All waste is shipped and handled in 55-gallon (208 L) drums; no other packaging is considered.
- No drums with more than average alpha activity 12.9 PE-Ci (477 PE-GBq) and the corresponding beta-, gamma- and neutron activities are taken into account.
- Maximally exposed individuals are not specifically analyzed; they are, however, included in the averaging.

- Somatic effects of radiation other than cancer are not evaluated.
- Human intrusions scenarios lead to the only post-closure effects considered.
- The FSEIS, the FSAR, and corresponding calculation briefs are the only sources used for calculation of baseline risks.

A constant value is assumed for the annual rate of activity emplacement in the repository. The annual rate of activity emplacement is an important factor for radiological risk assessment.

#### **2.4.2 Treatment Assumptions**

A treated waste has properties different from those of untreated waste resulting in changes of radiological risks. However, the following simplifications will be assumed:

- The gamma radiation spectrum and the neutron spectrum emitted by the variety of isotopes do not change with the waste form.
- The treatment of the waste is assumed not to affect isotopic leachability or isotopic composition.
- There is no attenuation of gamma radiation within the waste or its containment.
- The particle spectrum and the mean aerodynamic diameter of inhalable aerosols generated in an accident does not change with waste treatment, although the number of particles does.

All of these assumptions are basically conservative or at least neutral, because they apply to treated and untreated waste alike. However, due to their sometimes overly conservative nature, these assumptions do introduce biases, so that they should be eliminated, if possible. The spectra and the source-absorption of the gammas are conservative assumptions that can be removed by relatively simple calculations. The latter are not done here because of the limited scope of the study. The assumption of the generated particle spectrum being independent of waste treatment is borne out by the empirical particle generation model used here and thus has a low priority for replacement. The assumption of constant leachability, however, is more difficult to replace because, due to the preliminary nature of the treatment descriptions, the waste properties are not known sufficiently well to support a model for differential leachability. Note that it is a conservative assumption, which does, however, lead to an anti-treatment bias.

### **2.4.3 Location Assumptions**

The baseline case, transportation of "as received" waste only, is the same as the Location Option 1, with the TF at the WIPP. Consequently, transportation risks are the same in both cases. Other options involve the use of additional sections of road, not traveled over in the baseline case. The assumption is made here that the fractions of travel in urban, suburban, and rural regions and all other parameters are given by the same regional averages as those given in the FSEIS.

As treatment changes the density of the wastes, and thus the number of waste shipments, there is a reduction or increase in transport-kilometers, both loaded and empty, and thus a corresponding change of the risks in some of the contributions to the total transportation risk.

### **2.4.4 Weight Restrictions Due to Treatment**

The entire waste shipment consisting of three TRUPACT-IIs, waste, and truck/trailer assembly, must not exceed 80,000 pounds (36.2 metric tons), according to 23 CFR 658.17 (U.S. Department of Transportation, 1975). Treatment, with the corresponding volume reduction of the waste, may increase the weight of the waste form, thereby making complete utilization of the TRUPACT-II container unlikely. Each treatment option has an associated volume and weight reduction or increase, and from this information a utilization of the TRUPACT-II is obtained. Clearly, cementing of wastes increases weight to the point that complying with weight restrictions becomes an issue. The chances are greater that an increased number of shipments, above the much smaller number calculated using the volume reduction only, is required for Level II treated wastes.

Weight restrictions also seem to apply to forklift operations and forklift loading capacities. Depending on the treatment alternative, the number of forklift operations increases due to treatment. Yet, although treated drums are much heavier, a heavy-duty forklift is assumed to take care of the same number of drums as before without significant increase in accident rates.

### **2.4.5 Cause-Effect Functions**

The cause-effect relationships for cancer due to radiation are assumed to be of the linear no-threshold type (National Research Council, 1990). Although some of the calculations in the FSEIS are using the linear-quadratic approximation of BEIR III (National Research Council, 1980), the differences at the low doses encountered here are insignificant (DOE, 1990a). The choice of the linear no-threshold hypothesis is made here, because the linear-quadratic model does not allow the use of the person-Sievert (person rem) concept. The inability to use this concept would needlessly complicate the calculation.

#### 2.4.6 Significant Figures Given

The final values calculated are given with a number of digits determined by the standard error. Regardless of the precision of the input data, all intermediate data are given with at least one digit more than significant. This will avoid cumulation of rounding errors. Final results are normally given to one significant digit in the error because errors are rarely known to a better accuracy. This then determines the corresponding number of significant digits for the value.

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### 3.0 COMPARISON OF MULTI-COMPONENT RISKS

#### 3.1 COMPARISON OF MULTI-COMPONENT RISKS

##### 3.1.1 Definition of Risk

The concept of risk gives rise to many different definitions, which are mostly dependent on the immediate application. One of the more general definitions is that of Kaplan and Garrick (1981), which is used here. It defines risk in terms of a triplet of quantities: a scenario, a consequence, and a corresponding probability (for a more detailed description see Attachment B.21).

As an example, a risk can be defined by a scenario that postulates an exposure of the whole body of an individual to penetrating gamma rays for a short time, resulting in the consequence of leukemia five to ten years later with a probability of 0.1 percent. While more information such as the radiation dose absorbed by the body may be necessary to calculate the probability, it is implied by the value of that probability and is, therefore, not an absolutely necessary datum. Less information than the triplet, however, will result in ambiguities because the same scenario can also lead to acute radiation sickness in the short term or several other types of cancer, such as lung cancer, in the long term.

These different consequences illuminate an important property of almost all risks of an event or an activity: such risks consist of a number of different components. Only rarely is a single individual the subject of a risk assessment, and similarly, only rarely is an event completely described by one scenario. Thus, all three quantities that define a risk usually have a multi-component structure. An activity such as the operation of the WIPP entails hundreds of activities, events, and possible consequences. Also, it involves tens to hundreds of workers and, potentially, hundreds to thousands of persons in the general population. Total risks of activities such as the WIPP are thus quantities with a multi-component structure.

This multi-component structure of the total risk of an activity presents problems when the total risks of two alternate approaches, such as different waste treatments, are to be compared. Basically, it is only possible to compare two numbers, thus restricting a comparison to the values of two quantities measured in the same units. For any multi-component risk, this means that a formulation must be found to reduce the multitude of component values to one characteristic measure which then can be compared for two alternatives.

In this context, it is important to note that many decision makers prefer to compare all components of two total risks in a "seat-of-the-pants" procedure. While this may work well in many cases, it is not transparent and is, therefore, of dubious value in adversarial proceedings or other situations where decisions and their basis must be documented. The measures for risk comparison proposed here are fully transparent without unnecessarily fettering the valuation process of the decision maker. In order to accommodate decision makers that want to work with

the raw data for each component or for a decision maker on a higher level, these data are provided and discussed.

### 3.1.2 Uncertainties in Risk Assessment

Usually, risk calculations are beset by considerable uncertainties, which can be expressed numerically by assigning or calculating random and systematic standard errors (see for instance, Seiler, 1990). Random or statistical errors arise from many possible causes; their signs cannot be predicted, nor can they be prevented. These kinds of errors can be decreased, however, by increasing the amount of information on which the quantity is based, for example, the number of measurements taken. Systematic errors, on the other hand, usually have an identifiable cause, affect every measurement by the same mechanism, and if properly investigated, can sometimes be avoided or corrected for. They cannot, however, be decreased by increasing the number of measurements taken.

A typical example of random errors are the fluctuations in the count rate of a radiation counter exposed to a constant flux of particles. Typical systematic errors are those caused by the use of a defective scale, resulting in uniformly high or low measurements, or those caused by the use of a model that does not account for a pertinent effect, and therefore, yields systematically distorted values.

Both types of errors need to be taken into account in a risk assessment, although random errors are easier to evaluate and handle. Systematic errors are most often based on little more than an educated guess or some experimental evidence using different methods of measurement or calculation. In a comparison of risks, these standard errors play a major role in helping determine whether or not a difference between two risks is really significant. The fact of an insignificant difference in risk is an important datum in further evaluations using risk comparisons as input.

### 3.1.3 Comparison of a Single Risk Component

In comparing single risk components for a number of treatment/location options, it is advantageous to use a particular risk component as a baseline and perform all comparisons relative to that baseline risk. In the context of the comparison attempted here, the risk component for waste "as received" serves as baseline risk. If the comparison of the baseline risk and the risk of the alternative is in the form of a ratio, a risk reduction factor may be obtained which incorporates a number of advantages (Section B.2.2 and B.2.3). Due to the fact that risk components can be generally written as a product of a number of factors, all those that are common to both risks and do not change with treatment, will usually cancel. Among these factors are often the most uncertain ones, such as the probability of the initiating event and the probability of the consequence such as the lung cancer risk coefficient.

Risk reduction factors are, therefore, much less uncertain than absolute risks and often have a simple algebraic structure that allows the use of a simple algebraic procedure to estimate the standard errors of the result based on the standard errors of the input parameters. This process is called error propagation (Brandt, 1976; Bevington, 1969; Seiler, 1987). Also, systematic errors in quantities in the remaining factors that appear both in numerator and denominator of the ratio tend to cancel, if not completely then at least in part. This can be seen by examining a ratio with an unknown error factor in both numerator and denominator: as long as it affects both in a linear manner, the factor cancels; if its effect on both is nonlinear, it will cancel at least in part.

This risk comparison has the nature of a retrofit, imposing differently treated wastes to the risk assessment in the FSEIS. Evaluating the systematic errors in that assessment would, therefore, require an effort beyond the scope of this study. Consequently, it will be assumed that systematic errors also cancel for the largest part, leaving a small residual that does not contribute significantly to the total standard error of the risk reduction factors. The errors shown are thus exclusively of a random nature and total errors will, therefore, tend to be somewhat too small.

#### 3.1.4 Aggregation of Risk Reduction Factors

In order to keep the number of attributes or risk components of the multi-attribute utility functions to a reasonably low number, it is often necessary to aggregate components that contribute to the same generic type of consequence. A typical example is the aggregation of risks arising from different chemicals in the same scenario, or the aggregation of various contributions to the occupational cancer risk due to transportation. As shown in more detail in Sections B.3.4 and G.1 of this Appendix, aggregation in the first case is best performed at the level of risks, that is, by combining risks and then forming risk reduction factors.

In the second case, aggregation is best performed at the level of risk reduction factors. This is especially true in the case where some of the component risks are obtained from substantially different formulae. Aggregation then requires the knowledge of the values of the component risks, so that a large risk reduction factor, applied to a very small risk, cannot dominate the aggregation. Weighted averaging of the components will avoid this problem. For the averaging process over widely spread risk reduction factors, a weighted or unweighted geometric average is usually preferable over a weighted or unweighted arithmetic average (see Sections B.3.4 and C.2.1 of this Appendix).

In this aggregation phase, the decision maker responsible for the comparison first exerts his influence. It is he who decides which components to aggregate into supercomponents. This selection influences the societal valuation process and should be performed in a way that takes risk perceptions into account.

### 3.2 SOME TOOLS OF MULTI-ATTRIBUTE UTILITY THEORY (MAUT)

It is important for the understanding of the risk comparisons proposed that what is done here is very different from multi-attribute utility theory. Only some of its tools are being used in a manner that is designed to make the utmost of the similarities between risk components and avoid most of the criticisms of the multi-attribute utility approach.

#### 3.2.1 Single Attribute Utility Functions

From the field of economics and economic decision theory, the concept of the *utility of a commodity* can be adapted for use in the comparison of risk components. A risk reduction factor is, according to its magnitude, assigned a utility or in other words, a usefulness or value. It should be noted that in epidemiology the inverse of the risk reduction factor is called the relative risk. According to its magnitude, it is consequently assigned a dis-utility or negative utility.

There is a relationship between the quantity of a commodity and its utility, known as the *Law of Diminishing Marginal Utility* (LDMU). It states that the slope of a utility function decreases as the commodity increases (see, for instance, Samuelson, 1973). In risk assessment, the LDMU expresses the fact that, for example, a unit increase in the relative risk is most detrimental when the risk is 1; it is less detrimental when it is 10; and even less so when it is 100. Similarly, a unit increase in the risk reduction factor is most beneficial when it is 1; somewhat less beneficial when it is 10; and so on. Graphically, this type of relationship is shown in Figure I.B-1a, in Attachment B, where, as an example, a logarithmic dependence is plotted as a function of the argument. In risk management, the LDMU expresses the fact that a unit increase in a occupational risk of one fatality, would almost certainly result in a change of health and safety procedures. A unit increase in a projected total risk of 1,000, on the other hand, would not result in any significant change of procedure. The LDMU is, therefore, an integral part of this method of risk comparison.

In a discussion in Attachment B.3.2, it is shown that the requirements of the LDMU as applied to risk comparison and the needs of error propagation result in defining a class of utility functions of which the logarithmic dependence is the simplest example (Figure I.B-1b). It is, therefore, chosen as the form of the single attribute utility function for all risk components. Pre-defining the form of the utility function in this manner is a departure from the usual practice of MAUT. It is justified by the fact that, apart from a valuation factor, all risk components are subject in the same manner to the influence of the LDMU and should thus have the same dependence.

#### 3.2.2 Multi-Attribute Utility Functions

The combined utility function for all risk components is chosen to be a linear combination of their utility functions weighted by societal value judgments. This procedure is the simplest form that will most likely satisfy the needs of an error propagation calculation. In this manner, the value of the modified utility function, called the utility index, and its standard error are obtained. Larger

utility indices are preferred over smaller ones unless the difference is insignificant. Negative utility indices indicate an increase in overall risk over the baseline case, positive indices signal a reduction in total risk.

The weight with which the single-attribute utility functions are multiplied in the linear combination are the societal value judgements for each risk component. In another departure from the usual form of MAUT, these weights do not give a valuation of, say, a life lost to cancer, but rather a reduction in the risk of lives lost to cancer. This results in a set of weights which are quite different from the valuations usually applied in MAUT.

A mathematical analysis in Section B.3.3 of this Appendix shows that this multi-attribute utility function has a unique interpretation. It is the basis from which two quantities can be derived: the risk reduction index and its inverse, the risk augmentation index. These quantities are the weighted geometric averages of all component risk reduction factors or component relative risks, respectively. The weights are the societal valuations of small risk reductions or increases. In this report, the risk reduction index and its inverse are the quantities of choice for the comparison of risks.

### **3.3 RANKING AND UNCERTAINTIES**

The ranking process described here is another fundamental difference to conventional multi-attribute utility theory. Here, standard errors are available and the differences between risk reduction indices are a measure of preference. Thus, ranking is not only an ordinal process but a comparison of differences and errors and yields information on the significance of these differences.

#### **3.3.1 Calculation of Standard Errors**

The propagation of the uncertainty expressed in the standard error of a parameter or a variable to the value of the function in which it appears can be evaluated using different methods. Some of these are discussed in Attachment C as far as they are needed in this study. Basically, the approach taken here allows the derivation of an analytical expression for the standard error of a risk reduction factor, the utility function, and, finally, for the risk reduction index.

For numerical procedures, numerical methods have to be used. The standard error for that particular factor in the risk equation can then be inserted into the analytical expression for the standard error of the risk. Thus, numerical procedures that evaluate the entire risk reduction factors should be avoided. For the most part, the errors are small enough to use the error propagation formula in a simple approximation for normally distributed quantities (Bevington, 1969; Brandt, 1976; Seiler, 1987b). When the relative errors get larger, standard errors given for lognormally distributed quantities can be used (see Sections C.1.1.3 and C.1.2.2 of this

Appendix). Otherwise, higher approximations for the analytical expressions may be needed (Seiler, 1987b).

In this manner, the standard errors of the risk reduction factors and the risk reduction indices can be calculated. During the process of aggregating the component risks into classes, such as public cancer risks due to waste transportation, error propagation will be taken into account also, in order to provide an unbroken chain for the influence of all pertinent uncertainties.

### 3.3.2 Indifference to Ranking

Ranking of utility indices with standard errors is a simple evaluation as long as the difference between two adjacent indices is large compared to either one of the standard errors. Conversely, if the difference between them is small compared to either standard error, the difference is insignificant. For differences comparable to the standard errors, the situation is more difficult. Here, the two criteria developed by Goodman (1986) can be applied (see Sections B.4.3 and G.4.1 of this Appendix). Both are based on the fact that most of the information on the distributions of the utility indices is available for the central part of the distribution, not the tails. Thus, the criteria concentrate on the area of the mean and one or two standard errors around that mean. Using Goodman's criteria, the utility indices are then arranged in classes of one or more indices that are insignificantly different with significant differences between the classes.

## 4.0 SCALING AND AGGREGATION OF RISK COMPONENTS

### 4.1 SCALING OF BASELINE RISKS

Most risk components discussed in the FSEIS and the FSAR are affected in some manner by the treatment of wastes at some location or other. In order to evaluate the corresponding properties, the full algebraic expression for each risk component is given. Each parameter is then evaluated as to its dependence on either the waste treatment and/or the location option. This separates the risk into a constant and a dependent part. This property of the risk equation allows the appropriate scaling of the risk to the level required by the 16 treatment/location options.

Based on the scaling properties of a risk component, the risk reduction factors and their standard errors can be calculated. Some of the parameters needed for that scaling are based on models for the processes involved in creating or modifying the risk components. These models are discussed in Attachment D.

#### 4.1.1 Risks Due to Radiation Exposures

The risks of exposure to external radiations have public and occupational components, leading to both cancer and genetic damage in the long term, and for high doses, to acute radiation sickness in the short-term. Incorporated radioisotopes lead to internal organ doses with more focused damages and carcinogenic processes. Other somatic and short-term radiation effects are not generally considered here.

##### 4.1.1.1 Radiation Risks in Routine Handling

Routine handling involves a number of scenarios for internal exposures, discussed in Section E.1, and external exposures, discussed in Section E.2. For internal exposures only the inhalation route is considered. Due to general health and safety procedures, the ingestion route yields much lower risks. The baseline risks are not known for all risk components, leading to difficulties with aggregation later on.

The values for the risk reduction factors show widely differing values, reflecting different scaling properties. Values for the risk reduction factors range from slightly above and below 1 in Tables E.1-1 and E.1-3, which evaluate risks due to surface contamination of the drums, to 10,000,000 in Table E.1-2, which evaluates risks due to waste leakage out of a perforated drum. This risk is subject to a dramatic risk reduction, albeit in a small risk. When these three risk reduction factors are aggregated in a supercomponent, it is important to weight them properly so as to avoid a bias due to that large value.

#### 4.1.1.2 Radiation Risks Due to Handling Accidents

Handling accidents can lead to inhalation exposure of work crews and, after passing through HEPA filters and environmental dispersion, to exposures of the public. These risks are discussed in detail in Section E.3. Sometimes the corresponding risk reduction factors are the same; mostly they are different. The risk reduction factors for accidents are uniformly high, due to the fact that these scenarios involve inhalation exposures and treatment drastically curtails airborne particle production. The risk reduction factors range from one hundred thousand to one hundred million in Tables E.3-1, E.3-2, E.3-3 and E.3-4 and to ten and a hundred billion in Table E.3-5. The baseline risks range from  $10^{-4}$  and  $10^{-5}$  in most of these tables to an order of a hundred billion for a C2 accident. Proper weighting here will be essential because the largest risk reduction factors (ten and a hundred billion) are associated with an excessively small risk.

#### 4.1.1.3 Radiation Risks in Routine Transportation

The definition of "risks from routine transportation of the wastes" is that these risks arise exclusively from exposures to penetrating radiation of the crew and of the public using the same road and living or working along that road. The risk components for waste transport are those given and discussed in the code RADTRAN III (Madsen et al., 1986). These components are discussed in more detail in Section E.6.3. The data for the calculations have also been taken from the RADTRAN code and the FSEIS. The risk reduction factors for the public along the transport route given in Table E.6-3 are approximately 1; those for public risks at stops (Table E.6-4) have ranges that do not vary significantly from 1, nor do those for the public traveling in the same and the opposite direction (Tables E.6-5 and E.6-6). This is mostly due to the fact that, regardless of treatment, the same amount of radioactivity is transported. For the same reason, occupational transportation risks involving the transport crew, the handlers, and the warehouse personnel have reduction factors that do not deviate much from unity (Tables E.6-7 to E.6-9).

#### 4.1.1.4 Radiation Risks in Transportation Accidents

Serious transportation accidents are not expected to occur during the transportation period, but they carry the potential for population exposures. Again, the formulae and data of the RADTRAN III code were employed to evaluate the risk reduction factors for each scenario. These are discussed in detail in Section E.6.4. The risks due to direct exposure during non-dispersal accidents (Table E.6-4) again do not reduce significantly, that is, do not have risk reduction factors that deviate significantly from one. Those due to dispersal accidents, all assembled in Table E.6-10, vary from 1 to about 15. This denotes the suppression of risks due to waste dispersal in the atmosphere for the fraction of the transport which is done as treated waste.

#### 4.1.1.5 Radiation Risks in Post-Closure Human Intrusion

Radiation risks in three human intrusion scenarios are evaluated using the models in this report rather than those of the FSEIS. There is a direct exposure of the drilling crew to radioactive cuttings. Later, there is the potential for an inhalation exposure from these dried-out cuttings and an ingestion exposure from radioactivity reaching the surface via the Culebra aquifer. This risk component is discussed in Section E.7, and the reduction factors are given in Table E.7-1. For the E1 and E2 scenarios, the factors for the drilling crew cluster closely around a value of five, given essentially by the activity mobilization for the baseline case as compared to any treatment. For the E1E2 scenario the reduction factors for the risk to the drill crew ranges from 0.1 to about 6 but are applied to a very small risk (Table E.7-2). The reduction factors for the public risk by inhalation are the same as those for the drill crew for all scenarios. For ingestion, risk reduction factors for the E1 scenario lie between ten and one hundred thousand for an exceedingly small baseline risk of  $2 \cdot 10^{-13}$  (Table E.7-3); for the E2 scenario they range from 1 to 65 but for a baseline risk of  $6 \cdot 10^{-11}$ ; and for the E1E2 scenario, the factors range from about a million to ten billion, applied to a baseline risk of  $7.8 \cdot 10^{-6}$ .

#### 4.1.2 Risks Due to Chemical Toxicant Exposures

Exposures to volatile organic compounds lead to both public and occupational risks. The health effects can be carcinogenic or noncarcinogenic, depending on the chemical compound.

##### 4.1.2.1 Chemical Risks in Routine Handling

Volatile organic compounds in the waste are vented through the carbon filters of the drums, leading to low level chronic exposures, both public and occupational. Potentially the largest exposures occur underground next to a nearly filled room with 6,000 drums. This may lead to exposures of personnel below ground, above ground near the exhaust, and of the public outside the WIPP area. Here both cancer and noncarcinogenic effects are considered. Detailed evaluations are given in Section E.4. The cancer risk reduction factors for above ground exposures are independent of the chemical and range from values near unity to about 50,000 (Table E.4-2). These factors, however, are applied to exceedingly small cancer risks near  $10^{-14}$ . Risk reduction factors for below ground emissions have about the same range, 1 to 100,000, but some of the risks are at least in the  $10^{-7}$  range (Table E.4-3).

For noncancer health effects, risk reduction factors are again in the range of 1 to 50,000 (Table E.4-6) but the risks assigned for workers above ground are excessively low, lying in the range of  $10^{-12}$ ; for workers below ground, they reach up to  $10^{-4}$  (Table E.4-8).

#### **4.1.2.2 Chemical Risks Due to Handling Accidents**

In chemical accident exposures only non-carcinogenic effects are considered in the FSEIS, the short-term exposures to accidental releases being too small to result in cancer risks of any significance. The accident scenarios are discussed in detail in Section E.5. The risk reduction factors for a C2 or C3 accident range from 2 to 82,000 and are applied to very small baseline risks near  $10^{-10}$  (Table E.5-2); those for C4, C5, and C6 accidents range from about 20 to about  $1.67 \cdot 10^6$ , still applied to risks of about  $10^{-10}$  (Table E.5-4).

#### **4.1.2.3 Chemical Risks in Post-Closure Human Intrusion**

Only one chemical, lead, is evaluated in the post-closure human intrusion scenarios. These are discussed in detail in Section E.7.4. These morbidity baseline risks are exceedingly low and will not be pursued further.

#### **4.1.3 Conventional Transportation Accidents**

Public fatalities and injuries as direct effects of the impact in accidents involving the TRUPACT-II transports have the same risk reduction factors listed in Table E.6-2. These values range from roughly 0.5 to 4, but they are applied to the largest annual risks in the FSEIS, about 0.2 fatalities and about 3 injuries.

### **4.2 SCALING OF TREATMENT RISK**

In this evaluation, general occupational risks, external and internal radiation exposures from routine operations and from routine maintenance are examined. For chemical toxicants, only routine operations are considered as in maintenance only traces of VOCs should be encountered. Due to the limited scope of this study, no accidental exposures of any kind are included.

#### **4.2.1 General Occupational Risks**

Working in the WHB or the TF puts the crew at risk for occupational accidents resulting in fatalities and injuries. In particular, forklift accidents are considered because they tend to have more severe consequences. These issues are discussed in detail in Section F.2. The risk reduction factors for general accidents and injuries but also for forklift fatalities and injuries lie between 0.276 and 0.076, that is between a factor of 4 and 14 below 1, indicating an increase in risk by these factors (Tables F.2-1 and F.2-2). As they are applied to sizeable baseline risks, they will have a strong influence on the risk comparison.

#### 4.2.2 Radiation Risks in Routine Operation and Maintenance

Risks from exposure to penetrating radiations during treatment of wastes in different devices are discussed in detail in Section F.3.1 and F.3.2. The risk reduction factors for routine external exposure range from 0.1 to 0.5, that is, 2 to 10 times lower than 1; for maintenance the factors are 200 to 300 lower (Table F.3-2). By these factors, therefore, the risks are increased over the unknown baseline risk of external exposure during assay and certification. For routine internal exposures during operations, the risk reduction factors are 1/200 to 1/3000 as shown in Tables F.3-3 and F.3-4. During routine maintenance, the risk increases are factors 10,000 to 100,000 (Tables F.3-5 and F.3-6).

#### 4.2.3 Risks in Chemical Toxicant Exposures

These risks are due to VOCs, mostly released during shredding or sorting of the wastes and penetrating through the airlocks. They are discussed in Section F.4 for both cancer and noncarcinogenic effects. The risk reduction factors show a strong increase in risk due to the mobilization of the VOCs enclosed in drums, liners, and wrappings. The risk reduction factors for the much smaller public risks are the same. For routine operations, occupational and public risks are subject to risk reduction factors of roughly 1/100,000, indicating a strong increase. The baseline risks during assay and certification are not available. This holds for both cancer and non-cancer health effects (Tables F.4-1 and F.4-2).

### 4.3 AGGREGATION OF RISK COMPONENTS

#### 4.3.1 Problems of Aggregation

In this evaluation, 124 component risks are analyzed and their risk reduction factors derived. This includes all subcomponents. This number is too large to handle in a comparison and must, therefore, be lowered by aggregation. Many of these risks lead to the same consequence, and can thus be aggregated into supercomponents. Even so, it is expedient to discard some of the small risks because a larger risk of the same exposure is already being considered. Thus, genetic damage is usually smaller than the cancer risk from the same radiation exposure (National Research Council, 1980, 1988, 1990). Also, almost no information on genetic baseline risks are available in the FSEIS. These subcomponents are, therefore, not selected for aggregation. Similarly, health effects of lead poisoning for post-closure risks and the non-cancer risks due to exposure to chemical toxicant are not involved in the process either.

In this context, it is important to note that once a cure for cancer is found, cancer reverts from a fatality risk to a morbidity risk. Other somatic effects, such as lifespan shortening, and genetic effects will then become of main concern. From this point of view, genetic damages should be selected for aggregation. The main reason for not selecting these components is the fact that

the genetically relevant doses and the cumulative effective dose equivalents (CEDEs) are mostly non-linearly related and that the baseline risks are mostly unavailable.

As discussed before, the first task of the decision maker is to decide on the extent and the grouping of the aggregation of risk components. This must be done in a manner that groups components with the same societal valuations; not too detailed so as to make relative valuations difficult, and not too coarsely so as to erase significant differences.

In the case at hand, eight supercomponents are formed from the remaining 73 subcomponents:

1. Transportation fatalities
2. Transportation injuries
3. Occupational fatalities
4. Occupational injuries
5. Occupational cancers
6. Public cancers
7. Late occupational cancers
8. Late public cancers.

Six of these supercomponents are evaluated in the FSEIS. In addition, numbers 3 and 4, the occupational accident fatalities and injuries, are included here. In a comparison of treatment risks involving more or less personnel they are important and have thus been included.

In these aggregations, problems arise when no values for the baseline risk components are given in the FSEIS or the FSAR. In this case, the aggregation has to be done by unweighted averaging. A large risk reduction factor will then tend to dominate the average even if it is applied to a minute risk. This dominance can be reduced somewhat by using the geometrical average. Even so, unweighted averaging will introduce a residual bias. In the absence of data on the baseline risks, however, unweighted averaging must be used until a numerical risk value is available for the aggregate. From then on, appropriately weighted averaging will lead to the supercomponents without further bias.

After the aggregation into supercomponents, the total risks have been in effect sorted in terms of consequences, being at the same time summed over all scenarios and exposed individuals. This is the situation to which Equation (B.2.6) in Attachment B refers, where the total risk has been aggregated to form a vector of consequence components. From this point in the calculation onward, the aggregated risk reduction factors are, therefore, more aptly termed consequence reduction factors. Their numerical values are listed in Table I.4-1 as functions of treatment and location options.

TABLE I.4-1

## COMPILATION OF CONSEQUENCE REDUCTION FACTORS \*

CONSEQUENCE REDUCTION FACTORS	TREATMENT OPTION - 1 LOCATION				TREATMENT OPTION - 2 LOCATION			
	1	2	3	4	1	2	3	4
$\Gamma_{1x1}$	1.00 ± 0.00	0.760 ± 0.048	0.714 ± 0.057	0.715 ± 0.058	1.00 ± 0.00	0.719 ± 0.042	0.666 ± 0.048	0.666 ± 0.049
$\Gamma_{2x1}$	1.00 ± 0.00	0.760 ± 0.048	0.714 ± 0.057	0.715 ± 0.058	1.00 ± 0.00	0.719 ± 0.042	0.666 ± 0.048	0.666 ± 0.049
$\Gamma_{3x1}$	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015
$\Gamma_{4x1}$	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.276 ± 0.016	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015	0.260 ± 0.015
$\Gamma_{5x1}$	0.853 ± 0.031	0.814 ± 0.030	0.846 ± 0.031	0.852 ± 0.032	0.841 ± 0.030	0.801 ± 0.029	0.833 ± 0.030	0.840 ± 0.031
$\Gamma_{6x1}$	1.13 ± 0.00	2.64 ± 0.01	7.44 ± 0.02	9.47 ± 0.02	1.13 ± 0.00	2.65 ± 0.01	7.46 ± 0.02	9.49 ± 0.02
$\Gamma_{7x1}$	4.96 ± 0.48	4.96 ± 0.48	4.96 ± 0.48	4.96 ± 0.48	5.05 ± 0.49	5.05 ± 0.49	5.05 ± 0.49	5.05 ± 0.49
$\Gamma_{8x1}$	106 (2.3)	106 (2.3)	106 (2.3)	106 (2.3)	115 (2.2)	115 (2.2)	115 (2.2)	115 (2.2)
CONSEQUENCE RISK REDUCTION FACTORS	TREATMENT OPTION - 3 LOCATION				TREATMENT OPTION - 4 LOCATION			
	1	2	3	4	1	2	3	4
$\Gamma_{1x1}$	1.00 ± 0.00	1.10 ± 0.17	1.17 ± 0.26	1.18 ± 0.27	1.00 ± 0.00	2.00 ± 0.06	3.27 ± 0.21	3.51 ± 0.25
$\Gamma_{2x1}$	1.00 ± 0.00	1.10 ± 0.17	1.17 ± 0.26	1.18 ± 0.27	1.00 ± 0.00	2.00 ± 0.06	3.27 ± 0.21	3.51 ± 0.25
$\Gamma_{3x1}$	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.078 ± 0.0042	0.078 ± 0.0042	0.078 ± 0.0042	0.078 ± 0.0042
$\Gamma_{4x1}$	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.17 ± 0.01	0.078 ± 0.0042	0.078 ± 0.0042	0.078 ± 0.0042	0.078 ± 0.0042
$\Gamma_{5x1}$	0.704 ± 0.023	0.677 ± 0.025	0.699 ± 0.027	0.704 ± 0.028	0.460 ± 0.019	0.420 ± 0.017	0.435 ± 0.018	0.452 ± 0.019
$\Gamma_{6x1}$	1.13 ± 0.00	2.65 ± 0.01	7.46 ± 0.02	9.49 ± 0.02	1.13 ± 0.00	2.65 ± 0.01	7.47 ± 0.02	9.50 ± 0.02
$\Gamma_{7x1}$	6.86 ± 1.36	6.86 ± 1.36	6.86 ± 1.36	6.86 ± 1.36	9.39 ± 0.99	9.39 ± 0.99	9.39 ± 0.99	9.39 ± 0.99
$\Gamma_{8x1}$	221 (2.4)	221 (2.4)	221 (2.4)	221 (2.4)	2030 (2.6)	2030 (2.6)	2030 (2.6)	2030 (2.6)

\* Errors given in braces are geometric standard deviations of lognormal distributions.

#### **4.3.2 Aggregation Into Supercomponents**

##### **4.3.2.1 Supercomponents 1 and 2: Fatalities and Injuries in Transportation Accidents**

Due to volume changes resulting from treatment and thus transportation increases for Level II treatments, and transportation decreases for Level III treatments, the aggregated risk reduction factors for Supercomponent 1 range from between 0.5 and 1 for Level II treatments to values above 1 to about 4 for Level III treatments. This signals an increase in risk for Level II and a decrease for Level III. Although the departures of the factors from one are not large, they impact the largest risks in the study (0.2 fatalities and 3 injuries per year of operation) and the variations are thus of great importance. The supercomponents show little change with the location for Level II treatment, a small change in Treatment Option 3, but a substantial protective effect for Treatment Option 4 if done in distributed facilities near the originators. The aggregated risk reduction factors are listed in Table I.4-1.

##### **4.3.2.2 Supercomponents 3 and 4: Occupational Fatalities and Injuries**

The general occupational fatalities and injuries in working in the Treatment Facility and in the WHB show increases between factors of 4 to 13. These are applied to a baseline risk of  $2 \cdot 10^{-3}$  fatalities and 0.5 injuries per year of operation. Due to the assumption of the model, there is no location dependence, but a steady decrease in the risk reduction factors and, therefore, a strong increase in risk for more complex treatments (Table I.4-1).

##### **4.3.2.3 Supercomponent 5: Occupational Cancer**

This supercomponent aggregates the risk reduction factors of 22 components. Due to the lack of baseline data, they have to be aggregated without weights into four intermediate components, thereby introducing a bias. Further aggregation of these four intermediate components into Supercomponent 5 introduces no further bias because of appropriate weighting. The values show risk reduction factors of about 7 for Level II treatments and about 11 for Level III treatments. There is not much variation with the location parameter, indicating the expected insensitivity of this supercomponent to the location of the TF. With increased level of treatment, however, there is a distinct gain in occupational safety.

##### **4.3.2.4 Supercomponent 6: Public Cancers**

The supercomponent for public cancers is also aggregated from 22 risk reduction factors. Again, they have to be aggregated to four intermediate components for which baseline risk values are available, incurring a bias in the unweighted portion of the averaging process. The fully aggregated risk reduction factors range from 1 to 12. Here, there is a clear trend in each treatment alternative for an improvement in public safety if the TFs are located near the originators, and a trend toward an increase in these gains with more elaborate waste treatment.

#### 4.3.2.5 Supercomponent 7: Post-Closure Occupational Cancers

These are the unweighted aggregates of the risks to the drilling crews in the three human intrusion scenarios. The risk reduction factors range from about 5 to about 10. They are, however, applied to an exceedingly small risk of  $3 \cdot 10^{-8}$ .

#### 4.3.2.6 Supercomponent 8: Post-Closure Public Cancers

This component aggregates the public cancer risks due to inhalation and ingestion of radioactivity transported over time to the surface. Substantial risk reductions are achieved by treatment, ranging from about 100 to 2,000. The baseline risk, however, is again small with an expected cancer incidence of  $7 \cdot 10^{-5}$ .

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## 5.0 COMPARISON OF THE TOTAL RISKS

### 5.1 SOCIETAL WEIGHTS

The weighting needed to give each component its proper valuation is not the same as the weighting used in Multi-Attribute Utility Theory. This difference arises from the fact that the argument is not a risk but a risk reduction factor, and also from the use of the logarithm of the risk reduction factor as the utility of risk reduction. The usual valuations, such as setting the widespread practice of an occupational fatality or injury equal to one-half of a public fatality or injury, have to be re-examined in the light of a risk reduction or augmentation. As discussed in Attachment B, Section B.3.5, the valuation of a particular risk reduction depends on the magnitude of the baseline risk component. In this study, most of these components are small so that the valuations are relatively weak functions of the risk values.

Within the scope of this study, and taking into account that the selection of alternatives for waste treatment is essentially a technical decision, with societal input, the decision maker charged with making the risk comparison sought advice from a group of knowledgeable persons with diverse interests and views. They made their valuations known to him as well as the rationales leading to those weights. Based on this advice, the decision maker selected his own rationales and arrived at his own weights. He treated them as decision parameters without standard errors or as stochastic quantities.

In this context, it should be borne in mind that risk assessments and risk comparisons are usually done with an ulterior motive such as a selection process in mind. Thus the decision maker for the risk comparison works for another decision maker, charged with making that selection. The environment of the criteria other than risk that enter into the selection process has an influence on the weighting in the risk comparison. This dependence arises from the cross-relationships such as the one between cost, feasibility, and some components of the consequence vector. The decision maker for the risk comparison may thus not only have to balance the advice received and his own rationales, but also the needs of the decision at the higher level.

As an example for a weighting, a risk reduction or augmentation by a factor of two for the annual number of traffic fatalities and injuries depends on the absolute baseline values of 0.2 fatalities and 3 injuries when compared to the valuation of a risk reduction or augmentation by a factor of two for the occupational risk of fatalities (0.002 per year) and injuries (0.5 per year). While the need for a reduction of the traffic risk may seem paramount, it must be seen in the context of the annual deaths and injuries due to traffic accidents. In New Mexico alone, 538 traffic fatalities and 324,962 traffic injuries occurred in 1989 (New Mexico Highway and Transportation Department, 1990). The incremental risks due to WIPP transports is 0.04 percent for fatalities and 0.01

percent for injuries. On the basis of these relationships and the relative valuations of fatalities and injuries, some of which will be severe, absolute weights of 10, 7, 5 and 4, for example, can be established by a particular expert for transportation fatalities, transportation injuries, general occupational fatalities, and occupational injuries, respectively. By considering similar relationships between all the supercomponents, a complete set of weights can be established (see Section G.2.2.1 of this Appendix).

The normalized societal weights selected by the decision maker as decision parameters are given in Table I.5-1, together with numerical values for the annual baseline risk components. These values are then used to arrive at the risk reduction or risk augmentation indices to be used in decision making. Here only the interpretation of the indices will be reported. The use made of this information is contained in the main body of this report.

## 5.2 COMPARISON OF THE ALTERNATIVES

### 5.2.1 Consequence Reduction and Augmentation Indices

The values of the consequence augmentation index  $\Psi_{\alpha}$  resulting from the weighting of the previous section are given in Table I.5-2, grouped first by treatment options (first index) and then by location options (second index). The augmentation index is chosen for presentation here because there is a net increase in that index for 14 of the 16 treatment/location options, and 2 of the 14 (Options 33 and 34) are compatible with 1, which means that the overall consequence is about the same as that for the baseline case. Only two options (43 and 44) show a decrease in the index, that is, values lower than one.

An application of Goodmann's criteria of indifference (see Section G.3.1.2 of this Appendix) shows that only 12 of the 120 possible combinations of indices lead to a confirmed or possible indifference between indices. A better idea of the groupings within options can be obtained by a visual inspection of the probability distributions of the consequence augmentation indices (Figure I.5-1). These distributions give the probability of finding a given index at a particular value. Here, instead of lognormal distributions, normal distributions are used (for narrow distributions the differences are small). Thus for Level III treatments there are clear trends with regard to location. Options 31 and 41, with treatment exclusively at the WIPP, have the highest increases in the index for Treatment Options 3 and 4, respectively. For Treatment Option 3, locations near the waste originators lead to no substantial change in the indices, whereas for Treatment Option 4, a location of the facilities near the originators leads to the only decrease in overall consequence indices. Level II Treatment Options 1 and 2, with eight distributions, have indices that lie very closely together, particularly when it is considered that errors are likely to be low estimates (see Section 3.1.3). They thus lead, almost independent of location, to increases in consequence indices between 1.3 and 1.6.

**TABLE I.5-1**  
**SOCIETAL VALUATIONS, NORMALIZED WEIGHTS**

<b>RISK SUPERCOMPONENT</b>	<b>ANNUAL BASELINE RISK</b>	<b>NORMALIZED WEIGHT</b>
1 Transportation fatalities	0.2	0.33
2 Transportation injuries	3	0.23
3 Occupational fatalities	0.002	0.17
4 Occupational injuries	0.5	0.13
5 Occupational cancers	0.005	0.033
6 Public cancer	0.02	0.10
7 Late occupational cancers	$3 \cdot 10^{-6}$	0.003
8 Late public cancers	$7 \cdot 10^{-5}$	0.007

TABLE I.5-2

## RISK AUGMENTATION INDICES FOR 16 TREATMENT/LOCATION OPTIONS

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
$\Psi_{11}$	1.40 $\pm$ 0.02	
$\Psi_{12}$	1.51 $\pm$ 0.04	
$\Psi_{13}$	1.41 $\pm$ 0.05	
$\Psi_{14}$	1.37 $\pm$ 0.05	
$\Psi_{21}$	1.43 $\pm$ 0.02	
$\Psi_{22}$	1.58 $\pm$ 0.04	
$\Psi_{23}$	1.49 $\pm$ 0.05	
$\Psi_{24}$	1.45 $\pm$ 0.05	
$\Psi_{31}$	1.62 $\pm$ 0.02	
$\Psi_{32}$	1.42 $\pm$ 0.09	
$\Psi_{33}$	1.23 $\pm$ 0.11	
$\Psi_{34}$	1.20 $\pm$ 0.11	
$\Psi_{41}$	2.06 $\pm$ 0.03	
$\Psi_{42}$	1.28 $\pm$ 0.02	
$\Psi_{43}$	0.88 $\pm$ 0.03	Decrease by a factor of 1.14 $\pm$ 0.03
$\Psi_{44}$	0.82 $\pm$ 0.03	Decrease by a factor of 1.21 $\pm$ 0.04

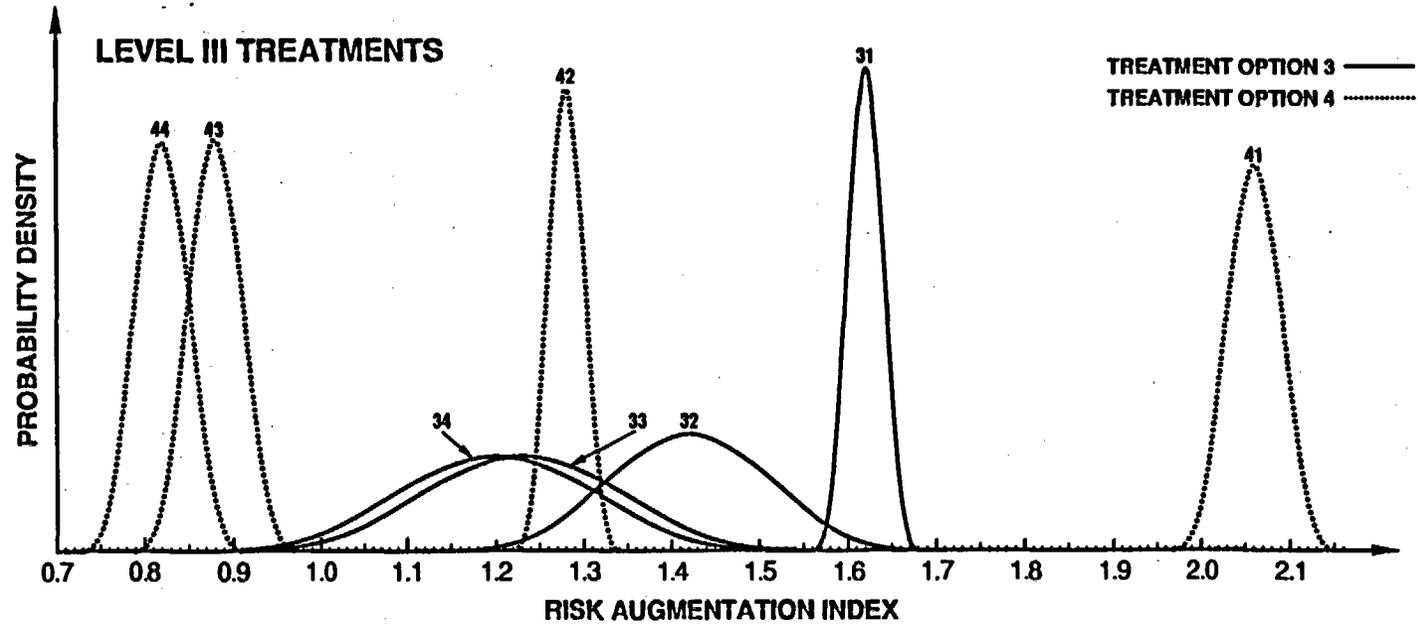
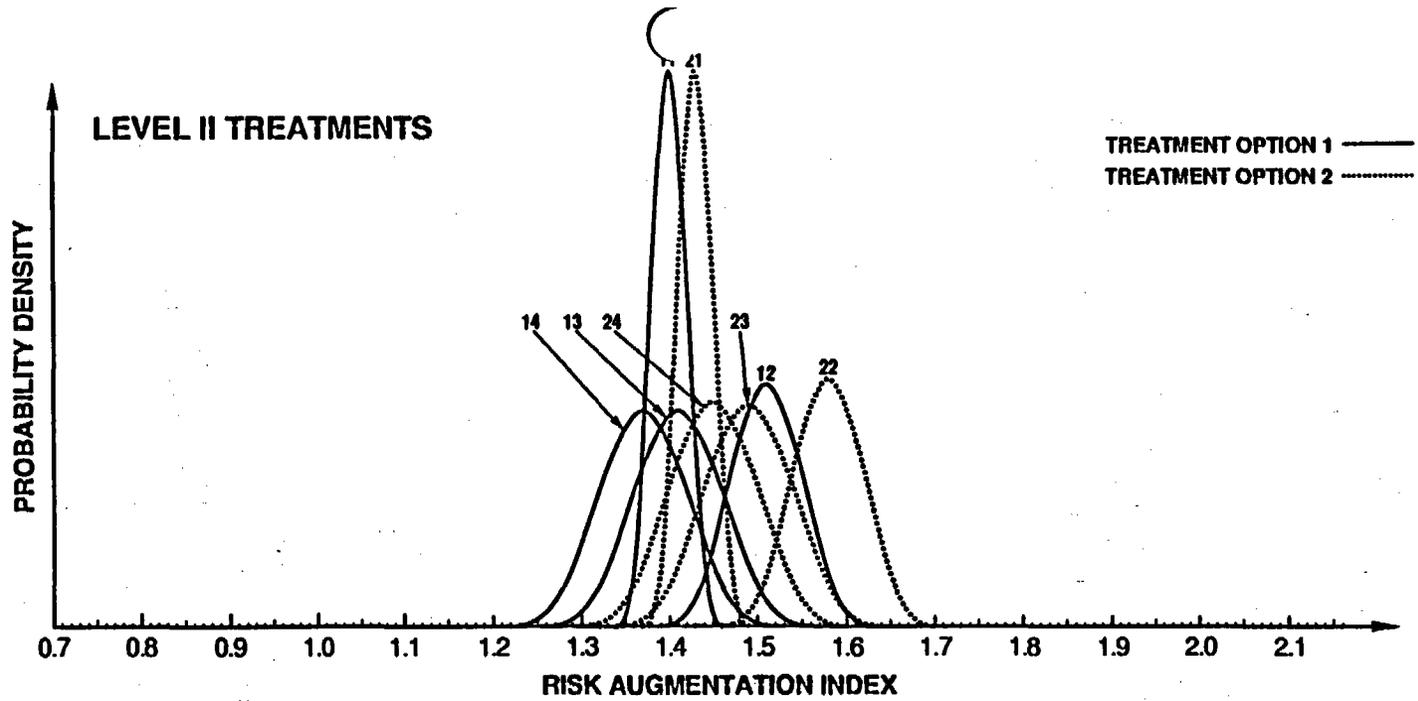


Figure I.5-1 Risk Augmentation Indices for the 16 Treatment/Location Options

The same information is once again displayed in Figure I.ES-1 in the Executive Summary, which lists facility locations in rows and treatment options in columns. There is very little variation between the values of the risk augmentation index of the Level II treatments. For Treatment Option 3, a Level III treatment, there is a trend toward the periphery (waste originators) leading down to an insignificant increase in the index. As in Figure I.5-1, there is a dramatic location dependence for Treatment Option 4, the most extensive treatment of all, leading from the largest increase in the consequence augmentation index (2.1) to the largest decrease in the index for overall risk (0.8). As an aid to the eye, the very light pattern selected in that figure for Group 1 shows the largest increase in consequence augmentation; Group 2 with a denser pattern is clustered between 1.2 and 1.5; Group 3 is almost neutral, that is, almost compatible with 1, whereas Group 4 with the densest pattern is composed of the two options that result in a consequence reduction.

### 5.2.2 Interpretation of the Results

An analysis of the different contributions to the consequence augmentation or reduction indices shows that the transportation risks and the occupational accident risks contribute substantially to the value of the indices. The post-closure risks due to human intrusion, on the other hand, contribute at most a few percent to the value of the indices, that is, about as much as the average standard error. For the short-term components, transportation volume increases for Level II treatment options and decreases for Level III treatments. Manpower requirements and thus general occupational accidents and injuries increase substantially from Treatment Option 1 to Treatment Option 4.

For Location Option 1, treatment at the WIPP, waste transport contributes the same risks as in the baseline case. The treatment, however, causes additional risks which result in the highest indices for the two Level III treatment options but nearly the lowest for the two Level II treatment options. The trend for more decentralized facilities for Level II treatments is undefined, for Level III treatments, however, it is clearly toward lower values. This shows the opposing influences of the transportation risks and the treatment risks.

For Level II treatment options, the modest increases in both transportation and occupational accident consequences result in an almost uniform increase in consequences with an augmentation index of about 1.5. For Level III treatment options the opposing influence of the changes in risk due to transportation and manpower are responsible for the moderate spread due to location in Treatment Option 3, and the wide spread with locations for Treatment Option 4.

An analysis of the eight factors that form the consequence reduction indices (see Section G.4) shows that the traffic accidents are responsible for most of the location-dependence in the treatment/location matrix, whereas the occupational accidents cause most of the treatment dependence. Radiological risks form only a small part of the total risk, the largest contribution being the public cancer risk in transportation accidents. This clearly reflects societal priorities

according to which radiological risks are most coherently and most successfully pushed down to low levels, whereas occupational accidents are less vigorously suppressed, and traffic accidents are attacked with only little effort. The same analysis shows post-closure cancer risks contributing a few tenths of a percent for occupational risks, and a few percent for public risks; altogether an almost negligible influence.

### 5.2.3 Influence of Biases

Additional, more detailed evaluations of the numbers generated for the indices meet with several difficulties. One arises from the biases due to the unweighted aggregation of many risk reduction factors. Another arises from the biases introduced by some of the model assumptions that do not give credit to treatment where credit is due, or do not assign an additional risk component where one should be assigned. The last difficulty is the weighting chosen here with values that could easily be chosen differently.

The unavoidable use of unweighted aggregation introduces biases of unknown amounts and signs. It is believed that, by the choice of supercomponents and the use of the geometrical averages, their influence is kept as small as possible. The model assumptions made for the entire risk comparison and for some parts of it also add biases of indeterminate signs and unknown magnitude. Again, they are believed to be small, but some of them could be significant.

Quite generally, these biases are due to the fact that this risk comparison is a retrofit to the FSEIS; that is, it did not grow organically out of it. Thus a lot of detail was lost, information that would be necessary for appropriate aggregation. In a different application of this method for risk comparison, this bias would not arise.

There is, however, another source of bias, at the same time more prevalent and more subtle. It arises from the widespread use of bounding calculations, worst-case models, and upper limits. Any risk values derived on this basis clearly overstates the risk, resulting in a bias. For risk comparisons it is, therefore, imperative to have risk values derived by the use of best-science models as well as their standard errors. The use of biased models and biasing assumptions should be minimized.

An unavoidable third type of bias arises from the value system of the decision maker and those of his set of advisors. The influence of either a different decision maker or a different set of advisors will result in different societal weights. The set of valuation questions have a very narrow scope, however, so that the valuations of the risk reduction factors for a given baseline risk do not vary strongly. Even that bias is not seen to be critical.

The first two biases are expected to result in perturbations of the risk augmentation indices, mostly in the nature of positive or negative shifts. It is not believed that their elimination would lead to major differences. The third bias, however, can potentially lead to more pronounced

shifts. The valuations of a different decision maker with a different set of advisors might well loosen the close association of all Level II treatment options and might even establish a small location trend. The main facts that arise from this analysis, however, are expected to remain. In sum, then, it is not thought that these effects will lead to major changes in trends, although noticeable shifts within these trends are probable.

#### **5.2.4 Conclusions of the Risk Comparison**

The risk comparison in this study results in some clear groupings and trends among the risk augmentation indices for various treatment and location options:

- The baseline risks are very small, so that even clear-cut increases in consequences still result in very small risks for all treatment and location options.
- Level II treatment options show little or no discernible trends for different locations. However they uniformly show an increase for the consequences, that is a consequence augmentation index near 1.4. In the context of interpreting these indices, it is of importance to realize that consequence reduction and augmentation indices are not linearly related to the actual set of baseline risks. Thus an index of 1.4 does not mean a 40 percent increase in the baseline risks. However, it does signify an increase in the total consequences. This nonlinearity also means that no absolute treatment risks can be inferred from these indices.
- Level III treatment options show a distinct trend in location dependence with the risk decreasing as the TFs are located closer to the waste producers. For Treatment Option 3, this results at best in total risks about equal to that of the baseline case. For Treatment Option 4, however, an actual increase to a risk augmentation index of 2.1 and decreases down to 0.8 can be realized for the two most decentralized location options, respectively.
- These increases and decreases of the societally weighted risk augmentation indices are almost independent of the long-term risks. This is due to the low valuation of the long-term risk components and their independence from the location options. It is, therefore, the balance between the short-term risk components that drives this risk comparison.

In these evaluations the standard errors of the consequence reduction or augmentation indices play an indispensable role. Even though the circumstances discussed in Section 3.1.3 lead to underestimates of the standard errors, the values quoted or somewhat larger ones would result in the conclusions given above. This is quite evident from a visual inspection of Figure I.5-1, where even a doubling of the widths would not change the groupings of the Level II treatments or the moderate to strong dispersion of the Level III treatments. This is probably the outstanding characteristic of the method of risk comparison used in this evaluation.

## ATTACHMENT A

**TABLE A.1**  
**SUMMARY OF RISK COMPONENTS**

Risk Component Number:	1
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N1 Scenario
Risk Scenario:	Surface contamination mobilized and suspended in air
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$p_{1o}$ and $p_{1p}$
Annual Baseline Risk Symbol(s):	$R_{1o}$ and $R_{1p}$
Appendix I Location:	Section E.1.2; Table E.1-1
Risk Component Number:	2
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N2 Scenario
Risk Scenario:	Perforated drum being handled
Risks Addressed:	Occupational and public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$p_{2o}$ and $p_{2p}$
Annual Baseline Risk Symbol(s):	$R_{2o}$ and $R_{2p}$
Appendix I Location:	Section E.1.3; Table E.1-2
Risk Component Number:	3
Risk Component Name:	Cancer Risk from Routine Internal Exposures to Ionizing Radiation in an N3 Scenario
Risk Scenario:	Underground, drum contamination mobilized and suspended in air
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$p_{3o}$ and $p_{3p}$
Annual Baseline Risk Symbol(s):	$R_{3o}$ and $R_{3p}$
Appendix I Location:	Section E.1.4; Table E.1-3
Risk Component Number:	4
Risk Component Name:	Cancer Risk from Routine External Exposures to Ionizing Radiation in an N4 Scenario
Risk Scenario:	Handling activities in the WHB and TF
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$p_{4o}$
Annual Baseline Risk Symbol(s):	$R_{4o}$
Appendix I Location:	Section E.2.2; Table E.2-1

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>5</b>
<b>Risk Component Name:</b>	<b>Cancer Risk from Routine External Exposures to Ionizing Radiation in an N5 Scenario</b>
<b>Risk Scenario:</b>	<b>Handling activities in the WHB and TF; geometries differ from Component 4 scenario</b>
<b>Risks Addressed:</b>	<b>Occupational cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol:</b>	$\rho_{5o}$
<b>Annual Baseline Risk Symbol:</b>	$R_{5o}$
<b>Appendix I Location:</b>	<b>Section E.2.3</b>
<b>Risk Component Number:</b>	<b>6</b>
<b>Risk Component Name:</b>	<b>Cancer Risk in WHB and TF Due to Accident Scenario C2</b>
<b>Risk Scenario:</b>	<b>Above ground; drum falls off forklift in WHB or TF, lid separates and liner ruptures</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	$\rho_{6o}$ and $\rho_{6p}$
<b>Annual Baseline Risk Symbol(s):</b>	$R_{6o}$ and $R_{6p}$
<b>Appendix I Location:</b>	<b>Section E.3.2.1; Table E.3-1</b>
<b>Risk Component Number:</b>	<b>7</b>
<b>Risk Component Name:</b>	<b>Cancer Risk in WHB or TF Due to Accident Scenario C3</b>
<b>Risk Scenario:</b>	<b>Above ground; two drums pierced, one loses lid and integrity of its liners</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	$\rho_{7o}$ and $\rho_{7p}$
<b>Annual Baseline Risk Symbol(s):</b>	$R_{7o}$ and $R_{7p}$
<b>Appendix I Location:</b>	<b>Section E.3.2.2; Table E.3-2</b>
<b>Risk Component Number:</b>	<b>8</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Underground Due to Accident Scenario C4</b>
<b>Risk Scenario:</b>	<b>Drum knocked off a pallet in the Underground Storage Area and loses integrity</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	$\rho_{8o}$ and $\rho_{8p}$
<b>Annual Baseline Risk Symbol(s):</b>	$R_{8o}$ and $R_{8p}$
<b>Appendix I Location:</b>	<b>Section E.3.3.1 and Table E.3-3</b>

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>9</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Underground Due to Accident Scenario C5</b>
<b>Risk Scenario:</b>	<b>Drum knocked off a forklift</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol:</b>	<b><math>p_{9o}</math> and <math>p_{9p}</math></b>
<b>Annual Baseline Risk Symbol:</b>	<b><math>R_{9o}</math> and <math>R_{9p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.3.3.2; Table E.3-3</b>
<b>Risk Component Number:</b>	<b>10</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Underground Due to Accident Scenario C6</b>
<b>Risk Scenario:</b>	<b>Underground; forklift pierces two drums and knocks another one down.</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{10o}</math> and <math>p_{10p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{10o}</math> and <math>R_{10p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.3.3.3; Table E.3-4</b>
<b>Risk Component Number:</b>	<b>11</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Underground Due to Accident Scenario C10</b>
<b>Risk Scenario:</b>	<b>Underground; spontaneous combustion in drum, drum bursting with release of suspended particles</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{11o}</math> and <math>p_{11p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{11o}</math> and <math>R_{11p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.3.3.4; Table E.3-5</b>
<b>Risk Component Number:</b>	<b>12</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Due to Routine Chemical Exposures in an N1 Scenario</b>
<b>Risk Scenario:</b>	<b>VOCs vent continuously through a filter</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{12o}</math> and <math>p_{12p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{12o}</math> and <math>R_{12p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.4.2.1; Tables E.4-1 and E.4-2</b>

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>13</b>
<b>Risk Component Name:</b>	<b>Cancer Risk Due to Routine Chemical Exposures in an N3 Scenario</b>
<b>Risk Scenario:</b>	<b>Routine underground emissions from each drum</b>
<b>Risks Addressed:</b>	<b>Occupational (above and below ground) and public cancer</b>
<b>Risk Reduction Factor Symbol:</b>	<b><math>p_{13o}</math>, <math>p_{13a}</math> and <math>p_{13p}</math></b>
<b>Annual Baseline Risk Symbol:</b>	<b><math>R_{13o}</math>, <math>R_{13a}</math> and <math>R_{13p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.4.2.2; Tables E.4-3 and E.4-4</b>
<b>Risk Component Number:</b>	<b>14</b>
<b>Risk Component Name:</b>	<b>Noncancer Risk in WHB Due to Routine Chemical Exposure (N1 Scenario)</b>
<b>Risk Scenario:</b>	<b>VOCs vent continuously through a filter</b>
<b>Risks Addressed:</b>	<b>Occupational and public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{14o}</math>, <math>p_{14a}</math> and <math>p_{14p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{14o}</math>, <math>R_{14a}</math> and <math>R_{14p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.4.3.1; Tables E.4-5 and E.4-6</b>
<b>Risk Component Number:</b>	<b>15</b>
<b>Risk Component Name:</b>	<b>Noncancer Risk Underground Due to Routine Chemical Exposure (N3 Scenario)</b>
<b>Risk Scenario:</b>	<b>Routine underground emissions from each drum</b>
<b>Risks Addressed:</b>	<b>Occupational and public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{15o}</math>, <math>p_{15a}</math> and <math>p_{15p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{15o}</math>, <math>R_{15a}</math> and <math>R_{15p}</math></b>
<b>Appendix I Location:</b>	<b>Section E.4.3.2; Table E.4-7</b>
<b>Risk Component Number:</b>	<b>16</b>
<b>Risk Component Name:</b>	<b>Noncancer Risk Due to Accident Scenario C2, Above Ground Accident</b>
<b>Risk Scenario:</b>	<b>Drum dropped from forklift</b>
<b>Risks Addressed:</b>	<b>Occupational morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>p_{16o}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{16o}</math></b>
<b>Appendix I Location:</b>	<b>Section E.5.2.1; Tables E.5-1 and E.5-2</b>

TABLE A.1 (Con't)

## SUMMARY OF RISK COMPONENTS

Risk Component Number:	17
Risk Component Name:	Risk Due to Accident Scenario C3
Risk Scenario:	Two drums punctured by a forklift; third drum falls and ruptures
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol:	P <sub>17o</sub>
Annual Baseline Risk Symbol:	R <sub>17o</sub>
Appendix I Location:	Section E.5.2.2; Tables E.5-1 and E.5-2
Risk Component Number:	18
Risk Component Name:	Underground Risk Due to Accident Scenario C4
Risk Scenario:	Drum drops from pallet, loses lid and integrity of the liner
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	P <sub>18o</sub>
Annual Baseline Risk Symbol(s):	R <sub>18o</sub>
Appendix I Location:	Section E.5.3.1; Tables E.5-3 and E.5-4
Risk Component Number:	19
Risk Component Name:	Underground Risk Due to Accident Scenario C5
Risk Scenario:	Drum drops off a forklift
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	P <sub>19o</sub>
Annual Baseline Risk Symbol(s):	R <sub>19o</sub>
Appendix I Location:	Section E.5.3.2; Tables E.5-3 and E.5-4
Risk Component Number:	20
Risk Component Name:	Underground Risk Due to Accident Scenario C6
Risk Scenario:	Forklift pierces two drums and knocks another one down
Risks Addressed:	Occupational morbidity
Risk Reduction Factor Symbol(s):	P <sub>20o</sub>
Annual Baseline Risk Symbol(s):	R <sub>20o</sub>
Appendix I Location:	Section E.5.3.3; Tables E.5-3 and E.5-4

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>21</b>
<b>Risk Component Name:</b>	<b>Risk of Traffic Accidents</b>
<b>Risk Scenario:</b>	<b>Fatalities by impact</b>
<b>Risks Addressed:</b>	<b>Public fatalities</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>21 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>21 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.2.1; Table E.6-2</b>
<b>Risk Component Number:</b>	<b>22</b>
<b>Risk Component Name:</b>	<b>Risk of Traffic Accidents</b>
<b>Risk Scenario:</b>	<b>Injuries by impact</b>
<b>Risks Addressed:</b>	<b>Public injuries</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>22 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>22 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.2.2; Table E.6-2</b>
<b>Risk Component Number:</b>	<b>23</b>
<b>Risk Component Name:</b>	<b>Cancer Risk from Routine Transportation</b>
<b>Risk Scenario:</b>	<b>Risk to public near road taken by TRUPACT-II transports</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>23 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>23 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.3.2; Table E.6-3</b>
<b>Risk Component Number:</b>	<b>24</b>
<b>Risk Component Name:</b>	<b>Cancer Risk from Routine Transportation</b>
<b>Risk Scenario:</b>	<b>Risk to public during stops</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>24 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>24 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.3.3; Table E.6-4</b>
<b>Risk Component Number:</b>	<b>25</b>
<b>Risk Component Name:</b>	<b>Cancer Risk from Routine Transportation</b>
<b>Risk Scenario:</b>	<b>Risk to public traveling in the opposite direction</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>25 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>25 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.3.4; Table E.6-5</b>

TABLE A.1 (Con't)

## SUMMARY OF RISK COMPONENTS

Risk Component Number:	26
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Risk to public traveling in the same direction as TRUPACT-II transport
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	$P_{26 p}$
Annual Baseline Risk Symbol(s):	$R_{26 p}$
Appendix I Location:	Section E.6.3.5; Table E.6-6
Risk Component Number:	27
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to crew during transport
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$P_{27 o}$
Annual Baseline Risk Symbol(s):	$R_{27 o}$
Appendix I Location:	Section E.6.3.6; Table E.6-7
Risk Component Number:	28
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to waste handlers
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$P_{28 o}$
Annual Baseline Risk Symbol(s):	$R_{28 o}$
Appendix I Location:	Section E.6.3.7; Table E.6-8
Risk Component Number:	29
Risk Component Name:	Cancer Risk from Routine Transportation
Risk Scenario:	Cancer risk to warehouse personnel
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	$P_{29 o}$
Annual Baseline Risk Symbol(s):	$R_{29 o}$
Appendix I Location:	Section E.6.3.8; Table E.6-9
Risk Component Number:	30
Risk Component Name:	Risks Due to Nondispersal Accidents
Risk Scenario:	Early fatalities due to nondispersal accidents
Risks Addressed:	Public fatalities (radiation syndrome)
Risk Reduction Factor Symbol(s):	$P_{30 p}$
Annual Baseline Risk Symbol(s):	$R_{30 p}$
Appendix I Location:	Section E.6.4.2.1; Table E.6-4

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>31</b>
<b>Risk Component Name:</b>	<b>Risks Due to Nondispersal Accidents</b>
<b>Risk Scenario:</b>	<b>Early morbidity due to nondispersal accidents</b>
<b>Risks Addressed:</b>	<b>Public injuries (radiation syndrome)</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>31 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>31 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.4.2.2; Table E.6-4</b>
<b>Risk Component Number:</b>	<b>32</b>
<b>Risk Component Name:</b>	<b>Cancer Risks Due to Nondispersal Accidents</b>
<b>Risk Scenario:</b>	<b>Delayed health effects due to nondispersal accidents</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>32 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>32 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.4.2.3; Table E.6-4</b>
<b>Risk Component Number:</b>	<b>33</b>
<b>Risk Component Name:</b>	<b>Risks Due to Dispersal Accidents</b>
<b>Risk Scenario:</b>	<b>Risk of early fatalities due to inhalation</b>
<b>Risks Addressed:</b>	<b>Public fatalities</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>33 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>33 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.4.3.1; Table E.6-10</b>
<b>Risk Component Number:</b>	<b>34</b>
<b>Risk Component Name:</b>	<b>Risks Due to Dispersal Accidents</b>
<b>Risk Scenario:</b>	<b>Risk of early morbidity due to inhalation</b>
<b>Risks Addressed:</b>	<b>Public injuries</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>34 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>34 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.4.3.2; Table E.6-10</b>
<b>Risk Component Number:</b>	<b>35</b>
<b>Risk Component Name:</b>	<b>Cancer Risks Due to Dispersal Accidents</b>
<b>Risk Scenario:</b>	<b>Risk of delayed health effects due to inhalation</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>35 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>35 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.6.4.3.3; Table E.6-10</b>

TABLE A.1 (Con't)

## SUMMARY OF RISK COMPONENTS

Risk Component Number:	36
Risk Component Name:	Cancer Risks Due to Dispersal Accidents
Risk Scenario:	Risk of delayed health effects due to cloudshine
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>36 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>36 p</sub>
Appendix I Location:	Section E.6.4.3.4; Table E.6-10
Risk Component Number:	37
Risk Component Name:	Cancer Risks Due to Dispersal Accidents
Risk Scenario:	Risk of delayed health effects due to groundshine
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>37 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>37 p</sub>
Appendix I Location:	Section E.6.4.3.5; Table E.6-10
Risk Component Number 38 cancelled	
Risk Component Number:	39
Risk Component Name:	Risk of Monetary Losses Due to Decontamination Procedures
Risk Scenario:	Potential financial losses
Risks Addressed:	Public funds
Risk Reduction Factor Symbol(s):	P <sub>39 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>39 p</sub>
Appendix I Location:	Section E.6.5; Table E.6-10
Risk Component Number:	40
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E1
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>40 o</sub>
Annual Baseline Risk Symbol(s):	R <sub>40 o</sub>
Appendix I Location:	Section E.7.2.1; Table E.7-1

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

Risk Component Number:	41
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E2
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>41 o</sub>
Annual Baseline Risk Symbol(s):	R <sub>41 o</sub>
Appendix I Location:	Section E.7.2.2; Table E.7-1
Risk Component Number:	42
Risk Component Name:	Post-Closure Occupational Radiation Risks from Drilling Operations
Risk Scenario:	Risk of drilling operations in Scenario E1E2
Risks Addressed:	Occupational cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>42 o</sub>
Annual Baseline Risk Symbol(s):	R <sub>42 o</sub>
Appendix I Location:	Section E.7.2.3; Table E.7-2
Risk Component Number:	43
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E1
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>43 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>43 p</sub>
Appendix I Location:	Section E.7.3.2.1; Table E.7-1
Risk Component Number:	44
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>44 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>44 p</sub>
Appendix I Location:	Section E.7.3.2.2; Table E.7-1
Risk Component Number:	45
Risk Component Name:	Inhalation Risks from Dried Up Ponds of Drilling Mud
Risk Scenario:	Public inhalation risk due to drilling in Scenario E1E2
Risks Addressed:	Public cancer and genetic damage
Risk Reduction Factor Symbol(s):	P <sub>45 p</sub>
Annual Baseline Risk Symbol(s):	R <sub>45 p</sub>
Appendix I Location:	Section E.7.3.2.3; Table E.7-2

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

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<b>Risk Component Number:</b>	<b>46</b>
<b>Risk Component Name:</b>	<b>Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E1</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>46 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>46 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.3.3.1; Table E.7-3</b>

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<b>Risk Component Number:</b>	<b>47</b>
<b>Risk Component Name:</b>	<b>Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E2</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>47 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>47 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.3.3.2; Table E.7-4</b>

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<b>Risk Component Number:</b>	<b>48</b>
<b>Risk Component Name:</b>	<b>Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E1E2</b>
<b>Risks Addressed:</b>	<b>Public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>48 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>48 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.3.3.3; Table E.7-5</b>

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**Risk Component Number 49 cancelled**

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<b>Risk Component Number:</b>	<b>50</b>
<b>Risk Component Name:</b>	<b>Post-Closure Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E1</b>
<b>Risks Addressed:</b>	<b>Public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>50 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>50 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.4.2.1; Table E.7-3</b>

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**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>51</b>
<b>Risk Component Name:</b>	<b>Post-Closure Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E2</b>
<b>Risks Addressed:</b>	<b>Public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>51 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>51 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.4.2.2; Table E.7-4</b>
<b>Risk Component Number:</b>	<b>52</b>
<b>Risk Component Name:</b>	<b>Post-Closure Public Ingestion Risks Due to Drilling Operations</b>
<b>Risk Scenario:</b>	<b>Public ingestion risks due to beef contaminated by stock well water in Scenario E1E2</b>
<b>Risks Addressed:</b>	<b>Public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>52 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>52 p</sub></b>
<b>Appendix I Location:</b>	<b>Section E.7.4.2.3; Table E.7-5</b>
<b>Risk Component Number:</b>	<b>53</b>
<b>Risk Component Name:</b>	<b>Industrywide Occupational Accidents</b>
<b>Risk Scenario:</b>	<b>Fatal occupational accidents</b>
<b>Risks Addressed:</b>	<b>Occupational fatalities</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>53 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>53 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.2.1.1; Table F.2-1</b>
<b>Risk Component Number:</b>	<b>54</b>
<b>Risk Component Name:</b>	<b>Industrywide Occupational Accidents</b>
<b>Risk Scenario:</b>	<b>Nonfatal accidents</b>
<b>Risks Addressed:</b>	<b>Occupational injuries</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>54 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>54 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.2.1.2; Table F.2-1</b>

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>55</b>
<b>Risk Component Name:</b>	<b>Forklift Accidents</b>
<b>Risk Scenario:</b>	<b>Fatal forklift accidents in TF</b>
<b>Risks Addressed:</b>	<b>Occupational fatalities</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>55 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>55 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.2.2.2.1; Table F.2-2</b>
<b>Risk Component Number:</b>	<b>56</b>
<b>Risk Component Name:</b>	<b>Forklift Accidents</b>
<b>Risk Scenario:</b>	<b>Nonfatal forklift accidents in TF</b>
<b>Risks Addressed:</b>	<b>Occupational injuries</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>56 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>56 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.2.2.2.2; Table F.2-2</b>
<b>Risk Component Number:</b>	<b>57</b>
<b>Risk Component Name:</b>	<b>Risk of Radiation Exposures</b>
<b>Risk Scenario:</b>	<b>Routine operations: External exposure in TF</b>
<b>Risks Addressed:</b>	<b>Occupational cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>57 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>57 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.3.1.1; Table F.3-1</b>
<b>Risk Component Number:</b>	<b>58</b>
<b>Risk Component Name:</b>	<b>Risk of Radiation Exposures</b>
<b>Risk Scenario:</b>	<b>Routine maintenance: External exposure in TF</b>
<b>Risks Addressed:</b>	<b>Occupational cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>58 o</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>58 o</sub></b>
<b>Appendix I Location:</b>	<b>Section F.3.1.2; Table F.3-2</b>
<b>Risk Component Number:</b>	<b>59</b>
<b>Risk Component Name:</b>	<b>Risk of Internal Radiation Exposures</b>
<b>Risk Scenario:</b>	<b>Occupational risks due to internal routine exposures originating from TF</b>
<b>Risks Addressed:</b>	<b>Occupational and public cancer and genetic damage</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b>P<sub>59 o</sub> and P<sub>59 p</sub></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b>R<sub>59 o</sub> and R<sub>59 p</sub></b>
<b>Appendix I Location:</b>	<b>Sections F.3.2.1.1 and F.3.2.1.2; Tables F.3-3 and F.3-4</b>

**TABLE A.1 (Con't)**  
**SUMMARY OF RISK COMPONENTS**

<b>Risk Component Number:</b>	<b>60</b>
<b>Risk Component Name:</b>	<b>Risk of Internal Radiation Exposures</b>
<b>Risk Scenario:</b>	<b>Cancer risk due to maintenance operations in TF</b>
<b>Risks Addressed:</b>	<b>Occupational and public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>\rho_{60 o}</math> and <math>\rho_{60 p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{60 o}</math> and <math>R_{60 p}</math></b>
<b>Appendix I Location:</b>	<b>Sections F.3.2.2.1 and F.3.2.2.2; Tables F.3-5 and F.3-6</b>
<b>Risk Component Number:</b>	<b>61</b>
<b>Risk Component Name:</b>	<b>Risk of Cancer by Exposure to VOCs</b>
<b>Risk Scenario:</b>	<b>Routine operations in TF: Occupational and public exposures</b>
<b>Risks Addressed:</b>	<b>Occupational and public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>\rho_{61 o}</math> and <math>\rho_{61 p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{61 o}</math> and <math>R_{61 p}</math></b>
<b>Appendix I Location:</b>	<b>Sections F.4.1.1 and F.4.1.2; Tables F.4-1 and F.4-2</b>
<b>Risk Component Number:</b>	<b>62</b>
<b>Risk Component Name:</b>	<b>Risk of Noncancer Health Effects</b>
<b>Risk Scenario:</b>	<b>Routine operations in TF: Occupational and public exposures</b>
<b>Risks Addressed:</b>	<b>Occupational and public morbidity</b>
<b>Risk Reduction Factor Symbol(s):</b>	<b><math>\rho_{62 o}</math> and <math>\rho_{62 p}</math></b>
<b>Annual Baseline Risk Symbol(s):</b>	<b><math>R_{62 o}</math> and <math>R_{62 p}</math></b>
<b>Appendix I Location:</b>	<b>Sections F.4.2.1 and F.4.2.2; Table F.4-1</b>

**ATTACHMENT B****THEORETICAL BASIS FOR RISK COMPARISONS  
USING SOME OF THE TOOLS OF MULTI-ATTRIBUTE UTILITY THEORY****B.1 INTRODUCTION**

Scenarios considered in risk assessment rarely lead to a single consequence; usually the total risk of one or more events consists of a number of different components such as fatalities, injuries, and dollars lost. Quite generally, risks are multidimensional quantities with components of widely different character, measured in different units. For two reasons, this makes the comparison of risks nontrivial: (1) a numerical comparison can only involve two numbers and (2) only numbers measured in the same units can be compared.

Therefore, for a comparison of multicomponent quantities, all components must be converted to the same units through multiplication by an appropriate scale or conversion factor, and all components must be combined in a manner prescribed by some rationale to form a single number. Two such numbers can then be compared unequivocally, provided that the algorithm used for the combination is, mathematically speaking, a well-behaved function. For rationales such as the ones discussed here, the functions used are rather simple and do not present any mathematical difficulties.

The fields of economics and decision theory offer the required rationales in the form of multi-attribute utility functions (Covello, 1987; Fishburn, 1978; Keeney, 1978; Von Neumann and Morgenstern, 1944). These functions not only convert all components to the same units, but also involve societal value judgements, for instance, by explicitly defining a dollar equivalent for a human life lost. Their function values are called utility indices and are the quantities to be used here for risk comparisons. In risk management, this generic approach was successfully used to select the three finalist sites for the high-level radioactive waste repository (Gregory and Lichtenstein, 1987; Keeney, 1987; Merkhofer and Keeney, 1987). In that selection process, a number of different attributes, such as aesthetic, cultural, and socio-economic impacts, as well as repository cost, were considered in addition to some components of the total risk. It is demonstrated here that this theoretical framework can not only be applied to comparing utility indices based on risk components alone but that the similarity of the components may be used to advantage.

It is, however, important to realize that the use made of multi-attribute utility theory proposed here differs in several significant aspects from the conventional approach. Indeed, except for the derivation, this application to the comparison of total risks has few aspects in common with the usual multi-attribute utility approach to decision making. Most important among the differences

is that the purpose of the procedure to be developed is exclusively to compare two or more risks, which are quite similar quantities. It is not the intent to make management or policy decisions, such as those indicated in the last paragraph, on the basis of often widely different criteria. As a consequence, full advantage is taken of all similarities, particularly with regard to the valuations of reductions in risk.

In the applications of multiattribute utility theory to date, ranking is based purely on the concept of *preference* without recourse to the numerical uncertainties of the utility indices; that is, the indices are treated as if they had no standard errors. Consequently, this approach is not able to make explicit use of the other basic concept of value theory: that of *indifference* to the ranking of two utility indices (Fishburn, 1978; Von Neumann and Morgenstern, 1944). In ranking risks using utility functions, the fact of indifference to ranking two alternatives is a highly significant datum, particularly if the alternatives differ in attributes other than risk, such as cost, technical viability, and reliability. In an additional procedure, these aspects can then be taken into account to make management or policy decisions.

Normally, risk comparisons are not or should not be stand-alone procedures (Seiler, 1990b). They are more likely tied into a larger framework for the evaluation of alternatives. In this environment, it is imperative that a close interaction exist between the decision makers at both levels, because the viewpoints and valuations in a stand-alone risk comparison are not the same as those in a risk comparison embedded into another study that depends on its results.

It is the purpose of this theoretical approach to apply the tools of multi-attribute utility theory to the comparison of risks, to propose a particular form of writing risks and utility functions for making these comparisons, to discuss the properties of that particular form and similar forms in detail, and, finally, to introduce an uncertainty evaluation for the utility index and apply it to two indifference criteria for the ranking process.

## B.2 COMPARISONS OF RISK COMPONENTS

### B.2.1 Risk as a Multicomponent Quantity

The basic quantity risk will be used here in the form defined by Kaplan and Garrick (1981),

$$R_i \equiv (S_i, C_i, P_i), \quad (\text{B.2.1})$$

where  $S_i$  defines a particular scenario,  $C_i$  one of its consequences, and  $P_i$  the probability of that consequence. The complete set of  $I$  scenarios and outcomes of a given activity describes its

total risk. In set notation

$$R = \{R_i | i=1, I\} = \{(S_i, C_i, P_i) | i=1, I\} . \quad (B.2.2)$$

The possible scenarios  $S_i$  include different people at risk with individual risks  $R_i$  which can be summed to obtain a total risk  $R$  for all  $J$  possible consequences  $C_j$ , each of which is expected to occur  $E_j$  times. In other words,  $E_j$  is the expectation value for the effects in all exposed individuals. The total risk can then be written as a set of all  $J$  combinations of scenarios and consequences,

$$R = \{R_j | j=1, J\} = \{(S_j, C_j, P_j) | j=1, J\} . \quad (B.2.3)$$

Alternately, this total risk can be written as a vector

$$R = (R_1, R_2, \dots, R_j, \dots, R_J) , \quad (B.2.4)$$

where the components  $R_j$  of the total risk are given by the same expectation value of the number of effects  $E_j$  as in Equation (B.2.3)

$$R_j = E_j , \quad (B.2.5)$$

where the index  $j$  now has to imply both scenario and consequence. The meaning of the real number  $E_j$  can thus range from the number of traffic or latent cancer fatalities to the number of dollars necessary to clean up an accident site. Potentially, the number of components  $J$  is quite large. Methods to aggregate some of them to decrease their number to a manageable size will be discussed in the context, weighting the components in Section B.3.4. Regardless of the number of components, however, the notation of Equation (B.2.4) clearly indicates the multicomponent nature of most total risks.

The comparison of total risks is made difficult by this multi-component structure, because there exists no unique mathematical framework for comparing these risks at the present time. Yet risk comparisons are needed in many risk assessments and in most risk management activities. It is, therefore, of importance to develop tools that allow a comparison of total risks, such as an index that summarizes the combined impacts of all components of the risks being compared.

In this context, it is important to realize that the risk defined in Equation (B.2.1) and the total risk defined by Equations (B.2.3) or (B.2.4) are two different quantities. However, for want of a more appropriate term, both are usually called risks. The terminology used here is to apply the qualified term total risk to the second set of equations, defining the expectation values for each consequence. As long as the index  $j$  implies both scenario and consequence this usage will be maintained.

In the aggregation mentioned above, the number of components is reduced from  $J$  to a more manageable number  $J_0$ . This implies a summation (or integration) over the number of scenarios and over the persons exposed. The resulting quantities are more in the nature of an expectation value of a total risk than a risk, and call for a different term. Taking into account that Equations (B.2.2) and (B.2.3) contain exactly the same information, yet another formulation for this data set is

$$C = (C_1, C_2, \dots, C_j, \dots, C_{J_0}) , \quad (\text{B.2.6})$$

where the components  $C_j$  are given by the analog to Equation (B.2.5).

$$C_j = E_j . \quad (\text{B.2.7})$$

Note that the only real difference between Equations (B.2.4) and (B.2.6) is the range of the index  $j$ , which runs from 1 to  $J$  in Equation (B.2.4) and over the much reduced range from 1 to  $J_0$  in Equation (B.2.7). In the latter, the index runs exclusively over the different consequences  $C_j$ , selected in the aggregation process. The quantity  $C$  defined by Equation (B.2.6) is, therefore, termed the consequence vector.

### B.2.2 Uncertainties in Risk Comparisons

In many risk assessments, the numerical analysis of uncertainties is either not performed at all or then just perfunctorily, more as an afterthought. This may in part be due to the fact that the treatment of uncertainties is often difficult; at any rate it is more involved and more delicate than the actual risk calculation (Bevington, 1969; Brandt, 1976; Iman and Helton, 1988; Seiler, 1987b). However, in any state-of-the-art risk assessment, an appropriate numerical error analysis is a central and time-consuming part of the entire effort (see Section B.4.2 and Attachment C). Also, its results should be reflected in the final quotations of the risks, even if it is only by the number of significant digits given (LaGoy, 1989).

When two or more total risks are compared, the uncertainties of each component of the total risk become of paramount importance, because the task of a risk comparison is not merely to rank risks according to some criterion or other, but rather to do so while keeping track of risks that are not significantly different from others. These comparable risks can only be assigned to a particular group but cannot be ranked within it. Failure to follow this procedure can result in considerable losses of money or other societal goods due to more efficient alternatives which were mistakenly ranked lower and consequently rejected. In order to follow the procedure outlined here, criteria that indicate an indifference to ranking need to be applied, such as Goodman's criteria of an insignificant difference (Goodmann, 1986).

The uncertainties of most risk components are usually rather large due to such uncertain factors as the probability of the primary event in a scenario or the risk coefficient for lung cancer due to high-LET irradiation of the respiratory tract by inhaled  $^{238}\text{Pu}$ . However, closer inspection of risk

comparisons shows that these errors have the character of errors of scale which can sometimes hide even highly significant differences (Seiler, 1990b). These scale errors should either be removed by appropriate methods (Seiler, 1990b) or they can be eliminated by an appropriate normalization of the risk component.

### B.2.3 Normalizing a Risk Component

The most elegant way to reduce the error of a risk component is a normalization, that is, a recalibration of the component in different units. In this operation, many common factors cancel. Quite generally, a component  $R_{jk}$  of the total risk can be separated into a product of  $n_j$  different factors  $F_{jkv}$ , often with some of the factors being sums of products,

$$R_{jk} = F_{jk1} F_{jk2} \dots F_{jkn_j} = \prod_{v=1}^{n_j} F_{jkv}, \quad (\text{B.2.8})$$

where the indices  $j$ ,  $k$ , and  $v$  stand for the risk component, the alternative being compared and the risk factor, respectively. For use as a normalization quantity, a number of different risks can serve. Convenient choices are the baseline risk components, or the average of every component over all  $K$  alternatives. In this context, it is important to realize that normalization is a shift of scale that does not change relative uncertainties.

Denoting the normalization risk by the index  $k = 0$ , the normalized risk component  $r_{jk}$  is the old risk component  $R_{jk}$  measured in units of the normalization risk  $R_{j0}$  or, in the terminology of epidemiology, the new risk  $r_{jk}$  is a relative risk. In the normalization, a number of the factors in numerator and denominator will usually cancel; often only one or two factors remain. If the number of remaining factors is  $n_j$ , the relative risk is given by

$$r_{jk} \equiv \frac{R_{jk}}{R_{j0}} = \frac{F_{jk1} F_{jk2} \dots F_{jkn_j}}{F_{j01} F_{j02} \dots F_{j0n_j}} = \frac{\prod_{v=1}^{n_j} F_{jkv}}{\prod_{v=1}^{n_j} F_{j0v}}. \quad (\text{B.2.9})$$

The error of this ratio is thus much smaller than the error of an absolute risk, and error propagation can be handled in the usual first-order or Gaussian approximation for small relative errors (Bevington, 1969; Brandt, 1976). If some relative errors are not small, higher order terms in the Taylor series may have to be used (Seiler, 1987b).

Sometimes the same parameter appears in both numerator and denominator, but does not cancel as in Equation (B.2.9), because the factor containing it is a sum of products. In this case, the error propagation formula should not be used on the absolute risks  $R_{jk}$ , but on the relative risk function  $r_{jk}(x) = r_{jk}(x_1, x_2, \dots, x_p)$  with a set of  $P$  independent parameters  $\{x_p\} = \{x_p | p = 1, P\}$

that influence the uncertainty of the final result. The Gaussian approximation, which consists of the first correction term of a multi-dimensional Taylor (Korn and Korn, 1968) expansion of  $r_{jk}(x)$  around the point  $x$ , then yields

$$(\Delta r_{jk})^2 = \sum_{k=1}^P \left( \frac{\partial r_{jk}(x_p)}{\partial x_k} \right)^2 (\Delta x_k)^2. \quad (\text{B.2.10})$$

Analogously, numerical methods (Cox and Baybutt, 1981; Helton, 1961; Iman and Helton, 1988) should focus on the relative risk  $r_{jk}$  rather than on the product of the residual factors  $F_{jkv}$  of the absolute risks in numerator and denominator. Some of the aspects relevant to this report will be discussed in more detail in Attachment C.1.

### B.3 TOOLS OF MULTI-ATTRIBUTE UTILITY FUNCTIONS

#### B.3.1 Decision Theory

Decision theory is a discipline grown out of economics and operations research that has developed rapidly in the last few decades. It is a system of concepts and mathematical procedures which are helpful in making decisions while pursuing multiple objectives. Some approaches are based on the economic concepts of *preference* and *utility* (Fishburn, 1978; Keeney, 1978), collectively often called value theory, and incorporate individual and societal value judgments in a mathematical framework combining different attributes.

Von Neumann and Morgenstern (1944) are credited with the primary development of modern axiomatic theory of utility functions for decision processes; more recent developments have resulted in a mature axiomatic theory. Central to this economic theory are the binary relations of preference theory based on the concepts of *preference* (the consumer prefers A to B, actually he 'strictly prefers' A to B; or in mathematical symbolism:  $A \succ B$ ) and *indifference* (the consumer is indifferent to a choice between A and B, or in mathematical symbols:  $A \sim B$ ). Utility functions describe the consumer's valuation of various amounts of commodities such as money, goods, and services. The numerical value of a utility function is called the utility index (Henderson and Quandt, 1971).

#### B.3.2 Single Attribute Utility Functions

Utility indices are used to rank alternatives; the differences between the values of different alternatives, however, are not necessarily indicative of the intensity of preference. Utility functions, as usually constructed, are thus deemed to have ordinal, but not necessarily cardinal properties (Fishburn, 1978; Henderson and Quandt, 1971; Keeney, 1978). However, for the purposes of comparing risks, cardinal properties are desirable in order to facilitate error propagation calculations and evaluate the significance of differences between utility indices.

Utility functions with the necessary properties can be constructed in a manner that avoids sizeable higher-order derivatives, for example, by using linear or logarithmic functions of gains or losses. For these functions, it is then possible to calculate standard errors for the utility indices and use them in a meaningful discussion of significant differences. The discussions here are given in terms of unaggregated risk components but hold equally well for aggregated components.

From the utility point of view a risk contribution or a number of expected health or environmental effects  $E_{jk}$  are a disutility  $d_{jk}$  or a negative utility  $-u_{jk}$ . If the disutility  $d_{jk}$  is assumed to be directly equal to the number of effects, it is given by the expression

$$d_{jk} = -u_{jk} = E_{jk}, \quad (\text{B.3.1})$$

where the indices  $j$  and  $k$  denote the component and the alternative, respectively. As long as the value of  $E_{jk}$  is larger than one but not too large, the linear utility function is a good measure for the loss of value. If  $E_{jk}$  is considerably less than one, the linear function does not give a reasonable measure for a risk reduction by - say - an order of magnitude; it undervalues that risk reduction. If  $E_{jk}$  is much larger than one, on the other hand, it will tend to overvalue a risk reduction by the same factor of ten. The same arguments can be made for a linear utility that involves normalized risks.

In economic terms, the use of the linear form disregards the relationship between the quantity of a commodity and its utility, known as the *Law of Diminishing Marginal Utility* (Fishburn, 1978; Samuelson, 1973). Put in mathematical terms, it states that the derivative of the utility decreases as the quantity of the commodity increases. Thus the use of the term 'marginal' in economics does not agree with its mathematical definition (see for instance Korn and Korn, 1968). In order to limit the use of this term to its mathematical meaning, the acronym *LDMU* will be used from now on to denote the law.

In risk management, the *LDMU* expresses the fact that, for example, a unit increase in the relative risk is most detrimental when  $r_{jk}$  is 1, it is less detrimental when  $r_{jk}$  is 10, and even less so when  $r_{jk}$  is 100. Similarly, a unit increase in the denominator is most beneficial when the relative risk is 1, less beneficial when it is 1/10, and so on. Graphically, this type of relationship is shown in Figure I.B-1a, where, as an example, a logarithmic dependence  $f(x) = \log_a x$  is plotted as a function of the argument  $x$ . Given in Figure I.B-1b is its derivative,  $df(x) / dx = 1 / (x \ln a)$  as a function of  $x$ . The function  $f(x)$  adds one unit of disutility for every factor,  $a$ , by which the argument  $x$  increases.

Using a logarithmic form with base,  $a$ , for the disutility inherent in a risk component leads to the second form of the utility function to be discussed here. The formulation

$$d_{jk} = \log_a r_{jk}, \quad (\text{B.3.2})$$

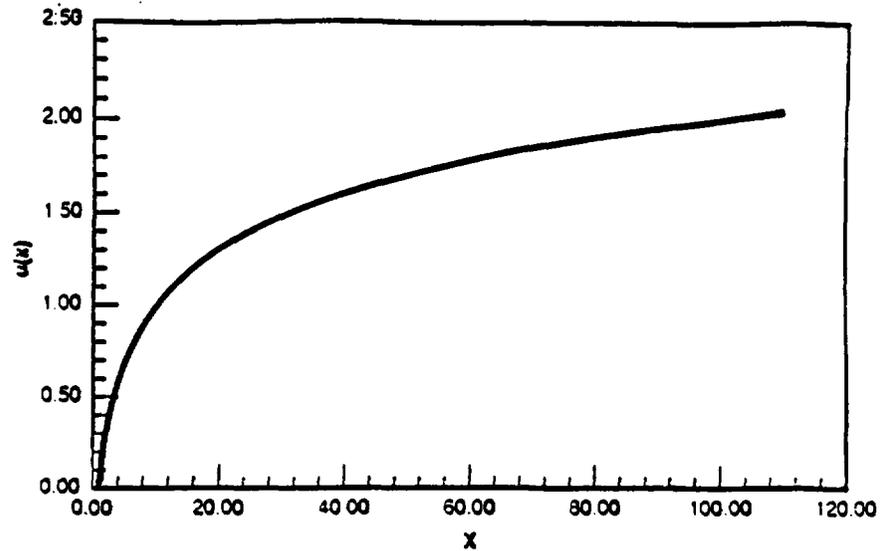


FIGURE I.B-1a. LOGARITHMIC DEPENDENCE OF A FUNCTION ON ITS ARGUMENT

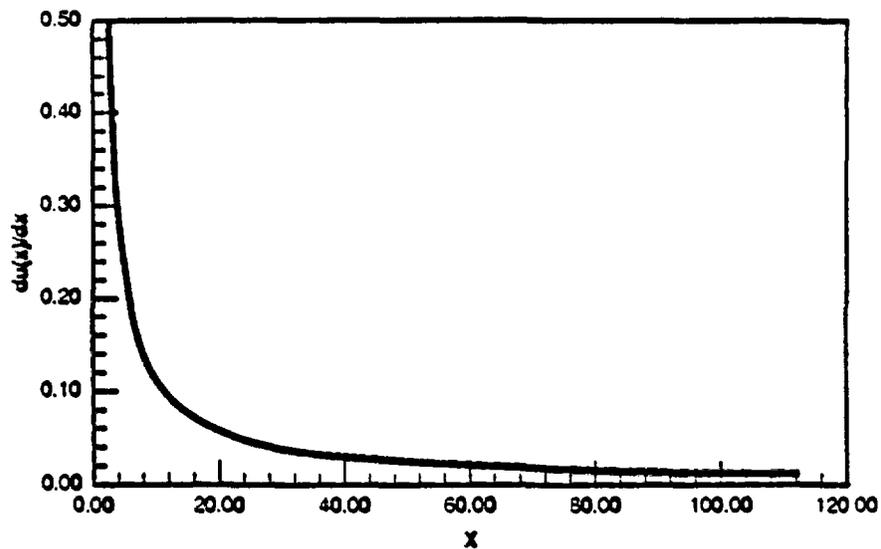


FIGURE I.B-1b. DEPENDENCE OF THE DERIVATIVE OF A FUNCTION ON ITS ARGUMENT

The *Law of Diminishing Marginal Utility* shown here (Figure I.B-1.a) for the single-attribute utility function  $U(x) = \log_a x$ . For each factor,  $a$ , by which the argument  $x$  increases or decreases, the utility increases or decreases by one unit. The change per unit increase of argument  $x$ , that is, its derivate  $du(x)/dx = 1/(x \ln a)$  is shown in Figure I.B-1.b. As required by the *LMDU*, it continuously decreases as the argument increases.

removes the asymmetry about the point  $r_{jk} = 1$ , except for a sign. It is, therefore, antisymmetric with respect to unity and able to cover large variations in the relative risk  $r_{jk}$ . In fact the definition of a risk reduction factor  $\rho_{jk}$  by

$$\rho_{jk} \equiv \frac{1}{r_{jk}} = \frac{R_{j\sigma}}{R_{jk}}, \quad (\text{B.3.3})$$

allows the writing of the modified utility function in the form

$$\begin{aligned} \theta_{jk} &= -d_{jk} = -\log_a r_{jk} = \log_a \left( \frac{1}{r_{jk}} \right) \\ &= \log_a \rho_{jk} = \frac{\ln \rho_{jk}}{\ln a} = Q \ln \rho_{jk}, \end{aligned} \quad (\text{B.3.4})$$

with the definition of the 'modulus' of the logarithm with base  $a$

$$Q \equiv \frac{1}{\ln a}. \quad (\text{B.3.5})$$

This type of utility function is antisymmetric in the arguments  $r_{jk}$  and  $\rho_{jk}$  and symmetric with respect to risk increases and risk reductions.

Utility functions that appear most useful in the comparison of total risks combine most of the qualities discussed above. The set of these single-attribute utility functions will be called class  $\mathfrak{R}_s$  utility functions in this paper and is defined by the following properties:

1. Exhibiting the behavior required by the *LDMU*, and having a parameter that allows it to approximate the dependence of the utility function on the risk reduction factor.
2. Exhibiting antisymmetry with respect to an argument of unity, i.e., it is symmetric, except for the sign, with respect to  $r_{jk} = 1$ , and thus also  $\rho_{jk} = 1$ .
3. Being "mathematically well behaved functions," i.e., they are continuous, monotonic, differentiable, and have, in addition, only small values of the higher derivatives.
4. Being *measurable*, i.e., a larger difference of the utility function for two different values of the argument means a larger difference in the intensity of the preference for the higher argument over the lower one, and vice versa (Dyer and Sarin, 1979).

From the discussions above, the need for most of these properties is evident; the requirement of small higher derivatives is needed in order to justify the use of the Gaussian approximation for the propagation of errors. Together with the requirement of *measurability*, this condition assures

a meaningful mapping of the uncertainty distribution onto the utility function. Clearly, the functions discussed in Equations (B.3.2) and (B.3.4) fulfill all of these requirements, whereas Equation (B.3.1) fails with regard to the first condition, except for small deviations of the argument from unity.

### B.3.3 Aggregation of Components

Among the J components of the total risk, many involve the same incident or the same type of incident, say, routine occupational whole-body exposure to low-LET radiation, as well as the same consequence, say, leukemia five to fifteen years later. The expected value of leukemia cases among the workers for several different exposure scenarios is a typical candidate for aggregating components into the single risk component of leukemia due to routine occupational low-LET whole-body radiation exposure. All contributions to this combined risk would have the same societal weight  $\gamma_1$ , i.e., be subject to the same valuation.

There are essentially three ways to aggregate similar components: (1) aggregate before forming the risk reduction factor; (2) aggregate risk reduction factors before forming the utility function; and (3) aggregate after forming the utility functions. Each method has its area of applicability, although in many cases the method of choice is not necessarily evident. The basic requirement for aggregation, however, is that the components lead to the same consequence, typically a health or environmental effect.

The first method is indicated, for instance, when the index j differentiates solely between individuals exposed in the same event and at risk for the same health effect. This aggregation is of the type that leads to the number  $E_j$  of health effects in Equation (B.2.5). For the aggregation labeled  $\xi$ , which combines the  $n_\xi$  components between the labels  $J_{\xi-1}$  and  $J_\xi$ , with indices given by the limits  $1 \leq J_{\xi-1} \leq J_\xi \leq J$ , the combined risk reduction ratio becomes a sum of products, quite likely multiplied by some common factors. This can be seen by rewriting Equation (B.3.3) as a risk reduction factor  $\rho_{\xi k}$  for the combined component  $\xi$

$$\rho_{\xi k} = \frac{\sum_{j=J_{\xi-1}}^{J_\xi} R_{j0}}{\sum_{j=J_{\xi-1}}^{J_\xi} R_{jk}} \quad . \quad (\text{B.3.6})$$

The detailed derivation of the algebraic form of  $\rho_{\xi k}$  and its properties are given in Attachment C.2, Aggregation of Risk Components. Also discussed there is the calculation of the error for the risk reduction factor,  $\Delta \rho_{\xi k}$ , which requires the application of the Gaussian approximation.

The second method should be used when it seems justified to add risk reduction factors in some appropriately weighted fashion. This is indicated in some studies where only several conditional

accident scenarios are discussed, that is, the results given are subject to the condition that the initiating event has occurred, but little information is available on the probability of that event. Also, some highly uncertain low-probability events may be more amenable to the estimation of the risk reduction factor than to the estimation of the absolute risk. In these cases, it may be useful to estimate the combined risk reduction factor as a weighted arithmetic or geometric average of the individual factors,

$$\rho_{\xi k} = \sum_{j=J_{\xi-1}}^{J_{\xi}} w_{\xi j} \rho_{jk} , \quad (\text{B.3.7})$$

or

$$\rho_{\xi k} = \prod_{j=J_{\xi-1}}^{J_{\xi}} (\rho_{jk})^{w_{\xi j}} . \quad (\text{B.3.8})$$

Equations (B.3.7) and (B.3.8) do not have the usual form for weighted means because the sum of the weights is normalized to unity. Once this is taken into account, the equations assume the correct form.

The choice between the arithmetic and the geometric average depends on the characteristics of the evaluation. In risk comparisons, risk reduction factors often vary widely. In that case, a geometric mean may be preferable. For the aggregation of more densely clustered risk reduction factors, the arithmetic average may be preferable.

The problem in using Equations (B.3.7) and (B.3.8) lies in finding an adequate rationale for the determination of the weights  $w_{\xi j}$ . It may, however, be easier to approximate the influence of a particular risk reduction factor on a combined factor than to estimate its absolute value. In some of these cases, the relative contribution of that component to the total baseline risk of the aggregation  $\xi$  may be deemed appropriate,

$$w_{\xi j} = \frac{R_{j0}}{\sum_{v=J_{\xi-1}}^{J_{\xi}} R_{v0}} . \quad (\text{B.3.9})$$

In other cases, equal weights may be more adequate. Generally, the second method is indicated when separate risk reduction factors are needed, but there is no rationale for a separate attribute in the multi-attribute utility function.

The third method should be used when component utilities should be added and weighted with the same societal valuation  $\gamma_j$ . This is often the case with the risk components targeted by the

risk reduction methods that distinguish the alternatives  $k$ . For these components a direct evaluation of the utilities is indicated. In some instances, however, these contributions to the utility index tend to overwhelm other contributions by their sheer numbers, even though they should be viewed more as a single contribution. To avoid this situation, the composite single-attribute utility function may be written as

$$U_{\xi k} = Q \sum_{v=J_{\xi-1}}^{J_{\xi}} w_{\xi v} \ln(\rho_{vk}) ,$$

with relative weights  $w_{\xi j}$ . These weights are often most appropriate when set equal to each other, that is to

$$w_{\xi j} = \frac{1}{n_{\xi}} = \frac{1}{J_{\xi} - J_{\xi-1}} , \quad (\text{B.3.11})$$

with a sum over the  $n_{\xi}$  weights normalized to unity. In some situations, however, another way of weighting may be more appropriate. Some additional thoughts on the best choice of method and on the implementation of that choice are presented in Attachment C.2, Aggregation of Risk Components.

In the aggregation process from  $J$  different components down to  $J_0$  components, the terminology changes because this summation leads to a quantity in the nature of an expectation value (see Section B.2.1, above). This is recognized by the definition of the consequence reduction factor

$$\Gamma_{jk} = \Phi_a(\{\rho_{jk}\}) , \quad (\text{B.3.12})$$

aggregated by one of the functions  $\Phi_a$  in Equations (B.3.7 to B.3.8) from a subset of the set of all risk reduction factors. This quantity is used in the formulation of the multi-attribute utility theory.

#### B.3.4 Multi-Attribute Utility Functions

Utility functions for multiple attributes, such as the risk reduction components of a relative total risk, can be written as some combination of their marginal utility functions, the modified single-attribute utilities  $\theta_{jk}$ , weighted by societal value judgments (Covello, 1987; Keeney, 1978; Merkhofer and Keeney, 1987). The corresponding mathematical weights  $g_j$  express the valuation by society of different components, such as cancer fatalities, monetary losses, loss of limbs, and workdays lost in accidents. As in the case of single attribute utility functions, the value of the function is called the utility index  $U_k$ .

There are many ways to decompose the multi-attribute utility function into combinations of their marginal utilities (French, 1986; Keeney and Raiffa, 1976; Zeleny, 1982). For risk comparisons, the most interesting one is the additive decomposition. In the approach used here, two forms of the multi-attribute utility function will be discussed: both are additive, one using linear and the other logarithmic marginal utility functions. Thus

$$U_k = \text{const} \sum_{j=1}^J g_j \theta_{jk}, \quad (\text{B.3.13})$$

where the marginal utility functions are given either by Equation (B.3.1) or Equation (B.3.4), and where const is a constant scale factor.

Apart from these properties, these multi-attribute utility functions fulfill the other conditions of what we shall call class  $\mathfrak{R}_m$  functions:

1. Their marginal utilities are class  $\mathfrak{R}_s$  utility functions.
2. Similar to the requirements of condition 3) for class  $\mathfrak{R}_s$  functions, they are mathematically 'well behaved' and represent a smooth n-dimensional surface without large curvatures in (n+1)-dimensional space.
3. The utility functions are measurable, i.e., a larger difference between the function values of two alternatives means a larger difference in the intensity of preference between the two alternatives.

The exact nature of the intensity of preference (French, 1986) discussed in the third condition is not of direct relevance here, because, as stated before, the requirement of measurability is introduced in order to ascertain a meaningful mapping of the uncertainties onto the utility indices. The second condition is the reason why the multiplicative decomposition of the multiattribute utility function is not used here. Multiplicative functions have considerably more potential for large surface curvatures than additive functions.

The first additive function to be discussed here is the weighted linear combination of linear utility functions for each attribute according to Equations (B.3.1) and (B.3.4). It leads to a multi-attribute function of

$$U_k = \frac{1}{S} \sum_{j=1}^J g_j p_{jk}, \quad (\text{B.3.14})$$

where  $S$  is an arbitrary normalization factor. If it is chosen as the sum of weights  $g_j$ ,

$$S = \sum_{j=1}^J g_j, \quad (\text{B.3.15})$$

then normalized weights  $\gamma_j$  can be defined by

$$\gamma_j \equiv \frac{g_j}{S}, \quad (\text{B.3.16})$$

resulting in a utility index  $U_k$  that corresponds to the weighted arithmetic mean of all component utilities,

$$U_k = \sum_{j=1}^J \gamma_j p_{jk}. \quad (\text{B.3.17})$$

These linear combinations of linear utility functions are best used when the total risks to be compared are rather similar in most components. In these cases, the linearity of utility with a small increase or reduction in risk is a useful concept. The range of applicability is restricted, however, because of the asymmetry with regard to the unit relative risk and the inability to give expression to the *LDMU*.

If the marginal utilities  $\theta_{jk}$  are given by the logarithm of the risk reduction component according to Equation (B.3.4), the additive form yields a multi-attribute utility,  $U_{k,a}$  which is the weighted arithmetic mean in a logarithmic space with base,  $a$ ,

$$U_k = Q \sum_{j=1}^J \gamma_j \ln p_{jk}. \quad (\text{B.3.18})$$

This function thus has the global properties required of a class  $\mathfrak{R}_m$  function. The wide range of relative risks due to risk management and remediation efforts, often many orders of magnitude, can be covered easily by assigning an appropriate base,  $a$ , to the logarithm to be used in the marginal utility functions.

Intuitively, the use of the weighted arithmetic and the weighted logarithmic mean of the component utilities as measures of the multi-attribute utility makes sense. The first is appropriate when the values  $\Gamma_{jk}$  are clustered relatively closely around the value of 1, the second is more appropriate when there are wide spreads between component values.

The selection of the weighted logarithmic average in Equation (B.3.11) as the multi-attribute utility function of choice in this paper may be less obvious. It is mostly justified by the desirable properties of a class  $\mathfrak{R}_m$  multi-attribute utility function and the fact that function (B.3.11) is the most simple representative of this class. This choice is arbitrary, but it is based on a rationale that should be sufficient for the general purpose of comparing risks.

For the comparison of risks with logarithmic utility functions, the unique property of these functions may be used directly by defining with the anti-logarithm a risk reduction index which is the weighted geometric mean of all the risk reduction factors  $\Gamma_{jk}$

$$\Theta_k = a^{u_k} = \prod_{j=1}^{J_k} (\Gamma_{jk})^{y_j} \quad (\text{B.3.19})$$

or its inverse, the risk augmentation index

$$\Psi_k = a^{-u_k} = \frac{1}{\Theta_k} \quad (\text{B.3.20})$$

It is these quantities which will be used here for risk comparisons. In this form of the indices, contributions from the different components are the factors

$$\Phi_{jk} \equiv (\Gamma_{jk})^{y_j}, \quad (\text{B.3.21})$$

so that

$$\Theta_k = \prod_{j=1}^{J_k} \Phi_{jk} \quad (\text{B.3.22})$$

Writing the consequence reduction index as a product allows a simple analysis of the contribution of each component  $j$  to the index.

### B.3.5 Determination of Weights

Together with the selection of the utility function, the assignment of the weights  $g_j$  is a crucial part of the comparison of risks or consequences, because it involves the numerical evaluation of societal value judgments such as the value of a human life, the true societal cost of temporarily or permanently displacing people from their home or workplace, or the losses incurred in damaging or destroying an environmental system (Covello, 1987; Edwards, 1987; Graham and Vaupel, 1981; Svenson and Karlsson, 1989). An appropriate representation of different technical and non-technical viewpoints is, therefore, of paramount importance.

This purpose is best accomplished by eliciting the judgmental values of a group of experts. In this group, the viewpoint of political authorities at the local and state level, of the regulating agencies, and the operational engineer must be represented, as well as the concerns and values of the local population, and the needs and priorities of society as a whole. The group of experts will, therefore, have to comprise technical specialists, risk assessors and managers, as well as social scientists and others that can introduce regulatory and popular concerns into the evaluation. In this context, it is important to keep in mind the use to which the comparison of total risks or consequences is put. The composition of the group of experts will be quite different for different uses, such as selection of technological alternatives for a project already decided on, or the determination of whether to do a project or not. In the second case, much more societal input is needed, whereas in the first case a corresponding viewpoint needs to be represented.

In economics and decision theory, the weights  $g_i$  or  $\gamma_i$  are often called value trade-offs or scaling factors, and convert the risk component given in its appropriate units into a new quantity measured in dollars. This leads to the difficult question of the monetary value of a human life (Edwards, 1987; Graham and Vaupel, 1981; Gregory and Lichtenstein, 1987; Keeney and Raiffa, 1976; Merkhofer and Keeney, 1987), and to the problem of the appropriate discount rate for that value if the life is lost to cancer in 10 or 20 years instead of being lost in an occupational accident today. These problems become paramount, if not insoluble, when - as an example - the risk comparison involves different versions of a repository for radioactive wastes, and thus needs to balance the values of money and lives lost today and 5,000 or 10,000 years from now (Graham and Vaupel, 1981; Svenson and Karlsson, 1989).

This difficulty, however, seems to arise not so much from having to make the actual value judgment, but from the practice of expressing the results of that judgment in dollars and using traditional economic methods to discount them. Recent experience has shown that monetary values are not an adequate measure of many societal issues such as health and environmental risks (Keeney, 1990a; Keeney, 1990b; Svenson and Karlsson, 1989). In public perception, many risks carry a price that cannot be measured in dollars (Slovic, 1987; Svenson and Karlsson, 1989). The concern for the safety of future generations is a typical example: since our society has decided to worry about lives that may be lost in the far-off future, it clearly assigns weights which are largely independent of absolute dollar values or meaningful discount rates. By many people, weights are more likely to be assigned on the basis of a rationale such as: every generation should take care of its own wastes and not burden future generations with problems caused by less than optimal methods of disposal.

The normalization of risk components used here side-steps the difficulty of assigning absolute dollar values. Using either the relative risks  $r_{jk}$  or the risk reduction factors  $\Gamma_{jk}$  for disutility or utility, respectively, involves dimensionless quantities. In weighting them, there is also an important change in the question posed: It is no longer "What is the value of a human life lost today relative to the dollar?" but rather "What is the value of a reduction by a factor  $F$  in the risk

of lives lost today relative to the same reduction in the risk of monetary losses?" Appropriate aggregation into consequence components does not change this valuation.

The value of a consequence reduction, however, still depends on the absolute value of the consequence. For a relatively large value, a reduction by a factor  $F$  is more valuable than for a value that is already small. In part, this is but an alternate form of the *LDMU*, reformulated for the fact that risk is a disutility. Class  $\mathfrak{R}_m$  multi-attribute utility functions such as the one in Equation (B.3.11) account in part for this property and the corresponding weights should thus be assigned for the part of the function near unity, i.e., for the neighborhood of  $r_{jk} = 1$  and thus also  $\Gamma_{jk} = 1$ . This takes care of the variability of the utility with respect to the risk reduction factor. The weighting, however, still depends on the absolute value of the baseline risk  $R_{j0}$  for that component. For the relatively small values often encountered for highly controlled operations, the dependence is usually weak. For substantial or large total consequences, with several tens or hundreds of fatalities, however, that dependence is quite strong. Thus, considering the absolute consequence component together with the consequence reduction factor will yield a meaningful weight.

There are a considerable number of methods for eliciting and evaluating expert judgment discussed in the literature (French, 1986; Keeney and Raiffa, 1976). However, the totally different type of valuation needed here will require extra care. Some aspects of importance in this particular type of consequence comparison are discussed in more detail in Attachment G.

## B.4 THE RANKING PROCESS AND UNCERTAINTY

### B.4.1 The Ranking Process and Its Robustness

The values of the utility indices provide a basis to establish a ranking among alternative risks. Some of these rankings, however, may be spurious because the numerical values of the uncertainties in the utility indices may be larger than or comparable to the differences by which preference is established. Due to the uncertainties of the utility functions, two risks may actually be indistinguishable and should be ranked equally.

The ranking of the set  $A$  of  $K$  different alternatives thus leads to sorting them into  $B$  Indifference classes  $I_b$  with one or more members which are mutually indifferent to ranking (French, 1986). Thus, in set notation, the Indifference class  $I_b$  is defined by

$$I_b = \{ \alpha \in A \mid \Theta_\alpha - \Theta_b \}. \quad (\text{B.4.1})$$

It can be shown, however, that there exists a strict preference relationship between the B indifference classes

$$I_{b_1} \succ I_{b_2} \succ \dots \succ I_{b_n} \succ \dots \succ I_{b_m} \quad (\text{B.4.2})$$

where the strict preference between indifference classes is denoted by  $\succ$  and defined by

$$I_a \succ I_b \Leftrightarrow \alpha \succ \beta \quad \text{for any} \quad \begin{array}{l} \alpha \in I_a \\ \beta \in I_b \end{array} \quad (\text{B.4.3})$$

i.e., by the requirement that all elements of the preferred class are strictly preferred to all elements of the other class. On this basis, the classification in Equation (B.4.2) characterizes the ranking information needed in risk comparisons. The value of a consequence reduction index  $\Theta_k$  and its uncertainty  $\Delta\Theta_k$  provide the data for the uncertainty analysis of the ranking process, resulting in a ranking and a multiplicity at equal rank (French, 1986; Goodmann, 1986). The procedure is discussed in Section B.4.3.

#### B.4.2 Standard Error of the Utility Indices

The uncertainty  $\Delta\Theta_k$  of the consequence reduction index arises from the set  $\{x_p\}$  of all P stochastic quantities that enter into the calculation of the index. The Gaussian approximation (Bevington, 1969; Brandt, 1976; Seiler, 1987b) yields for the standard error

$$(\Delta\Theta_k)^2 = \sum_{v=1}^P \left( \frac{\partial \Theta_k(\{x_p\})}{\partial x_v} \right)^2 (\Delta x_v)^2 \quad (\text{B.4.4})$$

An analogous expression can be derived for the risk augmentation index  $\Psi_k$ .

This approximation for small errors contains only the linear term of a multidimensional Taylor series (Korn and Korn, 1968) but should suffice for most cases. If a given risk component involves larger uncertainties, an approximation which is appropriate for large errors, may be required. Examples are the use of lognormal distributions for highly uncertain parameters, the use of higher terms in the Taylor series (Seiler, 1987b), or the use of numerical methods (Cox and Baybutt, 1981; Helton, 1961; Iman and Helton, 1988).

#### B.4.3 Criteria for Indifferent Ranking

Two aspects of risk comparison are important in the process of ranking relative risks or risk reduction factors and using that result in risk management: the *preference* of one alternative over the other, and, conversely, an *indifference to ranking* two alternatives. Membership in these two

sets is determined by a comparison between the difference in consequence reduction indices of two risks and their uncertainties, i.e., by some kind of a statistical test.

The problem of indifference when comparing risks with overlapping probability distributions is different from that encountered in the usual statistical tests. It has been discussed in detail by Goodmann (1986), who derived two criteria for an insignificant difference between two risks by assuming that only the two first moments of the probability distributions, i.e., the means and the standard deviations, are known.

The first is based on a measure of the divergence  $D(X_1, X_2)$  between two distributions  $f_1(x)$  and  $f_2(x)$  derived in information theory

$$D(X_1, X_2) = \int [f_1(x) - f_2(x)] \ln \left( \frac{f_1(x)}{f_2(x)} \right) dx . \quad (\text{B.4.5})$$

The divergence is positive semi-definite, the null value being obtained only for identical distributions. As long as the divergence is smaller than a limiting value  $D_0$ ,

$$D(X_1, X_2) \leq D_0 , \quad (\text{B.4.6})$$

the distributions have an insignificant difference.

The second criterion is of a more statistical nature. At a preset confidence level  $V_0$ , the confidence intervals with the confidence limits  $x_{hi}^{(i)}$  and  $x_{lo}^{(i)}$ ,

$$\int_{x_{lo}^{(i)}}^{x_{hi}^{(i)}} f_i(x) dx = V_0 . \quad (\text{B.4.7})$$

are determined for  $i = 1, 2$ . The confidence levels  $V_{ij}$  for distribution  $i$  within the confidence limits of the distribution  $j$  are then determined by,

$$\int_{x_{lo}^{(j)}}^{x_{hi}^{(j)}} f_i(x) dx = V_{ij} . \quad (\text{B.4.8})$$

From these cross-function confidence levels, the test quantities  $\epsilon_{ij}$  are determined as the relative changes from the confidence level  $V_0$ ,

$$\epsilon_{ij} \equiv \frac{|V_{ij} - V_0|}{V_0} . \quad (\text{B.4.9})$$

These relative increments  $\epsilon_{ij}$  in the confidence levels must be smaller than the limiting relative increment  $\epsilon_0$ , resulting in the two conditions

$$\epsilon_{ij} \leq \epsilon_0 . \quad (\text{B.4.10})$$

Criteria (B.4.6) and (B.4.10) for an insignificant difference between two probability distributions can be combined to sort a set of probability distributions into indifference classes. The limiting values for the two criteria are given in Goodmann's paper for normal and lognormal distributions.

Clearly, Goodmann's method can also be used to establish the indifference between two or more consequence reduction or augmentation indices. As long as the nature of their probability distributions can be estimated with a reasonable degree of confidence, Goodmann's criteria should yield useful results.

Values for the risk reduction indices and their standard errors can be used with Goodmann's criteria for normally or lognormally distributed quantities to establish preference or indifference to ranking between the K indices. It should be noted in this context, that in establishing indifference among three or more quantities, transitivity does not necessarily hold. Therefore, indifference to ranking has to be established for all possible pairs of a set of alternatives. These comparisons then identify the indifference classes  $I_b$ .

#### B.4.4 Distributions of the Consequence Reduction Indices

The errors of the risk reduction indices can be estimated using traditional methods. If it is assumed that the  $n_j$  remaining factors in numerator and denominator of the normalized risk of Equation (B.2.9) are all lognormally distributed, then the multi-attribute utility function (B.3.12) is normally distributed and the standard error can be estimated directly. According to Equation (B.3.19), the consequence reduction indices are then lognormally distributed.

Remaining factors with normal or mixed distributions in Equation (B.2.9) can give rise to problems. In that case Mellin transforms can be used (Springer, 1979) or numerical methods such as Monte Carlo calculations. However, such complex methods may not be needed. As long as the total number I of contributions to the J components of the total risk is relatively large, say 10 or so, and a sizeable fraction of these I terms contributes substantially to the total, the central limit theorem of probability theory states that the multi-attribute utility index is approximately

normally distributed (Korn and Korn, 1968). The consequence reduction indices are then lognormally distributed, and for narrow distributions, an approximate normal distribution can be used. In that case, the tables for lognormal or normal distributions in Goodman's paper can be used to determine the limiting criteria (Goodman, 1986).

## **B.5 PRACTICAL APPLICATIONS**

### **B.5.1 Utility Index as Weighted Arithmetic Mean**

Practical applications of the utility function defined by Equation (B.3.10) to problems involving risk among the attributes already exist (Keeney and Raiffa, 1976). A similar approach has been suggested for the selection of routes for the transport of hazardous materials (Seiler, 1988). Although the marginal utilities in Equation (B.3.10) do not allow for the *LDMU*, the conditions for which linearity is a useful concept are met quite often, typically in a choice among pre-selected alternatives, where those with sizeable differences in important risk components are no longer present.

The evaluation of sites for the high-level radioactive waste repository, leading to a reduction of the number of sites from five to three (Keeney, 1987; Merkhofer and Keeney, 1987), is a typical example in which the less appropriate sites have already been eliminated. In this example, considerations other than risk were included also. However, the final decision by the Department of Energy dropped a number of attributes such as cost and made the decision based mostly on risk components. In these evaluations, no consideration was given to the uncertainty of the utility indices, and indices with rather small differences were ranked as different, although there is a suspicion that some of them might be indifferent to ranking.

A widely used method of multiple criterion decision making that is in many ways similar to the linear combinations of utility functions is the Analytical Hierarchy Process of Saaty (Saaty, 1980; Saaty and Vargas, 1982; Zahedi, 1986). It can be viewed as incorporating most aspects of the utility function and its weight into the weighting of the hierarchy. Formally this can be viewed as setting the marginal functions in an additive value function to unity at every level (Kamenetzky, 1982). The hierarchy process is ordinal and does not allow for the incorporation of distribution functions for the parameters, which would result in a standard error for the total weight.

### **B.5.2 Logarithmic Utility Functions**

The utility functions most likely to meet the needs of risk comparisons are class  $\mathcal{X}_m$  functions. Among the functions of this class, the weighted logarithmic average of Equation (B.3.17) seems to be the easiest to use. Risk comparisons often involve components that are dramatically different due to determined attempts at risk reduction. Efforts to reduce some components of the total risk, however, almost always result in increasing some other components, often by a

considerable factor. The logarithmic dependence of Equation (B.3.17) covers these ranges quite easily. It is for these reasons that in the first practical application of the approach presented here, this function will be used in a comparison of the total risks of engineered alternatives for the treatment of transuranic wastes to be emplaced in the WIPP.

Apart from the logarithmic single-attribute utility functions, the two major differences between the approaches discussed in the last section and the one discussed here are the calculation of dimensionless relative risks or risk reduction factors, and the use of error estimates for the utility indices. The dimensionless approach avoids the necessity to estimate the value of social costs and losses in terms of dollars or some other unit, and allows a direct valuation in terms of an increase or decrease of a consequence reduction factor. The use of uncertainties allows the application of the concept of indifference to ranking, resulting in groups of indistinguishable consequence reduction indices.

## B.6 DISCUSSION

Some of the tools of multi-attribute utility theory have been used to construct a framework for the comparison of multicomponent risks. Contrary to its application in economics or in public policy decisions, however, the aim is not to predict an optimal course of action for public policy or the investment behavior of an individual or a corporate entity. The intent is rather to provide a transparent method for ranking multicomponent risks, using a somewhat arbitrary but intuitively appealing rationale.

No attempt is made to arrive at a single, 'correct' solution for all segments of society. On the contrary, the ranking obtained here is clearly not unique but depends on the numerical values assigned to the weights for each risk component. This method can thus be used by anyone with a different system of societal values to derive his or her own ranking of the same risks, based on the same set of values for the marginal utility functions in Equation (B.3.13). This approach is in effect an attempt to put the comparison of risks on a rational basis without ignoring different sets of subjective, personal, or institutional valuations.

On the other hand, this method allows a direct evaluation of the influence of different value judgements on the ranking process. In many cases, the information that widely different valuations that do or do not have a drastic impact on the ranking process may be an important datum to come out of the risk comparison.

In this context, it should be noted that the method introduced here is a quite general procedure which is applicable for the comparison of many multi-component quantities. Of course, the use of class  $\mathcal{X}_m$  and  $\mathcal{X}_s$  functions must be justified for each particular case; otherwise, other classes can be defined which have the appropriate properties for the utility functions of the particular problem at hand.

Another important aspect of the method proposed here is the use of the standard errors of the consequence reduction indices to determine the significance of a difference between two total risks and, thus, to determine a possible indifference to ranking. This is a neglected aspect of comparisons which can be addressed here because of the normalization to relative risks and risk reduction factors proposed, and because both first-order and higher-order approximations are available for the calculations of error propagation.

It should be noted that these error estimates only address the random but not the systematic errors in the risk calculations. Due to their nature, the treatment of systematic errors is difficult, if it is possible at all (Seiler, 1990a). However, in the normalization process, systematic errors may cancel entirely or at least in part. Combined with the use of class  $\mathcal{R}_m$  multi-attribute utility functions, in particular that of Equation (B.3.17), this approach thus allows to make a routine estimate for the standard errors of the utility indices which are needed in this process.

The use of the weighted geometric mean in Equation (B.3.18) as the multi-attribute utility function of choice is, of course, arbitrary and is defensible mainly as one of the simplest choices among class  $\mathcal{R}_s$  and class  $\mathcal{R}_m$  functions. It is important in this context, to remember that the intent of the method presented here is not to make valid predictions of economic or social behavior but to provide a framework for the comparison of risks according to different valuations.

Comparisons of total risks are usually made in order to support the making of technical or public policy decisions. For that use of the comparison of the risks of alternatives, the main points are:

1. A ranking of risks is merely a decision tool; it should not and cannot replace the decision maker.
2. A ranking of risks is only rarely the sole basis for a decision; many other criteria enter into that process.
3. The existence of an insignificant difference between some total risks allows focusing on the question which of the other attributes exert the largest influence on the decision.

The ranking of several risks into a number of groups of insignificantly different utility indices can support many types of decisions. Important among them are decisions between technological options in all phases of the process of realizing a complex project. As pointed out above, an important facet of these decisions is the fact that risk is just one of the factors that influence the outcome and is by no means the most important one. In most applications where risk is introduced as one of the final decisive factors, risk assessment is not used to best advantage. A frequent use of risk comparisons in every decision phase of a project will make more appropriate use of the process (Seiler, 1990b).

In this context it is important to remember that two decision makers are involved in such a process: one at the level of the risk comparison and one at the level of the subsequent technical or policy decision. The concerns of both have to be injected into the weighting, taking into account the contribution of each consequence component. This interaction between the two decision makers is an essential step in the integration of the risk comparison into the next higher decision process.

## ATTACHMENT C

### UNCERTAINTIES AND AGGREGATION OF RISK COMPONENTS

#### C.1 PROPAGATION OF ERRORS

##### C.1.1 Gaussian Approximation

##### C.1.1.1 General Considerations

The uncertainties of parameters and variables in a function result in an uncertainty in the function value. This is called propagation of errors of the input values through the function. Analytical expressions for the propagation of errors through algebraic expressions are normally based on a number of assumptions such as the requirements that all stochastic variables contributing to the result are normally distributed, that all partial derivatives of second or higher order are very small, and that the relative errors of the stochastic variables are small. The absence of correlations between the stochastic variables makes the formulae much more manageable; however, if correlations do occur, they are assumed to be limited to correlations between only two variables.

The existence of an analytical expression for the propagation of errors, although often cumbersome algebraically, brings several advantages to the error analysis. The most important is that the algebraic properties of the expression can be studied independent of the size of the contributing standard errors. Another is that the contribution of each variable to the total uncertainty of the result can easily be isolated, making sensitivity studies relatively simple.

In numerical evaluations of differential equations and other mathematical procedures, it is obviously impossible to obtain an algebraic expression for error propagation, but numerical methods are available to obtain the necessary information (Cox and Baybutt, 1981; Iman and Helton, 1988). Often, these results can then be inserted into the algebraic expression for the rest of the calculation, thus restoring the advantages of the analytical solution.

Even so, it is generally recognized that it is more difficult and often more time consuming to determine the standard error of a stochastic variable than to actually measure it. Similarly, error propagation is a more difficult and complex procedure than the direct evaluation of the numerical value of a risk or some other quantity.

### C.1.1.2 Gaussian Approximation for Normally Distributed Quantities

To study the propagation of standard errors through an arbitrary algebraic function  $F$ , it is assumed that all needed derivatives of that function with regard to its variables and parameters  $x_i$  exist. Thus,

$$F = \Phi(\mathbf{x}) = \Phi(x_1, \dots, x_n), \quad (\text{C.1.1})$$

where all parameters are normally distributed stochastic variables and parameters have a mean  $x_i$  and standard errors  $\Delta x_i$ . The variables can be arranged as a vector  $\mathbf{x} = (x_1, \dots, x_n)$ . As long as the relative errors are small, i.e.,  $\Delta x_i \ll x_i$ , a multidimensional Taylor series (Korn and Korn, 1969), can be used to approximate the function  $\Phi(\mathbf{x})$  and terminated after the first term. For independent variables  $x_i$ , statistical theory requires an incoherent superposition of the amplitudes (Bevington, 1969; Brandt, 1976; Seiler 1987b) in the expansion

$$(\Delta F)^2 = \sum_{i=1}^n \left\{ \left( \frac{\partial \Phi(\mathbf{x})}{\partial x_i} \right) \Delta x_i \right\}^2. \quad (\text{C.1.2})$$

Here the partial derivatives (in braces) are to be evaluated at the point  $\mathbf{x}$ . This approximation is only valid for small errors. For larger errors, additional terms in the Taylor series expansion are needed. When using higher order terms, care must be taken to ensure convergence of the series. In algebraic forms, such as  $F = x^{-1}$ , the pole near  $x = 0$  may lead to semiconvergence or outright divergence (Seiler, 1987b).

Expression (C.1.2) assumes that the quantities  $x_i$  and their errors  $\Delta x_i$  are uncorrelated. If the errors  $\Delta x_i$  are correlated, more terms are needed in a coherent superposition of amplitudes (Bevington, 1969; Brandt, 1976; Seiler 1987b). The Gaussian approximation is then

$$(\Delta F)^2 = \sum_{i=1}^n \sum_{j=1}^n \left( \frac{\partial \Phi(\mathbf{x})}{\partial x_i} \right) \left( \frac{\partial \Phi(\mathbf{x})}{\partial x_j} \right) \sigma_{ij}^2, \quad (\text{C.1.3})$$

where the quantities  $\sigma_{ij}^2$  are the elements of the covariance matrix between the variables  $x_i$  and  $x_j$ , and the partial derivatives are again evaluated at the point  $\mathbf{x}$ . The diagonal elements are the standard errors

$$\sigma_{ii}^2 = (\Delta x_i)^2, \quad (\text{C.1.4})$$

and the off-diagonal elements  $\sigma_{ij}^2$  are the covariances which measure the degree of correlation between the corresponding variables.

### C.1.1.3 Gaussian Approximation for Lognormally Distributed Quantities

A lognormal distribution for a variable  $x$  is a distribution with the property that the distribution for  $\log_e x$  is a normal distribution. It is most often used in evaluating the standard error of highly uncertain stochastic variables. The lognormal distribution in linear space is characterized by a mean  $X$  and the geometrical standard deviation  $\sigma_g(X)$ . It is related to the upper and lower 68% limits  $X_+$  and  $X_-$  by the relations

$$X_+ = X \sigma_g(X), \quad (\text{C.1.5})$$

and

$$X_- = \frac{X}{\sigma_g(X)}. \quad (\text{C.1.6})$$

Similarly, the upper and lower 95% limits  $X_{hi}$  and  $X_{lo}$  are given by

$$X_{hi} = X \sigma_g^2(X), \quad (\text{C.1.7})$$

and

$$X_{lo} = \frac{X}{\sigma_g^2(X)}, \quad (\text{C.1.8})$$

Error propagation using Equations (C.1.2) or (C.1.3) can be studied by a transformation of the function in Equation (C.1.1) into logarithmic space. Obviously, this is most profitable for products or products of powers, which reduce to linear combinations in logarithmic space.

### C.1.1.4 Approximations for Quantities With Different Distributions

If an expression contains stochastic variables with different distributions, an algebraic approach is sometimes possible using Mellin transformations (Springer, 1979). Normally, however, numerical methods such as Monte Carlo calculations have to be used. A number of numerical procedures and spreadsheet codes have recently become available. They will not be used here, however.

## C.1.2 Basic Expressions Often Used in This Report

### C.1.2.1 Error Propagation for Normally Distributed Quantities

From the general equation, special expressions for error propagation in simple algebraic forms can be generated. For more complex forms, some of the more advanced tools of calculus may be needed to generate the error propagation formulae. Here, only the simplest forms will be discussed explicitly. The assumption is made that the stochastic variables  $x_i$  are uncorrelated.

#### C.1.2.1.1 Sums and Differences

For direct sums and differences of stochastic variables, written in a general way as

$$F_1 = \Phi_1(x) = \sum_{i=1}^n (\pm 1) x_i, \quad (\text{C.1.9})$$

where  $x$  is the parameter vector;  $x = (x_1, \dots, x_n)$  and the factor  $(\pm 1)$  indicates a free choice of sign for every term. The general equation then yields the expression

$$(\Delta F_1)^2 = \sum_{i=1}^n (\Delta x_i)^2. \quad (\text{C.1.10})$$

Thus, for sums or differences, the square of the standard error is equal to the sum of the squares of the standard errors for all terms.

Often, linear combinations of stochastic variables are encountered, such as

$$F_2 = \Phi_2(x) = \sum_{i=1}^n (\pm 1) a_i x_i. \quad (\text{C.1.11})$$

If the parameters  $a_i$  are non-stochastic parameters, the standard error is

$$(\Delta F_2)^2 = \sum_{i=1}^n (a_i \Delta x_i)^2. \quad (\text{C.1.12})$$

It should be noted that the expressions above are exact, because there are no second order terms in the Taylor series.

If the parameters  $a_i$  are stochastic quantities with standard errors  $\Delta a_i$ , however, the standard error is given by

$$(\Delta F_2)^2 = \sum_{i=1}^n \left\{ (a_i \Delta x_i)^2 + (x_i \Delta a_i)^2 \right\}, \quad (\text{C.1.13})$$

which is no longer exact, but an approximation of the Gaussian type.

#### C.1.2.1.2 Products and Ratios

For a function  $\Phi$  which is a product of the form

$$F_3 = \Phi_3(x) = \prod_{i=1}^n x_i^{\pm 1}, \quad (\text{C.1.14})$$

where the exponent ( $\pm 1$ ) indicates a free choice of exponent for every factor, the application of Equation (C.1.2) yields the expression

$$\left( \frac{\Delta F_3}{F_3} \right)^2 = \sum_{i=1}^n \left( \frac{\Delta x_i}{x_i} \right)^2. \quad (\text{C.1.15})$$

Thus for products and ratios, the square of the relative standard error is the sum of the squares of the relative standard errors of all factors. More generally, for a product of powers

$$F_4 = \Phi_4(x) = \prod_{i=1}^n x_i^{p_i}, \quad (\text{C.1.16})$$

the basic equation for the Gaussian approximation yields

$$\left( \frac{\Delta F_4}{F_4} \right)^2 = \sum_{i=1}^n p_i^2 \left( \frac{\Delta x_i}{x_i} \right)^2. \quad (\text{C.1.17})$$

All these equations are no longer exact but are approximations. Also, for ratios, care must be exercised with large errors due to the proximity of the pole for  $1/x_i^n$  at  $x = 0$ . For larger errors, it is advisable to express standard errors as geometric standard deviations for lognormal distributions.

### C.1.2.2 Error Propagation for Lognormally Distributed Quantities

The most appropriate application of lognormal distribution involves products of powers of variables, such as

$$F_s = \Phi_s(x) = \prod_{i=1}^n x_i^{p_i}. \quad (\text{C.1.18})$$

In logarithmic space to base  $a$ , the function value  $F_s$  is then a normally distributed quantity because the variables  $\log_a x_i$  are normally distributed and the factors  $p_i$  are non-stochastic,

$$\log_a F_s = \sum_{i=1}^n p_i \log_a x_i. \quad (\text{C.1.19})$$

By defining the transformed variables as

$$y_s = \log_a F_s,$$

$$y_i = \log_a x_i, \quad (\text{C.1.20})$$

$$S_i = \log_a [\sigma_g(x_i)],$$

the function  $y_s$  is a linear combination of normally distributed stochastic variables

$$y_s = \sum_{i=1}^n p_i y_i. \quad (\text{C.1.21})$$

This expression has the same structure as Equation (C.1.11) and the exact expression for error propagation is given by

$$(\Delta y_s)^2 = \sum_{i=1}^n (p_i S_i)^2. \quad (\text{C.1.22})$$

Transformation back into linear space yields

$$\sigma_g(F_5) = a^{\Delta y_5}, \quad (\text{C.1.23})$$

because of the relationship

$$\Delta y_5 = \log_a [\sigma_g(F_5)]. \quad (\text{C.1.24})$$

### C.1.3 Useful Approximations for Error Propagation

#### C.1.3.1 Function of Normally Distributed Variables

Writing the expression for error propagation in the Gaussian approximation in the general form,

$$(\Delta f)^2 = (a\Delta\alpha)^2 + (b\Delta\beta)^2 + \dots, \quad (\text{C.1.25})$$

can be useful to study the influence of standard errors of different relative magnitudes. Assume that the terms on the right-hand are rearranged with  $(a\Delta\alpha)$  being the largest term. The expression can then be rearranged again to give

$$\begin{aligned} \Delta f &= (a\Delta\alpha) \left\{ 1 + \left( \frac{b\Delta\beta}{a\Delta\alpha} \right)^2 + \dots \right\}^{1/2} \\ &= (a\Delta\alpha) \sqrt{1 + (B)^2 + \dots} \\ &= (a\Delta\alpha) [1 + C]. \end{aligned} \quad (\text{C.1.26})$$

This last equation can be used to obtain a limit for the ratio B which yields a negligible contribution C to the total error. Thus, setting  $B = 1/3$  shows that a term  $(b\Delta\beta)$ , which is three times smaller than  $(a\Delta\alpha)$ , contributes only five percent to the final error. This is due to the "sums of squares" structure of Equation (C.1.2) (Seiler, 1987b). For other ratios of B, the contributions are given in Table C.1-1 and shown in Figure C.1-1. According to the judgment of the investigator, the contribution of the smaller error can be neglected for a critical ratio B, say below  $B = 1/3$ . In this context, it should be borne in mind that, as second moments of a distribution, standard errors are always more uncertain than the means themselves (first moments). It is also important to note that, according to Equation (C.1.2), the ratio B is not always the ratio of the standard errors but the ratio of the products of the derivatives with the standard errors.

TABLE C.1-1

RELATIVE CONTRIBUTION OF THE SMALLER STANDARD ERROR IN  
THE GAUSSIAN APPROXIMATION

RATIO B	CONTRIBUTION C
1/1	41%
1/2	12%
1/3	5%
1/4	3%
1/5	2%
1/6	1%

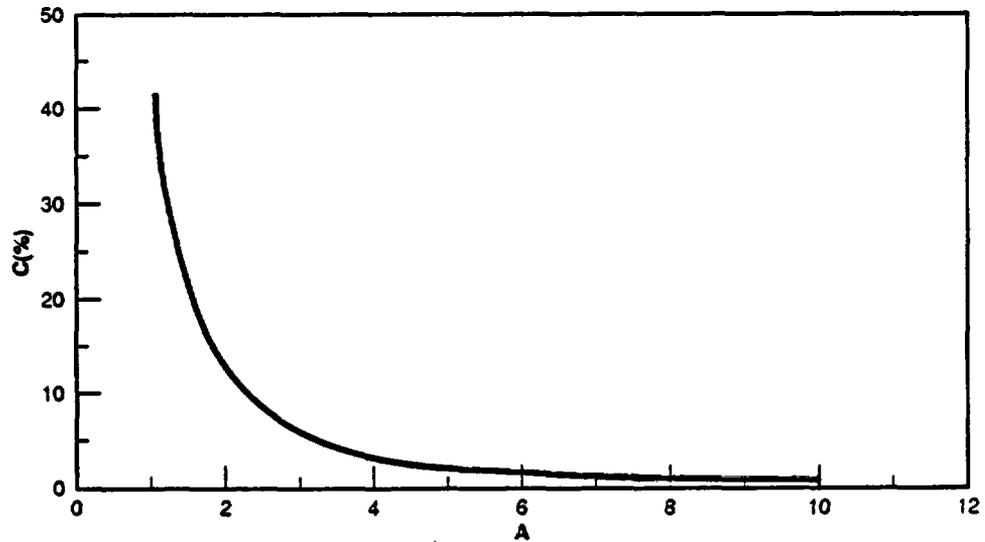


FIGURE C.1-1 Relative Contribution of the Smaller Standard Error in the Gaussian Approximation

### C.1.3.2 Lognormal Distributions

Sums or differences of lognormally distributed variables are no longer lognormally distributed variables. An approximation useful for error propagation is to fit two different normal distributions to the upper and the lower parts of the lognormal distributions of each term and treat them separately. Thus, the lognormally distributed terms  $a_i$  in the sums or differences with geometric standard deviations  $\sigma_g(a_i)$  have upper and lower 68% limits of

$$a_{i,hi} = a_i \sigma_g(a_i), \quad (C.1.27)$$

and

$$a_{i,lo} = \frac{a_i}{\sigma_g(a_i)}. \quad (C.1.28)$$

A normal distribution with the same limits has standard errors of

$$\Delta a_{i,hi} = [\sigma_g(a_i) - 1] \quad (C.1.29)$$

for the upper limit, and

$$\Delta a_{i,lo} = \left[ 1 - \frac{1}{\sigma_g(a_i)} \right] \quad (C.1.30)$$

for the lower limit. These are assigned for every term in sums or differences. The sum of a number of these terms

$$S = \sum_{i=1}^n (\pm 1) a_i, \quad (C.1.31)$$

where the factor  $(\pm 1)$  indicates an arbitrary sign for each term, has an upper limit of

$$S_{hi} = S + \sqrt{\sum_{i=1}^n a_i^2 [\sigma_g(a_i) - 1]^2}, \quad (C.1.32)$$

and a lower limit of

$$S_{lo} = S - \sqrt{\sum_{i=1}^n a_i^2 \left[1 - \frac{1}{\sigma_g(a_i)}\right]^2}. \quad (C.1.33)$$

The distribution of S is approximately normal for a large number of terms (10 to 20) according to the Central Limit Theorem (Korn and Korn, 1968). For only a few terms, the largest term is likely to determine the resulting distribution. These may thus be approximately lognormal. Similarly, if a large number of terms is dominated by one contribution, the distribution of the sum resembles a lognormal distribution.

In a lognormal approximation to the resulting distribution of the sum S, the geometric standard deviation is approximated by

$$\sigma_g(S) = \left(\frac{S_{hi}}{S_{lo}}\right)^{1/2}. \quad (C.1.34)$$

The mean is best derived by the first or second expression on the right-hand side

$$S \equiv S_{lo} \sigma_g(S) = \frac{S_{hi}}{\sigma_g(S)}. \quad (C.1.35)$$

In a normal approximation to the resulting distribution of the sum S, the mean is given by

$$S \equiv \frac{1}{2} (S_{hi} + S_{lo}), \quad (C.1.36)$$

and the standard error by

$$\Delta S \equiv \frac{1}{2} (S_{hi} - S_{lo}). \quad (C.1.37)$$

A choice between the two approximations is best made on the basis of the actual values  $a_i$  and  $\sigma_g(a_i)$  involved.

## C.2 AGGREGATION OF RISK COMPONENTS

### C.2.1 Weighted Averages for the Aggregation Risk Reduction Factors

#### C.2.1.1 Aggregations Using Weighted Arithmetic Averages

The arithmetic mean is most often used for the process of weighted averaging

$$X = \sum_{i=1}^n w_i x_i, \quad (\text{C.2.1})$$

where the average is performed over the set  $\{x_n\}$  of quantities using the normalized weights  $w_i$

$$\sum_{i=1}^n w_i = 1. \quad (\text{C.2.2})$$

For the aggregations encountered in this risk assessment, baseline risk components are used to generate the weights according to

$$w_i = \frac{R_{i\delta\kappa\lambda}}{\sum_{\tau=\{n_i\}} R_{\tau\delta\kappa\lambda}}, \quad (\text{C.2.3})$$

where  $\delta = 'o'$  or  $'p'$  for occupational and public, respectively, and  $\{n_i\}$  is the set of baseline risks being aggregated. The aggregated risk reduction factor then becomes

$$\Gamma_{j\kappa\lambda} = \sum_{\xi=\{n_i\}} w_\xi \rho_{\xi\delta\kappa\lambda}. \quad (\text{C.2.4})$$

Note that factors common to all component risks  $R_{j\delta\kappa\lambda}$  cancel in Equation (C.2.3). This is a characteristic common to this kind of weighting processes which are independent of multiplication by an arbitrary factor. Consequently, in radiation risks, for instance, it is sufficient to know the doses in order to perform a weighted average; there is no need to actually convert doses to risks. Usually weights thus have errors that are rather small compared to those of the risks. In many cases they can be neglected in comparison to those of the risk reduction factors being aggregated. Then, the error of the aggregated risk reduction factor  $\Gamma_{j\kappa\lambda}$  is given by the equation

$$(\Delta \Gamma_{j\kappa\lambda})^2 = \sum_{\xi \in \{n_j\}} (w_{\xi} \Delta \rho_{\xi\delta\kappa\lambda})^2 . \quad (\text{C.2.5})$$

As long as the weight can be regarded as a non-stochastic quantity, this expression is exact and holds even for large relative errors of  $\rho_{\xi\delta\kappa\lambda}$ .

In cases where the standard error of the aggregation weight cannot be neglected, it is useful to note that the denominator of Equation (C.2.3), after all common factors in the numerator and denominator have been eliminated, contains one term with the same factors as the numerator. An evaluation of the standard error using the general Gaussian error propagation formula will, therefore, lead to a partial compensation of the component errors. The resulting standard error of the weighting factor  $\Delta w_{\xi}$  can then be used to calculate the error of the aggregated risk reduction factor according to Equation (C.1.13),

$$(\Delta \Gamma_{j\kappa\lambda})^2 = \sum_{\xi \in \{n_j\}} \left\{ (w_{\xi} \Delta \rho_{\xi\delta\kappa\lambda})^2 + (\rho_{\xi\delta\kappa\lambda} \Delta w_{\xi})^2 \right\} . \quad (\text{C.2.6})$$

This expression is not exact and holds for small relative errors of both factors only. If the relative errors of  $\rho_{\xi\delta\kappa\lambda}$  and  $w_{\xi}$  are not small, an exact expression can be derived (Seiler, 1987b).

### C.2.1.2 Aggregations Using Weighted Geometric Average

The geometric average is an arithmetic average taken in logarithmic space. Using the definition  $y_i = \log_a x_i$ , the weighted arithmetic mean is given by

$$Y = \sum_{i=1}^n w_i y_i . \quad (\text{C.2.7})$$

A transformation back into linear space leads to the expression

$$X = \prod_{i=1}^n x_i^{w_i} . \quad (\text{C.2.8})$$

The usual exponent of  $1/n$  is not in evidence here, because the sum of the weights is normalized to unity according to Equation (C.2.2). Here again, the weights are independent of common factors. This form of weighted averaging is best employed when the values  $x_i$  are distributed over a wide range, for instance over many orders of magnitude. In such cases, the arithmetic mean has a tendency to a bias in favor of the highest value.

In the aggregation of risk reduction factors with weights given by Equation (C.2.3), the aggregated risk reduction factor is given by

$$\Gamma_{j\kappa\lambda} = \prod_{\xi=\{n_i\}} (\rho_{\xi\delta\kappa\lambda})^{w_\xi}. \quad (\text{C.2.9})$$

For weights with small standard errors that can be neglected compared to those of the risk reduction factors, the standard error of the aggregated risk reduction factor is

$$\left( \frac{\Delta \Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}} \right)^2 = \sum_{\xi=\{n_i\}} \left( w_\xi \frac{\Delta \rho_{\xi\delta\kappa\lambda}}{\rho_{\xi\delta\kappa\lambda}} \right)^2. \quad (\text{C.2.10})$$

For non-negligible but still small relative errors of the weights  $w_\xi$ , the error propagation formula yields the expression

$$\left( \frac{\Delta \Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}} \right)^2 = \sum_{\xi=\{n_i\}} \left\{ \left( w_\xi \frac{\Delta \rho_{\xi\delta\kappa\lambda}}{\rho_{\xi\delta\kappa\lambda}} \right)^2 + (\ln \rho_{\xi\delta\kappa\lambda} \Delta w_\xi)^2 \right\}. \quad (\text{C.2.11})$$

For larger relative errors, a sufficient approximation can be obtained (Seiler, 1987b).

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**ATTACHMENT D**  
**AUXILIARY MODELS FOR HANDLING AND TREATMENT**  
**OF THE WASTES**

**D.1 HANDLING AND TREATMENT OF WASTE**

**D.1.1 Baseline Case**

The baseline case assumes no treatment of the waste, either prior to or after its arrival at the WIPP facility. The waste is handled for assay and certification and transported through two separate areas: the Waste Handling Building (WHB) at ground level, and the Underground Storage Area. The baseline scenario for untreated waste comprises all routine operations and accident events incorporated in the FSEIS (DOE, 1990a). However, only average drums are considered in this report, even though the FSEIS addresses special drums, such as those with an activity of 1000 PE-Ci (37 TBq).

The handling operation that is best suited to serve as the baseline operation is the initial handling of the wastes in the Waste Handling Building, in particular the assay and certification of the waste. It is already included in the baseline, but can serve well as a standard for risk increases. Unfortunately, it is a small operation and baseline risks for many aspects are not available in the FSEIS.

**D.1.1.1 Operations in the WHB**

The waste is brought into the WHB in TRUPACT-II containers through entry air locks, inspected and unloaded. In the Receiving and Inspection Area, the drums are then assayed and certified, and loaded onto facility pallets. The facility pallet is subsequently transferred to the hoist air lock by forklift. The total crew working inside the WHB consists of 12 people (DOE, 1989a): 9 waste handlers, 2 health physicians, and 1 Quality Assurance person. Two forklift operations are required inside the WHB: one to transport the TRUPACT-II, one to transfer the palletized load to the hoist air lock.

All operations in the WHB are assumed to be independent of waste treatment. Drums heavier due to treatment are assumed to be handled by proportionally heavier equipment at equal risk.

**D.1.1.2 Operations Underground**

Once inside the hoist air lock, the facility pallet is transferred to the underground station by waste hoist. Operations below ground consist of transferring the waste to the diesel transporter and transportation to the final waste storage area. In the final waste storage area, the drums are removed from the transporter by forklift, and emplaced in the selected location. Underground

operations total two forklift and one diesel transporter operation. Total crew underground consist of four people (DOE, 1989a): two waste handlers, one health physicist, and one Quality Assurance person. In this assessment, it is assumed that neither personnel, forklift, nor transporter operations are influenced by waste treatment. For heavier drums, heavier forklifts are used.

#### **D.1.2 Treatment Facility**

In the limited scope of this study, the Treatment Facility (TF) is assumed to consist of a number of identical modules, each consisting of up to six different operational areas, according to the Treatment Option selected. According to the location option, these modules are grouped into one, three, five or seven facilities of appropriate capacity. In Level II treatments, that is, in Treatment Options 1 and 2, only two operations are needed: shredding and cementing. Additional operations are needed for the two Level III treatments. In Treatment Option 3, incineration and cementing of the ashes are added, resulting in a total of four operations: sorting, shredding, incinerating, and cementing. In the most complex Treatment Option cementing is dropped and two more operations are added: smelting and vitrifying.

The seven groups of modules are planned to operate independently from one another, regardless of their location and distribution. This model of the treatment plant, therefore, does not account for any economies of size, thereby introducing a slight bias in favor of decentralized treatment facilities. This bias is mostly monetary, but the risk is influenced mainly by potential economies of manpower, which are not addressed here.

One additional assumption is made concerning the average drum. Sludges are usually in drums by themselves. Thus the appropriate fraction of sludge-filled drums is assumed (Vetter, 1990), with the rest filled by a mix of combustibles, metals, and glasses in the proper proportions.

#### **D.1.3 Risk Components Considered Here**

The risk components associated with specific operations of handling and transportation of the waste during the waste treatment, that are discussed in the FSEIS, are included in that part of the evaluation of the total risk. The risk components considered here stem from radiation and hazardous chemicals encountered during the actual treatment process, and from general work accidents found in similar industrial operations.

As general occupational accidents and injuries, not directly related to effects of radiation and toxic chemicals, are important in comparing different levels of treatment with different manpower requirements, two risk components are added to those considered in the FSEIS: occupational accident fatalities and occupational accident and exposure injuries. These components will change with increasing manpower needed for the more complex treatments of the waste.

#### **D.1.3.1 Radiation and Chemical Risk of the Actual Treatment Process**

Despite containment of the wastes and shielding against nuclear radiation, workers are exposed to low levels of radiation and hazardous chemicals originating from the waste. Normal operational releases would encompass radiation exposures at a certain distance from the waste, and inhalation of volatile organic chemicals present in the waste. Accident releases would encompass larger radiation doses due to loss of containment for radioisotopes, and larger exposure to chemicals in the waste.

#### **D.1.3.2 General Work Accidents in Similar Industry**

The majority of the operations conducted with the waste, before, during and after the treatment process, involve handling and transportation. Within those operations, there are risks associated with manual and mechanized work, which are unrelated to the nature or composition of the waste. Since the largest number of man-hours during handling are spent on forklift operations, data for injuries and fatalities, and corresponding risk components associated with forklift operations, have been obtained. Other accidents, associated with malfunctions and breakdowns of a mechanical nature, are not treated separately, due to the assumption that such an accident would not result in direct injuries or fatalities.

Within the risk components mentioned, both public and occupational risks arising from normal operations (such as routine handling and maintenance) and accident events are taken into account.

#### **D.1.4 Risk Components Not Considered Here**

For the actual waste treatment, the risks due to operational accidents are not considered in this report, due to the large effort required for the evaluation of the overall risk associated with numerous potential accidents. This decision will tend to slightly bias the evaluation in favor of treatment. This bias, however, should not be too noticeable because the risk of process accidents is usually not very large, compared to other components.

In the evaluation of internal exposures to radioisotopes, only inhalation risks are considered. Direct ingestion risks are neglected, due to the much smaller probability of occupational ingestion of CH TRU waste. Even in the case of externally contaminated drums, where waste could come into direct contact with the handlers, protective clothing and initial radiological surveys would minimize the risk of waste ingestion. For such cases, the major component of the risk would arise from possible inhalation of suspended waste.

Also not taken into consideration, but referenced in the FSEIS and FSAR documents (DOE, 1989a), are risks arising from inhalation of diesel exhaust from the waste transporters, and from the operation and maintenance of electric-powered forklifts. It is assumed that transporters and

forklifts are electric powered and they have the appropriate power to handle the drums of the waste treatment chosen. Thus no changes are foreseen with waste treatment.

## D.2 MODELS FOR TREATMENT OPERATIONS

### D.2.1 General Considerations

The basic assumption in modeling treatment operations in the TF is that the same health and safety standards based on the As Low As Reasonably Achievable (ALARA) concept are observed here as in the WHB. Thus, any perceived risk will be minimized within the limits generally observed in nuclear research and industry, based on DOE and NRC guidelines.

Shielding against penetrating radiation will be based on routine time-motion studies for normal operation and maintenance. Monitors for direct radiation, continuous air monitors for high- and low-LET radiation are in operation for an early indication of potential health and safety problems. The risk of exposure to volatile organic compounds is the only one involving chemical agents that is evaluated here. Exposure to metals and halogenated and other toxic organics by ingestion or skin contamination is not treated in the FSEIS and will, therefore, not be considered.

Maintenance operations are assumed to be driven by ALARA considerations. Their frequency is aimed at keeping the contamination remaining after self-decontamination of the device within bounds. The frequency is thus assumed to be a design parameter without uncertainty. The operation and maintenance of a treatment plant results in a considerable amount of secondary wastes from operation and, above all, from maintenance (decontamination). From health physics operations in existing facilities, this secondary waste is assumed to amount to 2 to 3 percent of the wastes treated. A simple linear model that accounts for secondary wastes increases the number of drums received annually from 40,000 to 41,000, that is, feeds the secondary wastes back into the incoming waste stream. Note, however, that the baseline load remains at 40,000 drums annually.

Effluent controls are needed to bring the facility into compliance with all applicable regulations. Ventilation air is passed through HEPA filters, liquids are processed, and filters and process waste added to the secondary waste.

### D.2.2 Treatment Operations

#### D.2.2.1 Assay and Certify Operations

This operation is the same for all drums that arrive at the TF and the WHB. No credit is taken for the easier operation at the WHB for treated waste with more reliable certification. However, increased forklift operations and general industrial risks are accounted for.

Routine and maintenance operations are defined to serve as baseline for other operations. Intra-site transport by forklift, crane, and conveyor belts is designed to minimize human exposures.

Assay and certify operations are assumed to need 0.6 man-hours per drum with a standard error of about 10 percent. For maintenance of the area,  $96 \pm 12$  man-hours are estimated for every maintenance operation. Maintenance is estimated to be necessary after processing 1000 drums.

#### D.2.2.2 Sorting Operations

Sorting is needed only for Level III treatments, that is, for Treatment Options 3 and 4. It involves breaking the liners and all wrappings, allowing all gases in the headspace to vent into the containment. Sorting is either done in bubble suits inside the containment or by operators working with gloveboxes and conveyor belts.

Routine sorting is assumed to require  $1.5 \pm 0.15$  man-hours per drum; for the maintenance of the sorter containment  $96 \pm 12$  man-hours are estimated. It is again estimated that maintenance is needed after 1,000 drums.

#### D.2.2.3 Shredding Operations

The shredding operation will be doubly contained with an air lock system to transfer waste containers to the shredder. Waste containers will be additional waste, assumed to be passed through the shredder. Shredding is a high dust producing operation that will require an efficient air cleaning system, monitoring, routine cleanup, and maintenance.

Risks from exposure to penetrating radiation during routine operations are reduced by shielding. During maintenance operations, these risks are reduced by self-decontamination of devices and structures, short allowable exposure times, and frequency of decontamination. Internal exposures can occur through inhalation of suspended wastes outside the containment, and through leakage through the airlock from inside the containment.

Chemical risks are assumed to be smaller here as most volatile organics are assumed to have escaped by the time the waste reaches the shredder. The rest, partly encapsulated by solids, is assumed to be released in this operation.

Shredding operations are estimated to require  $1.0 \pm 0.06$  man-hours per drum. For maintenance  $240 \pm 18$  man-hours are estimated. Maintenance is assumed to be needed after every 1,000 drums.

#### **D.2.2.4 Cementing Operations**

In Treatment Option 1, only shredded metals/glasses and combustibles are cemented and in Treatment Option 2, sludges are also cemented. In Treatment Option 3, all three waste forms are cemented, but combustibles only after incineration.

The cementation process consists of metering waste and cement into drums through a system of feed hoppers. Waste and cement can be mixed within the feed system prior to loading into drums or by in-drum mixing. A protective sleeve is used to channel material from the feed system into an open drum. This sleeve prevents waste from spilling outside the drum and acts as a barrier between workers and contaminated waste. Decontamination and maintenance of cementation equipment will be more extensive if mixing occurs within the feed system, as opposed to in-drum mixing.

The cementing operation is assumed to require  $0.60 \pm 0.06$  man-hours per drum. Maintenance is assumed to occur every 1,000 drums and need  $48 \pm 6$  man-hours.

#### **D.2.2.5 Incineration Operations**

After sorting and shredding, combustibles are incinerated and the ashes sent to cementing in Treatment Option 3 and to vitrification in Treatment Option 4.

Waste enters the incineration process through an air-lock. From the air-lock, waste is fed into the combustion chamber by gravity or a mechanical ram. Ash resulting from the combustion process is collected in traps at the bottom of the incinerator. Ash from the incineration process becomes feed material for solidification or vitrification.

An incineration off-gas system removes any particulates, acid gases, and radionuclides which pass through the incinerator. The off-gas system is a source of secondary wastes in the form of scrubbing solutions and filters. Filters can be recycled through the incinerator, while scrubbing solutions require solidification. The incinerator and off-gas systems require routine maintenance in the form of ash removal, filter replacement, scrubbing solution treatment, etc. Decontamination activities for the incineration process tend to be labor-intensive due to the complexity and number of components comprising the system.

Normal operations are estimated to require  $0.30 \pm 0.03$  man-hours per drum; maintenance  $48 \pm 6$  man-hours. Maintenance is postulated to be needed every 1,000 drums.

#### **D.2.2.6 Metal Melting Operations**

After sorting and shredding, metals and glasses are melted together with frit. This operation potentially involves multiple melting operations such as an induction melter (for steels) and a

melting pot (for lead) to accommodate ranges of melting temperatures for various WIPP metallic wastes. Operators will manually feed metallic wastes into the melter. Once melting is complete (radionuclides are assumed to partition preferentially into the slag), slag is removed from the melter. The contaminated slag will not form a nonporous glass waste form and must be re-melted with glass frit to form the final homogeneous glass waste form. Decontaminated liquid metal will be poured into molds, allowed to cool, and is then packaged for disposal as Low Level Waste (LLW). Maintenance and decontamination activities will be labor intensive for metal melting processes as refractory material or the melters themselves will require periodic replacement.

Decontamination by melting is a time-consuming operation;  $8.0 \pm 0.6$  man-hours are estimated per drum treated. Maintenance is also needed often, once after every ten melting operations; maintenance itself is estimated to require less effort,  $24 \pm 3$  man-hours for every operation.

#### D.2.2.7 Vitrification Operations

Vitrification of sludges and incinerator ash can be accomplished through the use of a joule-heated melter, microwave melter, or a plasma furnace. In these processes waste and glass frit are metered into the heating chamber and melted to form a glass liquid. Feed waste does not require handling by operators for these processes. Microwave heating is an in-drum vitrification process whereas joule-heated melters and plasma furnaces utilize heating chambers. Once a drum has been filled with vitrified ash/sludge, it is placed in storage where the contents are allowed to cool. These vitrification processes have off-gas systems similar to those described in Section D.2.2.5. Microwave melting does not involve extensive maintenance and decontamination because the microwave cavity is the only component in the system subjected to contamination (aside from the off-gas system). The joule-heated melter and the plasma furnace will require labor intensive maintenance and decontamination.

Vitrification operations are estimated to require  $2.0 \pm 0.2$  man-hours; maintenance  $48 \pm 6$  man-hours, needed once every 200 drums.

#### D.2.2.8 Assembly of Manpower Needs for Operation and Maintenance

Time and manpower needs estimated for each operation and given in the preceding section are assembled in Table D.2-1. The size of the crews and the time required are estimated using operational concerns from the manpower figures. As the uncertainty of the manpower was estimated, it can be assigned exclusively to the factor time.

The maintenance schedule and the man-years of manpower needed are listed in Table D.2-2. The throughput is 41,000 drums per year, independent of treatment. For safety reasons, the smelters are assumed to be small 1-drum melting pots or furnaces, leading to a large number of maintenance operations, requiring the largest amount of manpower.

**TABLE D.2-1**  
**TIME AND MANPOWER NEEDS FOR ROUTINE**  
**OPERATIONS AND MAINTENANCE \***

v	OPERATION	ROUTINE OPERATIONS (PER DRUM HANDLED)		ROUTINE MAINTENANCE (PER OPERATION)	
		MANPOWER <sup>a</sup>	TIME (hrs) <sup>b</sup>	MANPOWER <sup>c</sup>	TIME (hrs) <sup>d</sup>
0	Assay	3	0.20 ± 0.02	6	16 ± 2
1	Sort	3	0.50 ± 0.05	6	16 ± 2
2	Shred	2	0.50 ± 0.03	6	40 ± 3
3	Cement	3	0.20 ± 0.02	3	16 ± 2
4	Incinerate	3	0.10 ± 0.01	3	16 ± 2
5	Smelt	2	4.0 ± 0.3	3	8 ± 1
6	Vitrify	2	1.0 ± 0.1	3	16 ± 2

<sup>a</sup> This is quantity  $N_{06}^{(v)}$  used later.

<sup>b</sup> This is quantity  $t_{57}^{(v)}$  used later.

<sup>c</sup> This is quantity  $N_{07}^{(v)}$  used later.

<sup>d</sup> This is quantity  $t_{58}^{(v)}$  used later.

\* Standard errors given here are based on an estimate of the relative error of the man-hours needed. Accordingly, the error is attached here to the time estimate only.

TABLE D.2-2  
MAINTENANCE SCHEDULE \*

v	OPERATION	FREQUENCY (PER DRUM)	NUMBER OF ANNUAL MAINTENANCE OPERATIONS **					TIME SPENT ANNUALLY ON MAINTENANCE (MAN-YEARS) ***				
			TREATMENT OPTION					TREATMENT OPTION				
			0	1	2	3	4	0	1	2	3	4
0	Assay	1/1000	0 <sup>a</sup>	41	41	41	41	0 <sup>a</sup>	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2
1	Sort	1/1000	0	0	0	33	33	0	0	0	1.5 ± 0.2	1.5 ± 0.2
2	Shred	1/1000	0	33	33	33	33	0	3.8 ± 0.3	3.8 ± 0.3	3.8 ± 0.3	3.8 ± 0.3
3	Cement	1/1000	0	33	41	30 <sup>b</sup>	0	0	0.8 ± 0.1	1.0 ± 0.1	0.7 ± 0.09 <sup>b</sup>	0
4	Incinerate	1/1000	0	0	0	16	16	0	0	0	0.4 ± 0.05	0.4 ± 0.05
5	Smelt	1/10	0	0	0	0	1640	0	0	0	0	18.9 ± 2.4
6	Vitrify	1/200	0	0	0	0	68 <sup>c</sup>	0	0	0	0	1.6 ± 0.2 <sup>c</sup>

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- \* Assuming an annual throughput of 41,000 drums.
- \*\* This is the function  $\Phi_{50x}^{(v)}$  used later.
- \*\*\* This is the function  $\Phi_{60x}^{(v)}$  used later.
- <sup>a</sup> Maintenance is already included in baseline case.
- <sup>b</sup> Cement ash from combustibles.
- <sup>c</sup> Vitrify ash from combustibles.

### D.3 MODIFICATION OF BASELINE DATA

#### D.3.1 Increase in Manpower Needs Due to Treatment

The manpower reduction factor  $F_{m\kappa}$  is defined by

$$F_{m\kappa} = \frac{N_{01}^{(0)}}{N_{01}^{(\kappa)}}, \quad (\text{D.3.1})$$

where  $N_{01}^{(\kappa)}$  are the number of workers needed for treatment  $\kappa$  and  $N_{01}^{(0)}$  are the 12 workers in the WHB for the baseline case. The manpower reduction factor  $F_{m\kappa}$  for treatment  $\kappa$  is smaller than one, denoting an increase in manpower needs. On the basis of the assumption that the treatment facility is subject to the same health and safety restrictions as the Waste Handling Building, the evaluation can regard it as an extension of the WHB with additional people. The main exposures occur during handling and equipment maintenance.

The numerical values are estimated from the total number of man-years for operations and maintenance needed to treat 41,000 drums annually. Data from Tables D.2-1 and D.2-2 are used to generate the data listed in Table D.3-1. Since these values are annual needs in man-years, the totals for each treatment option can be translated directly into crew sizes, from which the ratios  $F_{m\kappa}$  can be calculated.

Included in the uncertainties are systematic errors due to the differences between potential treatment facilities. This is done because  $F_{m\kappa}$  is a basic quantity for the treatment that appears everywhere. These systematic uncertainties are estimated to be equal in size to the random standard errors. The latter are, therefore, multiplied by a factor of  $\sqrt{2}$ , according to the relation (Seiler, 1990b)

$$S_{\text{tot}}^2 = S_r^2 + S_s^2, \quad (\text{D.3.2})$$

where  $S_{\text{tot}}$  is the total standard error,  $S_r$  the random standard error, and  $S_s$  the systematic random error. The final values and standard errors are also listed later in Table D.3-3.

#### D.3.2 Reduction Factor for Public Exposure

For the public risk due to emissions from the TF, the change in the risk equation appears in the function  $\Phi_{i,d}^{(\kappa)}$  and thus the number  $N_{p,1}^{(\kappa)}$  of exposed persons incorporated in that function. In a simplified model for the four locations discussed here, it will be assumed that the functions  $\Phi_{i,d}^{(\kappa)}$  are independent of treatment  $\kappa$  and depend only on the number and locations of the  $N_{p,1}^{(\kappa)}$

TABLE D.3-1

MANPOWER NEEDS FOR TREATMENT, MANPOWER REDUCTION FACTORS  $F_{m\kappa}$  \*

OPERATION	INDEX v	ANNUAL WORKTIME FOR OPERATION AND MAINTENANCE (MAN-YEARS)				
		TREATMENT OPTION $\kappa$				
		0	1	2	3	4
Assay <sup>a</sup>	0	11.5	13.7 ± 1.2	13.7 ± 1.2	13.7 ± 1.2	13.7 ± 1.2
Sort	1	--	--	--	25.2 ± 2.4	25.2 ± 2.4
Shred	2	--	19.6 ± 1.0	19.6 ± 1.0	19.6 ± 1.0	19.6 ± 1.0
Cement	3	--	10.2 ± 1.0	12.8 ± 1.2	9.4 ± 0.9	--
Incinerate	4	--	--	--	2.7 ± 0.2	2.7 ± 0.2
Smelt	5	--	--	--	--	82 ± 5.3
Vitrify	6	--	--	--	--	14.7 ± 1.3
Total		11.5	43.5 ± 1.8	46.1 ± 1.9	70.6 ± 2.9	157.9 ± 6.1
Workforce <sup>b</sup> , $N_{o,1}$ <sup>(c)</sup>		12 <sup>c</sup>	44 ± 3	46 ± 3	71 ± 4	158 ± 9
$F_{m\kappa}$		--	0.276 ± 0.016	0.260 ± 0.015	0.170 ± 0.010	0.0760 ± 0.0042

\* Errors calculated using data from Table D.2-1.

<sup>a</sup> 40,000 drums processed, other entries 41,000 drums processed due to secondary wastes. No maintenance included in baseline, assumed to be included in FSEIS data.

<sup>b</sup> Errors increased by  $\sqrt{2}$  due to the assumption of a systematic error of equal magnitude.

<sup>c</sup> Manpower in WHB, baseline: 12 above ground.

persons exposed. This relation is incorporated in the public exposure reduction factor

$$F_{ex} \equiv \frac{\Phi_{idd}^{(0)}}{\Phi_{idd}^{(x)}} = \frac{N_{p1}^{(0)}}{N_{p1}^{(x)}} \quad (D.3.3)$$

Due to the increase in exposed persons, the factor  $F_{ex}$  is expected to be less than one. For location at the WIPP, the treatment facility will affect the same area and population. The dispersion function and the number and locations of the exposed members of the public are the same, but there are now two sources, assuming that the same health and safety concerns dictate the allowable releases for WHB and TF. For locations elsewhere, the same additional population risk is assumed to be allowed, leading to the same factor  $F_{ex}$ , regardless of location. The exposure from handling operations is then estimated to be about twice that due to the WHB emissions alone with a random error of about 15 percent, i.e.,

$$F_{ex} = 0.50 \pm 0.08 \quad (D.3.4)$$

The error is obtained from the observation that for similar operations a spread of  $\pm 30\% = 60\%$  for a 95 percent confidence level is incompatible with the health and safety goals. This results in the standard random error of 15 percent used above.

The systematic error of the public exposure reduction factors is obviously much larger and will have to encompass the treatment/location dependence of the public exposure ratio. Rather than estimating it, it would be more profitable to amend the model to show the appropriate dependence on treatment and location.

### D.3.3 Volume Reduction Factor Due to Treatment

In waste treatment, the large void spaces in the drums are reduced and in some treatment options the actual volume of the wastes is reduced also. The numerical values for the volume reduction factors, averaged over the different waste forms, are given by the weighted arithmetic average

$$F_{vx} = \frac{\sum_{w=1}^W n_w f_{wx}}{\sum_{w=1}^W n_w} \equiv \sum_{w=1}^W \eta_w f_{wx} \quad (D.3.5)$$

where the definition of the weights is given by

$$\eta_w = \frac{n_w}{\sum_{\tau=1}^W n_\tau} \quad (D.3.6)$$

with the normalization property

$$\sum_{\tau=1}^W \eta_w = 1 \quad (D.3.7)$$

Here  $W$  is the number of different waste forms,  $n_w$  is the number of drums of waste form  $w$  produced per year,  $f_{w\kappa}$  is the volume reduction factor for waste form  $w$  due to treatment  $\kappa$ . The relative weights,  $\eta_w$ , defined in the second part of Equation (D.3.5) add to unity. The values are  $\eta_s = 0.2$  for sludges, and  $\eta_c = \eta_m = 0.4$  for combustibles and metals, respectively (Vetter, 1990). The volume reduction factors for different waste forms are estimated on the basis of the methods reviewed for the main report. Their errors,  $\Delta f_{w\kappa}$ , are assigned on the basis of prudent upper and lower limits for the processes. For the total volume reduction factor  $F_{v\kappa}$  the errors are

$$(\Delta F_{v\kappa})^2 = \sum_{w=1}^W (\eta_w \Delta f_{w\kappa})^2 \quad (D.3.8)$$

assuming that the standard errors of the  $\eta_w$  relative weights are at least a factor of three smaller than those of the individual volume reduction factors  $f_{w\kappa}$ .

For Treatment Option 1, which leaves sludges unaltered while combustibles and metals are shredded and cemented, the volume reduction factors are estimated to be  $f_{s,1} = 1 \pm 0$  for sludges,  $f_{c,1} = 1.2 \pm 0.2$  for combustibles, and  $f_{m,1} = 1.2 \pm 0.2$  for metals. The combination according to Equation (3.15) results in an average volume reduction factor of

$$F_{v,1} = 1.2 \pm 0.1 \quad (D.3.9)$$

For Treatment Option 2, which cements sludges while again shredding and cementing combustibles and metals, the volume reduction for cementing sludges is again assumed to be 1 by filling the headspace with cement. All waste forms thus have the same volume reduction factors as those of Treatment Option 1,

$$F_{v,2} = 1.2 \pm 0.1 \quad (D.3.10)$$

Treatment Option 3 cements sludges, incinerates combustibles, and cements the ashes while it shreds and cements the metals. The volume reduction is  $f_{s,3} = 1.0 \pm 0$  for sludges, and the overall volume reduction for the incineration of combustibles is estimated to be  $f_{c,3} = 3 \pm 1$ . As this procedure is based on the PREPP process (Tait, 1983), which also shreds the drums, the

volume reduction factor for metals is somewhat higher than that for Treatment Options 1 and 2, and is estimated to be  $f_{m3} = 2 \pm 0.5$ . The composite volume reduction factor is

$$F_{v3} = 2.2 \pm 0.5 . \quad (D.3.11)$$

For Treatment Option 4, which vitrifies sludges, incinerates combustibles and vitrifies their ashes, while it melts and decontaminates metals, the volume reduction factors are larger. Sludge vitrification by microwave heating is well known (Petersen et al., 1987), yielding a reduction factor of  $f_{s4} = 9 \pm 1$ . For metals and combustibles, the maximum fissile radionuclide content of a drum by the WAC provides the limits. If concentration is assumed to result in an average of 80 percent of the limits, the volume reduction factor is  $f_{m4} = f_{c4} = 9.4 \pm 1.5$ . The composite volume reduction is then

$$F_{v4} = 9.3 \pm 0.9 . \quad (D.3.12)$$

These data are assembled in Table D.3-3.

#### D.3.4 Transportation Reduction Factor

The volume reduction factor  $F_{vx}$  leads to a reduction in the number of barrels handled annually by the factor  $F_{vx}$ . The maximum transport weight is set at 80,000 pounds (36.2 metric tons), however, so that the full reduction cannot be realized. Therefore, a correction factor needs to be applied.

The number of treated drums per TRUPACT-II can be calculated using the effective payload for the 14 drums of 7,265 pounds (3.3 metric tons) and data on the weights of treated drum (see main report). The weighted average over the three waste forms is

$$n_{dx} = \frac{W_0}{\sum_{z=1}^3 f_w W_{wz}} , \quad (D.3.13)$$

where

- $n_{dx}$  = Number of drums per TRUPACT-II,
- $W_0$  = Load limit of TRUPACT-II (kg),
- $f_w$  = Fraction of waste form  $w$ , and
- $W_w$  = Mass of treated drum of waste form  $W$  (kg).

These numbers are given in Table D.3-2 based on the data in the main report. The load factor  $f_{1\kappa}$ , that is the fraction of the 14 drums that can on average be loaded into the TRUPACT-II is

$$f_{1\kappa} = \frac{n_{d0}}{n_{d\kappa}}, \quad (\text{D.3.14})$$

where

$n_{d0}$  = Number of untreated drums per TRUPACT-II,  
 $n_{d\kappa}$  = Number of treated drums per TRUPACT-II.

The transportation reduction factor,  $F_{1\kappa}$ , is then calculated from the number,  $n_t^{(\kappa)}$ , of transports needed annually after treatment  $\kappa$

$$n_t^{(\kappa)} = \frac{n_d^{(0)}}{F_{v\kappa} f_{1\kappa}}, \quad (\text{D.3.15})$$

where

$n_d^{(0)}$  = Number of untreated drums handled annually,  
 $F_{v\kappa}$  = Volume reduction factor for treatment  $\kappa$ ,  
 $f_{1\kappa}$  = TRUPACT-II load factor for treatment  $\kappa$ ,

and with  $F_{v0} = f_{10} = 1$ . The factor  $F_{1\kappa}$  is then

$$F_{1\kappa} = \frac{n_t^{(0)}}{n_t^{(\kappa)}} = F_{v\kappa} f_{1\kappa}. \quad (\text{D.3.16})$$

The relative errors of the load factor  $f_{1\kappa}$ , derived from the survey of a large number of drums are estimated to be a lot smaller than those of the volume reduction factor. The error of the transport reduction factor is, therefore, given by

$$\frac{\Delta F_{1\kappa}}{F_{1\kappa}} = \frac{\Delta F_{v\kappa}}{F_{v\kappa}}. \quad (\text{D.3.17})$$

The numerical values for most of these factors are listed in Table D.3-2 and also in Table D.3-3.

### D.3.5 Ratio of Forklift Operations

The reduction factors  $F_{1\kappa}$  for forklift operations in different treatments are clearly smaller than one, and are based on an operations model that adds one forklift operation to the first treatment device

**TABLE D.3-2**  
**TRANSPORTATION REDUCTION FACTORS**

TREATMENT OPTION	$n_{dx}$ <sup>a</sup>	$f_{tx}$ <sup>b</sup>	$F_{vx}$ <sup>c</sup>	$F_{tx}$ <sup>d</sup>
1	8.15	0.582	1.2 ± 0.1	0.70 ± 0.06
2	7.58	0.542	1.2 ± 0.1	0.65 ± 0.05
3	7.38	0.527	2.2 ± 0.5	1.2 ± 0.3
4	6.42	0.458	9.3 ± 0.9	4.3 ± 0.4

<sup>a</sup> Number of treated drums that can be transported in TRUPACT-II.

<sup>b</sup> Load factor of TRUPACT-II.

<sup>c</sup> Average volume reduction factor.

<sup>d</sup> Transportation reduction factor.

**TABLE D.3-3**  
**SUMMARY TABLE FOR THE REDUCTION FACTORS**  
 **$F_{vk}$ ,  $F_{mk}$ ,  $F_{ek}$ ,  $F_{fk}$ , AND  $F_{tk}$**

TREATMENT OPTION	$F_{vk}$ <sup>a</sup>	$F_{mk}$ <sup>b</sup>	$F_{ek}$ <sup>c</sup>	$F_{fk}$ <sup>d</sup>	$F_{tk}$ <sup>e</sup>
1	1.2 ± 0.1	0.276 ± 0.016	0.50 ± 0.08	0.517 ± 0.010	0.70 ± 0.06
2	1.2 ± 0.1	0.260 ± 0.015	0.50 ± 0.08	0.517 ± 0.010	0.65 ± 0.05
3	2.2 ± 0.5	0.170 ± 0.010	0.50 ± 0.08	0.566 ± 0.010	1.2 ± 0.3
4	9.3 ± 0.9	0.0760 ± 0.0042	0.50 ± 0.08	0.644 ± 0.002	4.3 ± 0.4

- <sup>a</sup> Average volume reduction factor, from Equations D.3.9 through D.3.12. .  
<sup>b</sup> Manpower reduction factor, from Table D.3-1.  
<sup>c</sup> Public exposure reduction factor, from Equation D.3.4.  
<sup>d</sup> Reduction factor for forklift operations, from Equations D.3.18 and D.3.19.  
<sup>e</sup> Transportation reduction factor, from Table D.3-2.

and  $1/F_{v\kappa}$  forklift operations back to the storage area to the operations in the WHB. By normalizing the latter to one, the reduction factors are

$$F_{i\kappa} = \frac{1}{\sum_{w=1}^3 \eta_w \left\{ 1 + \frac{1}{2} \left( 1 + \frac{1}{f_{w\kappa}} \right) \right\}}, \quad (\text{D.3.18})$$

where  $f_{w\kappa}$  is the volume reduction factor of treatment  $\kappa$  for waste form  $w$ , and  $\eta_w$  is the abundance of waste form  $w$ . The standard error of this expression is

$$\left( \frac{\Delta F_{i\kappa}}{F_{i\kappa}} \right)^2 = \sum_{w=1}^3 \left( \frac{\eta_w F_{i\kappa}}{2 f_{w\kappa}} \right)^2 \left( \frac{\Delta f_{w\kappa}}{f_{w\kappa}} \right)^2. \quad (\text{D.3.19})$$

The parameters  $f_{w\kappa}$  and  $\eta_w$  were given in the discussions of equations (D.3.9) to (D.3.12), resulting in the values listed in Table D.3-3. Note the implicit assumption that the number of forklift operations is independent of the final drum weight. For heavier drums, heavier forklifts are assumed to be used.

### D.3.6 Particle Generation in Accidents

#### D.3.6.1 Particle Spectrum Generated

In the baseline waste, some fine particles are already present, while others may be generated by impacts. In treated wastes, the numbers of free particles are drastically reduced, and it is assumed here that particles are produced by impact. Empirical models have been made on the basis of experimental data for the spectrum of particles produced by impact (Bennet et al., 1980). Using data on the shattering of rocks, the model for the cumulative distribution function for particles with diameter  $y$  yields

$$\Phi_{d\kappa}(y) = c_{m\kappa} \dot{\epsilon}_\kappa^{4/3} y^2, \quad (\text{D.3.20})$$

where  $c_{m\kappa}$  is a constant of the material impacted,  $\epsilon_\kappa$  is the strain or relative deformation in elastic deformation process, so that  $\dot{\epsilon}_\kappa$  is the rate at which strain builds before going beyond the fracture limit. Static strain rates are typically  $10^{-4} \text{ s}^{-1}$ , while rock blasting achieves 1 to  $10^3 \text{ s}^{-1}$ . With the impacted drum cushioning the impact on its contents, a strain rate of  $(0.10 \pm 0.03) \text{ s}^{-1}$  is assumed for creating the perforation. A comparison of dynamic tensile fracture strengths (Grady and Hallenbach, 1979) leads to an assignment of  $c_{m\kappa} = 100$  for cemented and  $c_{m\kappa} = 200$  for vitrified wastes. This is based on a comparison of the dynamic tensile strengths of oil shale, for which a  $c_{m\kappa}$  value is available and of several types of stone, such as sandstone, limestone and basalt. Although dynamic tensile fracture strength does not correlate well with the constant  $c_{m\kappa}$  for all materials, it can provide scaling between not too different materials (Grady, 1991). Treated waste

forms, cemented or vitrified are inhomogeneous conglomerates, in many ways similar to oil shales, sandstones, limestones, and basalts. The uncertainties in these assignments for the constant  $c_{m\kappa}$  are obtained from a comparison with the value 157 for oil shale. Assuming a range of 50 around the value of 100, and of 40 around the value of 200, yields error estimates of  $\pm 12$  and  $\pm 14$ , respectively. The standard error of the cumulative distribution function for the constant  $c_{m\kappa}$  is then

$$\left( \frac{\Delta \Phi_{d\kappa}(y)}{\Phi_{d\kappa}(y)} \right)^2 = \left( \frac{4}{3} \frac{\Delta \dot{\epsilon}_{\kappa}}{\dot{\epsilon}_{\kappa}} \right)^2 + \left( \frac{\Delta c_{m\kappa}}{c_{m\kappa}} \right)^2 \quad (D.3.21)$$

This model will be used to estimate the particle size distributions for all events resulting in the creation of particles from solidified wastes.

#### D.3.6.2 Suspendability Ratio $S_{1\kappa}$

In Section E.1.1.2 in Equation (E.1.20), the ratio of particles suspended in inhalable form for treated and untreated wastes is needed. These reduction factors for particle suspendability  $S_{1\kappa}$  are estimated here on the basis of some assumptions and the model discussed in the last section. The baseline risk assumes that a perforated drum releases one percent of the waste mass, that a fraction of  $10^{-3}$  is suspended from the floor due to the activities in the Waste Handling Building, and that 5 percent of the total activity is in inhalable form. The scenario implies that this release escapes detection by the monitoring devices. However, one percent of the mass of the average drum (DOE, 1990a) is 1.5 kg, which can hardly escape visual detection and will, therefore, be treated as an incident and not lead to a routine exposure. In order to cancel the influence of this assumption, it will be assumed here that, in the baseline case, a certain undetermined fraction of the inhalable waste which amounts to 5 percent of the activity is spilled from the perforation.

In the incident in Section E.1.1.2 involving a perforated drum with treated waste, the impact that creates the perforation also creates a certain fraction of the mass pulverized in particles of sizes below  $10 \mu\text{m}$ . For diameters above  $10 \mu\text{m}$ , the fraction of particles that is inhaled drops toward zero. It is now assumed that, independent of treatment, the same fraction  $f_{22}^{(k)}$  of these particles is spilled on the floor and the same fraction  $f_{24}^{(k)}$  resuspended. Thus, these factors cancel in the ratio  $S_{1\kappa}$  and the only remaining factor is the fraction  $f_{23}^{(k)}$  of particles with diameter below  $10 \mu\text{m}$ ,

$$S_{1\kappa} = \frac{\phi_2^{(0)}}{\phi_2^{(k)}} = \frac{f_{23}^{(0)}}{\Phi_{d\kappa}(10^{-5})} \quad (D.3.22)$$

with the inhalable fraction of the total activity of a drum  $f_{23}^{(0)} = 0.05$  (DOE 1989b, DOE 1990a).

The inhalable fractions of the total mass generated by the impact are  $(4.6 \pm 1.9) \cdot 10^{-10}$  for cemented and  $(9.3 \pm 3.7) \cdot 10^{-10}$  for vitrified wastes and the corresponding reduction factors  $S_{1x}$  are listed in Table D.3-4.

### D.3.6.3 Suspendability Ratio $S_{2x}$

The suspendability reduction factors  $S_{2x}$  are needed in the evaluation of a C2 accident in which a drum falls off a forklift (see Section E.3.1.1). They are defined by

$$S_{2x} \equiv \frac{f_{61}^{(0)} f_{62}^{(0)} f_{63}^{(0)}}{f_{61}^{(x)} f_{62}^{(x)} f_{63}^{(x)}} \quad (D.3.23)$$

where the factors in numerator and denominator are the fraction  $f_{61}^{(x)}$  of the material spilling out of the drum, the fraction  $f_{62}^{(x)}$  of that material suspended in air, and the fraction  $f_{63}^{(x)}$  of the activity that is in inhalable form, i.e., with diameters less than  $10 \mu\text{m}$ . The baseline scenario assumes 25 percent of the drum's content is spilled, containing a fraction of 5% inhalable activity, and that a fraction of  $10^{-3}$  is suspended due to the dynamics of the accident. In the case of treated wastes, the particles are created in the accident by impact. The elastic deformation rate to be used in the impact model in the fall from the forklift is estimated at  $0.05 \text{ s}^{-1}$  with an error of 20 percent.

The cemented waste is fragmented, with a cumulative distribution function for the mass fraction with diameters below  $10 \mu\text{m}$  of  $\Phi_{dx}(10^{-5}) = (1.8 \pm 0.5) \cdot 10^{-10}$  and for the vitrified waste the fraction is  $\Phi_{dx}(10^{-5}) = (3.7 \pm 1.0) \cdot 10^{-10}$ , according to Equations (D.3.20) and (D.3.21). Assuming the fraction of  $f_{62}^{(x)}$  of suspended particles below  $10 \mu\text{m}$  to be the same, and the fractions of waste spilled at 25 percent and 100 percent (upper limit), respectively, yields

$$S_{2x} = \frac{f_{61}^{(0)} f_{63}^{(0)}}{f_{61}^{(x)} f_{63}^{(x)}} = \frac{f_{61}^{(0)} f_{63}^{(0)}}{f_{61}^{(x)} \Phi_{dx}(10^{-5})} \quad (D.3.24)$$

Again, these reduction factors, given in Table D.3-4, are quite large, signalling an effective suppression of the corresponding component of the risk.

TABLE D.3-4

**REDUCTION FACTORS  $S_{1x}$  AND  $S_{2x}$  IN SUSPENDED FRACTION OF  
INHALABLE WASTES IN AN N2 AND A C2 SCENARIO**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
$S_{11}$	$(0.9 \pm 0.3) \cdot 10^8$	Only 80% of drums affected
$S_{12}$	$(1.1 \pm 0.4) \cdot 10^8$	
$S_{13}$	$(1.1 \pm 0.4) \cdot 10^8$	
$S_{14}$	$(0.5 \pm 0.2) \cdot 10^8$	
$S_{21}$	$(5.4 \pm 1.4) \cdot 10^7$	Only 80% of drums affected  $S_{2x} = S_{4x} = S_{6x}$
$S_{22}$	$(6.8 \pm 1.8) \cdot 10^7$	
$S_{23}$	$(6.8 \pm 1.8) \cdot 10^7$	
$S_{24}$	$(3.4 \pm 0.9) \cdot 10^7$	

- The reduction factor  $S_{1x}$  for the fraction of waste suspended in inhalable form is defined in Equation (D.3.22).
- The reduction factor  $S_{2x}$  for the fraction of waste suspended in inhalable form is defined in Equation (D.3.24).

**D.3.6.4 Suspendability Ratio  $S_{3x}$** 

The suspendability reduction factors  $S_{3x}$  are needed in the evaluation of the C3 scenario in Section E.3.1.2. The factors are defined by

$$S_{3x} \equiv \frac{\phi_{31}^{(0)}}{\phi_{31}^{(x)}}, \quad (\text{D.3.25})$$

where the factors  $\phi_{31}^{(x)}$  are the fractions of inhalable particles suspended in the accident.

Numerical estimates for the parameters  $S_{3x}$  are given in Table D.3-5 and are based on the same impact fragmentation as those in the two preceding sections. If the perforation is assumed to have been made by the tine of a forklift, two tines impacting on two drums will share the impact energy. The strain rate is thus estimated to be  $(0.7 \pm 0.2) \text{ s}^{-1}$ , and equation (D.3.20) yields  $(0.62 \pm 0.24) \cdot 10^{-8}$  for cemented waste and  $(1.24 \pm 0.47) \cdot 10^{-8}$  for vitrified waste. The errors are calculated according to equation (D.3.21).

**D.3.6.5 Suspendability Ratio  $S_{10x}$** 

The reduction factors  $S_{10}^{(x)}$  are needed in the evaluation of the C10 accidents (see Section E.3.1.6). They are defined there by

$$S_{10} \equiv \frac{f_{11}^{(0)}}{f_{11}^{(x)}}, \quad (\text{D.3.26})$$

where the factors  $f_{11}^{(x)}$  are again the fractions of activity suspended in inhalable form.

These reduction factors are assumed to be ten times lower than the factors  $S_{2x}$  in the C2 and C4 scenarios. This assignment stems from the fact that the baseline inhalable suspended fraction is  $f_{p0} = 1.25 \cdot 10^{-4}$ , ten times higher than the fraction  $\phi_a^{(0)}$  in the C2 scenario, yet for treated waste the aerosolization is assumed to be about the same. The fraction  $f_{p0}$  is derived from the 0.25 percent of the total activity which is aerosolized in the C10 scenario (DOE, 1990a) and the additional assumption that five percent of that activity is in inhalable form, that is, it has diameters below 10  $\mu\text{m}$ . This is supported by the fact that no other drums are damaged, i.e., that it is a low-grade overpressure explosion that essentially does not much more than break the containment.

**D.3.6.6 Suspendability Ratio  $S_{33x}$** 

The reduction factors  $S_{33x}$  are needed in the evaluation of the C10 scenario involving the self-ignition of pyrophoric material in a drum (see Section E.3.1.6). Therefore definition of the factor

**TABLE D.3-5**  
**SUSPENDABILITY REDUCTION FACTORS  $S_{3x}$ ,  $S_{10x}$ , and  $S_{33x}$**   
**AS A FUNCTION OF TREATMENT OPTION**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
$S_{31}$	$(6.4 \pm 2.5) \cdot 10^6$	Only 80% of drums treated
$S_{32}$	$(8.0 \pm 3.1) \cdot 10^6$	
$S_{33}$	$(8.0 \pm 3.1) \cdot 10^6$	
$S_{34}$	$(4.0 \pm 1.5) \cdot 10^6$	
$S_{101}$	$(5.4 \pm 1.4) \cdot 10^6$	Only 80% of drums treated
$S_{102}$	$(6.8 \pm 1.8) \cdot 10^6$	
$S_{103}$	$(6.8 \pm 1.8) \cdot 10^6$	
$S_{104}$	$(3.4 \pm 0.9) \cdot 10^6$	
$S_{331}$	$(4.0 \pm 1.6) \cdot 10^6$	Only 80% of drums treated
$S_{332}$	$(5.0 \pm 2.0) \cdot 10^6$	
$S_{333}$	$(5.0 \pm 2.0) \cdot 10^6$	
$S_{334}$	$(2.5 \pm 1.0) \cdot 10^6$	

- Reduction factor  $S_{3x}$  for fraction of waste suspended in inhalable form defined in Equation (D.3.25).
- Reduction factor  $S_{10x}$  for fraction of waste suspended in inhalable form defined in Equation (D.3.26).
- Reduction factor  $S_{33x}$  for fraction of waste suspended in inhalable form defined in Equation (D.3.27).

is again

$$S_{33\kappa} \equiv \frac{\phi_{33}^{(0)}}{\phi_{33}^{(\kappa)}} = \frac{f_{331}^{(0)} f_{332}^{(0)}}{f_{331}^{(\kappa)} f_{332}^{(\kappa)}} \quad (D.3.27)$$

that is the reduction in suspendability of waste in inhalable form. These values are estimated from the baseline value of  $\phi_{33}^{(0)} = 2 \cdot 10^{-4}$  given in the FSEIS, Vol. II, Table D.3.29 (DOE, 1990a). If it is assumed that the accident modeled in the baseline case, essentially only mobilized radioactive fines already present in the waste and that  $f_{332}^{(0)} = 0.05$  of the activity is present in sizes smaller than  $10 \mu\text{m}$ , the suspended fraction is  $f_{331}^{(0)} = 4 \cdot 10^{-3}$ . As the mobilizing force of fire is the same in all cases, it is reasonable to assume that  $f_{331}^{(\kappa)} = 4 \cdot 10^{-3}$  also. For cemented or vitrified waste, however, the small particles are no longer present and must be created by the impact.

Equation (D.3.20) can be used to determine the fraction of particles below  $10 \mu\text{m}$

$$f_{332}^{(\kappa)} = \Phi_{d\kappa} (10^{-5}) = c_{m\kappa} \dot{\epsilon}_{\kappa}^{4/3} (10^{-10}) \quad (D.3.28)$$

For truck accidents, higher loading rates are to be expected than from dropping or ramming drums, but here also, the overpack will soften the impact on the drum. The best estimate for  $\dot{\epsilon}_{\kappa}$  is  $(1.0 \pm 0.3) \text{ s}^{-1}$ . This yields the values given in Table D.3-5.

### D.3.7 Probability of a C10 Accident

A C10 accident involves the self-ignition of pyrophoric material in a drum, leading to the drum bursting open and releasing toxic materials (see Section E.3.1.6). The reduction factors  $F_{p\kappa}$  for the probability of a C10 type event is defined by

$$F_{p\kappa} \equiv \frac{P_{10}^{(0)}}{P_{10}^{(\kappa)}} \quad (D.3.29)$$

where  $P_{10}^{(0)}$  is the baseline probability for self-ignition and  $P_{10}^{(\kappa)}$  is that probability after treatment. This reduction factor is estimated on the basis that the pyrophoric material is not removed from the waste except by smelting and decontamination in Treatment Option 4. Shredding increases the surface of the pyrophoric material on the one hand and cementing or vitrification reduces the oxygen available for combustion on the other. In the model used here, no credit is taken for removal of organics because they may not be needed for ignition. It is assumed that the pyrophoric material will ignite in the presence of oxygen. In the baseline case, the one event in  $1.8 \cdot 10^6$  drum-years (DOE, 1990a) will be used to assign an annual probability of  $6 \cdot 10^{-7}$  per drum. The reduction of the probability of ignition is assigned to the lack of oxygen to generate enough pressure to burst the drum. The reduction of connected void space is, therefore, assumed to be proportional to the reduction in the probability of a drum bursting open. Only in

the case of removing the pyrophoric substance by decontamination will an additional reduction of the probability by a factor of  $100 \pm 20$  be assumed. The void space decreases from 147 L in the baseline case to three to five percent of the drum volume of  $0.25 \text{ m}^3$ , i.e., down to  $(10 \pm 2 \text{ L})$ . Numerical values are listed in Table D.3-6.

### D.3.8 Emission of VOC Through Carbon Filter

Routine emissions of VOCs through the carbon filter of the drum are discussed in Section E.4.2.1. The reduction factors for the routine emissions of a single drum are defined by the ratio

$$F_{o \pm j} \equiv \frac{q_{12j}^{(0)}}{q_{12j}^{(k)}} \quad (D.3.30)$$

where  $q_{12j}^{(k)}$  is the emission rate for chemical  $j$ . These ratios are estimated on the basis of the baseline emission rates and the rates after incineration of the wastes. The model used here assumes that shredding and cementing does not change the vapor pressure (saturation) in the void space, it just retards its attainment. The corresponding emission values  $q_{12j}^{(k)}$  for chemical  $j$  are, therefore, constant

$$q_{12j}^{(0)} = q_{12j}^{(1)} = q_{12j}^{(2)} \quad (D.3.31)$$

and thus

$$F_{o1j} = F_{o2j} = 1 \pm \epsilon \quad (D.3.32)$$

where  $\epsilon$  is a small fraction. Due to the model assumption above,  $\epsilon$  is set to zero. It is small enough to warrant this assumption without loss of accuracy in the error calculation [see equation (C.1.26)]. Similarly, the fact of incineration to regulatory levels which requires 99.99 percent destruction effectiveness for organics (U.S. Environmental Protection Agency, 1989) or better leads to

$$q_{12j}^{(3)} = q_{12j}^{(4)} \quad (D.3.33)$$

An approximation for Equation (D.3.20) can be obtained by assuming that the quantity of organics in the void connected spaces is at least sufficient to maintain saturation vapor pressure and by taking no credit for the safety margin that burning aims to achieve below regulatory limits. Thus

$$F_{o3j} = F_{o4j} = (1.0 \pm 0.3) \cdot 10^{-4} \quad (D.3.34)$$

None of these ratios, with a large error assigned due to the uncertainties in the assumptions above, depend on the compound, and the estimates for numerical values are listed in Table D.3-7.

TABLE D.3-6

**VALUES FOR THE REDUCTION IN SELF-IGNITION RISK IN A C10 ACCIDENT  
AS A FUNCTION OF THE TREATMENT OPTION**

QUANTITY *	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
$F_{p1}$	$12 \pm 2$	Only 80 % of drums treated
$F_{p2}$	$15 \pm 3$	100% of drums treated
$F_{p3}$	$15 \pm 3$	100% of drums treated
$F_{p4}$	$1500 \pm 400$	100% of drums treated

\* The reduction factor for the probability of self-ignition  $F_{p\kappa}$  is defined in Equation (D.3.29).

**TABLE D.3-7**  
**VALUES FOR THE REDUCTION FACTORS  $F_{c,k}$  FOR CHEMICAL EMISSIONS**

CHEMICAL	QUANTITY *	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
All VOCs considered	$F_{c1j}$	$1 \pm 0$	
	$F_{c2j}$	$1 \pm 0$	
	$F_{c3j}$	$(1.0 \pm 0.3) \cdot 10^4$	
	$F_{c4j}$	$(1.0 \pm 0.3) \cdot 10^4$	

- \* Reduction factor for routine emissions of a drum (Eq. D.3.30).

### D.3.9 Ratios of VOC Mass in Headspace

Venting the headspace of a drum in an accident leads to the emission of the gases accumulated there. The reduction factors  $F_{g \kappa j}$  for the mass of gas  $j$  in the headspace are defined by

$$F_{g \kappa j} = \frac{q_{18j}^{(0)}}{q_{18j}^{(\kappa)}} \quad , \quad (D.3.35)$$

where the quantities  $q_{18j}^{(\kappa)}$  are the quantities of gas  $j$  contained in the void spaces.

The numerical values for the parameters  $F_{g \kappa j}$  are again estimated by assuming a combustion efficiency of 99.99 percent for organics and by taking into account the reduction of connected void volume from 147 L to  $(4.0 \pm 0.5)$  percent of the drum volume of 208 L (Butcher, 1989). The factor  $F_{g \kappa j}$  for alternatives  $\kappa = 1$  and 2 is then given by the ratio of the void volumes, and for Treatment Options 3 and 4 by the product of that ratio with the burn escape ratio. The numerical values are listed in Table D.3-8.

### D.3.10 Location Function for Treatment Plant

In loading and unloading the TRUPACT-II containers, the handling crew is exposed to penetrating radiation from the drums. The handling is increased when the TF is located between the originator and the WIPP. This is taken into account by the location/function factor  $\Phi_{283\omega}^{(\kappa\lambda)}$  used in Section E.6.3.7. Numerical values for this function are given in Table D.3-9 and their errors in Table D.3-10. For treatment at the WIPP, one load/unload unit is incurred, equivalent to the baseline risk evaluated in the FSEIS. For treatment at the originator  $\omega$ , the number of transports is reduced by the transportation reduction factor  $F_{1\kappa}$  of the treatment option. For the location options with regional treatment facilities, outside suppliers incur one unit of loading and unloading of wastes "as received" and one unit reduced by the volume reduction factor  $F_{1\kappa}$  of the treatment option. This evaluation is based on the assumption that the ALARA concept is fully implemented, minimizing both doses and dose-rates for the shipments reduced by the factor  $F_{1\kappa}$  the higher dose-rates will then be reduced by different health and safety protocols, leaving the gain in exposure reduction intact.

### D.3.11 Extension Function for Storage Time

The personnel in the warehouse used for temporary storage of the drums until they can be transported are exposed to additional penetrating radiation if the frequency of transports decreases due to treatment. This effect is taken into account in Section E.6.3.8, where the time extension function  $\Phi_{292\omega}^{(\kappa\lambda)}$  is used. Effective use of the ALARA concept is again assumed, leading to the same dose rates, but longer storage times lead to a proportionate increase in dose.

**TABLE D.3-8**  
**VALUES FOR THE REDUCTION FACTORS  $F_{g\kappa j}$  FOR CHEMICAL EMISSIONS**

CHEMICAL	QUANTITY*	VALUE $\pm$ STANDARD ERROR	COMMENTS/ REFERENCES
Methylene Chloride	$F_{g1j}$	$17.7 \pm 2.2$	
Carbon Tetrachloride	$F_{g2j}$	$17.7 \pm 2.2$	
Trichloroethylene	$F_{g3j}$	$(1.8 \pm 0.2) \cdot 10^5$	
Trichloroethane	$F_{g4j}$	$(1.8 \pm 0.2) \cdot 10^5$	
Freon			

\* Reduction factor for mass of gas j in headspace after treatment option  $\kappa$ , according to Equation (D.3.35).

**TABLE D.3-9**  
**LOCATION FUNCTION  $\Phi_{283\omega}^{(x\lambda)}$**

ORIGINATOR	$\omega$	$\lambda$	$\Phi_{283\omega}^{(x\lambda)}$	ORIGINATOR	$\omega$	$\lambda$	$\Phi_{283\omega}^{(x\lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	1	Oak Ridge National Laboratory, Tennessee	6	1	1
	1	2	$1/F_{1x}$		6	2	1
	1	3	$1/F_{1x}$		6	3	$1 + 1/F_{1x}$
	1	4	$1/F_{1x}$		6	4	$1/F_{1x}$
Rocky Flats Plant, Colorado	2	1	1	Nevada Test Site, Nevada	7	1	1
	2	2	$1/F_{1x}$		7	2	1
	2	3	$1/F_{1x}$		7	3	1
	2	4	$1/F_{1x}$		7	4	1
Hanford Reservation, Washington	3	1	1	Argonne National Laboratory - East, Illinois	8	1	1
	3	2	$1 + 1/F_{1x}$		8	2	1
	3	3	$1/F_{1x}$		8	3	$1 + 1/F_{1x}$
	3	4	$1/F_{1x}$		8	4	1
Savannah River Site, South Carolina	4	1	1	Lawrence Livermore National Laboratory, California	9	1	1
	4	2	1		9	2	1
	4	3	$1/F_{1x}$		9	3	1
	4	4	$1/F_{1x}$		9	4	1
Los Alamos National Laboratory, New Mexico	5	1	1	Mound Laboratory, Ohio	10	1	1
	5	2	1		10	2	1
	5	3	1		10	3	$1 + 1/F_{1x}$
	5	4	$1/F_{1x}$		10	4	1

The location function  $\Phi_{283\omega}^{(x\lambda)}$  evaluates the increase in handling after treatment  $x$  of the wastes at location  $\lambda$ .

TABLE D.3-10

STANDARD ERRORS OF LOCATION FUNCTION  $\Delta \Phi_{2830}^{(\kappa \lambda)}$ 

ORIGINATOR	$\omega$	$\lambda$	$\Delta \Phi_{2830}^{(\kappa \lambda)}$	ORIGINATOR	$\omega$	$\lambda$	$\Delta \Phi_{2830}^{(\kappa \lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	0	Oak Ridge National Laboratory, Tennessee	6	1	0
	1	2	A		6	2	0
	1	3	A		6	3	A
	1	4	A		6	4	A
Rocky Flats Plant, Colorado	2	1	0	Nevada Test Site, Nevada	7	1	0
	2	2	A		7	2	0
	2	3	A		7	3	0
	2	4	A		7	4	0
Hanford Reservation, Washington	3	1	0	Argonne National Laboratory - East, Illinois	8	1	0
	3	2	A		8	2	0
	3	3	A		8	3	A
	3	4	A		8	4	0
Savannah River Site, South Carolina	4	1	0	Lawrence Livermore National Laboratory, California	9	1	0
	4	2	0		9	2	0
	4	3	A		9	3	0
	4	4	A		9	4	0
Los Alamos National Laboratory, New Mexico	5	1	0	Mound Laboratory, Ohio	10	1	0
	5	2	0		10	2	0
	5	3	0		10	3	A
	5	4	A		10	4	0

$$A = \Delta F_{1\kappa} / F_{1\kappa}^2$$

For the time extension functions  $\Phi_{292\lambda}^{(\kappa\lambda)}$ , the model assumes that for treatment at the originator, no additional storage is incurred except that mandated by the volume reduction, i.e., the additional time required to fill the 42 drums in a TRUPACT-II transport measured in units of the baseline storage time  $\Delta t_s$ .

$$\Phi_{292\lambda}^{(\kappa\lambda)} = F_{1\kappa} . \quad (D.3.36)$$

For treatment at the WIPP site, the storage time is again that of the baseline case,  $\Delta t_s$ . For an originator going to a regional treatment facility and from there to the WIPP, the storage time at the originator remains the same, but the storage time at the treatment facility has to be added. It consists of pre-treatment storage assumed to be  $1/2 \Delta t_s$  and post-treatment storage assumed to be  $1/2 \Delta t_s$ ,  $F_{1\kappa}$ . Thus the total time is  $\Phi_{292\lambda}^{(\kappa\lambda)} \Delta t_s$  with

$$\Phi_{292\lambda}^{(\kappa\lambda)} = 1 + \frac{1}{2} (1 + F_{1\kappa}) . \quad (D.3.37)$$

The functions are tabulated in Table D.3-11 and their errors in Table D.3-12.

#### D.4 MODELS FOR TREATMENT OPERATION

##### D.4.1 Accidents

###### D.4.1.1 Occupational Accidents

Occupational fatalities and injuries in various industries are published by the U. S. Department of Labor (1986, 1990). For the evaluation of risks of workers in the WHB or the TF, data for warehouse workers were used. The average annual rate of injuries per worker over the years 1987 and 1988 is  $6.6 \cdot 10^{-2}$  with an error of 5 percent (Tables 3 and A-1 of Ref. U.S. Department of Labor, 1990). For fatalities, the same report provides data for the years 1987 and 1988 for transportation and public utility workers. The average annual rate of occupational fatalities is  $1.29 \cdot 10^{-4}$  with a standard error estimated to be about 10 percent.

###### D.4.1.2 Forklift Accidents

Forklift accidents are particularly severe occupational events. Although they make up only 1 percent of the accident incidence, they are responsible for 10 percent of the workdays lost (U.S. Department of Labor, 1986). For occupational injuries, the incidence of these accidents is separated from the incidence of general occupational injuries and considered separately with a ten times higher risk coefficient. The rationale for this decision is that severe accidents are ten times more likely, but disappear in the statistical averaging in the tables. For fatalities, the same procedure is adopted, using the rationale that if accidental injuries are ten times more severe, fatalities are likely to be ten times more frequent.

TABLE D.3-11  
TIME EXTENSION FUNCTION  $\Phi_{2920}^{(\kappa, \lambda)}$

ORIGINATOR	$\omega$	$\lambda$	$\Phi_{2920}^{(\kappa, \lambda)}$	ORIGINATOR	$\omega$	$\lambda$	$\Phi_{2920}^{(\kappa, \lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	1	Oak Ridge National Laboratory, Tennessee	6	1	1
	1	2	$F_{1\kappa}$		6	2	1
	1	3	$F_{1\kappa}$		6	3	$1 + 1/2(1+F_{1\kappa})$
	1	4	$F_{1\kappa}$		6	4	$F_{1\kappa}$
Rocky Flats Plant, Colorado	2	1	1	Nevada Test Site, Nevada	7	1	1
	2	2	$F_{1\kappa}$		7	2	1
	2	3	$F_{1\kappa}$		7	3	1
	2	4	$F_{1\kappa}$		7	4	1
Hanford Reservation, Washington	3	1	1	Argonne National Laboratory - East, Illinois	8	1	1
	3	2	$1 + 1/2(1 + F_{1\kappa})$		8	2	1
	3	3	$F_{1\kappa}$		8	3	$1 + 1/2(1+F_{1\kappa})$
	3	4	$F_{1\kappa}$		8	4	1
Savannah River Site, South Carolina	4	1	1	Lawrence Livermore National Laboratory, California	9	1	1
	4	2	1		9	2	1
	4	3	$F_{1\kappa}$		9	3	1
	4	4	$F_{1\kappa}$		9	4	1
Los Alamos National Laboratory, New Mexico	5	1	1	Mound Laboratory, Ohio	10	1	1
	5	2	1		10	2	1
	5	3	1		10	3	$1 + 1/2(1+F_{1\kappa})$
	5	4	$F_{1\kappa}$		10	4	1

The time extension function  $\Phi_{2920}^{(\kappa, \lambda)}$  evaluates the extension of the total storage time due to treatment  $\kappa$  of the waste at location  $\lambda$  according to Equations (D.3.36) and (D.3.37).

TABLE D.3-12

ERROR OF THE TIME EXTENSION FUNCTION  $\Delta \Phi_{2920}^{(\kappa \lambda)}$ 

ORIGINATOR	$\omega$	$\lambda$	$\Delta \Phi_{2920}^{(\kappa \lambda)}$	ORIGINATOR	$\omega$	$\lambda$	$\Delta \Phi_{2920}^{(\kappa \lambda)}$
Idaho National Engineering Laboratory, Idaho	1	1	0	Oak Ridge National Laboratory, Tennessee	6	1	0
	1	2	$\Delta F_{1\kappa}$		6	2	0
	1	3	$\Delta F_{1\kappa}$		6	3	$1/2 \Delta F_{1\kappa}$
	1	4	$\Delta F_{1\kappa}$		6	4	$\Delta F_{1\kappa}$
Rocky Flats Plant, Colorado	2	1	0	Nevada Test Site, Nevada	7	1	0
	2	2	$\Delta F_{1\kappa}$		7	2	0
	2	3	$\Delta F_{1\kappa}$		7	3	0
	2	4	$\Delta F_{1\kappa}$		7	4	0
Hanford Reservation, Washington	3	1	0	Argonne National Laboratory - East, Illinois	8	1	0
	3	2	$1/2 \Delta F_{1\kappa}$		8	2	0
	3	3	$\Delta F_{1\kappa}$		8	3	$1/2 \Delta F_{1\kappa}$
	3	4	$\Delta F_{1\kappa}$		8	4	0
Savannah River Site, South Carolina	4	1	0	Lawrence Livermore National Laboratory, California	9	1	0
	4	2	0		9	2	0
	4	3	$\Delta F_{1\kappa}$		9	3	0
	4	4	$\Delta F_{1\kappa}$		9	4	0
Los Alamos National Laboratory, New Mexico	5	1	0	Mound Laboratory, Ohio	10	1	0
	5	2	0		10	2	0
	5	3	0		10	3	$1/2 \Delta F_{1\kappa}$
	5	4	$\Delta F_{1\kappa}$		10	4	0

#### D.4.2 Manpower Needs for Treatment

The manpower requirements to treat one drum of waste form  $w$  in device  $v$  are needed in Section F.4.1.1. The quantity  $\phi_{57\kappa}^{(wv)}$  denotes that effort measured in manhours expended,

$$\phi_{57\kappa}^{(wv)} \equiv \eta_w N_{06} t_{57}^{(v)}. \quad (D.4.1)$$

Here  $\eta_w$  is the waste form weight defined in Equation (D.3.5),  $N_{06}$  is the manpower to handle one drum (Table D.2-1), and  $t_{57}^{(v)}$  is the time required for the operation of device  $v$ . The associated standard error is approximated by the largest contribution

$$\frac{\Delta \phi_{57\kappa}^{(wv)}}{\phi_{57\kappa}^{(wv)}} \approx \frac{\Delta t_{57}^{(v)}}{t_{57}^{(v)}}. \quad (D.4.2)$$

The numerical values derived for the effort  $\phi_{57\kappa}^{(wv)}$  and its error which are needed in Section F.4.1.1, are tabulated in Table D.4-1. The two entries with footnotes are due to the ashes from incineration being added to the cementation and vitrification flow.

#### D.4.3 Manpower for Maintenance

The manpower needed for maintenance, defined by the manpower factor

$$\phi_{58\kappa}^{(wv)} \equiv \eta_w N_{07} \Phi_{58\kappa}^{(v)} t_{58}^{(v)}, \quad (D.4.3)$$

where the quantities  $\eta_w$  are the waste fractions given in Equation (D.3.5),  $N_{07}^{(v)}$  the number of persons needed for maintenance,  $\Phi_{58\kappa}^{(v)}$  the number of maintenance operations needed annually, and  $t_{58}^{(v)}$  the time needed for maintenance of device  $v$ . All of these values are given in Table D.2-1 and their product is listed in Table D.4-2. Again, footnotes identify ashes being cemented or vitrified.

#### D.4.4 Releases Into Device Containment

Some of the treatment devices are likely to generate inert and radioactive breakup particles and suspended particles. Although the treatment apparatus must contain self-cleaning devices, a certain fraction will adhere to surfaces, leading to direct exposures to penetrating radiations during maintenance. The release fraction  $f_{582}^{(wv)}$  is estimated for the baseline case ( $v=0$ ) from the releases arising from punctured drums during the process of assay and certification. It is assumed that the entire release postulated in the FSEIS for such an event occurs during the assay and certification phase. The baseline case assumes that only a fraction of  $10^{-3}$  of the drums is perforated and releases one percent of its total mass. It is assumed here that the

**TABLE D.4-1**  
**AVERAGE EFFORT  $\phi_{37\%}^{(w)}$  PER DRUM (IN MAN-HOURS)**  
**ON DEVICE v FOR TREATING WASTEFORM w IN ALTERNATIVE k**

k	w*	v	ASSAY	SORT	SHRED	CEMENT	INCINERATE	SMELT	VITRIFY
			0	1	2	3	4	5	6
0	1		0.12	0	0	0	0	0	0
	2		0.24	0	0	0	0	0	0
	3		0.24	0	0	0	0	0	0
1	1		0.12	0	0	0	0	0	0
	2		0.24	0	0.4	0.24	0	0	0
	3		0.24	0	0.4	0.24	0	0	0
2	1		0.12	0	0	0.12	0	0	0
	2		0.24	0	0.4	0.24	0	0	0
	3		0.24	0	0.4	0.24	0	0	0
3	1		0.12	0	0	0.12	0	0	0
	2		0.24	0.6	0.4	0.08 <sup>a</sup>	0.12	0	0
	3		0.24	0.6	0.4	0.24	0	0	0
4	1		0.12	0	0	0	0	0	0.4
	2		0.24	0.6	0.4	0	0.12	0	0.267 <sup>b</sup>
	3		0.24	0.6	0.4	0	0	3.2	0

\* w = 1: sludges;  
w = 2: combustibles;  
w = 3: glass/metals.

<sup>a</sup>  $0.24 / f_{c_3} = 0.08$ , cement ash.  
<sup>b</sup>  $0.8 / f_{c_3} = 0.267$ , vitrify ash.

TABLE D.4-2

AVERAGE ANNUAL MAINTENANCE EFFORT  $\phi_{50\kappa}^{(w)}$  (IN MAN-YEARS)  
ON DEVICE  $v$  FOR TREATING WASTEFORM  $w$  IN ALTERNATIVE  $\kappa$

$\kappa$	$w^*$	$v$	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		0.37	0	0	0	0	0	0
	2		0.74	0	0	0	0	0	0
	3		0.74	0	0	0	0	0	0
1	1		0.38	0	0	0	0	0	0
	2		0.76	0	1.90	0.38	0	0	0
	3		0.76	0	1.90	0.38	0	0	0
2	1		0.38	0	0	0.19	0	0	0
	2		0.76	0	1.90	0.38	0	0	0
	3		0.76	0	1.90	0.38	0	0	0
3	1		0.38	0	0	0.19	0	0	0
	2		0.76	0.76	1.90	0.13 <sup>a</sup>	0.37	0	0
	3		0.76	0.76	1.90	0.38	0	0	0
4	1		0.38	0	0	0	0	0	0.94
	2		0.76	0.76	1.90	0	0.37	0	0.63 <sup>b</sup>
	3		0.76	0.76	1.90	0	0	18.9	0

\*  $w = 1$ : sludges;  
 $w = 2$ : combustibles;  
 $w = 3$ : glass/metals.

<sup>a</sup> Cement ash from incineration.  
<sup>b</sup> Vitrify ash from incineration.

release thus contains a fraction of  $10^{-5}$  of a drum mass per drum handled. For the other devices, it is assumed that health and safety concerns, particularly for maintenance, are the driving factors. Releases, therefore, have to be kept low, in order to keep maintenance frequency and the radiation dose budget of the maintenance crew low. The relatively large uncertainties in the release factors are accounted for by using a broad symmetrical Gaussian distribution but pushing it toward the upper limit of the range estimated for the quantity. The numerical values estimated for the release fractions are listed in Table D.4-3.

#### D.4.5 Releases From Containment

A certain fraction of the waste suspended in the containment device  $v$  is assumed to penetrate airlocks and reach the air inside the treatment unit (see Section F.3.2.1.1). The quantity  $f_{50\kappa}^{(v)}$  is the fraction of waste in form  $w$  suspended and released from containment in inhalable form due to treatment  $v$  in alternative  $\kappa$ . This release fraction for every drum treated is estimated to be  $10^{-9}$  in the drum. In Table D.4-4, the fraction of the drums treated at each device and the fraction escaping from containment are listed.

#### D.4.6 Suspension During Maintenance

During maintenance and decontamination, a certain fraction of the contamination is resuspended in air (see Section F.3.2.2.1). The fraction  $f_{503}^{(wv)}$  of the waste which is resuspended during cleanup of device  $v$  is a quantity needed in that part of the risk assessment.

Numerical values of fractions  $f_{503}^{(wv)}$  which are needed in the following are given in Table D.4-5. The baseline value here assumes that in maintenance operations a fraction of about  $(1.0 \pm 0.3) 10^{-4}$  is resuspended. Similarly, the values from Table D.4-4 are multiplied with this factor to assess the activity remobilized during maintenance. The standard errors of the combination are estimated in the Gaussian approximation.

#### D.4.7 Routine Releases of VOCs During Treatment

For shredding and sorting, the drums and the liners and wrappings are opened, letting all accumulated gases escape. The gas release function  $\Phi_{61j}^{(\kappa)}$  for agent  $j$  and alternative  $\kappa$ , is defined by

$$F_{r\kappa j} \equiv \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}}, \quad (\text{D.4.4})$$

where the functions  $\Phi_{61j}^{(\kappa)}$  account for the gas releases from the void space. Also accounted for are the fractions of drums not opened (sludges in Treatment Option 1). The baseline releases

TABLE D.4-3

FRACTION  $f_{592}^{(w)}$  OF THE WASTE RELEASED INTO THE CONTAINMENT OF DEVICE v

K	w*	v	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		A	0	0	0	0	0	0
	2		A	0	0	0	0	0	0
	3		A	0	0	0	0	0	0
1	1		A	0	0	0	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
2	1		A	0	0	C	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
3	1		A	0	0	C	0	0	0
	2		A	C	C	B <sup>a</sup>	C	0	0
	3		A	C	C	C	0	0	0
4	1		A	0	0	0	0	0	C
	2		A	C	C	0	C	0	B <sup>b</sup>
	3		A	C	C	0	0	C	0

\* w = 1: sludges;  
w = 2: combustibles;  
w = 3: glass/metals.

A =  $(1.0 \pm 0.3) \cdot 10^{-5}$   
B =  $(1.0 \pm 0.3) \cdot 10^{-4}$   
C =  $(1.0 \pm 0.3) \cdot 10^{-3}$

<sup>a</sup> Cement ash from incineration  
<sup>b</sup> Vitrify ash from incineration

TABLE D.4-4

**FRACTION  $f_{50\%}^{(M)}$  OF THE WASTE ACTIVITY SUSPENDED  
AND RELEASED FROM CONTAINMENT OF DEVICE v**

TREATMENT v	TREATMENT Operation	FRACTION OF 41,000 DRUMS HANDLED ANNUALLY (PERCENT)					FRACTION $f_{50\%}^{(M)}$ OF WASTE ACTIVITY				
		TREATMENT OPTION					TREATMENT OPTION				
		0	1	2	3	4	0	1	2	3	4
0	Assay	97.6 <sup>a</sup>	100	100	100	100	$(1.0 \pm 0.3) \cdot 10^{-5}$	$(1.0 \pm 0.3) \cdot 10^{-5}$	$(1.0 \pm 0.3) \cdot 10^{-5}$	$(1.0 \pm 0.3) \cdot 10^{-5}$	$(1.0 \pm 0.3) \cdot 10^{-5}$
1	Sort	0	0	0	80	80	0	0	0	$(0.8 \pm 0.3) \cdot 10^{-9}$	$(0.8 \pm 0.3) \cdot 10^{-9}$
2	Shred	0	80	80	40	80	0	$(0.8 \pm 0.3) \cdot 10^{-9}$	$(0.8 \pm 0.3) \cdot 10^{-9}$	$(0.4 \pm 0.1) \cdot 10^{-9}$	$(0.8 \pm 0.3) \cdot 10^{-9}$
3	Cement	0	80	100	44 <sup>b</sup>	0	0	$(0.8 \pm 0.3) \cdot 10^{-9}$	$(1.0 \pm 0.3) \cdot 10^{-9}$	$(0.44 \pm 0.3) \cdot 10^{-9}$	0
4	Incinerate	0	0	0	40	40	0	0	0	$(0.4 \pm 0.1) \cdot 10^{-9}$	$(0.4 \pm 0.1) \cdot 10^{-9}$
5	Smelt	0	0	0	0	40	0	0	0	0	$(0.4 \pm 0.1) \cdot 10^{-9}$
6	Vitrify	0	0	0	0	24 <sup>c</sup>	0	0	0	0	$(0.24 \pm 0.07) \cdot 10^{-9}$

<sup>a</sup> Only 40,000 drums present in baseline case.

<sup>b</sup> Cement ash from combustibles.

<sup>c</sup> Vitrify ash from combustibles.

TABLE D.4-5

FRACTION  $f_{003}^{(w)}$  OF THE WASTE RELEASED WHICH IS RESUSPENDED IN MAINTENANCE OPERATIONS

$\kappa$	$w^*$	$v$	ASSAY 0	SORT 1	SHRED 2	CEMENT 3	INCINERATE 4	SMELT 5	VITRIFY 6
0	1		A	0	0	0	0	0	0
	2		A	0	0	0	0	0	0
	3		A	0	0	0	0	0	0
1	1		A	0	0	0	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
2	1		A	0	0	C	0	0	0
	2		A	0	C	C	0	0	0
	3		A	0	C	C	0	0	0
3	1		A	0	0	C	0	0	0
	2		A	C	0	B <sup>a</sup>	C	0	0
	3		A	C	C	C	0	0	0
4	1		A	0	0	0	0	0	C
	2		A	C	0	0	C	0	B <sup>b</sup>
	3		A	C	0	0	0	C	0

\*  $w = 1$ : sludges;  
 $w = 2$ : combustibles;  
 $w = 3$ : glass/metals.

A =  $(1.0 \pm 0.3) \cdot 10^{-9}$   
 B =  $(1.0 \pm 0.3) \cdot 10^{-6}$   
 C =  $(1.0 \pm 0.3) \cdot 10^{-7}$

<sup>a</sup> Cement ash from incineration  
<sup>b</sup> Vitrify ash from incineration

are taken to be those through the carbon filter on the drum during the assay and certification process. Table D.4-6 lists, in the second column, the release rates for the five chemical agents given in Table 5.35 of the FSEIS (DOE, 1990a). During the 0.2 hours of the process, the mass of gas given in the third column is released. The concentrations of the chemicals in the void space of the drums (147 liters) are taken from Table 5.33 of the FSEIS (DOE, 1990a) and are given in the next column together with the total mass of gas for agent j.

As expected for the slow, diffusion-limited gas release in the baseline case, the fraction of the total gas released in a short time is independent of the agent, with an average value of  $(6.4 \pm 0.7) \cdot 10^{-5}$ . In Table D.4-7, the values for the reduction factors for gas release  $F_{r,j}$  are listed. These values show the dramatic increase in releases due to handling, and demonstrate that the release reduction factors and, thus, the risk reduction factors are independent of the chemical considered. No aggregation is, therefore, needed.

## D.5 HUMAN INTRUSION SCENARIOS

### D.5.1 Radioactivity in Cuttings Brought to Surface

Drill cuttings brought to the surface in a human intrusion scenario will contain radioisotopes if the repository is intersected. The activity mobilized and transported to the surface for different treatments of waste is reduced by a factor

$$F_{ax} = \frac{\Phi_{40,1}^{(0)}}{\Phi_{40,1}^{(x)}}, \quad (D.5.1)$$

where the function  $\Phi_{40,1}^{(x)}$  is the time average of the activity brought to the surface. An approximation by a step function leads to a value given by the total activity mobilized. The total activity mobilized is evaluated for baseline and alternative waste using the methodology described in Section B.22 of Appendix B. The resulting values for  $F_{ax}$  are given in Table D.5-1. They range from about 4 for Level II treatments down to about 2 for Treatment Option 3 and to a risk increase by a factor of about 2 for Treatment Option 4.

### D.5.2 Radioactivity Transported to the Culebra

After the drill hole is plugged, the connection to the Culebra aquifer may still exist, or will when the hole casing corrodes. This contamination depends not only on waste treatment but also on the drilling scenario.

#### D.5.2.1 The E1 Human Intrusion Scenario

In this scenario, both the repository and a brine pocket in the Castile formation are penetrated. After plugging the hole, contaminated brine can still reach the Culebra aquifer, a stock well, and

TABLE D.4-6

## DATA ON RELEASE RATES AND MASS OF GASES IN DRUMS

CHEMICAL	RELEASE RATE (g/s) <sup>a</sup>	RELEASE OF MASS (g) <sup>b</sup>	GAS CONCENTRATION (g/L) <sup>c</sup>	MASS OF GAS IN VOID (g)	RELEASE FRACTION (12 min)
Methylene chloride	$7.8 \cdot 10^{-9}$	$5.6 \cdot 10^{-6}$	$0.5 \cdot 10^{-3}$	0.074	$7.6 \cdot 10^{-5}$
Carbon tetrachloride	$2.3 \cdot 10^{-8}$	$1.7 \cdot 10^{-5}$	$1.9 \cdot 10^{-3}$	0.28	$5.9 \cdot 10^{-5}$
Trichloro- ethylene	$9.3 \cdot 10^{-9}$	$6.7 \cdot 10^{-6}$	$0.7 \cdot 10^{-3}$	0.10	$6.5 \cdot 10^{-5}$
1,1,1-trichloroethane	$1.7 \cdot 10^{-7}$	$1.2 \cdot 10^{-4}$	$13 \cdot 10^{-3}$	1.94	$6.3 \cdot 10^{-5}$
Freon	$1.4 \cdot 10^{-8}$	$1.0 \cdot 10^{-5}$	$1.2 \cdot 10^{-3}$	0.18	<u><math>5.7 \cdot 10^{-5}</math></u>
				Average	$(6.4 \pm 0.7) \cdot 10^{-5}$

<sup>a</sup> From Table 5.35 of the FSEIS (DOE, 1990a); this is the rate  $q_{12j}^{(g)}$ .

<sup>b</sup> Mass released in the assay time of 0.2 hours.

<sup>c</sup> From Table 5.33 of the FSEIS (DOE, 1990a); this is  $q_{10j}^{(g)}$ .

**TABLE D.4-7**  
**REDUCTION FACTOR  $F_{r,kj}$  FOR RELEASE OF AGENT J**

ALTERNATIVE $\kappa$	FRACTION OF DRUMS OPENED	RELEASE FRACTION	REDUCTION FACTOR $F_{r,kj}$
0	0.0 *	$(6.4 \pm 0.7) \cdot 10^{-5}$	--
1	0.8	0.8	$(5.1 \pm 0.6) \cdot 10^{-5}$
2	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$
3	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$
4	1.0	1.0	$(6.4 \pm 0.7) \cdot 10^{-5}$

\* No drums opened routinely. Emission is that of drum releases through vent during 0.2 hours

**TABLE D.5-1**  
**REDUCTION FACTORS FOR MOBILIZED ACTIVITIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
F <sub>a1</sub>	3.9 $\pm$ 0.5	
F <sub>a2</sub>	4.0 $\pm$ 0.5	
F <sub>a3</sub>	2.4 $\pm$ 0.5	
F <sub>a4</sub>	0.5 $\pm$ 0.5	

man via the consumption of beef. The concentration of radioactivity in the stock well and, therefore, in the beef, depends on the rate with which the activity is mobilized in the repository and transported to the Culebra aquifer. The reduction factor for this long-term mobilization and transport rate  $\Phi_{481}^{(\infty)}$  is

$$F_{b,c} \cong \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\infty)}} \quad (D.5.2)$$

The solution to the two-dimensional equation governing contaminant migration in a uniform unidirectional flow from a continuous point source without adsorption or radioactive decay states that the activity concentration in the stock well is proportional to the product of the total radionuclide activity concentration entering the Culebra and the injection rate entering the Culebra (Walton, 1989). The total radionuclide activity concentration entering the Culebra was calculated by using

$$Q_T = \sum_{\alpha=1}^A \frac{s_{\alpha} q_{\alpha} \Phi_w}{\Phi_I} \quad (D.5.3)$$

where

- $Q_T$  = Total activity concentration entering the Culebra,
- $s_{\alpha}$  = Solubility of radionuclide  $i$  in brine ( $\text{g m}^{-3}$ ) (evaluated in subroutine RADSOLUB of the Design Analysis Model, Section B.21 of Appendix B),
- $q_{\alpha}$  = Specific activity of radionuclide  $i$  ( $\text{Ci g}^{-1}$ ),
- $\Phi_w$  = Flowrate of brine through the waste/backfill composite ( $\text{m}^3 \text{s}^{-1}$ ), and
- $\Phi_I$  = Total steady-state injection rate entering the Culebra ( $\text{m}^3 \text{s}^{-1}$ ).

The steady-state flowrates  $\Phi_w$  and  $\Phi_I$  are evaluated through parametric equations in subroutine ISE1 of the Design Analysis Model as described in Section B.23. The numerical values for  $F_{b,c}$  are given in Table D.5-2 with their geometric standard deviations.

**TABLE D.5-2**  
**REDUCTION FACTORS FOR MOBILIZED ACTIVITIES**

SCENARIO	QUANTITY	VALUE	GSD
E1	$F_{b1}$	$9.5 \cdot 10^3$	(20)
	$F_{b2}$	$9.5 \cdot 10^3$	(20)
	$F_{b3}$	$9.7 \cdot 10^3$	(20)
	$F_{b4}$	$10.7 \cdot 10^3$	(20)
E2	$F_{c1}$	1.0	(3)
	$F_{c2}$	1.1	(3)
	$F_{c3}$	0.8	(5)
	$F_{c4}$	7.0	(50)
E1E2	$F_{d1}$	$6 \cdot 10^5$	(80)
	$F_{d2}$	$8 \cdot 10^5$	(60)
	$F_{d3}$	$2 \cdot 10^6$	(80)
	$F_{d4}$	$2 \cdot 10^8$	(40)

GSD - Geometrical Standard Deviation.

**D.5.2.2 The E2 Human Intrusion Scenario**

In this scenario, only the repository is penetrated. The reduction factor for the long-term mobilization and transport rate  $\Phi_{471}^{(\kappa)}$  is

$$F_{c\kappa} \equiv \frac{\Phi_{471}^{(0)}}{\Phi_{471}^{(\kappa)}}. \quad (\text{D.5.4})$$

The release of activity from a panel to the Culebra was assumed to occur as a slug point source. The solution to the two-dimensional equation governing contaminant migration in uniform one-directional flow from a slug point source without adsorption or radioactive decay indicates that the concentration at the stock well is proportional to the total activity injected into the Culebra (Walton, 1989). The numerical values for  $F_{c\kappa}$  are given in Table D.5-2 with their geometric standard deviations.

**D.5.2.3 The E1E2 Human Intrusion Scenario**

In this scenario, an E1 event is postulated to occur first, then an E2 event into the repressurized repository. Thus, both drill holes will, after plugging, connect to the Culebra aquifer. The reduction factor for the long-term mobilization and transport rate  $\Phi_{481}^{(\kappa)}$  is

$$F_{d\kappa} \equiv \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\kappa)}}. \quad (\text{D.5.5})$$

The activity concentration entering the Culebra for an alternative was assumed to be independent of an alternative and equal to the saturation activity concentration. Thus the risk reduction factor  $f_{c\kappa}$  was calculated as the ratio of the volume of contaminated brine released to the Culebra for the baseline design to the total volume of contaminated brine released to the Culebra for alternative  $\kappa$ . Numerical values are given in Table D.5-2.

## ATTACHMENT E

ROUTINE AND ACCIDENT RISKS OF TRANSPORTING, HANDLING,  
AND EMPLACING CH TRU WASTEE.1 CANCER RISKS FROM ROUTINE INTERNAL EXPOSURES TO IONIZING RADIATIONE.1.1 Basic Considerations

The risks discussed in this section are risks associated with the inhalation of alpha, beta, and gamma emitters. Cumulative Effective Dose Equivalents (CEDE) are calculated and used to estimate the global lifetime cancer risks using the methodology and the data provided in ICRP 26 and ICRP 30 (International Commission on Radiological Protection, 1977 and 1979).

To determine the different risks of releases, it is essential to understand that the occupational and the public risks arise from the same source term, defined as  $\{Q_i^{(k)}\}$  for scenario  $i$  and treatment/location option  $k = (\kappa, \lambda)$ . This source term is denoted in the formulae by the quantity in braces. Occupational and public risks are distinguished by different exposure conditions. For the occupational risks, the factor  $f_{exp}^{(k)}$  takes into account the conditions of the exposure and the factor  $f_{dos}^{(k)}$  accounts for the dosimetry conditions of the average worker. In order to convert the CEDE to risk in terms of latent cancer fatalities, the risk factor  $a_1$  must be incorporated into the risk formula as a cancer risk coefficient. The basic form for the occupational cancer risk formula (denoted by subscript 'o') is then the following

$$R_{io k} = \{Q_i^{(k)}\} f_{exp}^{(k)} f_{dos}^{(k)} a_1 . \quad (E.1.1)$$

The public cancer risk formula has the same source term  $\{Q_i^{(k)}\}$  and cancer risk coefficient  $a_1$  as Equation (E.1.1). The factor  $f_{dep}^{(k)}$  accounts for the depletion of activity before the filter duct. The factor  $f_{rem}^{(k)}$  accounts for the removal efficiency of the high efficiency particulate air (HEPA) filters in the Waste Handling Building (WHB) or Treatment Facility (TF). The factor  $\Phi_{idd}^{(k)}$  describes the environmental dispersion from the source to the various receptors via different pathways and the dosimetry for each receptor. This factor also accounts for the accumulation of a 50-year CEDE according to the computer code AIRDOS (Moore et al., 1979). The basic form for the public cancer risk formula (denoted by subscript 'p') is, therefore, given as:

$$R_{ip k} = \{Q_i^{(k)}\} f_{dep}^{(k)} f_{rem}^{(k)} \Phi_{idd}^{(k)} a_1 . \quad (E.1.2)$$

The function  $\Phi_{idd}^{(k)}$  also incorporates different types and properties of all ionizing radiations in the source term. Further, via AIRDOS, the doses for all exposed members of the public are incorporated into this function. From an inspection of Equations (E.1.1) and (E.1.2), it follows that the risk reduction factors (i.e., the inverse of the relative risks) remain the same for occupational

and public risks, provided there is no change with alternative k in the quantities of the risk formula other than the source term  $\{Q_j^{(k)}\}$ .

There are four major health effects arising from internal radiation exposures: acute radiation syndrome; somatic effects other than cancer; and cancer and genetic effects. In the risk assessments of the FSEIS (DOE, 1990a) and FSAR (DOE, 1989a), the acute radiation syndrome is only postulated to occur in transportation accidents of severity category VIII (RADTRAN; Madsen et al., 1986). Somatic effects, mostly manifested as a shortening of the lifespan, are well known from animal experiments, but human data are lacking for the quantification of risk. The risks of cancer and genetic damage are assumed to be proportional to different parts of the CEDE. Assuming different dosimetry factors in Equations (E.1.1) and (E.1.2) and a risk coefficient  $b_1$  for genetic effects shows that, for scenarios in which only the source term changes with the alternatives, the risk reduction factors are the same,

$$\begin{aligned} \rho_{iok}^{(ca)} &= \rho_{iok}^{(gen)} \\ \rho_{ipk}^{(ca)} &= \rho_{ipk}^{(gen)}. \end{aligned} \tag{E.1.3}$$

In order to simplify the equations and keep the number of equations as low as possible, the superscripts (ca) and (gen) will not be carried explicitly in the formulae. It should be noted that all quantified risks will be given in terms of per year of operation.

For the routine operations addressed in this section, it is assumed that the quantity and dispersion of contamination is low and subtle enough so that the radiation monitors, particularly the Continuous Air Monitors (CAMs) are not triggered and that normal work without special protection (respirators) continues. This assumption results in the low-level chronic exposures implied by the scenarios. Once the CAMs or other monitors are triggered, the workers don respirators and leave the area according to Health and Safety instructions, thereby ending the exposure. Such incidents are treated as accidents in Section E.3.

#### E.1.2 Risk From Routine Internal Exposures in an N1 Scenario

In Scenario N1, a fraction of surface contamination of the drums allowable under the Waste Acceptance Criteria (WAC) (DOE, 1989b) is mobilized by the handling of the contaminated drums and is suspended in air. Assuming constant handling activities, instantaneous mixing, and homogeneous distribution within the WHB, the specific activity in air is estimated to be at its equilibrium level. The inhalation over eight hours per workday, the deposition of particles in lung, and the dosimetry leading to effective dose equivalents are described by corresponding factors in the risk equation. The dose-effect relationship for cancer or genetic effects is assumed to be of the linear, no-threshold type. These risks do not depend on the location index  $\lambda$ ; they vary only with treatment  $\kappa$ . It is assumed that nobody dons a respirator and there is no alarm sounded by the CAMs.

With these assumptions, Scenario N1 leads to Risk Component 1, with four subcomponents: occupational and public, cancer and genetic. Using the symbols

- $n_r^{(\kappa)}$  = Number of drums handled routinely per year ( $\text{yr}^{-1}$ ),
- $f_{11}^{(\kappa)}$  = Fraction of drums externally contaminated,
- $f_{12}^{(\kappa)}$  = Suspended, inhalable fraction of surface activity,
- $q_1^{(\kappa)}$  = Total alpha surface activity per drum (Bq),
- $L_1$  = Annual ventilation volume in the building ( $\text{m}^3$ ),
- $V_1$  = Annual breathing volume of worker ( $\text{m}^3$ ),
- $f_{13}^{(\kappa)}$  = Fraction of inhalable airborne particles deposited in lung,
- $f_{14\alpha}^{(\kappa)}$  = Fraction of type  $\alpha$  radiation in total activity,
- $\Phi_{11\alpha}^{(\kappa)}$  = Dosimetry function for type  $\alpha$  radiation ( $\text{Sv Bq}^{-1}$ ),
- $A$  = Total number of different radiation types  $\alpha$ ,
- $N_{o1}^{(\kappa)}$  = Number of occupationally exposed persons in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $C_1$  = Constant parts of the equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{1o\kappa\lambda}$  = Risk of occupational cancer per year of operation ( $\text{yr}^{-1}$ ),

the expression for the occupational cancer risk incurred for every year of operation is

$$R_{1o\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{11}^{(\kappa)} f_{12}^{(\kappa)} q_1^{(\kappa)} \right\} \frac{1}{L_1} V_1 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{o1}^{(\kappa)} a_1, \quad (\text{E.1.4})$$

where the quantity in braces corresponds to the source term of Equations (E.1.1) and (E.1.2) and the four indices of the risk  $R$  are the component number 1, the risk type index, 'o' for occupational or 'p' for public, the treatment index  $\kappa$ , and the location index  $\lambda$ .

An inspection of this equation with respect to changes due to different treatment/location options shows that most of the factors do not change with  $\kappa$  and now with  $\lambda$ . Due to the assumptions about suspended particle size and activity distributions, the deposition probability and the dosimetry factors are constant. The fraction of drums contaminated is mostly dependent on work practices and these are assumed to result in a constant fraction for newly generated wastes. For old wastes, this assumption may result in an overestimate for the treatment options. The surface activity  $q_1^{(\kappa)}$  is set at the maximum allowable limit (DOE, 1990a, Table A.1.1, Appendix A) and thus does not change either. The number of drums treated annually  $n_r^{(\kappa)}$  changes, however, because its product with the average activity per drum  $q_2^{(\kappa)}$  is the annual rate of activity emplacement  $Q_o$  in the repository and is assumed to be a constant  $C_o$ , i.e.,

$$Q_o = n_r^{(\kappa)} q_2^{(\kappa)} = C_o. \quad (\text{E.1.5})$$

The extra handling in the treatment facility, regardless of location, leads to an air concentration of radioactivity in that building. Assuming that the health and safety requirements lead to the same ventilation rates everywhere, and the modular construction of the treatment facilities, the same fraction  $f_{15}$  of the total personnel  $N_{o1}^{(\kappa)}$  is assumed to be exposed. This is the crew of the module in which the exposure occurs. Therefore, the only difference lies in the number of people exposed,  $N_{o1}^{(\kappa)}$ . This dependence is incorporated in the manpower reduction factor

$$F_{m\kappa} \equiv \frac{N_{o1}^{(0)}}{N_{o1}^{(\kappa)}}, \quad (\text{E.1.6})$$

which, in this simple model, is assumed to be independent of the location of the treatment facilities. The numerical values for the manpower reduction factor are given in Attachment D, Table D.3-1.

For the public risk component, the change in Equation (E.1.2) appears in the function  $\Phi_{idd}^{(\kappa)}$  and within that function in the number  $N_{p1}^{(\kappa)}$  of exposed persons. As explained in the main text, it is assumed that the functions  $\Phi_{idd}^{(\kappa)}$  are independent of treatment  $\kappa$  and location  $\lambda$  and depend only on the number and locations of the  $N_{p1}^{(\kappa)}$  of persons exposed. This relation is incorporated in the public exposure reduction factor

$$F_{ex} \equiv \frac{\Phi_{idd}^{(0)}}{\Phi_{idd}^{(\kappa)}} = \frac{N_{p1}^{(0)}}{N_{p1}^{(\kappa)}}. \quad (\text{E.1.7})$$

The dependence on  $\kappa$  signifies the dependence on any of the four treatments. Due to this factor, the addition of risk components due to waste treatment thus leads to different reduction factors for occupational and public risk. Numerical values for this factor for these assumptions are listed in Attachment D, Table D.3-3.

With these assumptions, the scaling property of this risk component depends only on the product of the number of drums handled per year, and the number of persons exposed during handling

$$R_{1o\kappa\lambda} = C_1 n_r^{(\kappa)} N_{o1}^{(\kappa)}. \quad (\text{E.1.8})$$

The risk reduction factor is then the ratio of the number of drums handled per unit time and the ratio of the persons exposed and is thus equal to the product of the manpower reduction factor  $F_{m\kappa}$  with the volume reduction factor  $F_{v\kappa}$  of the treatment defined by

$$F_{v\kappa} \equiv \frac{n_r^{(0)}}{n_r^{(\kappa)}}. \quad (\text{E.1.9})$$

The explicit form of the risk reduction factor is

$$\rho_{10\kappa\lambda} = \frac{R_{1000}}{R_{10\kappa\lambda}} = \frac{n_r^{(0)} N_{o1}^{(0)}}{n_r^{(\kappa)} N_{o1}^{(\kappa)}} = F_{v\kappa} F_{m\kappa}. \quad (\text{E.1.10})$$

Its standard error according to the Gaussian approximation to error propagation, [Equation (C.1.15), and Seiler, 1987b, Table 1] is

$$\left( \frac{\Delta \rho_{10\kappa\lambda}}{\rho_{10\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (\text{E.1.11})$$

For this first risk component, the public risk for this release will be discussed in detail; later it will only be addressed if needed. Using the additional symbols

- $f_{\text{dep}}^{(\kappa)}$  = Fraction of release that escapes deposition in the WHB or TF,
- $f_{\text{rem}}^{(\kappa)}$  = Fraction of activity that escapes removal by the HEPA filters,
- $\Phi_{1\text{dd}}^{(\kappa)}$  = Dispersion-dosimetry function for all  $N_{p1}^{(\kappa)}$  persons exposed ( $\text{Sv Bq}^{-1}$ ),
- $R_{1p\kappa\lambda}$  = Risk of cancer in the public per year of operation ( $\text{yr}^{-1}$ ),

it is given by the expression

$$R_{1p\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{11}^{(\kappa)} f_{12}^{(\kappa)} q_1^{(\kappa)} \right\} f_{\text{dep}}^{(\kappa)} f_{\text{rem}}^{(\kappa)} \Phi_{1\text{dd}}^{(\kappa)} a_1. \quad (\text{E.1.12})$$

The first two factors outside the source term in braces do not change with treatment option  $\kappa$ , and in the source term all but the first factor have already shown to be constant by an application of Equation (E.1.5). There remains thus only the number of drums  $n_r^{(\kappa)}$  handled and the number of people  $N_{p1}^{(\kappa)}$  exposed in the factor  $\Phi_{1\text{dd}}^{(\kappa)}$ . Except for the substitution of the public exposure reduction factor  $F_{o\kappa}$  for the factor  $F_{m\kappa}$ , the reduction factor for the public risk  $\rho_{1p\kappa\lambda}$  and its standard error are thus the same as those for the occupational risks in Equations (E.1.10) and (E.1.11),

$$\rho_{1p\kappa\lambda} = F_{v\kappa} F_{o\kappa}, \quad (\text{E.1.13})$$

with standard errors of

$$\left( \frac{\Delta \rho_{1p\kappa\lambda}}{\rho_{1p\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{o\kappa}}{F_{o\kappa}} \right)^2. \quad (\text{E.1.14})$$

The numerical values of the risk reduction factors and their errors are given in Table E.1-1. For the occupational risks, the risk reduction factors range from 0.3 to 0.7, signaling an increase of the risk from a factor of about 3 for the Level II treatments down to about 1.4 for the most complex treatment. These factors balance the increase of persons exposed and the decrease in the number of barrels handled. The public risks balances the same influences. However, the spread of values is wider here, ranging from an increase by a factor of 1.7 for the Level II treatments, to the same risk for Treatment Option 3, and an actual risk reduction by a factor of more than 4 for Treatment Option 4. The relative standard errors of the reduction factors for occupational risks range from 10 to 20 percent, for public risks the range is 15 to 30 percent. The only available baseline risk is relatively small.

### E.1.3 Risk From Routine Internal Exposures in an N2 Exposure

In N2 Scenario, a perforated drum contaminates the WHB and the handling activities lead to a suspension of radioactivity in the air and an inhalation exposure of the work crew during a time interval that does not depend on the treatment of the wastes. With the same assumptions as in the model for Scenario N1, particularly with regard to the alarms, Risk Component 2 has four subcomponents. With the symbols

$n_r^{(k)}$	=	Number of drums routinely handled per year ( $\text{yr}^{-1}$ ),
$f_{21}^{(k)}$	=	Fraction of drums perforated,
$f_{22}^{(k)}$	=	Fraction of waste mass spilled from perforated drum,
$f_{23}^{(k)}$	=	Fraction of activity in size fraction below $10 \mu\text{m}$ ,
$f_{24}^{(k)}$	=	Fraction of spilled material which is resuspended,
$q_2^{(k)}$	=	Total activity in drum (Bq),
$L_1$	=	Annual ventilation volume in WHB and TF ( $\text{m}^3$ ),
$V_1$	=	Annual breathing volume ( $\text{m}^3$ ),
$f_{13}^{(k)}$	=	Fraction of inhalable airborne particles deposited in lung,
$f_{14\alpha}^{(k)}$	=	Fraction of type $\alpha$ radiation in total activity,
$\Phi_{11\alpha}^{(k)}$	=	Dosimetry factor for type $\alpha$ radiation ( $\text{Sv Bq}^{-1}$ ),
$A$	=	Number of different radiation types $\alpha$ ,
$N_{o1}^{(k)}$	=	Number of persons in WHB and TF,
$f_{15}$	=	Fraction of personnel occupationally exposed,
$C_1$	=	Constant parts of the equations,
$a_1$	=	Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
$R_{2o\alpha\lambda}$	=	Occupational cancer risk per year of operation ( $\text{yr}^{-1}$ ),

TABLE E.1-1

## RISK REDUCTION FACTORS FOR N1 ACTIVITIES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
P <sub>1o1λ</sub>	0.331 ± 0.034	
P <sub>1o2λ</sub>	0.312 ± 0.032	
P <sub>1o3λ</sub>	0.374 ± 0.088	
P <sub>1o4λ</sub>	0.707 ± 0.079	
<b>Public:</b>		
P <sub>1p1λ</sub>	0.600 ± 0.108	
P <sub>1p2λ</sub>	0.600 ± 0.108	
P <sub>1p3λ</sub>	1.1 ± 0.31	
P <sub>1p4λ</sub>	4.65 ± 0.87	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
R <sub>1o00</sub>	3.9 · 10 <sup>-4</sup>	FSEIS (DOE 1990a), Table 5.24
<b>Public:</b>		
R <sub>1p00</sub>	---	Not available in FSEIS

the occupational risk equation is

$$R_{20\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{21}^{(\kappa)} f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} q_2^{(\kappa)} \right\} \frac{1}{L_1} V_1 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{01}^{(\kappa)} a_1 . \quad (\text{E.1.15})$$

Note that, apart from the source term, the equation is the same as Equation (E.1.4). Assumption of constant annual activity disposal rate  $Q_0$  in Equation (E.1.5) and the constant factors discussed in the last section, reduce the risk to the scaling form

$$R_{20\kappa\lambda} = C_1 f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{01}^{(\kappa)} , \quad (\text{E.1.16})$$

and as the first three factors after the constant are really the fraction  $\phi_2^{(\kappa)}$  of the total activity which is suspended in inhalable form in a N2 scenario, the scaling relation is

$$R_{20\kappa\lambda} = C_2 \phi_2^{(\kappa)} N_{01}^{(\kappa)} , \quad (\text{E.1.17})$$

with

$$\phi_2^{(\kappa)} \equiv f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} . \quad (\text{E.1.18})$$

This uses the same assumptions about the treatment facility as those made in the last section. The risk reduction factors for the occupational risks are

$$P_{20\kappa\lambda} = \frac{f_{22}^{(0)} f_{23}^{(0)} f_{24}^{(0)} N_{01}^{(0)}}{f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{01}^{(\kappa)}} = S_{1\kappa} F_{m\kappa} , \quad (\text{E.1.19})$$

where the reduction factor in particle resuspension,  $S_{1\kappa}$ , measures the reduction in suspension of waste in a N2 activity,

$$S_{1\kappa} \equiv \frac{\phi_2^{(0)}}{\phi_2^{(\kappa)}} . \quad (\text{E.1.20})$$

The standard errors are

$$\left( \frac{\Delta \rho_{20\kappa\lambda}}{\rho_{20\kappa\lambda}} \right)^2 = \left( \frac{\Delta S_{1\kappa}}{S_{1\kappa}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (\text{E.1.21})$$

Numerical values for this factor and its errors are tabulated in Attachment D in Tables D.2-2 and D.2-4.

The public risk equation uses the same symbols as those given above, and in addition

$$\begin{aligned} f_{\text{dep}}^{(\kappa)} &= \text{Activity depletion due to deposition,} \\ f_{\text{rem}}^{(\kappa)} &= \text{Removal efficiency of HEPA filters,} \\ \Phi_{2\text{dd}}^{(\kappa)} &= \text{Dispersion-dosimetry factor for all exposed persons (Sv Bq}^{-1}\text{).} \end{aligned}$$

The risk is therefore given by

$$R_{20\kappa\lambda} = \left\{ n_r^{(\kappa)} f_{21}^{(\kappa)} f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} q_2^{(\kappa)} \right\} f_{\text{dep}}^{(\kappa)} f_{\text{rem}}^{(\kappa)} \Phi_{2\text{dd}}^{(\kappa)} a_1. \quad (\text{E.1.22})$$

With the same constant quantities as for occupational exposure, the scaling part of the public risk is

$$R_{2p\kappa\lambda} = C_3 f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} \Phi_{2\text{dd}}^{(\kappa)} = C_3 \phi_2^{(\kappa)} \Phi_{2\text{dd}}^{(\kappa)}, \quad (\text{E.1.23})$$

and the risk reduction factor for the public risk is

$$\rho_{2p\kappa\lambda} = \frac{f_{22}^{(0)} f_{23}^{(0)} f_{24}^{(0)} N_{p1}^{(0)}}{f_{22}^{(\kappa)} f_{23}^{(\kappa)} f_{24}^{(\kappa)} N_{p1}^{(\kappa)}} = S_{1\kappa} F_{\bullet\kappa}, \quad (\text{E.1.24})$$

where the factor  $F_{\bullet\kappa}$  is given in Attachment D, in Table D.3-2. The standard error is

$$\left( \frac{\Delta \rho_{2p\kappa\lambda}}{\rho_{2p\kappa\lambda}} \right)^2 = \left( \frac{\Delta S_{1\kappa}}{S_{1\kappa}} \right)^2 + \left( \frac{\Delta F_{\bullet\kappa}}{F_{\bullet\kappa}} \right)^2. \quad (\text{E.1.25})$$

Numerical values for the two factors in Equation (E.1.24) are listed in Attachment D in Tables D.3-2 and D.3-4. This results in the values for risk reduction factors given in Table E.1-2.

With an exposure reduction factor of 1/2 and a suspendability reduction factor of tens to hundreds of million, the risk reduction factors are very large, on the order of a few million to a few tens of millions. The standard errors are in the neighborhood of 20 to 30 percent. For this exposure

TABLE E.1-2

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS  
IN THE N2 SCENARIOS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{2o1\lambda}$	$(2.48 \pm 0.84) \cdot 10^7$	
$P_{2o2\lambda}$	$(2.86 \pm 1.05) \cdot 10^7$	
$P_{2o3\lambda}$	$(1.87 \pm 0.69) \cdot 10^7$	
$P_{2o4\lambda}$	$(4.10 \pm 1.54) \cdot 10^6$	
<b>Public:</b>		
$P_{2p1\lambda}$	$(4.50 \pm 1.66) \cdot 10^7$	
$P_{2p2\lambda}$	$(5.50 \pm 2.19) \cdot 10^7$	
$P_{2p3\lambda}$	$(5.50 \pm 2.19) \cdot 10^7$	
$P_{2p4\lambda}$	$(2.70 \pm 1.09) \cdot 10^7$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{2o00}$	--	Not available in FSEIS
<b>Public:</b>		
$R_{2p00}$	--	Not available in FSEIS

scenario, no baseline risks are available. As the risk reduction factors here are much larger than those for Component 1, unweighted aggregation will introduce a bias later on.

#### E.1.4 Risk From Routine Internal Exposures in an N3 Scenario

Except for the fact that the exposure occurs underground, Scenario N3 is the same as N1. Thus, although the number of persons exposed are different, that number does not depend on treatment. The ventilation rates can also be assumed to be different due to different tasks performed but constant. The deposition and dosimetry factors, however, are the same independent of waste treatment. For this scenario, no additional risk component due to treatment of the wastes has to be considered. Risk Component 3 has four subcomponents as did the previous components. With the symbols:

- $n_r^{(k)}$  = Number of drums routinely handled per year ( $\text{yr}^{-1}$ ),
- $f_{11}^{(k)}$  = Fraction of drums contaminated,
- $f_{32}^{(k)}$  = Fraction of surface activity suspended in inhalable form by underground handling,
- $q_1^{(k)}$  = Total surface activity per drum (Bq),
- $L_3$  = Annual ventilation volume in Underground Storage Area ( $\text{m}^3$ ),
- $V_1$  = Annual breathing volume of workers ( $\text{m}^3$ ),
- $f_{13}^{(k)}$  = Fraction of airborne particles deposited in lung,
- $f_{14\alpha}^{(k)}$  = Fraction of type  $\alpha$  radiation in total activity,
- $\Phi_{11\alpha}^{(k)}$  = Dosimetry function for type  $\alpha$  radiation ( $\text{Sv Bq}^{-1}$ ),
- $A$  = Number of different radiation types  $\alpha$ ,
- $N_{o2}^{(k)}$  = Number of persons occupationally exposed underground,
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{3o\kappa\lambda}$  = Risk of occupational cancer per year of operation ( $\text{yr}^{-1}$ ),

the occupational cancer risk can be written as

$$R_{3o\kappa\lambda} = \left\{ n_r^{(k)} f_{11}^{(k)} f_{32}^{(k)} q_1^{(k)} \right\} \frac{1}{L_3} V_1 f_{13}^{(k)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(k)} \Phi_{11\alpha}^{(k)} \right) N_{o2}^{(k)} a_1 . \quad (\text{E.1.26})$$

In this scenario, the number of persons exposed does not depend on treatment and, again, the deposition fraction and the dosimetry factors remain constant as well as the suspended waste fraction  $f_{32}^{(k)}$ . Thus in the source term, only the number of drums handled per year changes with alternatives, and the annual risk can be scaled by

$$R_{3o\kappa\lambda} = C_1 n_r^{(k)} . \quad (\text{E.1.27})$$

The risk ratio is thus the same for the occupational and public risks,

$$\rho_{30\kappa\lambda} = \rho_{3p\kappa\lambda} = \frac{n_r^{(0)}}{n_r^{(\kappa)}} = F_{v\kappa} \quad (\text{E.1.28})$$

with a standard error of

$$\Delta \rho_{30\kappa\lambda} = \Delta \rho_{3p\kappa\lambda} = \Delta F_{v\kappa} \quad (\text{E.1.29})$$

Thus the numerical values of the risk reduction factors are given by the values in Attachment D, in Table D.3-2, and are listed in Table E.1-3. Clearly, only the Treatment Option 4 leads to a risk reduction factor that is substantially different from 1.

The baseline risk of occupational cancer is  $3.1 \cdot 10^{-4}$ . This value is derived from the effective dose equivalent given in the FSEIS (DOE, 1990a, Vol. 1, p. 5-69, Table 5.24) of 2.5 person·rem per year of operation and uses a lifetime cancer risk coefficient of  $2.8 \cdot 10^{-4}$  (DOE, 1990a, Vol. 1, p. 5-77, Table 5.29, Footnote B).

## E.2 CANCER RISK FROM ROUTINE EXTERNAL EXPOSURES

### E.2.1 Basic Considerations

The risks discussed here are risks of cancer due to direct external exposure to low-LET radiation. With the public far removed from the sources of external irradiation, the reduction of the public risk components will not be calculated. There are two kinds of operations in which occupational external irradiation risks arise; the first are operations aboveground in the WHB and TF, and the second are the disposal operations underground. Each of the components has two subcomponents with end points cancer and genetic damage, respectively. It is again assumed that the total activity handled per year is constant (see Equation E.1.5).

The contribution of neutrons to the external dose is taken into account by the dosimetry function which makes the assumption that the neutron source strength is proportional to the total activity in the drum. It is further assumed throughout this analysis that there is no gamma or neutron absorption occurring in the waste. The density of the untreated waste would reduce the external dose rate somewhat, so this assumption of no self absorption is slightly conservative because air shows very little absorption. If the waste is treated, the head space is reduced, the density increased and therefore the self-absorption would be greater, thus lowering the external dose rate and leading to an anti-treatment bias. The bias is small because consideration of self-absorption would make the already low risk from routine external exposures somewhat lower.

TABLE E.1-3

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS  
DUE TO N3 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{301\lambda}$	$1.2 \pm 0.1$	$P_{3p\kappa\lambda} = P_{30\kappa\lambda}$
$P_{302\lambda}$	$1.2 \pm 0.1$	
$P_{303\lambda}$	$2.2 \pm 0.5$	
$P_{304\lambda}$	$9.3 \pm 0.9$	
<b>Annual Baseline Risks:</b>		
$R_{3000}$	$7 \cdot 10^{-4}$	FSEIS (DOE, 1990a) Table 5.24, p. 5-69
$R_{3p00}$	--	Not available in FSEIS

## E.2.2 Risk From Routine External Exposures in an N4 Scenario

Scenario N4 encompasses the handling activities in the WHB and the TF. The proximity of the workers to different drum configurations has to be considered in the time-motion study which is accounted for in the dosimetry factor. This ranges from the TRUPACT-II assembly and the management of single drums to multi-drum stacks for intermediate storage. The geometrical drum configuration factors are assumed to be independent of the waste treatment. Risk Component 4 has two subcomponents, cancer and genetic. With the symbols:

- $n_r^{(k)}$  = Number of drums handled annually ( $\text{yr}^{-1}$ ),
- $q_4^{(k)}$  = Gamma activity per drum (Bq),
- $f_{41}^{(k)}$  = Gamma activity to surface dose rate conversion factor ( $\text{Sv Bq}^{-1} \text{s}^{-1} \text{m}^2$ ),
- $A_d$  = Number of drum assemblies,
- $f_{42a}^{(k)}$  = Drum assembly factor, number of drums and geometry of assembly a,
- $N_{o1}^{(k)}$  = Number of persons in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $\Phi_{4a}^{(k)}$  = Dosimetry factor for all  $N_{o1}^{(k)}$  persons exposed by assembly a ( $\text{m}^{-2}$ ),
- $\Delta t_{o1a}^{(k)}$  = Exposure time, also, time interval for rms distance for assembly a (s),
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{4ok\lambda}$  = Cancer risk per year of operation ( $\text{yr}^{-1}$ ),

the cancer risk for occupational external exposure in the WHB and TF is

$$R_{4ok\lambda} = n_r^{(k)} q_4^{(k)} f_{41}^{(k)} \left( \sum_{a=1}^{A_d} f_{42a}^{(k)} \Phi_{4a}^{(k)} \Delta t_{o1a}^{(k)} \right) f_{15} N_{o1}^{(k)} a_1. \quad (\text{E.2.1})$$

Assuming that the inverse root mean square (r.m.s.) distance in  $\Phi_{4a}^{(k)}$  and the drum configurations do not change, that the total activity,  $Q_o$ , disposed of per year is constant according to Equation (E.1.5), that the dosimetry does not change, and that the influence of self-absorption on the dose rate constant  $f_{41}^{(k)}$  can be neglected, the scaling of the risk in Equation (E.2.1) depends only on the factor  $N_{o1}^{(k)}$ , i.e., on the number of persons exposed,

$$R_{4ok\lambda} = C_1 N_{o1}^{(k)}, \quad (\text{E.2.2})$$

and the risk reduction factor is, therefore, equal to

$$P_{4ok\lambda} = F_{mk}. \quad (\text{E.2.3})$$

Its standard error is

$$\Delta \rho_{40\kappa\lambda} = \Delta F_{m\kappa} \quad (E.2.4)$$

The risk reduction factors are given by the data in Attachment D, Table D.3-2, and are listed in Table E.2-1. All values are smaller than 1, corresponding to an increase in risk between a factor of 3.6 and 13.

### E.2.3 Risk From Routine External Exposures in an N5 Scenario

This scenario differs from N4 only in the geometries of source and surroundings and the number of people exposed; all other factors are the same. Thus, the Risk Component 5 has only one subcomponent for cancer and one for genetic damage. Using the symbols:

- $n_r^{(\kappa)}$  = Number of drums handled per year ( $\text{yr}^{-1}$ ),
- $q_4^{(\kappa)}$  = Gamma activity per drum (Bq),
- $f_{41}^{(\kappa)}$  = Gamma activity to surface dose rate conversion function ( $\text{Sv Bq}^{-1} \text{s}^{-1} \text{m}^2$ ),
- $A'_d$  = Number of different drum assemblies during disposal,
- $f_{52a'}^{(\kappa)}$  = Drum assembly function, number of drums and geometry of assembly  $a'$ ,
- $\Phi_{5a'}^{(\kappa)}$  = Dosimetry function for all persons underground and assembly  $a'$  ( $\text{m}^{-2}$ ),
- $\Delta t_{02a'}^{(\kappa)}$  = Exposure time, also, time interval for rms distance for assembly  $a'$  (s)
- $N_{02}^{(\kappa)}$  = Number of persons working underground,
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{50\kappa\lambda}$  = Cancer risk per year of operation ( $\text{yr}^{-1}$ ),

the cancer risk for occupational external exposure underground is given by the expression

$$R_{50\kappa\lambda} = n_r^{(\kappa)} q_4^{(\kappa)} f_{41}^{(\kappa)} \left( \sum_{a'=1}^{A'_d} f_{52a'}^{(\kappa)} \Phi_{5a'}^{(\kappa)} \Delta t_{02a'}^{(\kappa)} \right) N_{02}^{(\kappa)} a_1 \quad (E.2.5)$$

It is assumed again that the geometrical arrangements of the drums and the time-motion study do not change with waste treatment, and that the total activity disposed of per year is constant according to Equation (E.1.5). As the number of workers  $N_{02}^{(\kappa)}$  and the conversion factor  $f_{41}^{(\kappa)}$  do not depend on treatment, risk in Equation (E.2.6) is independent of treatment option  $\kappa$  also

$$R_{50\kappa\lambda} = C_1 \quad (E.2.6)$$

and the risk reduction factor is, therefore, equal to 1

$$\rho_{50\kappa\lambda} = 1 \quad (E.2.7)$$

TABLE E.2-1

**RISK REDUCTION FACTORS FOR  
OCCUPATIONAL RISKS DUE TO ACTIVITIES IN THE N4 SCENARIO**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{4011}$	$0.276 \pm 0.016$	
$P_{4021}$	$0.260 \pm 0.017$	
$P_{4031}$	$0.170 \pm 0.010$	
$P_{4041}$	$0.0760 \pm 0.0042$	
<b>Annual Baseline Risks:</b>		
$R_{4000}$	--	Not available in FSEIS

Its standard error is, therefore, zero

$$\Delta \rho_{50\kappa\lambda} = 0. \quad (\text{E.2.8})$$

This result is intuitively obvious because, regardless of treatment, the same amount of activity has to be handled each year. The baseline risk of cancer per year of operation is (DOE, 1990a, Table 5.24, p. 5-69)

$$R_{5000} = 1.5 \cdot 10^{-9}. \quad (\text{E.2.9})$$

### E.3 CANCER RISKS FROM ACCIDENTAL EXPOSURES TO IONIZING RADIATION

#### E.3.1 Basic Considerations

The comments from Section E.1.1 on the differences between public and occupational risks apply here as well, although some factors differ from those in Equations (E.1.1) and (E.1.2). For accidents as well, both occupational and public risks arise from the same source term  $\{Q_i^{(\kappa)}\}$  for the event according to scenario  $i$  and treatment/location option  $k = (\kappa, \lambda)$ . In the formulae, the source term is again denoted by the quantity in braces, but the exposure conditions are quite different. In both cases, the annual probability rate,  $P_{ev}$ , of the initiating event is the same and is enclosed in square brackets. Also, these risks do not depend on the location of the TF but may depend strongly on the treatment.

For the occupational risks, the factor  $f_{exp}^{(\kappa)}$  takes into account characteristics of the exposure, the factor  $f_{dos}^{(\kappa)}$  those of the dosimetry, and the factor  $a_1$  is the cancer risk coefficient that converts effective CEDE dose to risk. The basic form of the occupational risk is then

$$R_{10\kappa\lambda} = [P_{ev}^{(\kappa)}] \{Q_i^{(\kappa)}\} f_{exp}^{(\kappa)} f_{dos}^{(\kappa)} a_1. \quad (\text{E.3.1})$$

For public risks, the factor  $f_{dep}^{(\kappa)}$  takes into account the depletion of the activity due to deposition before the filter duct, and  $f_{rem}^{(\kappa)}$  the removal efficiency of the HEPA filters. The environmental dispersion from source to the various receptors via different pathways, and the accumulation of a 50-year committed dose is, using the code AIRDOS (Moore et al., 1979), accounted for by the factor  $\Phi_{idd}^{(\kappa)}$  for dispersion and dosimetry. The basic form of the public risk due to the accident is then given by

$$R_{1p\kappa\lambda} = [P_{ev}^{(\kappa)}] \{Q_i^{(\kappa)}\} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{idd}^{(\kappa)} a_1. \quad (\text{E.3.2})$$

Note that the factor  $\Phi_{1, \text{cd}}^{(\kappa)}$  accounts for the different types and properties of radiations in the source term, as well as the doses for all exposed members of the public.

As long as the last three or four factors in Equations (E.3.1) and (E.3.2), respectively, are not treatment dependent, public and occupational risk reduction factors will again be the same. However, the number of forklift operations per drum handled, the number of persons exposed, and the probability of a given type of accident will in some cases depend on the waste treatment. This situation then results in different risk reduction factors for public and occupational risks.

For accident analysis, only internal exposure is assumed to contribute substantially to the risk. External radiation will not change appreciably during the accident and exposure will cease due to evacuation. Inhalation exposures are supposed to occur without respiratory protection and for the entire time it takes for the ventilation to remove the volume of contaminated air.

### E.3.2 Above Ground Accidents

These scenarios take place above ground in the WHB or in the TF regardless of location.

#### E.3.2.1 Risk In WHB and TF Due to Accident Scenario C2

Scenario C2 involves a drum falling off a forklift in the WHB or TF, the lid separating and the liner, if present, rupturing. Suspended particles from the debris are inhaled and deposited in lung tissue. Workers are present for the full dispersion and are assumed to not don respirators. The resulting Risk Component 6 has four subcomponents that involve cancer risk and genetic damage from both occupational and public exposures. Using the symbols:

$P_2$	= Probability of C2 accident per forklift operation,
$n_r^{(\kappa)}$	= Number of drums handled per year ( $\text{yr}^{-1}$ ),
$n_f^{(\kappa)}$	= Number of forklift operations needed per drum handled,
$f_{\theta 1}^{(\kappa)}$	= Fraction of material spilled out of drum,
$f_{\theta 2}^{(\kappa)}$	= Fraction of spilled material suspended in air,
$f_{\theta 3}^{(\kappa)}$	= Fraction of activity in respirable form,
$q_2^{(\kappa)}$	= Total activity in average drum (Bq),
$\Phi_6^{(\kappa)}$	= Local time-integrated dispersion function in WHB and TF ( $\text{s L}^{-1}$ ),
$v_6$	= Inhalation rate of workers in WHB and TF ( $\text{L s}^{-1}$ ),
$f_{13}^{(\kappa)}$	= Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$	= Fraction of type $\alpha$ radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$	= Dosimetry function for radiation type $\alpha$ ( $\text{Sv Bq}^{-1}$ ),
$A$	= Number of different radiation types $\alpha$ ,
$N_{o1}^{(\kappa)}$	= Number of people in the WHB and TF,
$f_{15}$	= Fraction of personnel occupationally exposed,
$C_1$	= Constant parts of equations,

$a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and  
 $R_{60\kappa\lambda}$  = Occupational cancer risk per year of operations ( $\text{yr}^{-1}$ ),

the risk of occupational cancer per year of operation is

$$R_{60\kappa\lambda} = [P_2 n_r^{(\kappa)} n_i^{(\kappa)}] \{ f_{61}^{(\kappa)} f_{62}^{(\kappa)} f_{63}^{(\kappa)} q_2^{(\kappa)} \} \quad (\text{E.3.3})$$

$$\Phi_6^{(\kappa)} v_6 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{01}^{(\kappa)} a_1,$$

where the dosimetry quantity in round brackets (the summation) again accounts for the effects of different radiation types. This model assumes that a constant fraction  $f_{15}$  of the  $N_{01}^{(\kappa)}$  workers always work in the WHB and TF area and are thus maximally exposed.

Observing a constant value of the annually emplaced activity  $Q_0$  in Equation (E.1.5), an independent dispersion function  $\Phi_6^{(\kappa)}$ , and a constant deposition fraction  $f_{13}^{(\kappa)}$ , the variable factors allow the risk to be written as scaling with

$$R_{60\kappa\lambda} = C_1 f_{61}^{(\kappa)} f_{62}^{(\kappa)} f_{63}^{(\kappa)} n_i^{(\kappa)} N_{01}^{(\kappa)} \quad (\text{E.3.4})$$

$$= C_1 \phi_6^{(\kappa)} n_i^{(\kappa)} N_{01}^{(\kappa)},$$

with the fraction  $\phi_6^{(\kappa)}$  denoting that part of the activity which is suspended by the C2 accident in inhalable form. Thus,

$$\phi_6^{(\kappa)} = f_{61}^{(\kappa)} f_{62}^{(\kappa)} f_{63}^{(\kappa)}. \quad (\text{E.3.5})$$

This fraction, or even its reduction factor  $S_{2\kappa}$ ,

$$S_{2\kappa} = \frac{f_{61}^{(0)} f_{62}^{(0)} f_{63}^{(0)}}{f_{61}^{(\kappa)} f_{62}^{(\kappa)} f_{63}^{(\kappa)}}, \quad (\text{E.3.6})$$

may be easier to estimate directly than the individual fractions. The risk reduction factor is, therefore,

$$\rho_{60\kappa\lambda} = \frac{N_{01}^{(0)} \phi_6^{(0)} n_i^{(0)}}{N_{01}^{(\kappa)} \phi_6^{(\kappa)} n_i^{(\kappa)}} = F_{m\kappa} S_{2\kappa} F_{i\kappa}, \quad (\text{E.3.7})$$

where  $F_{fk}$  is the ratio of the number of forklift operations in the handling of drums for different treatment options. The standard error is

$$\left( \frac{\Delta \rho_{\theta \theta \kappa \lambda}}{\rho_{\theta \theta \kappa \lambda}} \right)^2 = \left( \frac{\Delta S_{2\kappa}}{S_{2\kappa}} \right)^2 + \left( \frac{\Delta F_{fk}}{F_{fk}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (E.3.8)$$

As some of the factors outside the source term in the occupational risk change with alternative, the public risk is subject to different scaling, resulting in different risk reduction factors for the occupational risk.

The risk reduction factor for the public risk resulting from a C2 incident is, with the additional notation of

- $f_{dep}^{(\kappa)}$  = Activity depletion due to deposition,
- $f_{rem}^{(\kappa)}$  = Removal efficiency of HEPA filters,
- $\Phi_{\theta \theta d}^{(\kappa)}$  = Dispersion-dosimetry factor for all exposed persons (Sv Bq<sup>-1</sup>),

given by

$$R_{\theta \theta \kappa \lambda} = [P_2 n_r^{(\kappa)} n_f^{(\kappa)}] \left\{ f_{\theta 1}^{(\kappa)} f_{\theta 2}^{(\kappa)} f_{\theta 3}^{(\kappa)} q_2^{(\kappa)} \right\} \quad (E.3.9)$$

$$f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{\theta \theta d}^{(\kappa)} a_1.$$

With the assumptions that the factors in the second row, with the exception of  $N_{p1}^{(\kappa)}$  in  $\Phi_{\theta \theta d}^{(\kappa)}$  are independent of  $\kappa$ , and using Equation (E.1.5), the scaling property of the risk is

$$R_{\theta \theta \kappa \lambda} = C_3 \phi_{\theta}^{(\kappa)} n_f^{(\kappa)} \Phi_{\theta \theta d}^{(\kappa)}, \quad (E.3.10)$$

resulting in a risk reduction factor for the public risk of a C2 accident of

$$\rho_{\theta \theta \kappa \lambda} = \frac{\Phi_{\theta \theta d}^{(0)} \phi_{\theta}^{(0)} n_f^{(0)}}{\Phi_{\theta \theta d}^{(\kappa)} \phi_{\theta}^{(\kappa)} n_f^{(\kappa)}} = F_{\theta \kappa} S_{2\kappa} F_{fk}, \quad (E.3.11)$$

with standard error

$$\left( \frac{\Delta \rho_{\theta \theta \kappa \lambda}}{\rho_{\theta \theta \kappa \lambda}} \right)^2 = \left( \frac{\Delta S_{2\kappa}}{S_{2\kappa}} \right)^2 + \left( \frac{\Delta F_{fk}}{F_{fk}} \right)^2 + \left( \frac{\Delta F_{\theta \kappa}}{F_{\theta \kappa}} \right)^2. \quad (E.3.12)$$

The ratio of forklift operations  $F_{fx}$  for different treatments are given in Attachment D, Table D.3-2, and the ratios  $S_{2x}$  in Table D.3-4. The resulting risk reduction factors are listed in Table E.3-1. They are again very large due to the factors  $S_{2x}$ , ranging from several millions for occupational risks to several tens of millions for public risks. The relative errors for the risk reduction factors are about 30 percent. The baseline risk values show two dramatically different values. The occupational risk will be reduced from a small risk to a negligible risk. The public risk component, however, is already exceedingly small, so that a reduction, however large, is irrelevant.

### E.3.2.2 Risk in WHB or TF Due to Accident Scenario C3

In Scenario C3 two drums are pierced, and one drum loses its lid and the integrity of its liners. The contamination is assumed to appear instantaneously in the air and expand across the WHB and the TF, exposing a constant fraction of the crew for a certain time. Inhalation of the activity leads to organ exposures and the risk of cancer. Escape of the activity to the outside through HEPA filters leads to public exposures. The resulting Risk Component 7 thus has four subcomponents, and with the symbols

- $P_3$  = Probability rate of C3 accident per forklift operation,
- $n_r^{(k)}$  = Number of drums handled per year ( $\text{yr}^{-1}$ ),
- $n_f^{(k)}$  = Number of forklift operations in WHB and TF per drum,
- $n_3^{(k)}$  = Number of drums pierced in accident C3,
- $m_3^{(k)}$  = Number of drums losing lid in C3,
- $f_{71}^{(k)}$  = Fraction of material spilled from pierced drums,
- $f_{72}^{(k)}$  = Fraction of material spilled from drums with lids lost,
- $f_{73}^{(k)}$  = Fraction of spilled material suspended,
- $f_{74}^{(k)}$  = Fraction of activity in respirable form,
- $q_2^{(k)}$  = Total activity in average drum (Bq),
- $\Phi_6^{(k)}$  = Time-integrated dispersion function in WHB ( $\text{s L}^{-1}$ ),
- $v_6$  = Inhalation rate of workers ( $\text{L s}^{-1}$ ),
- $f_{13}^{(k)}$  = Fraction of particles deposited in lung,
- $f_{14\alpha}^{(k)}$  = Fraction of type  $\alpha$  radiation in total activity,
- $\Phi_{11\alpha}^{(k)}$  = Dosimetry function for radiation type  $\alpha$  ( $\text{Sv Bq}^{-1}$ ),
- $A$  = Number of different radiation types  $\alpha$ ,
- $N_{o1}^{(k)}$  = Number of persons occupationally exposed in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{70x\lambda}$  = Occupational cancer risk per year of operation ( $\text{yr}^{-1}$ ),

TABLE E.3-1

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS  
DUE TO C2 ACCIDENTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{801\lambda}$	$(7.71 \pm 2.05) \cdot 10^8$	
$P_{802\lambda}$	$(1.03 \pm 0.28) \cdot 10^7$	
$P_{803\lambda}$	$(7.40 \pm 2.02) \cdot 10^8$	
$P_{804\lambda}$	$(1.66 \pm 0.45) \cdot 10^8$	
<b>Public:</b>		
$P_{8p1\lambda}$	$(1.40 \pm 0.43) \cdot 10^7$	
$P_{8p2\lambda}$	$(1.97 \pm 0.61) \cdot 10^7$	
$P_{8p3\lambda}$	$(2.18 \pm 0.68) \cdot 10^7$	
$P_{8p4\lambda}$	$(1.09 \pm 0.34) \cdot 10^7$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{8000}$	$2.0 \cdot 10^{-4}$	FSEIS (DOE, 1990a) Table 5.28, p. 5-75
<b>Public:</b>		
$R_{8p00}$	$2.2 \cdot 10^{-11}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75

the occupational risk is

$$R_{70\kappa\lambda} = [P_3 n_i^{(\kappa)} n_j^{(\kappa)}] \left\{ (n_3^{(\kappa)} f_{71}^{(\kappa)} + m_3^{(\kappa)} f_{72}^{(\kappa)}) f_{73}^{(\kappa)} f_{74}^{(\kappa)} q_2^{(\kappa)} \right\} \quad (E.3.13)$$

$$\Phi_6^{(\kappa)} V_6 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) f_{15} N_{01}^{(\kappa)} a_1 .$$

As with Scenario C2 this formula is based on the assumption that the workers stay all the time inside the WHB or TF without respirators in use.

Except for  $N_{01}^{(\kappa)}$ , the factors outside the source term and the event probability do not change with the treatment option  $\kappa$ . Using Equation (E.1.5), it is apparent that only some of the factors in the source term and probability vary with treatment options: the number of forklift operations per drum handled, the suspended fraction of the total activity, and the number of persons exposed. The risk is then

$$R_{70\kappa\lambda} = C_1 n_i^{(\kappa)} \left( n_3^{(\kappa)} f_{71}^{(\kappa)} + m_3^{(\kappa)} f_{72}^{(\kappa)} \right) f_{73}^{(\kappa)} f_{74}^{(\kappa)} N_{01}^{(\kappa)} \quad (E.3.14)$$

$$= C_1 n_i^{(\kappa)} \left( n_3^{(\kappa)} \phi_{73}^{(\kappa)} + m_3^{(\kappa)} \phi_{72}^{(\kappa)} \right) N_{01}^{(\kappa)} .$$

with the suspended, inhalable fraction of the activity,

$$\phi_{7v}^{(\kappa)} \equiv f_{7v}^{(\kappa)} f_{73}^{(\kappa)} f_{74}^{(\kappa)} . \quad (E.3.15)$$

The form of Equation (E.3.14) is not optimal for cancellation of the relatively large errors for the fractions  $f_{\mu\nu}^{(\kappa)}$ . This cancellation can be accomplished by regarding the pierced and the fallen drums as two separate events to be evaluated separately. After the calculation of the risk reduction factors, the effects can be superposed linearly, using some of the parameters of the event as weights. With the definition

$$S_{3\kappa} \equiv \frac{\phi_{31}^{(0)}}{\phi_{31}^{(\kappa)}} , \quad (E.3.16)$$

and recognizing that

$$\frac{\phi_{32}^{(0)}}{\phi_{32}^{(k)}} = S_{2k}, \quad (\text{E.3.17})$$

two risk reduction factors can be calculated from Equation (E.3.14),

$$P_{70k\lambda\alpha} = S_{2k} F_{mk} F_{fk}, \quad (\text{E.3.18})$$

$$P_{70k\lambda\beta} = S_{3k} F_{mk} F_{fk}.$$

No risk reduction factors for additional exposures are needed because exposures due to irradiation by the radioactive cloud and exposure due to radiations from radioisotopes deposited on the ground are negligible.

Aggregation can be accomplished by a weighted average, using  $m_3$  and  $n_3$  as weights,

$$P_{70k\lambda} = \frac{1}{m_3 + n_3} (m_3 S_{2k} + n_3 S_{3k}) F_{mk} F_{fk}, \quad (\text{E.3.19})$$

with a standard error of

$$\begin{aligned} \left( \frac{\Delta P_{70k\lambda}}{P_{70k\lambda}} \right)^2 &= \frac{(m_3 \Delta S_{2k})^2 + (n_3 \Delta S_{3k})^2}{(m_3 S_{2k} + n_3 S_{3k})^2} \\ &+ \left( \frac{\Delta F_{fk}}{F_{fk}} \right)^2 + \left( \frac{\Delta F_{mk}}{F_{mk}} \right)^2. \end{aligned} \quad (\text{E.3.20})$$

The public risk due to a C3 accident is different and is given by

$$R_{7pk} = [P_3 n_i^{(k)} n_i^{(k)}] \left\{ (n_3^{(k)} f_{71}^{(k)} + m_3^{(k)} f_{72}^{(k)}) f_{73}^{(k)} f_{74}^{(k)} q_2^{(k)} \right\} \quad (\text{E.3.21})$$

$$f_{dep}^{(k)} f_{rem}^{(k)} \Phi_{7dd}^{(k)} a_1.$$

where, in addition to the symbols defined above, the definitions

- $f_{dep}^{(\kappa)}$  = Activity depletion due to deposition,  
 $f_{rem}^{(\kappa)}$  = Removal efficiency of HEPA filters,  
 $\Phi_{7dd}^{(\kappa)}$  = Dispersion-dosimetry factor for all exposed persons,

are used.

In the top row of Equation (E.3.21) the factors have the same variability as in the occupational risk; of the factors in the lower row, only  $\Phi_{7dd}^{(\kappa)}$  is  $\kappa$ -dependent because of  $N_{p1}^{(\kappa)}$ . Thus the scaling property of the public risk is

$$R_{7p\kappa\lambda} = C_3 n_i^{(\kappa)} \left( n_3^{(\kappa)} \phi_{31}^{(\kappa)} + m_3^{(\kappa)} \phi_{32}^{(\kappa)} \right) \Phi_{7dd}^{(\kappa)}. \quad (E.3.22)$$

Using the same approach to separation and re-aggregation as for the occupational risk, the risk reduction factors

$$\rho_{7p\kappa\lambda} = \frac{1}{m_3 + n_3} (S_{2\kappa} + S_{3\kappa}) F_{\sigma\kappa} F_{f\kappa}. \quad (E.3.23)$$

are obtained with the standard errors

$$\left( \frac{\Delta \rho_{7p\kappa\lambda}}{\rho_{7p\kappa\lambda}} \right)^2 = \frac{(m_3 \Delta S_{2\kappa})^2 + (n_3 \Delta S_{3\kappa})^2}{(m_3 S_{2\kappa} + n_3 S_{3\kappa})^2} + \left( \frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2 + \left( \frac{\Delta F_{\sigma\kappa}}{F_{\sigma\kappa}} \right)^2. \quad (E.3.24)$$

Estimates for the numerical values for the factors  $F_{f\kappa}$ ,  $F_{\sigma\kappa}$ ,  $F_{m\kappa}$ ,  $S_{2\kappa}$ , and  $S_{3\kappa}$  needed here are given in Attachment D, Tables D.3-3, D.3-4, and D.3-5. Based on these data, numerical values for the risk reduction factors  $\rho_{7o\kappa\lambda}$  and  $\rho_{7p\kappa\lambda}$  and their standard errors are given in Table E.3-2. Due to the large values of  $S_{2\kappa}$  and  $S_{3\kappa}$ , the risk reduction factors are also very large. They range from half a million to five million for the occupational risks, and from four to eight million for the public risk. Relative standard errors are about 25 percent. Again, however, the baseline occupational risk is small and is rendered exceedingly small by the treatment. The baseline public risk is already exceedingly small, so that the large risk reduction factor is ineffectual.

TABLE E.3-2

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND  
PUBLIC RISKS DUE TO C3 ACCIDENTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
P <sub>7o1λ</sub>	$(3.18 \pm 0.73) \cdot 10^8$	
P <sub>7o2λ</sub>	$(4.22 \pm 0.99) \cdot 10^8$	
P <sub>7o3λ</sub>	$(3.05 \pm 0.72) \cdot 10^8$	
P <sub>7o4λ</sub>	$(6.84 \pm 1.59) \cdot 10^5$	
<b>Public:</b>		
P <sub>7p1λ</sub>	$(5.20 \pm 1.43) \cdot 10^6$	
P <sub>7p2λ</sub>	$(7.35 \pm 2.04) \cdot 10^6$	
P <sub>7p3λ</sub>	$(8.11 \pm 2.26) \cdot 10^6$	
P <sub>7p4λ</sub>	$(4.07 \pm 1.13) \cdot 10^6$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
R <sub>7o00</sub>	$3.6 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
<b>Public:</b>		
R <sub>7p00</sub>	$3.9 \cdot 10^{-11}$	FSEIS, (DOE, 1990a), Table 5.28, p. 5-75

### E.3.3 Underground Accidents

#### E.3.3.1 Risk Underground Due to Accident Scenario C4

In Scenario C4 a transporter is assumed to strike a pallet in the Underground Storage Area, knocking a drum off the pallet. As for the consequences, this scenario is identical to Scenario C2. However, as this scenario takes place underground, ventilation and inhalation rates may change, as well as the number of persons exposed. For the calculation of the public risk, no credit is taken for the filtration of the exhaust through HEPA filters. The Risk Component 8 has four subcomponents, cancer and genetic damage and occupational and public risk. With the symbols

- $P_4$  = Probability of C4 accident per forklift operation,
- $n_r^{(\kappa)}$  = Number of drums handled per year ( $\text{yr}^{-1}$ ),
- $n_f^{(\kappa)}$  = Number of forklift operations per drum handled,
- $f_{s1}^{(\kappa)}$  = Fraction of waste material spilled,
- $f_{s2}^{(\kappa)}$  = Fraction of spilled material suspended,
- $f_{s3}^{(\kappa)}$  = Fraction of activity in respirable form,
- $Q_2^{(\kappa)}$  = Total activity in average drum (Bq),
- $\Phi_7^{(\kappa)}$  = Time-integrated dispersion function underground ( $\text{s L}^{-1}$ ),
- $v_6$  = Inhalation rate of workers ( $\text{L s}^{-1}$ ),
- $f_{13}^{(\kappa)}$  = Fraction of particles deposited in lung,
- $f_{14\alpha}^{(\kappa)}$  = Fraction of type  $\alpha$  radiation,
- $\Phi_{11\alpha}^{(\kappa)}$  = Dosimetry factor for radiation type  $\alpha$  ( $\text{Sv Bq}^{-1}$ ),
- $A$  = Number of different radiation types  $\alpha$ ,
- $N_{o2}^{(\kappa)}$  = Number of persons occupationally exposed underground,
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $R_{80\kappa\lambda}$  = Cancer risk per year of operation ( $\text{yr}^{-1}$ ),

the occupational cancer risk component is given by

$$R_{80\kappa\lambda} = [P_4 n_r^{(\kappa)} n_f^{(\kappa)}] \left\{ f_{s1}^{(\kappa)} f_{s2}^{(\kappa)} f_{s3}^{(\kappa)} Q_2^{(\kappa)} \right\} \quad (\text{E.3.25})$$

$$\Phi_7^{(\kappa)} v_6 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)} a_1$$

The risk is variable only in the source term because operations and personnel needed for the emplacement of waste are assumed to be independent of the physical state of the drum contents.

The changing factor is again the inhalable fraction of the suspended activity  $\phi_s^{(k)}$ , and occupational and public risk reduction factors are, therefore, the same. Scaling depends on

$$\begin{aligned} R_{sok\lambda} &= C_1 f_{s1}^{(k)} f_{s2}^{(k)} f_{s3}^{(k)} \\ &= C_1 \phi_s^{(k)}, \end{aligned} \quad (\text{E.3.26})$$

where the fraction suspended in inhalable form by a C4 accident is defined by

$$\phi_s^{(k)} \equiv f_{s1}^{(k)} f_{s2}^{(k)} f_{s3}^{(k)}. \quad (\text{E.3.27})$$

The risk reduction ratios (public and occupational) are then simply

$$P_{sok\lambda} = P_{spk\lambda} = S_{4k}, \quad (\text{E.3.28})$$

where  $S_{4k}$  is the reduction in suspension for Scenario C4

$$S_{4k} \equiv \frac{\phi_s^{(0)}}{\phi_s^{(k)}}. \quad (\text{E.3.29})$$

Numerically,  $S_{4k}$  is assumed to be equal to  $S_{2k}$ , the reduction in the C2 accident, because only the location of the accident changes and that should not influence  $S_{2k}$ . The values for the standard errors of the risk reduction factors are

$$\left( \frac{\Delta P_{sok\lambda}}{P_{sok\lambda}} \right)^2 = \left( \frac{\Delta P_{spk\lambda}}{P_{spk\lambda}} \right)^2 = \left( \frac{\Delta S_{4k}}{S_{4k}} \right)^2. \quad (\text{E.3.30})$$

The numerical values of the risk reduction factors, calculated with the  $S_{2k}$  values from Table D.3-4 in Attachment D, are given in Table E.3-3. The factors range from about 35 million to 70 million with relative standard errors of 25 to 30 percent. The baseline risks are small, both for workers and the public.

### E.3.3.2 Risk Underground Due to Accident Scenario C5

Scenario C5 involves a drum knocked off a forklift. Apart from having a different annual probability rate, it has the same consequences as a C4 accident and is similar to a C2 accident except for location related factors. The Risk Component 9 also has four subcomponents, and with the symbols

- $P_s$  = Probability of C5 accident per forklift operation,
- $n_r^{(k)}$  = Number of drums handled per year (yr<sup>-1</sup>),
- $n_f^{(k)}$  = Number of forklift operations per drum handled,

**TABLE E.3-3**  
**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS**  
**DUE TO A C4 ACCIDENT**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{801\lambda}$	$(5.40 \pm 1.40) \cdot 10^7$	$P_{8p\kappa\lambda} = P_{80\kappa\lambda}$
$P_{802\lambda}$	$(6.80 \pm 1.80) \cdot 10^7$	$P_{80\kappa\lambda} = P_{80\kappa\lambda}$
$P_{803\lambda}$	$(6.80 \pm 1.80) \cdot 10^7$	$P_{8p\kappa\lambda} = P_{80\kappa\lambda}$
$P_{804\lambda}$	$(3.40 \pm 0.90) \cdot 10^7$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{8000}$	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
$R_{9000}$	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
<b>Public:</b>		
$R_{8p00}$	$2.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75
$R_{9p00}$	$2.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.28, p. 5-75

- $f_{91}^{(\kappa)}$  = Fraction of waste material spilled,  
 $f_{92}^{(\kappa)}$  = Fraction of spilled material suspended,  
 $f_{93}^{(\kappa)}$  = Fraction of activity in respirable form,  
 $q_2^{(\kappa)}$  = Total activity in average drum (Bq),  
 $\Phi_7^{(\kappa)}$  = Time-integrated dispersion function underground (s L<sup>-1</sup>),  
 $v_8$  = Inhalation rate of workers (L s<sup>-1</sup>),  
 $f_{13}^{(\kappa)}$  = Fraction of particles deposited in lung,  
 $f_{14\alpha}^{(\kappa)}$  = Fraction of type  $\alpha$  radiation,  
 $\Phi_{11\alpha}^{(\kappa)}$  = Dosimetry factor for radiation type  $\alpha$  (Sv Bq<sup>-1</sup>),  
 $A$  = Number of different radiation types  $\alpha$ ,  
 $N_{92}^{(\kappa)}$  = Number of persons occupationally exposed underground,  
 $C_i$  = Constant parts of equations,  
 $a_1$  = Cancer risk coefficient (Sv<sup>-1</sup>),  
 $R_{90\kappa\lambda}$  = Cancer risk per year of operation (yr<sup>-1</sup>),

the occupational risk component for a C5 scenario is

$$R_{90\kappa\lambda} = [P_5 n_r^{(\kappa)} n_l^{(\kappa)}] \{ f_{91}^{(\kappa)} f_{92}^{(\kappa)} f_{93}^{(\kappa)} q_2^{(\kappa)} \} \quad (\text{E.3.31})$$

$$\Phi_7^{(\kappa)} v_8 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) N_{92}^{(\kappa)} a_1 .$$

As in the last section, the changing factors yield the same scaling properties and the same risk reduction factors

$$p_{90\kappa\lambda} = p_{9\rho\kappa\lambda} = \frac{\phi_9^{(\kappa)}}{\phi_9^{(\sigma)}} = S_{4\kappa} = p_{80\kappa\lambda} , \quad (\text{E.3.32})$$

where the factor  $\phi_9^{(\kappa)}$  is the fraction suspended in inhalable form by a C5 accident. Its numerical value is assumed to be the same as that of  $\phi_8^{(\kappa)}$  in a C4 accident. The standard error is

$$\left( \frac{\Delta p_{90\kappa\lambda}}{p_{90\kappa\lambda}} \right)^2 = \left( \frac{\Delta p_{9\rho\kappa\lambda}}{p_{9\rho\kappa\lambda}} \right)^2 = \left( \frac{\Delta p_{80\kappa\lambda}}{p_{80\kappa\lambda}} \right)^2 . \quad (\text{E.3.33})$$

The numerical values have already been given in Table E.3-3. The baseline risks are the same as those for a C4 accident because both are assumed to occur about once a year (DOE, 1990a, Table 5.26, p. 5-72).

### E.3.3.3 Risk Underground Due to Accident Scenario C6

Here a forklift pierces two drums and knocks another one down. The accident occurs in the Underground Storage Area. This scenario is identical to Scenario C3 except that the accident occurs underground. It assumes that no respirators are donned and no general exit is ordered; i.e., that the air monitors did not trigger the alarm that switches in the HEPA filters and work is continued without special precautions. The occupational exposures are modeled after a C4 scenario. This results in the Risk Component 10, which has four subcomponents. Using the symbols

$P_6$	= Probability rate of C6 accident per forklift operation,
$n_r^{(\kappa)}$	= Number of drums handled per year (yr <sup>-1</sup> ),
$n_i^{(\kappa)}$	= Number of forklift operations per drum handled,
$n_6^{(\kappa)}$	= Number of drums pierced in accident C6,
$m_6^{(\kappa)}$	= Number of drums losing lid in C6,
$f_{101}^{(\kappa)}$	= Fraction of waste material spilled from pierced drums,
$f_{102}^{(\kappa)}$	= Fraction of spilled from drums with lids lost,
$f_{103}^{(\kappa)}$	= Fraction of spilled material suspended,
$q_2^{(\kappa)}$	= Total activity in average drum (Bq),
$\Phi_7^{(\kappa)}$	= Time-integrated dispersion function in Waste Storage Area (s L <sup>-1</sup> ),
$v_6$	= Inhalation rate of workers (L s <sup>-1</sup> ),
$f_{13}^{(\kappa)}$	= Fraction of particles deposited in lung,
$f_{14\alpha}^{(\kappa)}$	= Fraction of type $\alpha$ radiation in total activity,
$\Phi_{11\alpha}^{(\kappa)}$	= Dosimetry function for radiation type $\alpha$ (Sv Bq <sup>-1</sup> ),
$A$	= Number of different radiation types $\alpha$ ,
$N_{o2}^{(\kappa)}$	= Number of persons occupationally exposed underground,
$C_1$	= Constant parts of equations,
$a_1$	= Cancer risk coefficient (Sv <sup>-1</sup> ), and
$R_{10\sigma\kappa\lambda}$	= Occupational cancer risk per year of operation (yr <sup>-1</sup> ),

the occupational cancer risk component is given by

$$R_{10\sigma\kappa\lambda} = [ P_6 n_r^{(\kappa)} n_i^{(\kappa)} ] \left( n_6^{(\kappa)} f_{101}^{(\kappa)} + m_6^{(\kappa)} f_{102}^{(\kappa)} \right) \Phi_7^{(\kappa)} v_6 f_{13}^{(\kappa)} \left( \sum_{\alpha=1}^A f_{14\alpha}^{(\kappa)} \Phi_{11\alpha}^{(\kappa)} \right) N_{o2}^{(\kappa)} a_1 \quad (E.3.34)$$

As in the case of a C3 accident, this component can be written as scaling by

$$\begin{aligned} R_{10o\kappa\lambda} &= C_1 \left( n_8 f_{101}^{(\kappa)} + m_8 f_{102}^{(\kappa)} \right) f_{103}^{(\kappa)} f_{103}^{(\kappa)} \\ &= C_1 \left( n_8^{(\kappa)} \phi_{101}^{(\kappa)} + m_8^{(\kappa)} \phi_{102}^{(\kappa)} \right), \end{aligned} \quad (\text{E.3.35})$$

with the fraction of the activity suspended in inhalable form by a C6 accident

$$\phi_{10v}^{(\kappa)} \equiv f_{10v}^{(\kappa)} f_{103}^{(\kappa)} f_{104}^{(\kappa)}. \quad (\text{E.3.36})$$

the risk reduction factors are then equal for public and occupational risk. However, the form of the equation is again not optimal for cancellation of the relatively large errors for the fractions  $f_{\mu\nu}^{(\kappa)}$ . As before (Section E.3.1.2), cancellation is accomplished by regarding the pierced and the fallen drums as two separate accidents. After the calculation of the two risk reduction factors, the effects can be superposed linearly, using number of drums involved as weights. The public risk reduction is the same as the occupational as only the  $\Phi_{7v}^{(\kappa)}$  value outside the source term changed.  $\Phi_{7v}^{(\kappa)}$  changes in the same way for 'o' or 'p' so that  $\rho_{10o\kappa\lambda} = \rho_{10p\kappa\lambda}$ . The aggregate risk reduction factor is then

$$\rho_{10o\kappa\lambda} = \rho_{10p\kappa\lambda} = \frac{1}{m_3 + n_3} (m_3 S_{2\kappa} + n_3 S_{3\kappa}), \quad (\text{E.3.37})$$

with a standard error of

$$\begin{aligned} \left( \frac{\Delta \rho_{10o\kappa\lambda}}{\rho_{10o\kappa\lambda}} \right)^2 &= \left( \frac{\Delta \rho_{10p\kappa\lambda}}{\rho_{10p\kappa\lambda}} \right)^2 \\ &= \frac{(m_3 \Delta S_{2\kappa})^2 + (n_3 \Delta S_{3\kappa})^2}{(m_3 S_{2\kappa} + n_3 S_{3\kappa})^2}, \end{aligned} \quad (\text{E.3.38})$$

The numerical values for the ratios  $S_{2\kappa}$  and  $S_{3\kappa}$  are given in Tables D.3-4 and D.3-5, Attachment D. The resulting reduction factors for public and occupational risks are given in Table E.3-4. They do not change much for the different treatments, ranging from 14 to 28 million, with relative errors between 25 and 30 percent. Assuming an annual occurrence of once a year, the baseline risks are given in the same table.

#### E.3.3.4 Risk Underground Due to Accident Scenario C10

Scenario C10 involves the spontaneous combustion in the contents of a drum, and the subsequent bursting of the drum leads to a release of suspended particles that reach the surface, disperse, and are inhaled by the public downwind. Note that, due to the assumptions in Section

TABLE E.3-4

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS  
DUE TO C6 ACCIDENTS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{1001\lambda}$	$(2.23 \pm 0.50) \cdot 10^7$	$P_{10p\kappa\lambda} = P_{100\kappa\lambda}$
$P_{1002\lambda}$	$(2.80 \pm 0.63) \cdot 10^7$	
$P_{1003\lambda}$	$(2.80 \pm 0.63) \cdot 10^7$	
$P_{1004\lambda}$	$(1.40 \pm 0.32) \cdot 10^7$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{10000}$	$2.3 \cdot 10^{-4}$	FSEIS (DOE 1990a), Table 5.28, p. 5-75
<b>Public:</b>		
$R_{10p00}$	$3.4 \cdot 10^{-5}$	FSEIS (DOE 1990a), Table 5.28, p. 5-75

E.1.1, the occupational risk is subject to the same reduction factors as the public risk, and could, therefore, be considered here. However, no worker exposure is assumed, because workers below ground are supposed to be upstream of the release. In the FSEIS this scenario is assumed to involve only public exposures because the disposal time is short compared to the time while a drum is open.

Still, due to the considerations above, the Risk Component 11 has four subcomponents. With the symbols:

- $P_{10}$  = Probability rate of C10 event per drum per year ( $\text{yr}^{-1}$ ),
- $n_c^{(\kappa)}$  = Average number of drums in undealed drifts,
- $f_{11}^{(\kappa)}$  = Fraction of activity mobilized in inhalable form,
- $q_2^{(\kappa)}$  = Average activity per drum (Bq),
- $f_{dep}^{(\kappa)}$  = Depletion factor due to deposition before the filter duct,
- $f_{rem}^{(\kappa)}$  = Transmission of the HEPA FILTERS
- $\Phi_{11 dd}^{(\kappa)}$  = Environmental dispersion and dosimetry factor ( $\text{Sv Bq}^{-1}$ ),
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk factor ( $\text{Sv}^{-1}$ ), and
- $R_{11 p \kappa \lambda}$  = Cancer risk per year of operation ( $\text{yr}^{-1}$ ),

the public cancer risk per year of operation is

$$R_{11 p \kappa \lambda} = \left\{ [ P_{10}^{(\kappa)} n_c^{(\kappa)} ] f_{11}^{(\kappa)} q_2^{(\kappa)} \right\} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{11 dd}^{(\kappa)} a_1 . \quad (\text{E.3.39})$$

Here, the event probability depends on the treatment option  $\kappa$ . If it is assumed that the product of  $n_c^{(\kappa)} q_2^{(\kappa)} = \text{const}$ , i.e., that the same amounts of activity are stored in a given time interval regardless of treatment, and that the product of the dispersion function  $\Phi_{11 dd}^{(\kappa)}$  with the two preceding factors does not depend on the waste treatment, then the risk scales as

$$R_{11 p \kappa \lambda} = C_1 P_{10}^{(\kappa)} f_{11}^{(\kappa)} , \quad (\text{E.3.40})$$

and the risk reduction factors are

$$P_{11 p \kappa \lambda} = P_{11 o \kappa \lambda} = \frac{P_{10}^{(0)} f_{11}^{(0)}}{P_{10}^{(\kappa)} f_{11}^{(\kappa)}} \equiv F_{p \kappa} S_{10 \kappa} , \quad (\text{E.3.41})$$

where  $F_{p \kappa}$  is the reduction factor for the probability of a drum fire and  $S_{10 \kappa}$  is the reduction factor

for the suspendabilities in inhalable form. The standard error is then

$$\left( \frac{\Delta p_{11 o \kappa \lambda}}{p_{11 o \kappa \lambda}} \right)^2 = \left( \frac{\Delta p_{11 p \kappa \lambda}}{p_{11 p \kappa \lambda}} \right)^2 = \left( \frac{\Delta F_{p \kappa}}{F_{p \kappa}} \right)^2 + \left( \frac{\Delta S_{10 \kappa}}{S_{10 \kappa}} \right)^2. \quad (\text{E.3.42})$$

Estimates for the values  $S_{10 \kappa}$  and  $F_{p \kappa}$  are given in Attachment D, Tables D.3-5 and D.3-6. On the basis of these data, numerical values for the risk reduction factors are calculated and tabulated in Table E.3-5. These risk reduction factors are very high, varying from six billion to 500 billion, but they are applied to an extremely small risk of  $1 \cdot 10^{-11}$ , and are, therefore, practically meaningless.

#### E.4 RISKS FROM ROUTINE CHEMICAL EXPOSURES

##### E.4.1 Basic Considerations

In the FSEIS, five representative volatile organic chemical agents are identified. Three of these are carcinogens: methylene chloride, carbon tetrachloride, and trichloroethylene (HEAST, 1990). All of these compounds are B2 carcinogens; that is, they are suspected to be human carcinogens on the basis of animal data. For these agents, only cancer risks are considered. For noncarcinogens, a "morbidity risk" is estimated on the basis of the hazard index. This is based on the assumption that every reference level  $L_j^{(ref)}$  for agent  $j$  corresponds to some particular risk value. As long as risk reduction factors are calculated before the aggregation of the effects of these chemical agents, the accuracy of these risks is of no consequence because these risks cancel. The two noncarcinogens of concern here are 1,1,1-trichloroethane and Freon (HEAST, 1990).

The risk equations are given here for individual agents, that is, for different values of the chemical index  $j$ . For cases of exposures to multiple agents, no interactions are assumed. As shown by Seiler (1987b), this is a reasonable assumption at these low exposures and low effects because even strongly synergistic interaction terms tend to be very small. It is only at higher doses and thus higher effects that interaction effects become more prominent. The occupational risks are parameterized in analogy to Equation (E.1.1) by

$$R_{10 \kappa \lambda j} = \left\{ Q_{ij}^{(\kappa)} \right\} f_{exp}^{(\kappa)} f_{dos j}^{(\kappa)} c_j, \quad (\text{E.4.1})$$

where the agent is denoted by the index  $j$ , the treatment option by the index  $\kappa$ , the type of exposure by the index 'o' or 'p', denoting occupational or public exposure, and the risk component by the index  $i$ . The quantity in braces,  $Q_{ij}^{(\kappa)}$ , is the source strength of the release,  $f_{exp}^{(\kappa)}$  characterizes the exposure,  $f_{dos}^{(\kappa)}$  the dosimetry, and  $c_j$  is the risk coefficient for chemical agents.

TABLE E.3-5

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC RISKS  
DUE TO C10 ACCIDENTS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{11012}$	$(6.48 \pm 2.00) \cdot 10^9$	$P_{11022} = P_{11032}$
$P_{11022}$	$(1.02 \pm 0.34) \cdot 10^{10}$	
$P_{11032}$	$(1.02 \pm 0.34) \cdot 10^{10}$	
$P_{11042}$	$(5.10 \pm 1.92) \cdot 10^{11}$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{11000}$	--	No exposure postulated
<b>Public:</b>		
$R_{11000}$	$5.9 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table 5.28, p. 5.75 *

- \* The risk given in the reference was calculated for a 1000 PE-Ci (37 TBq) drum as a conditional probability. The value given here assumes an average drum with 12.6 PE-Ci (466 PE-GBq) and includes the probability of the event ( $10^{-7}$ ) per year and assumes 6,000 drums per panel.

The corresponding public risk equation is

$$R_{1p\kappa\lambda j} = \left\{ Q_{ij}^{(\kappa)} \right\} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{iddj}^{(\kappa)} C_j, \quad (E.4.2)$$

with the notation of

- $f_{dep}^{(\kappa)}$  = Activity depletion due to deposition,  
 $f_{rem}^{(\kappa)}$  = Removal efficiency of HEPA filters, and  
 $\Phi_{iddj}^{(\kappa)}$  = Dispersion-dosimetry function for agent j.

Again, as long as the option-dependent terms are only those in the source term, public and occupational risk components have the same risk reduction factors. If the number of exposed persons is treatment-dependent, as for some occupational risks, the two risk reduction factors will be different.

#### E.4.2 Cancer Risk From Routine Handling

##### E.4.2.1 Risk Due To An N1 Scenario

Volatile Organic Compounds (VOCs) in drums will vent continuously through a filter, causing an exposure, mostly in enclosed spaces. With a certain average number of drums in the WHB and TF, an equilibrium exposure atmosphere can be estimated. These factors, however, apply to risk components that differ by several orders of magnitude. Similarly, venting of the gases outside the buildings leads to public exposures. Thus Risk Component 12 has two subcomponents, occupational and public cancer risks, for each of the three carcinogenic agents j. Using the symbols

- $n_a^{(\kappa)}$  = Number of drums present on average in WHB,  
 $q_{12j}^{(\kappa)}$  = Quantity of chemical j released per unit time per drum ( $\text{mg s}^{-1}$ ),  
 $\Phi_{121}^{(\kappa)}$  = WHB and TF dispersion function for all chemicals ( $\text{s m}^{-3}$ ),  
 $V_2$  = Respiratory volume per day ( $\text{m}^3 \text{day}^{-1}$ ),  
 $f_{12j}$  = Probability of absorption of chemical j into body of receptor,  
 $M$  = Receptor body mass (kg),  
 $N_{o1}^{(\kappa)}$  = Number of persons in WHB and TF,  
 $f_{15}$  = Fraction of personnel occupationally exposed,  
 $C_j$  = Cancer potency factor for lifetime exposure to chemical j ( $\text{kg day mg}^{-1}$ ),  
 $f_t$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{12o\kappa\lambda j}$  = Occupational cancer risk per year of operation ( $\text{yr}^{-1}$ ),

the occupational risk component is

$$R_{120\kappa\lambda j} = \left\{ n_a^{(\kappa)} q_{12j}^{(\kappa)} \right\} \Phi_{121}^{(\kappa)} V_2 f_{12j} \frac{1}{M} f_{15} N_{o1}^{(\kappa)} c_j f_l. \quad (\text{E.4.3})$$

In the source term, both factors vary. Of the other factors, the dispersion function  $\Phi_{121}^{(\kappa)}$  can be assumed constant, and with the variable factors combining to form the total release rate in the WHB, the risk scales according to

$$R_{120\kappa\lambda j} = C_1 n_a^{(\kappa)} q_{12j}^{(\kappa)} N_{o1}^{(\kappa)}, \quad (\text{E.4.4})$$

and the reduction factors are the ratios of these products

$$p_{120\kappa\lambda j} = \frac{n_a^{(0)} q_{12j}^{(0)} N_{o1}^{(0)}}{n_a^{(\kappa)} q_{12j}^{(\kappa)} N_{o1}^{(\kappa)}} = F_{v\kappa} F_{c\kappa j} F_{m\kappa}, \quad (\text{E.4.5})$$

where the quantity  $F_{v\kappa}$  is the volume reduction factor,  $F_{m\kappa}$  the manpower reduction factor, and  $F_{c\kappa j}$  is defined as the reduction factor for the emission rates for chemical  $j$  for an individual drum

$$F_{c\kappa j} = \frac{q_{12j}^{(0)}}{q_{12j}^{(\kappa)}}. \quad (\text{E.4.6})$$

This factor is modeled in Section D.3.8 of Attachment D. The standard errors of the risk reduction factors are

$$\left( \frac{\Delta p_{120\kappa\lambda j}}{p_{120\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (\text{E.4.7})$$

For the calculation of the public risk for routine emission of chemicals, the following additional symbols are needed

- $f_{out}^{(\kappa)}$  = Deposition losses before reaching the outside atmosphere,
- $\Phi_{12\text{dd}}^{(\kappa)}$  = Dispersion-dosimetry function for the persons exposed downwind ( $s \text{ day}^{-1}$ ).

Note that the dispersion-dosimetry function is assumed to be the same for all agents  $j$ . With these quantities, the public risk for chemical  $j$  is

$$R_{12p\kappa\lambda j} = \{n_a^{(\kappa)} q_{12j}^{(\kappa)}\} f_{out}^{(\kappa)} \Phi_{12dd}^{(\kappa)} \frac{1}{M} c_j f_i. \quad (E.4.8)$$

Again, the only treatment dependent factors are the two quantities in the source term and the dispersion-dosimetry term, giving the risk the scaling structure

$$R_{12p\kappa\lambda j} = C_2 n_a^{(\kappa)} q_{12j}^{(\kappa)} \Phi_{12dd}^{(\kappa)}, \quad (E.4.9)$$

leading to the reduction factors

$$\rho_{12p\kappa\lambda j} = \frac{n_a^{(0)} q_{12j}^{(0)} \Phi_{12dd}^{(0)}}{n_a^{(\kappa)} q_{12j}^{(\kappa)} \Phi_{12dd}^{(\kappa)}} = F_{vk} F_{ckj} F_{ek}, \quad (E.4.10)$$

with the standard errors

$$\left( \frac{\Delta \rho_{12p\kappa\lambda j}}{\rho_{12p\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{vk}}{F_{vk}} \right)^2 + \left( \frac{\Delta F_{ckj}}{F_{ckj}} \right)^2 + \left( \frac{\Delta F_{ek}}{F_{ek}} \right)^2. \quad (E.4.11)$$

The volume and manpower reduction factors are given in Attachment D, Table D.3-3, whereas estimates for the emission reduction factors  $F_{ckj}$  are given in Table D.3-6. The values calculated for the risk reduction factors using these parameters are given in Table E.4-1. The occupational risks for the three agents were obtained from Table 5.43 of the FSEIS (DOE, 1990a) by dividing the 20-year risks by 20.

As discussed in Section E.4.1, the risk reduction factors for different chemicals are aggregated at this level. Thus

$$\rho_{12o\kappa\lambda} = \sum_{j=1}^3 g_{12oj} \rho_{12p\kappa\lambda j}, \quad (E.4.12)$$

with the weights

$$g_{12oj} = \frac{R_{12o00j}}{\sum_{j=1}^3 R_{12o00j}}, \quad (E.4.13)$$

and errors

$$(\Delta \rho_{120\kappa\lambda})^2 = \sum_{j=1}^3 (g_{120j} \Delta \rho_{120\kappa\lambda j})^2. \quad (\text{E.4.14})$$

Note that for risk reduction factors that are independent of the agent  $j$ , all sets of weights  $g_{120j}$  will lead to the same result  $\rho_{120\kappa\lambda}$  and  $\Delta \rho_{120\kappa\lambda}$ . This arises from the fact that Equation (E.4.14) is valid for independent errors only, which is not the case here. The correct formula is obtained by an inspection of Equation E.4.12 for  $\rho_{120\kappa\lambda}$  independent of  $j$ .

The corresponding equations for the aggregation of the public risk reduction factors  $\rho_{12p\kappa\lambda}$  are obtained by substituting the index 'o' by 'p' in Equations (E.4.11) and (E.4.12). The numerical values of the baseline risks are given in Table E.4-1, and the final aggregated values in Table E.4-2. The risk reduction factors for the occupational risk indicate an increase in risk for Level II Treatments of about a factor of 3, whereas for public risks the increase is reduced to a factor of 1.7. For Level III Treatments, there is a risk reduction of about 4,000 and 7,000 for occupational risks and of about 11,000 and 46,000 for public risks. Increases and decreases are practically irrelevant, however, because they apply to an exceedingly small risk. This statement can be justified by the observation that the two baseline risks, applied to the entire world population ( $5 \cdot 10^9$  persons) would give rise to an expectation of a few times  $10^{-4}$  cancers at best.

#### E.4.2.2 Risk Underground Due To N3 Scenario

Routine emissions from each drum lead to releases underground, similar to Scenario N1, except for the underground environment and the far larger number of drums involved. Risk Component 13 also has three subcomponents, occupational, both below ground and above ground, and public cancer risks for each of the three carcinogenic agents  $j$ . Using the symbols

- $n_b^{(k)}$  = Number of drums present on average in underground drift,
- $q_{12j}^{(k)}$  = Quantity of chemical  $j$  released per unit time per drum ( $\text{mg s}^{-1}$ ),
- $\Phi_{131}^{(k)}$  = Underground dispersion function for all chemicals ( $\text{s m}^{-3}$ ),
- $V_2$  = Respiratory volume per workday ( $\text{m}^3 \text{day}^{-1}$ ),
- $f_{12j}$  = Probability of absorption of chemical  $j$  into body of receptor,
- $M$  = Receptor body mass (kg),
- $N_{o2}^{(k)}$  = Number of persons exposed underground,
- $c_j$  = Cancer potency factor for lifetime exposure to chemical  $j$  ( $\text{kg day mg}^{-1}$ ),
- $f_1$  = Exposure time correction factor for one year,
- $C_1$  = Constant parts of equations, and
- $R_{130\kappa\lambda}$  = Underground occupational cancer risk per year of operation ( $\text{yr}^{-1}$ ),

**TABLE E.4-1**  
**RISK REDUCTION FACTORS FOR N1 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{12o1\lambda j}$	$0.331 \pm 0.034$	$P_{14z\kappa\lambda j} = P_{12z\kappa\lambda j}$ with $z = o, p$
$P_{12o2\lambda j}$	$0.312 \pm 0.032$	
$P_{12o3\lambda j}$	$3740 \pm 1420$	
$P_{12o4\lambda j}$	$7070 \pm 2260$	
<b>Public:</b>		
$P_{12p1\lambda j}$	$0.600 \pm 0.108$	
$P_{12p2\lambda j}$	$0.600 \pm 0.108$	
$P_{12p3\lambda j}$	$11000 \pm 4500$	
$P_{12p4\lambda j}$	$46500 \pm 16400$	
<b>Annual Baseline Risks: *</b>		
<b>Occupational:</b>		
$R_{12o001}$	$1.5 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
$R_{12o002}$	$4.1 \cdot 10^{-14}$	FSEIS (DOE, 1990a), Table 5.43
$R_{12o003}$	$1.7 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
<b>Public:</b>		
$R_{12p001}$	$2.4 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43
$R_{12p002}$	$6.5 \cdot 10^{-14}$	FSEIS (DOE, 1990a), Table 5.43
$R_{12p003}$	$2.7 \cdot 10^{-15}$	FSEIS (DOE, 1990a), Table 5.43

\* The baseline risks from the FSEIS (DOE, 1990a, Table 5.43), were divided by 20 years to convert them to annual risks.

**TABLE E.4-2**  
**AGGREGATED RISK REDUCTION FACTORS FOR CARCINOGENIC CHEMICALS**  
**IN N1 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{12o1}$	$0.331 \pm 0.034$	
$P_{12o2}$	$0.312 \pm 0.032$	
$P_{12o3}$	$3740 \pm 1420$	
$P_{12o4}$	$7070 \pm 2260$	
<b>Public:</b>		
$P_{12p1}$	$0.600 \pm 0.108$	
$P_{12p2}$	$0.600 \pm 0.108$	
$P_{12p3}$	$11000 \pm 4500$	
$P_{12p4}$	$46500 \pm 16400$	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
$R_{12o00}$	$4.4 \cdot 10^{-14}$	Aggregated data from Table E.4-1
<b>Public:</b>		
$R_{12p00}$	$7.0 \cdot 10^{-14}$	Aggregated data from Table E.4-1

the underground occupational risk component is

$$R_{13\sigma\kappa\lambda j} = \{n_b^{(\kappa)} q_{12j}^{(\kappa)}\} \Phi_{131}^{(\kappa)} V_2 f_{12j} \frac{1}{M} N_{o2}^{(\kappa)} c_j f_1. \quad (\text{E.4.15})$$

Assuming both  $\Phi_{131}^{(\kappa)}$  and  $N_{o2}^{(\kappa)}$  to be constant and recognizing that the variable factors combine to form a constant total release rate underground, the risk scales according to

$$R_{13\sigma\kappa\lambda j} = C_1 n_b^{(\kappa)} q_{12j}^{(\kappa)}. \quad (\text{E.4.16})$$

The reduction factors are again the ratios of these release rates, which are the same for underground occupational and public risk. This leads to risk reduction factors

$$\rho_{13\sigma\kappa\lambda j} = \rho_{13\rho\kappa\lambda j} = \frac{n_b^{(0)} q_{12j}^{(0)}}{n_b^{(\kappa)} q_{12j}^{(\kappa)}} = F_{v\kappa} F_{c\kappa j}, \quad (\text{E.4.17})$$

where  $F_{v\kappa}$  is the volume reduction factor, and  $F_{c\kappa j}$  is the reduction factor for the emissions of chemical  $j$  defined by Equation (E.4.6). The standard errors are

$$\left( \frac{\Delta \rho_{13\sigma\kappa\lambda j}}{\rho_{13\sigma\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2. \quad (\text{E.4.18})$$

The reduction factors for waste volume and emissions of compound  $j$  are calculated using the same constants as for Component 12, listed in Tables D.3-3 and D.3-6 of Attachment D. They are given in Table E.4-3.

The routine emissions from drums underground also lead to exposures of workers aboveground. This is the third subcomponent of Risk Component 13. Using the symbols

- $n_b^{(\kappa)}$  = Number of drums present on average in underground drift,
- $q_{12j}^{(\kappa)}$  = Quantity of chemical  $j$  released per unit time per drum ( $\text{mg s}^{-1}$ ),
- $\Phi_{132}^{(\kappa)}$  = Underground/above ground dispersion function for all chemicals ( $\text{s m}^{-3}$ ),
- $V_2$  = Respiratory volume per workday ( $\text{m}^3 \text{day}^{-1}$ ),
- $f_{12j}$  = Probability of absorption of chemical  $j$  into body of receptor,
- $M$  = Receptor body mass (kg),
- $N_{o3}^{(\kappa)}$  = Number of persons exposed aboveground from underground source,
- $c_j$  = Cancer potency factor for lifetime exposure to chemical  $j$  ( $\text{mg}/(\text{kg day})$ ),
- $f_1$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{13\sigma\kappa\lambda j}$  = Above ground occupational cancer risk from underground N3 activities per year, of operation ( $\text{yr}^{-1}$ ),

**TABLE E.4-3**  
**RISK REDUCTION FACTORS FOR N3 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational (underground):</b>		
$P_{1301\lambda}$	$1.20 \pm 0.10$	$P_{13p\kappa\lambda} = P_{130\kappa\lambda}$
$P_{1302\lambda}$	$1.20 \pm 0.10$	
$P_{1303\lambda}$	$22000 \pm 8300$	$P_{13a\kappa\lambda} = P_{130\kappa\lambda}$
$P_{1304\lambda}$	$93000 \pm 29300$	
<b>Annual Baseline Risks: *</b>		
<b>Occupational (underground):</b>		
$R_{130001}$	$2.2 \cdot 10^{-8}$	FSEIS (DOE, 1990a), Table 5.43
$R_{130002}$	$6.0 \cdot 10^{-7}$	
$R_{130003}$	$2.4 \cdot 10^{-8}$	
<b>Public:</b>		
$R_{13p001}$	$4.6 \cdot 10^{-13}$	FSEIS (DOE, 1990a), Table 5.43
$R_{13p002}$	$1.3 \cdot 10^{-11}$	
$R_{13p003}$	$5.0 \cdot 10^{-13}$	
<b>Occupational (Above ground):</b>		
$R_{13a001}$	$5.5 \cdot 10^{-13}$	FSEIS (DOE, 1990a), Table 5.43
$R_{13a002}$	$1.5 \cdot 10^{-11}$	
$R_{13a003}$	$6.0 \cdot 10^{-13}$	

\* The baseline risks from the FSEIS (DOE, 1990a, Table 5.43), were divided by 20 years to convert them to annual risks.

the above ground occupational risk component from underground operations is

$$R_{13\alpha\kappa\lambda j} = \left\{ n_b^{(\kappa)} q_{12j}^{(\kappa)} \right\} \Phi_{132}^{(\kappa)} V_2 f_{12j} \frac{1}{M} N_{o3}^{(\kappa)} c_j f_j, \quad (\text{E.4.19})$$

and with  $N_{o3}^{(\kappa)}$  constant, and the variable factors again combining to form the total release rate underground, the risk scales as

$$R_{13\alpha\kappa\lambda j} = C_1 n_b^{(\kappa)} q_{12j}^{(\kappa)}. \quad (\text{E.4.20})$$

The reduction factors are again the same as for underground workers

$$\rho_{13\alpha\kappa\lambda j} = \rho_{13o\kappa\lambda j} = \frac{n_b^{(o)} q_{12j}^{(o)}}{n_b^{(\kappa)} q_{12j}^{(\kappa)}} = F_{v\kappa} F_{c\kappa j}. \quad (\text{E.4.21})$$

The standard errors are

$$\left( \frac{\Delta \rho_{13\alpha\kappa\lambda j}}{\rho_{13\alpha\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2. \quad (\text{E.4.22})$$

The reduction factors and the baseline risks are the same as those given in Table E.4-3.

Again, the three different risk reduction factors for the carcinogenic chemicals are aggregated at this level. Thus

$$\rho_{13\chi\kappa\lambda} = \sum_{j=1}^3 g_{13\chi j} \rho_{13\chi\kappa\lambda j}, \quad (\text{E.4.23})$$

with the indices  $\chi = o, p, \text{ and } a$ , that stand for occupational (underground), public, and occupational (above ground), respectively. The weights used here are defined by

$$g_{13\chi j} = \frac{R_{13\chi o o j}}{\sum_{i=1}^3 R_{13\chi o o i}}. \quad (\text{E.4.24})$$

and the standard errors are

$$(\Delta \rho_{13\chi\kappa\lambda})^2 = \sum_{j=1}^3 (g_{13\chi j} \Delta \rho_{13\chi\kappa\lambda j})^2. \quad (\text{E.4.25})$$

Again, this equation is not valid if the risk reduction factors are independent of agent  $j$ . The correct formula is obtained by inspection of Equation (E.4.23) for that case.

The numerical values of the baseline risks are given in Table E.4-3, and the final aggregated values in Table E.4-4. The risk reduction factors for Level II treatments are close to 1, whereas they are 20,000 and 90,000 for the two Level III treatments. The relative errors for Level II treatment risk reduction factors are about 7 percent; those for Level III treatments are about 30 percent. Still, the baseline risks are very small to exceedingly small. The largest risk occurs for the workers underground.

### E.4.3 Noncancer Risk Due to Routine Chemical Exposure

#### E.4.3.1 Noncancer Risk In WHB Due to N1 Scenario

This component of the risk has exposure conditions identical to those in Section E.4.2, only the action of the chemical agent on the human organism is different. The two non-carcinogenic agents considered are Freon and 1,1,1-trichloroethylene. Risk Component 14, therefore, consists of two subcomponents, occupational and public risk. With the symbols

- $n_s^{(k)}$  = Number of drums present on average in WHB and TF,
- $q_{12j}^{(k)}$  = Quantity of chemical  $j$  released per drum and per unit time ( $\text{mg s}^{-1}$ ),
- $\Phi_{121}^{(k)}$  = Dispersion function for all chemicals in WHB ( $\text{s m}^{-3}$ ),
- $V_2$  = Worker respiratory volume per workday ( $\text{m}^3 \text{day}^{-1}$ ),
- $f_{12j}$  = Transfer probability for absorption of chemical  $j$  into body,
- $M$  = Receptor body mass (kg),
- $L_j^{(ref)}$  = Reference level for chemical  $j$  ( $\text{mg (kg day)}^{-1}$ ),
- $r_{0j}$  = Risk of reference level  $L_j^{(ref)}$ ,
- $N_{01}^{(k)}$  = Number of persons in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $f_1$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{140\kappa\lambda j}$  = Occupational risk of noncancer health effects per year of operation ( $\text{yr}^{-1}$ ),

the occupational risk component for agent  $j$  is

$$R_{140\kappa\lambda j} = \left\{ n_s^{(k)} q_{12j}^{(k)} \right\} \Phi_{121}^{(k)} V_2 f_{12j} \frac{1}{M L_j^{(ref)}} f_{15} N_{01}^{(k)} r_{0j} f_1, \quad (\text{E.4.26})$$

and with all but  $N_{01}^{(k)}$  and the two factors in the source term constant, as before, the risk can be scaled as

$$R_{140\kappa\lambda j} = C_1 \left\{ n_s^{(k)} q_{12j}^{(k)} \right\} N_{01}^{(k)}. \quad (\text{E.4.27})$$

TABLE E.4-4

**AGGREGATED RISK REDUCTION FACTORS FOR CARCINOGENIC CHEMICALS  
IN N3 ACTIVITIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{13o1\lambda}$	$1.20 \pm 0.1$	$P_{13p\kappa\lambda} = P_{13o\kappa\lambda}$
$P_{13o2\lambda}$	$1.20 \pm 0.1$	$P_{13a\kappa\lambda} = P_{13o\kappa\lambda}$
$P_{13o3\lambda}$	$22000 \pm 8300$	
$P_{13o4\lambda}$	$93000 \pm 29300$	
<b>Annual Baseline Risks:</b>		
<b>Occupational Underground:</b>		
$R_{13o00}$	$6.5 \cdot 10^{-7}$	Aggregated from data in Table E.4-3
<b>Public:</b>		
$R_{13p00}$	$1.4 \cdot 10^{-11}$	Aggregated from data in Table E.4-3
<b>Occupational Above Ground:</b>		
$R_{13a00}$	$1.6 \cdot 10^{-11}$	Aggregated from data in Table E.4-3

This results in risk reduction factors that are again the same ratios as in the N1 and N3 scenarios for the cancer risk. This time, however, they are evaluated for the non-carcinogenic chemicals 4 and 5,

$$\begin{aligned} \rho_{14\sigma\kappa\lambda j} &= \frac{n_a^{(0)} q_{12j}^{(0)} N_{o1}^{(0)}}{n_a^{(\kappa)} q_{12j}^{(\kappa)} N_{o1}^{(\kappa)}} \\ &= F_{v\kappa} F_{c\kappa j} F_{m\kappa}, \end{aligned} \quad (\text{E.4.28})$$

with standard errors of

$$\left( \frac{\Delta \rho_{14\sigma\kappa\lambda j}}{\rho_{14\sigma\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (\text{E.4.29})$$

For the calculation of the public risk, again a few more symbols need to be defined

- $f_{out}^{(\kappa)}$  = Deposition losses before reaching the outside atmosphere,  
 $\Phi_{14\sigma\kappa\lambda j}^{(\kappa)}$  = Dispersion-dosimetry function for the  $N_{p2}^{(\kappa)}$  persons exposed (s day<sup>-1</sup>).

With these quantities, the public risk is

$$R_{14\sigma\kappa\lambda j} = \left\{ n_a^{(\kappa)} q_{12j}^{(\kappa)} \right\} f_{out}^{(\kappa)} \Phi_{14\sigma\kappa\lambda j}^{(\kappa)} \frac{1}{M L_j^{(ref)}} r_{oj}, \quad (\text{E.4.30})$$

where only the source term and the dispersion-dosimetry factor are treatment dependent. The risk can, therefore, be written in the form

$$R_{14\sigma\kappa\lambda j} = C_2 \left\{ n_a^{(\kappa)} q_{12j}^{(\kappa)} \right\} \Phi_{14\sigma\kappa\lambda j}^{(\kappa)}, \quad (\text{E.4.31})$$

to denote its scaling properties. The risk reduction factor is then

$$\begin{aligned} \rho_{14\sigma\kappa\lambda j} &= \frac{n_a^{(0)} q_{12j}^{(0)} \Phi_{14\sigma\kappa\lambda j}^{(0)}}{n_a^{(\kappa)} q_{12j}^{(\kappa)} \Phi_{14\sigma\kappa\lambda j}^{(\kappa)}} \\ &= F_{v\kappa} F_{c\kappa j} F_{\sigma\kappa}. \end{aligned} \quad (\text{E.4.32})$$

The standard errors are given by

$$\left( \frac{\Delta p_{14pk\lambda j}}{p_{14pk\lambda j}} \right)^2 = \left( \frac{\Delta F_{vk}}{F_{vk}} \right)^2 + \left( \frac{\Delta F_{ckj}}{F_{ckj}} \right)^2 + \left( \frac{\Delta F_{ek}}{F_{ek}} \right)^2 \quad (\text{E.4.33})$$

The values of the constants are again given in Attachment D. Numerical values for the occupational and corresponding public risk reduction factors are given in Table E.4-5. The risk reduction factors are the same as those given in Table E.4-1 for  $p_{12ok\lambda j}$  and  $p_{12pk\lambda j}$ .

The occupational risks for a 20-year operation are obtained from the hazard indices given in FSEIS (DOE, 1990a, Table 5.43) by a division by 20 and converted to annual risks by making the assumption that the risk corresponding to the reference level is  $10^{-4}$  for occupational exposures and  $10^{-5}$  for exposures of the public. These baseline risks are different from those given in Table E.4-1 for  $R_{12o00j}$  and  $R_{12p00j}$  even though the risk reduction factors are the same. These differences in risks, however, will result in different values after aggregation.

Again, the risk reduction factors for the two noncarcinogenic chemicals are aggregated at this level. Thus

$$p_{14\chi k\lambda} = \sum_{j=4}^5 g_{14\chi j} p_{14\chi k\lambda j} \quad (\text{E.4.34})$$

with  $\chi$  being either 'o' or 'p', and the weights

$$g_{14\chi j} = \frac{R_{14\chi 00j}}{\sum_{j=4}^5 R_{14\chi 00j}} \quad (\text{E.4.35})$$

with the standard errors

$$(\Delta p_{14\chi k\lambda})^2 = \sum_{j=4}^5 (g_{14\chi j} \Delta p_{14\chi k\lambda j})^2 \quad (\text{E.4.36})$$

The numerical values of the baseline risks are given in Table E.4-5, and the final aggregated values are listed in Table E.4-6. As for Risk Component 12, Level II treatments have small risk reduction factors near 1, whereas Level III treatments have values of 10,000 and 50,000. However, they are applied to risks one hundred times larger than those in Table E.4-2.

#### E.4.3.2 Noncancer Risk Underground Due to an N3 Scenario

This component of the risk has exposure conditions identical to those in Section E.4.2.1. Risk Component 15, therefore, consists of two subcomponents. With the symbols:

TABLE E.4-5

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC NONCANCER  
RISK IN N1 ACTIVITIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
$P_{14o124}$	$0.331 \pm 0.034$	$P_{14ok24} = P_{14ok25}$
$P_{14o224}$	$0.312 \pm 0.032$	
$P_{14o324}$	$3740 \pm 1420$	
$P_{14o424}$	$7070 \pm 2260$	
<b>Public:</b>		
$P_{14p125}$	$0.600 \pm 0.108$	$P_{14pk25} = P_{14pk24}$
$P_{14p225}$	$0.600 \pm 0.108$	
$P_{14p325}$	$11000 \pm 4500$	
$P_{14p425}$	$46500 \pm 16400$	
<b>Annual Baseline Risks: *</b>		
<b>Occupational:</b>		
$R_{14o004}$	$6.0 \cdot 10^{-12}$	FSEIS (DOE, 1990a), Table 5.44
$R_{14o005}$	$1.0 \cdot 10^{-13}$	
<b>Public:</b>		
$R_{14p004}$	$2.1 \cdot 10^{-12}$	FSEIS (DOE, 1990a), Table 5.44
$R_{14p005}$	$3.4 \cdot 10^{-14}$	

\* The data in Table 5.44 are divided by 20 to obtain the risk per year of operation.

TABLE E.4-6

**AGGREGATION OF RISK REDUCTION FACTORS FOR NONCARCINOGENIC  
CHEMICALS IN N1 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational:</b>		
P <sub>14o1λj</sub>	0.331 ± 0.034	P <sub>12oκλj</sub> = P <sub>14oκλj</sub> P <sub>12pκλj</sub> = P <sub>14pκλj</sub>
P <sub>14o2λj</sub>	0.312 ± 0.032	
P <sub>14o3λj</sub>	3740 ± 1420	
P <sub>14o4λj</sub>	7070 ± 2260	
<b>Public:</b>		
P <sub>14p1λj</sub>	0.600 ± 0.108	
P <sub>14p2λj</sub>	0.600 ± 0.108	
P <sub>14p3λj</sub>	11000 ± 4500	
P <sub>14p4λj</sub>	46500 ± 16400	
<b>Annual Baseline Risks:</b>		
<b>Occupational:</b>		
R <sub>14o00</sub>	6.1 · 10 <sup>-12</sup>	Aggregated from data in Table E.4-5
<b>Public:</b>		
R <sub>14p00</sub>	2.13 · 10 <sup>-12</sup>	Aggregated from data in Table E.4-5

- $n_b^{(\kappa)}$  = Number of drums present on average in unsealed waste disposal drifts,  
 $q_{12j}^{(\kappa)}$  = Quantity of chemical j released per drum and per unit time ( $\text{mg s}^{-1}$ ),  
 $\Phi_{132}^{(\kappa)}$  = Underground dispersion function for all chemicals ( $\text{s m}^{-3}$ ),  
 $V_2$  = Worker respiratory volume per workday ( $\text{m}^3 \text{day}^{-1}$ ),  
 $f_{12j}$  = Transfer probability for absorption of chemical j into body,  
 $M$  = Receptor body mass (kg),  
 $L_j^{(\text{ref})}$  = Reference level for chemical j ( $\text{mg (kg day)}^{-1}$ ),  
 $N_{o3}^{(\kappa)}$  = Number of persons exposed above ground from underground source,  
 $r_{oj}$  = Risk of reference level  $L_j^{(\text{ref})}$ ,  
 $f_t$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{15o\kappa\lambda j}$  = Risk of noncancer health effects per year of operations ( $\text{yr}^{-1}$ ),

the underground occupational risk of noncancer health effects for N3 operations is

$$R_{15o\kappa\lambda j} = \left\{ n_b^{(\kappa)} q_{12j}^{(\kappa)} \right\} \Phi_{132}^{(\kappa)} V_2 f_{12j} N_{o3}^{(\kappa)} \frac{1}{M L_j^{(\text{ref})}} r_{oj} f_t. \quad (\text{E.4.37})$$

With all but the source term constant, the risk scales as

$$R_{15o\kappa\lambda j} = C_1 \left\{ n_b^{(\kappa)} q_{12j}^{(\kappa)} \right\}. \quad (\text{E.4.38})$$

and results in risk reduction factors that are again the ratios of the global release rates

$$\begin{aligned}
 \rho_{15o\kappa\lambda j} = \rho_{15p\kappa\lambda j} &= \frac{n_b^{(0)} q_{12j}^{(0)}}{n_b^{(\kappa)} q_{12j}^{(\kappa)}} = F_{v\kappa} F_{c\kappa j} \\
 &= \rho_{13o\kappa\lambda j} = \rho_{13p\kappa\lambda j},
 \end{aligned} \quad (\text{E.4.39})$$

with standard errors of

$$\left( \frac{\Delta \rho_{15o\kappa\lambda j}}{\rho_{15o\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{c\kappa j}}{F_{c\kappa j}} \right)^2. \quad (\text{E.4.40})$$

Although the risk reduction factors for chemical j are the same as those for the N3 scenario for carcinogens, weighted aggregation will lead to different values. This subcomponent of the risk has an N3 release scenario but includes transport to the surface and exposure of workers there.

With the symbols

- $n_b^{(\kappa)}$  = Number of drums present on average in unsealed waste disposal drifts,
- $q_{12j}^{(\kappa)}$  = Quantity of chemical  $j$  released per drum and per unit time ( $\text{mg s}^{-1}$ ),
- $\Phi_{132}^{(\kappa)}$  = Underground dispersion function for all chemicals ( $\text{s m}^{-3}$ ),
- $V_2$  = Worker respiratory volume per workday ( $\text{m}^3 \text{day}^{-1}$ ),
- $f_{12j}$  = Transfer probability for absorption of chemical  $j$  into body,
- $M$  = Receptor body mass (kg),
- $L_j^{(\text{ref})}$  = Reference level for chemical  $j$  ( $\text{mg (kg day)}^{-1}$ ),
- $r_{oj}$  = Risk of reference level  $L_j^{(\text{ref})}$ ,
- $f_1$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),
- $N_{o3}^{(\kappa)}$  = Number of persons exposed above ground,
- $C_1$  = Constant parts of equations, and
- $R_{15\kappa\lambda j}$  = Risk of noncancer health effects per year of operations ( $\text{yr}^{-1}$ ),

the above ground occupational risk of noncancer health effects for N3 operations is

$$R_{15\kappa\lambda j} = \{n_b^{(\kappa)} q_{12j}^{(\kappa)}\} \Phi_{132}^{(\kappa)} V_2 f_{12j} N_{o3}^{(\kappa)} \frac{1}{M L_j^{(\text{ref})}} r_{oj} f_1. \quad (\text{E.4.41})$$

With all but the source term constant, the risk can also be written as

$$R_{15\kappa\lambda j} = C_1 \{n_b^{(\kappa)} q_{12j}^{(\kappa)}\}. \quad (\text{E.4.42})$$

which again results in the same risk reduction factors as those for Component 13

$$p_{15\kappa\lambda j} = p_{150\kappa j} = p_{130\kappa\lambda j} = p_{13p\kappa\lambda j}. \quad (\text{E.4.43})$$

with standard errors

$$\left(\frac{\Delta p_{15\kappa\lambda j}}{p_{15\kappa\lambda j}}\right)^2 = \left(\frac{\Delta p_{150\kappa j}}{p_{150\kappa j}}\right)^2 = \left(\frac{\Delta F_{v\kappa}}{F_{v\kappa}}\right)^2 + \left(\frac{\Delta F_{c\kappa j}}{F_{c\kappa j}}\right)^2. \quad (\text{E.4.44})$$

The equations for the risk reduction factors and their errors are the same as those for component 13. They are evaluated, however, for noncarcinogenic compounds 4 and 5. The numerical values are listed in Table E.4-7. The values for the baseline risks per year of operation given in the same table are taken from the FSEIS (DOE, 1990a).

The occupational risks for a 20-year operation are obtained from the hazard indices given in FSEIS (DOE, 1990a, Table 5.44) by a division by 20, and converted to annual risks by making

TABLE E.4-7

**RISK REDUCTION FACTORS FOR OCCUPATIONAL AND PUBLIC  
NONCANCER HEALTH EFFECTS FROM N3 ACTIVITIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
<b>Occupational (Below ground):</b>		
$P_{15o1j}$	$0.331 \pm 0.034$	$j = 4, 5$
$P_{15o2j}$	$0.312 \pm 0.032$	
$P_{15o3j}$	$3740 \pm 1420$	
$P_{15o4j}$	$7070 \pm 2260$	
<b>Public:</b>		
$P_{15p1j}$	$0.600 \pm 0.108$	
$P_{15p2j}$	$0.600 \pm 0.108$	
$P_{15p3j}$	$11000 \pm 4500$	
$P_{15p4j}$	$46500 \pm 16400$	
<b>Occupational (Above ground):</b>		
$P_{15a1j}$	$0.331 \pm 0.035$	
$P_{15a2j}$	$0.312 \pm 0.033$	
$P_{15a3j}$	$3740 \pm 1420$	
$P_{15a4j}$	$7070 \pm 2260$	
<b>Annual Baseline Risks: *</b>		
<b>Occupational (Below ground):</b>		
$R_{15o004}$	$9.0 \cdot 10^{-5}$	FSEIS (DOE, 1990a), Table 5.44
$R_{15o005}$	$1.5 \cdot 10^{-6}$	
<b>Public:</b>		
$R_{15p004}$	$4.1 \cdot 10^{-10}$	FSEIS (DOE, 1990a), Table 5.44
$R_{15p005}$	$6.5 \cdot 10^{-12}$	
<b>Occupational (Above ground):</b>		
$R_{15a004}$	$2.2 \cdot 10^{-9}$	FSEIS (DOE, 1990a), Table 5.44
$R_{15a005}$	$3.6 \cdot 10^{-11}$	

\* The annual baseline risks are obtained from the FSEIS (DOE, 1990a), Table 5.44, by dividing the values listed by 20 years.

the assumption that the risk corresponding to the reference level is  $10^{-4}$  for occupational exposures and  $10^{-5}$  for exposures of the public.

As discussed before, the risk reduction factors for different chemicals are aggregated at this level.

Thus

$$\rho_{15z\kappa\lambda} = \sum_{j=4}^5 g_{15zj} \rho_{15z\kappa\lambda j}, \quad (\text{E.4.45})$$

with the weights

$$g_{15zj} = \frac{R_{15z00j}}{\sum_{i=4}^5 R_{15z00i}}, \quad (\text{E.4.46})$$

and standard errors

$$(\Delta \rho_{15z\kappa\lambda})^2 = \sum_{j=4}^5 (g_{15zj} \Delta \rho_{15z\kappa\lambda j})^2. \quad (\text{E.4.47})$$

Note again that, for factors  $\rho_{150\kappa\lambda j}$  independent of agent  $j$ , this formula is not valid. The replacement is straightforward from a discussion of Equation (E.4.45) for this case.

The numerical values of the baseline risks are given in Table E.4-7, and the final aggregated values in Table E.4-8. For every risk reduction factor, the Level II treatments yield values near 1, whereas Level III treatments have values of several thousands to several tens of thousands. The occupational baseline risk is exceedingly small for underground workers and three to four orders of magnitude smaller for above ground occupational exposures and public exposures.

## E.5 RISKS FROM CHEMICAL ACCIDENT EXPOSURES

### E.5.1 Basic Considerations

For the accident scenarios involving chemicals, no cancer risks are calculated because the exposure times are too short, i.e., the doses are too low to yield any sizeable effects. Thus only noncancer risks are estimated, which are mostly based on Threshold Limit Values (TLVs) and Immediate Danger to Life and Health (IDLHs) in the FSEIS (DOE, 1990a). Here TLV-based hazard indices will be used exclusively to characterize the low-level occupational risks. These are already very low, so that public risks would be lower still. In these accidents, breaching the containment by losing the lid or piercing the drum is assumed to release the entire gas in the headspace at once, leading to a local exposure of the work crew. For the C10 scenario, the

TABLE E.4-8

**AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC  
HEALTH EFFECTS DUE TO N3 ACTIVITIES**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
Occupational (Below ground):		
P <sub>15o1λ</sub>	0.331 ± 0.034	
P <sub>15o2λ</sub>	0.312 ± 0.032	
P <sub>15o3λ</sub>	3740 ± 1420	
P <sub>15o4λ</sub>	7070 ± 2260	
Public:		
P <sub>15p1λ</sub>	0.600 ± 0.108	
P <sub>15p2λ</sub>	0.600 ± 0.108	
P <sub>15p3λ</sub>	11000 ± 4500	
P <sub>15p4λ</sub>	46500 ± 16400	
Occupational (Above ground):		
P <sub>15a1λ</sub>	0.331 ± 0.034	
P <sub>15a2λ</sub>	0.312 ± 0.032	
P <sub>15a3λ</sub>	3740 ± 1420	
P <sub>15a4λ</sub>	7070 ± 2260	
Annual Baseline Risks:		
R <sub>15o00</sub>	9.15 · 10 <sup>-5</sup>	Aggregated from data in Table E.4-7
R <sub>15p00</sub>	4.17 · 10 <sup>-10</sup>	
R <sub>15a00</sub>	2.24 · 10 <sup>-9</sup>	

same assumption is made as for the case of radioactivity; the probability of occupational exposure is considered too small, so that neither an occupational nor a public risk is calculated for a C10 accident.

## E.5.2 Above Ground Accidents

### E.5.2.1 Risk Due To Accident Scenario C2

Dropping a drum from the forklift leads to a loss of lid and liner containment and release of the headspace gas. This is Risk Component 16 with only one sub-component, occupational risk. Using the symbols

- $P_2$  = Probability of C2 accident per forklift operation,
- $n_r^{(k)}$  = Number of drums handled routinely per year ( $\text{yr}^{-1}$ ),
- $n_f^{(k)}$  = Number of forklift operations per drum handled,
- $q_{16j}^{(k)}$  = Quantity of chemical  $j$  contained in and released from void space (mg),
- $\Phi_{16,1}^{(k)}$  = Accident dispersion function in WHB and TF for all chemicals ( $\text{m}^{-3}$ ),
- $L_j^{(ref)}$  = TLV for chemical  $j$  ( $\text{mg m}^{-3}$ ),
- $r_{oj}$  = Risk associated with short term exposure to reference level  $L_j^{(ref)}$ ,
- $N_{o1}^{(k)}$  = Number of people in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $C_1$  = Constant parts of equations, and
- $R_{16\sigma\kappa\lambda j}$  = Noncancer health risk per year of operation ( $\text{yr}^{-1}$ ),

the occupational risk for a C2 accident is

$$R_{16\sigma\kappa\lambda j} = \{ [P_2 n_r^{(k)} n_f^{(k)}] q_{16j}^{(k)} \} \Phi_{16,1}^{(k)} \frac{1}{L_j^{(ref)}} f_{15} r_{oj} N_{o1}^{(k)}. \quad (\text{E.5.1})$$

The dispersion function  $\Phi_{16,1}^{(k)}$  is not dependent on waste treatment. Apart from the number of people exposed, the product of the only factors that change is the total mass of gas  $j$  contained in the headspace of the drums handled each year

$$R_{16\sigma\kappa\lambda j} = C_1 n_r^{(k)} q_{16j}^{(k)} n_f^{(k)} N_{o1}^{(k)}. \quad (\text{E.5.2})$$

The risk reduction factor is then the product of the volume reduction factor  $F_{v\kappa}$ , the reduction factor  $F_{g\kappa j}$  for the mass of gas in the headspace, defined by

$$F_{g\kappa j} = \frac{q_{18j}^{(0)}}{q_{18j}^{(\kappa)}}, \quad (\text{E.5.3})$$

and the factors  $F_{f\kappa}$  and  $F_{m\kappa}$ ,

$$\rho_{180\kappa\lambda j} = \frac{n_r^{(0)} q_{18j}^{(0)} n_f^{(0)} N_{o1}^{(0)}}{n_r^{(\kappa)} q_{18j}^{(\kappa)} n_f^{(\kappa)} N_{o1}^{(\kappa)}} = F_{v\kappa} F_{g\kappa j} F_{f\kappa} F_{m\kappa}. \quad (\text{E.5.4})$$

The error of the risk reduction factor is

$$\left( \frac{\Delta \rho_{180\kappa\lambda j}}{\rho_{180\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{g\kappa j}}{F_{g\kappa j}} \right)^2 + \left( \frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2 + \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2. \quad (\text{E.5.5})$$

The numerical values for the reduction factors  $F_{g\kappa j}$  are listed in Table D.3-8 of Attachment D. Use of these parameters results in the reduction factors in Table E.5-1. The baseline TLV-based hazard indices are taken from Table 5.46 of the FSEIS (DOE, 1990a) and multiplied with a factor of  $10^{-4}$  for conversion to an approximate risk. The accuracy of this factor is of no concern in the weighting because in the method used for the aggregation, all common factors such as this one cancel.

Aggregation of the risk reduction factors for different chemicals is done at this level. For C2 and C3 accidents, the aggregation procedure is the same, and using the symbol  $i$  for Components 16 or 17,

$$\rho_{10\kappa\lambda} = \sum_{j=4}^5 g_{10j} \rho_{10\kappa\lambda j}, \quad (\text{E.5.6})$$

with the weights

$$g_{10j} = \frac{R_{1000j}}{\sum_{\tau=4}^5 R_{1000\tau}}, \quad (\text{E.5.7})$$

**TABLE E.5-1**  
**VALUES FOR THE REDUCTION FACTORS FOR CHEMICAL EMISSIONS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{160124}$	$3.03 \pm 0.49$	$P_{160224} = P_{160225}$ $P_{170224} = P_{160225}$
$P_{160224}$	$3.20 \pm 0.52$	
$P_{160324}$	$(4.3 \pm 1.1) \cdot 10^4$	
$P_{160424}$	$(8.2 \pm 1.3) \cdot 10^4$	
<b>Annual Baseline Risks: *</b>		
$R_{160004}$	$1.7 \cdot 10^{-10}$	FSEIS (DOE, 1990a), Table 5.46
$R_{160005}$	$1.0 \cdot 10^{-11}$	
$R_{170004}$	$5.0 \cdot 10^{-10}$	FSEIS (DOE, 1990a), Table 5.46
$R_{170005}$	$3.1 \cdot 10^{-11}$	

\* The values in Table 5.46 of the FSEIS (DOE, 1990a) are multiplied by the risk of  $10^{-4}$  for the occupational reference level.

and the standard errors

$$(\Delta \rho_{10\kappa\lambda})^2 = \sum_{j=4}^5 (g_{10j} \Delta \rho_{10\kappa\lambda j})^2. \quad (\text{E.5.8})$$

Note again that this equation is valid only for risk reduction factors that depend on agent  $j$ . For  $j$ -independent factors, the numerical values of the baseline risks are given in Table E.5-1, and the final aggregated values in Table E.5-2. Here, Level II risk reduction factors lie near 3, and factors for Level III treatments between about 40,000 and 80,000. Relative errors for Level II factors are about 15 percent; for Level III factors they are about 30 percent. The baseline risks are exceedingly small.

### E.5.2.2 Risk Due To Accident Scenario C3

In this scenario two drums are punctured by a forklift. The third drum falls and ruptures as a result of the impact. The release of the headspace gases results in Risk Component 17. With the symbols

- $P_3$  = Probability of C3 accident per forklift operation,
- $n_r^{(\kappa)}$  = Number of drums handled routinely per year ( $\text{yr}^{-1}$ ),
- $n_f^{(\kappa)}$  = Number of forklift operations per drum handled,
- $n_3$  = Number of headspaces vented in C3 accident,
- $q_{18j}^{(\kappa)}$  = Quantity of chemical  $j$  released from headspace of a drum (mg),
- $\Phi_{121}^{(\kappa)}$  = Dispersion function in WHB and TF for all chemicals ( $\text{m}^{-3}$ ),
- $L_j^{(\text{ref})}$  = TLV for chemical  $j$  ( $\text{mg m}^{-3}$ ),
- $r_{0j}$  = Risk associated with short term exposure to reference level  $L_j^{(\text{ref})}$ ,
- $N_{01}^{(\kappa)}$  = Number of people in WHB and TF,
- $f_{15}$  = Fraction of personnel occupationally exposed,
- $C_1$  = Constant parts of equations, and
- $R_{170\kappa\lambda j}$  = Health risk per year of operation ( $\text{yr}^{-1}$ ),

the occupational risk component is

$$R_{170\kappa\lambda j} = \{ [P_3 n_r^{(\kappa)} n_f^{(\kappa)}] n_3 q_{18j}^{(\kappa)} \} \Phi_{121}^{(\kappa)} \frac{1}{L_j^{(\text{ref})}} r_{0j} f_{15} N_{01}^{(\kappa)}. \quad (\text{E.5.9})$$

The dispersion function  $\Phi_{121}^{(\kappa)}$  is assumed to be independent of treatment. The product of the treatment dependent factors is the total quantity of gas  $j$  in the headspace of the drums handled annually multiplied by the number of forklift operations and the number of people exposed. The

TABLE E.5-2

**AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC CHEMICALS  
IN C2 ACCIDENTS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{1601\lambda}$	$3.03 \pm 0.49$	$P_{160\kappa\lambda} = P_{170\kappa\lambda}$
$P_{1602\lambda}$	$3.20 \pm 0.52$	
$P_{1603\lambda}$	$(4.3 \pm 1.1) \cdot 10^4$	
$P_{1604\lambda}$	$(8.2 \pm 1.3) \cdot 10^4$	
<b>Annual Baseline Risks:</b>		
$R_{16000}$	$1.8 \cdot 10^{-10}$	Aggregated from data in Table E.5-1
$R_{17000}$	$5.3 \cdot 10^{-10}$	

risk component scales as

$$R_{170\kappa\lambda j} = C_1 n_r^{(\kappa)} q_{18j}^{(\kappa)} n_f^{(\kappa)} N_{01}^{(\kappa)}. \quad (\text{E.5.10})$$

This is the same dependence as the one for Component 16. The risk reduction factor is, therefore,

$$\rho_{170\kappa\lambda j} = \rho_{180\kappa\lambda j}, \quad (\text{E.5.11})$$

and its error

$$\Delta \rho_{170\kappa\lambda j} = \Delta \rho_{180\kappa\lambda j}. \quad (\text{E.5.12})$$

The numerical values for the risk reduction factors are given in Table E.5-2 for Component 16. The baseline risks are derived from the values given in Table 5.46 of the FSEIS (DOE, 1990a, p. 5-99) by means of multiplication by an occupational reference level risk of  $10^{-4}$ . Due to different weighting, the aggregated values in Table E.5-2 are different for the two risk reduction factors.

### E.5.3 Underground Accidents

#### E.5.3.1 Risk Due To Accident Scenario C4

In this scenario a drum drops and loses its lid and the integrity of the liner due to the collision of a transporter with a pallet of drums. This leads to Risk Component 18, which, using the symbols

- $P_4$  = Probability of C4 accident per forklift operation,
- $n_r^{(\kappa)}$  = Number of drums handled routinely per year ( $\text{yr}^{-1}$ ),
- $n_f^{(\kappa)}$  = Number of forklift operations per drum handled,
- $n_4$  = Number of headspaces vented in C4 accident,
- $q_{18j}^{(\kappa)}$  = Quantity of chemical j released from headspace of a drum (mg),
- $\Phi_{14j}^{(\kappa)}$  = Underground dispersion function for all chemicals ( $\text{m}^{-3}$ ),
- $L_j^{(\text{ref})}$  = TLV for chemical j ( $\text{mg m}^{-3}$ ),
- $r_{0j}$  = Risk associated with short term exposure to reference level  $L_j^{(\text{ref})}$ ,
- $N_{02}^{(\kappa)}$  = Number of people exposed in Underground Storage Area,
- $C_1$  = Constant parts of equations, and
- $R_{180\kappa\lambda j}$  = Health risk per year of operation ( $\text{yr}^{-1}$ ),

leads to an occupational risk of a C4 accident of

$$R_{18\sigma\kappa\lambda j} = \{ [P_4 n_r^{(\kappa)} n_l^{(\kappa)}] n_4 q_{16j}^{(\kappa)} \} \Phi_{14,1}^{(\kappa)} \frac{1}{L_j^{(ref)}} r_{o,j} N_{o2}^{(\kappa)}. \quad (E.5.13)$$

The factors  $n_r^{(\kappa)}$  and  $\Phi_{14,1}^{(\kappa)}$  are assumed to be constant, and the variable part is the total annual headspace at risk. The risk thus scales as

$$R_{18\sigma\kappa\lambda j} = C_1 n_r^{(\kappa)} q_{16j}^{(\kappa)}, \quad (E.5.14)$$

and the risk reduction factor is

$$\rho_{18\sigma\kappa\lambda j} = \frac{n_r^{(0)} q_{16j}^{(0)}}{n_r^{(\kappa)} q_{16j}^{(\kappa)}} = F_{vk} F_{g\kappa j}, \quad (E.5.15)$$

with standard errors

$$\left( \frac{\Delta \rho_{18\sigma\kappa\lambda j}}{\rho_{18\sigma\kappa\lambda j}} \right) = \left( \frac{\Delta F_{vk}}{F_{vk}} \right)^2 + \left( \frac{\Delta F_{g\kappa j}}{F_{g\kappa j}} \right)^2. \quad (E.5.16)$$

The numerical values of the risk reduction factors and the baseline risks derived from Table 5.46 of the FSEIS (DOE, 1990a) are listed in Table E.5-3.

Again, aggregation of the risk reduction factors for different chemicals is done at this level. For C4, C5, and C6 accidents, the aggregation procedure is the same, and using the symbol  $l$  for Components 18, 19, or 20,

$$\rho_{l\sigma\kappa\lambda} = \sum_{j=4}^5 g_{l\sigma j} \rho_{l\sigma\kappa\lambda j}, \quad (E.5.17)$$

with the weights

$$g_{l\sigma j} = \frac{R_{l\sigma 00j}}{\sum_{\tau=4}^5 R_{l\sigma 00\tau}}, \quad (E.5.18)$$

TABLE E.5-3

**VALUES FOR THE REDUCTION FACTORS FOR CHEMICAL EMISSIONS  
DURING ACCIDENTS C4, C5, AND C6**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
P <sub>180124</sub>	21.2 ± 3.2	P <sub>180κ14</sub> = P <sub>180κ15</sub>
P <sub>180214</sub>	21.2 ± 3.2	P <sub>190κ1j</sub> = P <sub>180κ1j</sub>
P <sub>180314</sub>	(3.96 ± 1.00) · 10 <sup>5</sup>	P <sub>200κ1j</sub> = P <sub>180κ1j</sub>
P <sub>180414</sub>	(1.67 ± 0.25) · 10 <sup>6</sup>	
<b>Annual Baseline Risks: *</b>		
R <sub>180004</sub>	2.4 · 10 <sup>-10</sup>	FSEIS (DOE, 1990a), Table 5.46
R <sub>180005</sub>	1.5 · 10 <sup>-11</sup>	
R <sub>190004</sub>	2.4 · 10 <sup>-10</sup>	FSEIS (DOE, 1990a), Table 5.46
R <sub>190005</sub>	1.5 · 10 <sup>-11</sup>	
R <sub>200004</sub>	7.2 · 10 <sup>-10</sup>	FSEIS (DOE, 1990a), Table 5.46
R <sub>200005</sub>	4.5 · 10 <sup>-11</sup>	

\* The values in Table 5.46 of the FSEIS (DOE, 1990a) are multiplied by the risk of 10<sup>-4</sup> for the occupational reference level.

and standard errors

$$(\Delta \rho_{i\sigma\kappa\lambda})^2 = \sum_{j=4}^5 (g_{i\sigma j} \Delta \rho_{i\sigma\kappa\lambda j})^2. \quad (\text{E.5.19})$$

The numerical values of the baseline risks are given in Table E.5-3, and the final aggregated values in Table E.5-4. The risk reduction factors are about 21 for Level II treatments, about 400,000 for Treatment 3 and about 1.7 million for Treatment Alternative 4. These factors are applied to exceedingly small baseline risks of several times  $10^{-10}$ .

#### E.5.3.2 Risk Due to Accident Scenario C5

A C5 accident in Risk Component 19 is essentially the same event as a C4 accident, except that the cause is a drop off a forklift. Apart from the probability of a C5 accident per forklift operation, all the factors are, therefore, the same as Component 18, i.e., as for the C4 accident. Thus

$$\rho_{19\sigma\kappa\lambda j} = \rho_{18\sigma\kappa\lambda j}, \quad (\text{E.5.20})$$

and

$$\Delta \rho_{19\sigma\kappa\lambda j} = \Delta \rho_{18\sigma\kappa\lambda j}. \quad (\text{E.5.21})$$

The risk reduction factors are thus given by Table E.5-3 and the baseline risks are the values given there. The aggregated risk reduction factors are given in Table E.5-4.

#### E.5.3.3 Risk Underground Due To Accident Scenario C6

In this scenario, leading to Risk Component 20, the headspaces of three drums are vented, because two are pierced and one loses its lid. Except for the probability of a C6 accident per forklift operation and the number of headspaces vented, all the factors are the same as for Components 18 and 19. Consequently, the risk reduction factors are the same as for the C3 accident of Component 18. Thus

$$\rho_{20\sigma\kappa\lambda j} = \rho_{18\sigma\kappa\lambda j}, \quad (\text{E.5.22})$$

and

$$\Delta \rho_{20\sigma\kappa\lambda j} = \Delta \rho_{18\sigma\kappa\lambda j}. \quad (\text{E.5.23})$$

The risk reduction factors are thus given in Table E.5-3 and the baseline risks shown there are derived from Table 5.46 of the FSEIS (DOE, 1990a), which gives estimated daily intakes at the receptor location in  $\text{mg} (\text{kg day})^{-1}$ . The aggregated risk reduction factors are given in Table E.5-4.

TABLE E.5-4

**AGGREGATED RISK REDUCTION FACTORS FOR NONCARCINOGENIC  
CHEMICALS IN C4, C5, AND C6 ACCIDENTS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{1801\lambda}$	$21.2 \pm 3.2$	$P_{190\kappa\lambda} = P_{180\kappa\lambda}$ $P_{200\kappa\lambda} = P_{180\kappa\lambda}$
$P_{1802\lambda}$	$21.2 \pm 3.2$	
$P_{1803\lambda}$	$(3.96 \pm 1.00) \cdot 10^5$	
$P_{1804\lambda}$	$(1.67 \pm 0.25) \cdot 10^8$	
<b>Annual Baseline Risks:</b>		
$R_{18000}$	$2.6 \cdot 10^{-10}$	Aggregated from data in Table E.5-3
$R_{19000}$	$2.6 \cdot 10^{-10}$	
$R_{20000}$	$7.7 \cdot 10^{-10}$	

## **E.6 PROPERTIES OF TRANSPORTATION RISKS**

### **E.6.1 Basic Considerations**

The transportation risk calculated in the FSEIS and in this study are based on the transportation risk methodology found in RADTRAN III (Madsen et al., 1986). RADTRAN III is a revised version of the RADTRAN code (Taylor and Daniel, 1977) which was developed in conjunction with the Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Means (USNRC 1977b). RADTRAN III combines meteorological, demographic, health physics, economic, transportation, packaging, and material factors to obtain the expected radiological risks resulting from transportation of radioactive material.

Two principal computations are performed by the code: the radiological impact due to "incident free" transport and due to vehicular accidents. There are several submodels used in the RADTRAN III code. The material model describes the physical character of the waste and measures the radiotoxicity of the dispersed materials. The transportation model used in RADTRAN III describes accident rates, traffic patterns, and shipment information. Accident rates are given for types of accident and population zone in which they occur. The traffic patterns contain the fraction of travel which occurs on various types of road, population zones, and time of day. The shipment information gives the number of persons per vehicle, separation distances, and timing data.

An accident severity and package release model describes eight categories of accident severity and the fractional release of material from packaging and determines the expected release of each accident. An atmospheric dispersion model uses basic dispersion calculations provided by the user to evaluate concentrations at receptor sites.

The population distribution model specifies population densities in three population zones, rural, suburban, and urban, as well as certain other areas such as pedestrian walkways. The health effects model, finally, considers health effects due to exposure to different radiations such as early fatalities, early morbidities, latent cancer fatalities, and genetic effects.

In transportation, the treatment alternative  $\kappa$  influences the risks mostly through the effect of waste volume reduction on the number of transports and through the reduction of the suspension fraction of wastes in an accident; the location option  $\lambda$  exerts influence mainly through the partition of the total distance, from the originator to the WIPP into the portion travelled as untreated waste and the portion covered as treated waste.

The largest transportation risks are those incurred in traffic accidents in which the TRUPACT-II transport is involved but its containment not breached. The risks are, therefore, those of normal traffic accidents involving truck transports. In the FSEIS, recent studies made in 23 states were considered in this context and systemwide averages computed. As the different location options

involve additional transport in the same general area, it is a reasonable assumption that the extra transportation distances do not alter these averages in an appreciable way.

The risk formulae in this section are those coded in RADTRAN III, generalized to yield the corresponding risks for treated and untreated wastes. In the FSEIS, transportation risks were estimated using an earlier version, RADTRAN II (Madsen, et al, 1983). The parameter values used for the calculations in this section are listed in Tables E.6-1a and E.6-1b.

## E.6.2 Risk of Traffic Accidents

### E.6.2.1 Risk Of Fatalities

Traffic fatalities, involving the TRUPACT-II transport, its crew, and both members and vehicles of the general population, are modeled to be proportional to the total distance traveled. This results in Risk Component 21 which is expressed with the symbols

$p_a$	=	Probability density of a fatal accident per unit length of road ( $m^{-1}$ ),
$\Omega$	=	Number of waste producers,
$L_{0\omega}^{(\lambda)}$	=	Distance traveled as untreated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	=	Distance traveled as treated waste from originator $\omega$ (m),
$L_{t\omega}^{(\lambda)}$	=	Total transport distance for originator $\omega$ in location option $\lambda$ (m),
$f_{21\omega}$	=	Fraction of total annual waste produced by originator $\omega$ ,
$n_t^{(\kappa)}$	=	Number of transports per year for treatment option $\kappa$ ( $yr^{-1}$ ),
$F_{t\kappa}$	=	Transport reduction factor for treatment $\kappa$ , and
$R_{21pk\lambda}$	=	Annual risk of traffic fatalities ( $yr^{-1}$ ),

in the equation

$$R_{21pk\lambda} = p_a \sum_{\omega=1}^{\Omega} f_{21\omega} \left\{ L_{0\omega}^{(0)} n_t^{(0)} + L_{1\omega}^{(\lambda)} n_t^{(\kappa)} \right\}. \quad (E.6.1)$$

**TABLE E.6-1a**  
**RADTRAN GENERAL INPUT DATA**

SYMBOL	PARAMETER	CH TRU TRUCK
$N_{c3}$	Number of crewmen	2
$N_{p1}$	Number of people exposed while stopped	50
$N_{p2}$	Number of people per vehicle	2
$\tau$	Time to catch up to TRUPACT-II (seconds)	2
$v_1$	Speed (km/hr):	
$v_3$	Urban population zone	24
$v_2$	Suburban population zone	40
$v_1$	Rural population zone	88
$d_1$	Population density, people/km <sup>2</sup>	
$d_3$	Urban population zone	3861
$d_2$	Suburban population zone	719
$d_1$	Rural population zone	6
$r_{max 1}$	$r_{max}$ (m):	
$r_{max 3}$	Urban population zone	800
$r_{max 2}$	Suburban population zone	800
$r_{max 1}$	Rural population zone	800
$r_{min 1}$	$r_{min}$ (m):	
$r_{min 3}$	Urban population zone	5
$r_{min 2}$	Suburban population zone	27
$r_{min 1}$	Rural population zone	27
$N_{25 1}$	One-way traffic count (vehicles/hr):	
$N_{25 3}$	Urban population zone	2800
$N_{25 2}$	Suburban population zone	780
$N_{25 1}$	Rural population zone	470

TABLE E.6-1b  
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
$L_{10}^{(A)}$ (km)										
$L_{10}^{(0)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{10}^{(1)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{10}^{(2)}$	2433.6	1398.4	3363.2	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{10}^{(3)}$	2433.6	1398.4	3060.8	2536.0	548.8	2920.0	2057.6	3763.2	2332.8	3422.4
$L_{10}^{(4)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{10}^{(A)}$ (km)										
$L_{10}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$L_{10}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$L_{10}^{(2)}$	2433.6	1398.4	2433.6	0	0	0	0	0	0	0
$L_{10}^{(3)}$	2433.6	1398.4	3060.8	2536.0	0	2536.0	0	2536.0	0	2536.0
$L_{10}^{(4)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	0	0	0	0
$L_{00}^{(A)}$ (km)										
$L_{00}^{(0)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{00}^{(1)}$	2433.6	1398.4	3060.8	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{00}^{(2)}$	0	0	929.6	2536.0	548.8	2160.0	2057.6	2219.2	2332.8	2355.2
$L_{00}^{(3)}$	0	0	0	0	548.8	384.0	2057.6	1227.2	2332.8	886.4
$L_{00}^{(4)}$	0	0	0	0	0	0	2057.6	2219.2	2332.8	2355.2
$f_{11}^{(A)}$										
$f_{11}^{(0)}$	0	0	0	0	0	0	0	0	0	0
$f_{11}^{(1)}$	0	0	0	0	0	0	0	0	0	0
$f_{11}^{(2)}$	0.85	0.823	0.85	0	0	0	0	0	0	0
$f_{11}^{(3)}$	0.85	0.823	0.857	0.743	0	0.743	0	0.743	0	0.743
$f_{11}^{(4)}$	0.85	0.823	0.857	0.743	0.901	0.786	0	0	0	0

TABLE E.6-1b  
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY  
(CONTINUED)

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
f <sub>12</sub> <sup>(A)</sup>										
f <sub>12</sub> <sup>(0)</sup>	0	0	0	0	0	0	0	0	0	0
f <sub>12</sub> <sup>(1)</sup>	0	0	0	0	0	0	0	0	0	0
f <sub>12</sub> <sup>(2)</sup>	0.138	0.157	0.138	0	0	0	0	0	0	0
f <sub>12</sub> <sup>(3)</sup>	0.138	0.157	0.134	0.251	0	0.251	0	0.251	0	0.251
f <sub>12</sub> <sup>(4)</sup>	0.138	0.157	0.134	0.251	0.099	0.207	0	0	0	0
f <sub>13</sub> <sup>(A)</sup>										
f <sub>13</sub> <sup>(0)</sup>	0	0	0	0	0	0	0	0	0	0
f <sub>13</sub> <sup>(1)</sup>	0	0	0	0	0	0	0	0	0	0
f <sub>13</sub> <sup>(2)</sup>	0.012	0.02	0.012	0	0	0	0	0	0	0
f <sub>13</sub> <sup>(3)</sup>	0.012	0.02	0.009	0.006	0	0.006	0	0.006	0	0.006
f <sub>13</sub> <sup>(4)</sup>	0.012	0.02	0.009	0.006	0	0.007	0	0	0	0
f <sub>01</sub> <sup>(A)</sup>										
f <sub>01</sub> <sup>(0)</sup>	0.85	0.823	0.857	0.743	0.901	0.786	0.868	0.781	0.862	0.754
f <sub>01</sub> <sup>(1)</sup>	0.85	0.823	0.857	0.743	0.901	0.786	0.868	0.781	0.862	0.754
f <sub>01</sub> <sup>(2)</sup>	0	0	0.852	0.743	0.901	0.786	0.868	0.781	0.862	0.754
f <sub>01</sub> <sup>(3)</sup>	0	0	0	0	0.901	0.786	0.868	0.766	0.862	0.766
f <sub>01</sub> <sup>(4)</sup>	0	0	0	0	0	0	0.868	0.781	0.862	0.754
f <sub>02</sub> <sup>(A)</sup>										
f <sub>02</sub> <sup>(0)</sup>	0.138	0.157	0.134	0.251	0.099	0.207	0.112	0.218	0.101	0.241
f <sub>02</sub> <sup>(1)</sup>	0.138	0.157	0.134	0.251	0.099	0.207	0.112	0.218	0.101	0.241
f <sub>02</sub> <sup>(2)</sup>	0	0	0.1284	0.251	0.099	0.207	0.112	0.218	0.101	0.241
f <sub>02</sub> <sup>(3)</sup>	0	0	0	0	0.099	0.2293	0.112	0.2293	0.101	0.2293
f <sub>02</sub> <sup>(4)</sup>	0	0	0	0	0	0	0.112	0.218	0.101	0.241

TABLE E.6-1b  
LIST OF RADTRAN PARAMETERS USED IN THIS STUDY  
(CONTINUED)

PARAMETER	INEL	RFP	HANFORD	SRS	LANL	ORNL	NTS	ANL-E	LLNL	MOUND
$f_{03 \mu}^{(A)}$										
$f_{03 \mu}^{(0)}$	0.012	0.02	0.009	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03 \mu}^{(1)}$	0.012	0.02	0.009	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03 \mu}^{(2)}$	0	0	0.0196	0.006	0	0.007	0.02	0.001	0.037	0.005
$f_{03 \mu}^{(3)}$	0	0	0	0	0	0.0048	0.02	0.0048	0.037	0.0048
$f_{03 \mu}^{(4)}$	0	0	0	0	0	0	0.02	0.001	0.037	0.005
$f_{25 \mu}^{(A)}$										
$f_{25 \mu}^{(1)}$	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
$f_{25 \mu}^{(2)}$	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
$f_{25 \mu}^{(3)}$	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
$g_{25 \mu}^{(1)}$										
$g_{25 \mu}^{(2)}$	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$g_{25 \mu}^{(3)}$	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
$h_{25 \mu}^{(1)}$										
$h_{25 \mu}^{(2)}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$h_{25 \mu}^{(3)}$	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$f_{21 \mu}$	0.194	0.365	0.148	0.126	0.099	0.011	0.004	0.001	0.046	0.007

The form for the risk reduction factor is thus

$$\begin{aligned}
 P_{21 \rho \kappa \lambda} &= \frac{n_i^{(0)} \sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i \omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21 \omega} \left( L_{0 \omega}^{(\lambda)} n_i^{(0)} + L_{1 \omega}^{(\lambda)} n_i^{(\kappa)} \right)} \\
 &= \frac{\sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i \omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21 \omega} \left( L_{0 \omega}^{(\lambda)} + L_{1 \omega}^{(\lambda)} \frac{1}{F_{i \kappa}} \right)} = \frac{V_{21 00}}{V_{21 \kappa \lambda}}
 \end{aligned}
 \tag{E.6.2}$$

The definition of the quantities  $V_{21 \kappa \lambda}$  in the last part of the equation are needed for the error calculations. Assuming that the errors of the distances and the waste fractions are much smaller than the error of the transport reduction factor, only the latter need be considered (see Attachment C, Equation C.1.26). The standard error of the risk reduction factor for this case is then

$$\left( \frac{\Delta P_{21 \rho \kappa \lambda}}{P_{21 \rho \kappa \lambda}} \right) = \frac{\Delta F_{i \kappa}}{V_{21 \kappa \lambda} F_{i \kappa}^2} \sum_{\omega=1}^{\Omega} f_{21 \omega} L_{1 \omega}^{(\lambda)}
 \tag{E.6.3}$$

The risk reduction factors for the four treatment alternatives and the four location options are given in Table E.6-2. The values of the risk reduction factors for Location Option 1 (TF at the WIPP) are equal to 1 because the transports are the same as those in the baseline case. For Level II treatments, there is an increase in this risk component; for Treatment 3, the risk component is about constant, whereas for Treatment Option 4, there are modest risk reductions of factors 2 or 3. These reductions, however, are applied to the largest baseline risk components and are thus of great importance.

#### E.6.2.2 Risk Of Injuries

The expression for Risk Component 22, evaluating the risk of traffic injuries in accidents involving the TRUPACT-II, is the same as Equation (E.6.1) except for the linear probability density for accident injuries,  $p_i$ , that replaces the probability density  $p_a$  for fatal accidents. The risk reduction factors are, therefore, the same and are given in Table E.6-2. The baseline risk component for traffic injuries, on the other hand, is given by the value taken from the FSEIS executive summary, divided by 20 to obtain a risk per year of operation, reduced to apply for CH-TRU waste only, and entered in Table E.6-2.

TABLE E.6-2

**RISK REDUCTION FACTORS AND BASELINE RISK  
OF TRAFFIC DEATHS AND INJURIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{21 p 11}$	1	$P_{22 p k l} = P_{21 p k l}$
$P_{21 p 12}$	$0.760 \pm 0.048$	
$P_{21 p 13}$	$0.714 \pm 0.057$	
$P_{21 p 14}$	$0.715 \pm 0.058$	
$P_{21 p 21}$	1	
$P_{21 p 22}$	$0.720 \pm 0.042$	
$P_{21 p 23}$	$0.666 \pm 0.048$	
$P_{21 p 24}$	$0.666 \pm 0.049$	
$P_{21 p 31}$	1	
$P_{21 p 32}$	$1.10 \pm 0.17$	
$P_{21 p 33}$	$1.17 \pm 0.26$	
$P_{21 p 34}$	$1.18 \pm 0.27$	
$P_{21 p 41}$	1	
$P_{21 p 42}$	$2.00 \pm 0.06$	
$P_{21 p 43}$	$3.27 \pm 0.21$	
$P_{21 p 44}$	$3.51 \pm 0.25$	
<b>Annual Baseline Risks:</b>		
$R_{21 p 00}$	0.2	FSEIS (DOE, 1990a), Table D.4.6, p. D-108
$R_{22 p 00}$	3	

### E.6.3 Cancer Risk From Routine Transportation Radiation Exposures

#### E.6.3.1 Basic Considerations

Incident-free radiological risks occur during routine transportation and are the result of public and occupational exposures to external radiation far below regulatory levels. These low doses will fall below natural background radiation levels (DOE, 1990a, D.3.2.2, p. D-62).

The public may be exposed during stops, near the road taken by the TRUPACT-II transport, or from travelling in the same or opposite direction from the transport. Routine occupational exposures result from external radiation from the transportation itself, during waste handling procedures and also exposures to warehouse personnel. The above-mentioned radiological exposures result from exposure to untreated waste. Even when the waste is treated, the source term (activity) will dictate the risk. It is assumed here that there is no shielding or self-attenuation of gamma radiation in either the treated or the untreated waste.

Due to the assumption that the total annual activity handled is independent of treatment,

$$Q_o = q_2^{(k)} n_d^{(k)} n_1^{(k)} = \text{const} , \quad (\text{E.6.4})$$

where  $q_2^{(k)}$  is the average activity per drum,  $n_d^{(k)}$  is the number of drums in the TRUPACT-II container, and  $n_1^{(k)}$  is the number of annual TRUPACT-II transports, and  $Q_o$  is the total activity produced, handled, and emplaced in the WIPP in an equilibrium situation. In essence, this is thus the same condition as the one expressed by Equation (E.1.5). Weight limitations are introduced in post-treatment transportation by the transportation reduction factor.

#### E.6.3.2 Cancer Risk To Public Near Road Taken by TRUPACT-II Transports

The public near the roads travelled by the TRUPACT-II transports is routinely exposed to the penetrating part of the radioactivity. The corresponding cancer and genetic risks are the two subcomponents of Risk Component 23. The symbols used in modeling this component are:

$q_2^{(k)}$	= Total activity per drum (Bq),
$n_d^{(k)}$	= Number of drums per TRUPACT-II transport (3 TRUPACT-II containers, 42 drums),
$n_1^{(k)}$	= Number of shipments per year ( $\text{yr}^{-1}$ ),
$f_{21\omega}$	= Fraction of waste generated by originator $\omega$ ,
$\Omega$	= Number of originators,
$L_{0\omega}^{(\lambda)}$	= Distance travelled as untreated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Distance travelled as treated waste from originator $\omega$ (m),
$L_{t\omega}^{(\lambda)}$	= Total distance travelled for originator $\omega$ and location option $\lambda$ (m),
$\Phi_{23}$	= TRUPACT-II's source shape function,
$K_o$	= Dose-Rate Conversion factor for point source ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),

- $v_i$  = Transport speed in area  $i$  ( $m\ s^{-1}$ ),  
 $f_{0i\omega}^{(\lambda)}$  = Fraction of travel as untreated waste from originator  $\omega$  in area  $i$ ,  
 $f_{1i\omega}^{(\lambda)}$  = Fraction of travel as treated waste from originator  $\omega$  in area  $i$ ,  
 $d_i$  = Population density in area  $i$  ( $m^{-2}$ ),  
 $r_{i,min}$  = Minimum distance to TRUPACT-II centerline (m),  
 $r_{i,max}$  = Maximum distance to TRUPACT-II centerline (m),  
 $a_1$  = Cancer risk factor ( $Sv^{-1}$ ),  
 $C_j$  = Constant parts of equations,  
 $R_{23p\kappa\lambda}$  = Annual cancer risk for transportation for treatment/location option  $k$  ( $yr^{-1}$ ), with  
 Index for rural areas  $i = 1$ ,  
 Index for suburban areas  $i = 2$ ,  
 Index for urban areas  $i = 3$ ,

and the expression for this risk component is

$$R_{23p\kappa\lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} K_0 \Phi_{23} a_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^3 \frac{d_i}{v_i} \ln \left( \frac{r_{i,max}}{r_{i,min}} \right) \left[ f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right]. \quad (E.6.5)$$

Note that the source term is independent of treatment due to Equation (E.6.4) and appears, therefore, in front of the sums. Thus, the risk scales according to

$$R_{23p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^3 \frac{d_i}{v_i} \ln \left( \frac{r_{i,max}}{r_{i,min}} \right) \left[ f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right], \quad (E.6.6)$$

and with the relationship

$$L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)} = L_{i\omega}^{(\lambda)}, \quad (E.6.7)$$

arising from the definitions of the quantities, as well as the fact that for the baseline case all travel is done with untreated waste, the risk reduction factors are

$$P_{23p\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{i\omega}^{(0)} \sum_{i=1}^3 \frac{d_i}{v_i} \ln \left( \frac{r_{i,max}}{r_{i,min}} \right) f_{0i\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^3 \frac{d_i}{v_i} \ln \left( \frac{r_{i,max}}{r_{i,min}} \right) \left[ f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right]} \quad (E.6.8)$$

These risk reduction factors are independent of the treatment option  $\kappa$ , but do depend explicitly on the location parameters  $\lambda$ .

The uncertainty of the risk reduction factor arises mostly from the population densities  $d_i$  and the speeds  $v_i$  in the various areas  $i$ . The rest of the parameters are geometrical or based on waste statistics and have much smaller standard errors. The uncertainties of the quantities  $d_i$  and  $v_i$  enter both in numerator and denominator and thus tend to cancel in part. As the resulting uncertainty in these risk reduction factors is much smaller than those in others, they will not be evaluated in detail but set at a few percent. The errors are then estimated to be

$$\left( \frac{\Delta \rho_{23p\kappa\lambda}}{\rho_{23p\kappa\lambda}} \right) = 0.03 . \quad (\text{E.6.9})$$

The risk reduction factors have to be assembled from the values for the ten originators  $\omega$ . They are given in Table E.6-3, with the values for the baseline risks from Table D.3.14 of the FSEIS (DOE, 1990a).

The numerical values for the risk reduction factors are about unity for all treatments. This is understandable, considering the fact that the same amount of radioactivity is being transported over slightly different routes, except for  $\lambda = 1$  and 4, where the same routes result in a reduction factor of 1. The baseline risk of about 1 in three million for the public along the route is very small.

### E.6.3.3 Cancer Risk To Public During Stops

During stops along the highway, the members of the public using the same facility as the TRUPACT-II transport, are exposed to the penetrating part of the total activity. Their cancer risk is Risk Component 24, and with the definitions:

$q_2^{(\kappa)}$	= Total activity per drum (Bq),
$n_d^{(\kappa)}$	= Number of drums per TRUPACT-II transport,
$n_t^{(\kappa)}$	= Number of shipments per year ( $\text{yr}^{-1}$ ),
$\Omega$	= Number of originators,
$f_{21\omega}$	= Fraction of waste generated by originator $\omega$ ,
$L_{0\omega}^{(\lambda)}$	= Distance travelled as untreated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Distance travelled as treated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Total distance travelled for originator $\omega$ and location option $\lambda$ (m),
$L_s$	= Average distance between stops (m),
$K_0$	= Dose-Rate Conversion factor for point source ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),
$\Phi_{241}$	= Dosimetry function of rms of inverse distance ( $\text{m}^{-2}$ ),
$N_{p1}$	= Average number of persons exposed at rest stops,
$\Delta t_s$	= Average time spent at rest stops (s),

TABLE E.6-3

**RISK REDUCTION FACTORS FOR ROUTINE  
TRANSPORTATION EXPOSURES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{23 \text{ p} \times 1}$	$1.00 \pm 0.03$	
$P_{23 \text{ p} \times 2}$	$0.94 \pm 0.03$	
$P_{23 \text{ p} \times 3}$	$0.99 \pm 0.03$	
$P_{23 \text{ p} \times 4}$	$1.00 \pm 0.03$	
<b>Annual Baseline Risks:</b>		
$R_{23 \text{ p} 00}$	$3.6 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table D.3.14

- $a_1$  = Cancer risk factor ( $\text{Sv}^{-1}$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{24 p \kappa \lambda}$  = Cancer risk for exposures at rest stops for option  $k = (\kappa, \lambda)$  per year of operation ( $\text{yr}^{-1}$ ).

the cancer risk component is

$$R_{24 p \kappa \lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} \frac{K_0}{L_s} \Phi_{241} N_{p1} \Delta t_s a_1 \quad (\text{E.6.10})$$

$$\sum_{\omega=1}^{\Omega} f_{21 \omega} \left( L_{0\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right) \dots$$

As the terms in the first row are all independent of the treatment/location options and using Equation (E.6.7) the risk can be scaled as

$$R_{24 p \kappa \lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i\omega}^{(\lambda)} \quad (\text{E.6.11})$$

The risk reduction coefficients are then again independent of treatment

$$\rho_{24 p \kappa \lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i\omega}^{(\lambda)}} \quad (\text{E.6.12})$$

with the standard error

$$\left( \frac{\Delta \rho_{24 p \kappa \lambda}}{\rho_{24 p \kappa \lambda}} \right) = 0.01 \quad (\text{E.6.13})$$

estimated again under the assumption that well known data on road and waste are used in a way in which the uncertainties largely cancel. The numerical values of the parameters have been taken from the RADTRAN III code (Madsen et al., 1986) and are tabulated in Table E.6-1. Use of these parameters leads to the numerical values given in Table E.6-4. They lie very closely to 1 as in Component 23, reflecting small changes in total route lengths. The baseline risk is relatively small.

TABLE E.6-4

**RISK REDUCTION FACTORS FOR PUBLIC RISKS AT STOPS  
AND FOR SOME ACCIDENTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{24 \text{ p } \kappa 1}$	$1.00 \pm 0.01$	$P_{30 \text{ p } \kappa \lambda} = P_{24 \text{ p } \kappa \lambda}$
$P_{24 \text{ p } \kappa 2}$	$0.98 \pm 0.01$	$P_{31 \text{ p } \kappa \lambda} = P_{24 \text{ p } \kappa \lambda}$
$P_{24 \text{ p } \kappa 3}$	$0.99 \pm 0.01$	$P_{32 \text{ p } \kappa \lambda} = P_{24 \text{ p } \kappa \lambda}$
$P_{24 \text{ p } \kappa 4}$	$1.00 \pm 0.01$	
<b>Annual Baseline Risks:</b>		
$R_{24 \text{ p } 00}$	$1.3 \cdot 10^{-4}$	FSEIS (DOE, 1990a), Table D.3.14
$R_{30 \text{ p } 00}$	---	Not available in FSEIS
$R_{31 \text{ p } 00}$	---	Not available in FSEIS
$R_{32 \text{ p } 00}$	---	Not available in FSEIS

### E.6.3.4 Cancer Risk To Public Due To Traveling In The Opposite Direction

Drivers proceeding in the opposite direction of the TRUPACT-II transport are exposed only shortly. This risk is Component 25, with the definitions,

- $q_2^{(k)}$  = Total activity per drum (Bq),
- $n_d^{(k)}$  = Number of drums per TRUPACT-II transport,
- $n_i^{(k)}$  = Number of shipments per year ( $\text{yr}^{-1}$ ),
- $f_{21\omega}$  = Fraction of waste generated by originator  $\omega$ ,
- $\Omega$  = Number of originators,
- $L_{0\omega}^{(\lambda)}$  = Distance travelled as untreated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Distance travelled as treated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Total distance travelled for originator  $\omega$  and location option  $\lambda$  (m),
- $K_0$  = Dose-Rate Conversion factor for point source ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),
- $\Phi_{21}$  = TRUPACT-II shape function,
- $v_i$  = Transport speed in area  $i$  ( $\text{m s}^{-1}$ ),
- $f_{0i\omega}^{(\lambda)}$  = Fraction of travel as untreated waste from originator  $\omega$  in area  $i$ ,
- $f_{1i\omega}^{(\lambda)}$  = Fraction of travel as treated waste from originator  $\omega$  in area  $i$ ,
- $f_{25i\omega}$  = Fraction of freeway travel, area  $i$ , originator  $\omega$ ,
- $g_{25i\omega}$  = Fraction of rush hour travel, area  $i$ , originator  $\omega$ ,
- $h_{25i\omega}$  = Fraction of city street travel, originator  $\omega$ ,
- $x_i$  = Minimum exposure distance (m),
- $N_{p2}$  = Average number of persons in vehicle on TRUPACT-II routes,
- $N_{25i}$  = One way traffic count of vehicles in area  $i$  ( $\text{s}^{-1}$ ),
- $a_1$  = Cancer risk factor ( $\text{Sv}^{-1}$ ),
- $C_j$  = Constant parts of equations, and
- $R_{25p\kappa\lambda}$  = Annual cancer risk for transportation for treatment/location option  $k$  ( $\text{yr}^{-1}$ ), with  
 Index for rural areas  $i = 1$ ,  
 Index for suburban areas  $i = 2$ ,  
 Index for urban areas  $i = 3$ ,

it can be written as

$$R_{25p\kappa\lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} \Phi_{21} K_0 N_{p2} a_1 \frac{\pi}{2} \quad (\text{E.6.14})$$

$$\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{i=1}^3 N_{25i} \left[ f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] H_{25i\omega}$$

with the definitions of auxiliary functions

$$H_{251\omega} = \frac{f_{251\omega} \frac{1}{x_1} + (1 - f_{251\omega}) \frac{1}{x_2}}{v_1^2}, \quad (\text{E.6.15})$$

and

$$H_{252\omega} = \frac{1}{x_1} f_{252\omega} \left[ \frac{8g_{252\omega}}{v_2^2} + \frac{1 - g_{252\omega}}{v_1^2} \right] + \frac{1}{x_2} (1 - g_{252\omega}) \left[ \frac{7g_{252\omega} + 1}{v_2^2} \right], \quad (\text{E.6.16})$$

and

$$H_{253\omega} = \frac{1}{x_2} (1 - h_{253\omega}) \left[ \frac{8g_{253\omega}}{v_2^2} + \frac{1 - g_{253\omega}}{v_1^2} \right] + \frac{1}{x_3} h_{253\omega} \left[ \frac{7g_{253\omega} + 1}{v_3^2} \right]. \quad (\text{E.6.17})$$

These three auxiliary functions have the dimension ( $s^2 m^{-3}$ ). Note that the source term is independent of treatment due to Equation (E.6.4) and so are the other factors on the first line of Equation (E.6.14). Thus the scaling property on this component is

$$R_{25\rho\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{l=1}^3 N_{25l} \left[ f_{0l\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1l\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] H_{25l\omega}, \quad (\text{E.6.18})$$

and the risk reduction factors are given by

$$\rho_{25\rho\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{l=1}^3 N_{25l} f_{0l\omega}^{(0)} L_{l\omega}^{(0)} H_{25l\omega}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \sum_{l=1}^3 N_{25l} [f_{0l\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1l\omega}^{(\lambda)} L_{1\omega}^{(\lambda)}] H_{25l\omega}}, \quad (\text{E.6.19})$$

with standard errors of a few percent,

$$\left( \frac{\Delta \rho_{25\rho\kappa\lambda}}{\rho_{25\rho\kappa\lambda}} \right) = 0.03, \quad (\text{E.6.20})$$

estimated again by assuming the partial compensation of the small uncertainties in road and vehicle density data.

The risk reduction factors are independent of treatment, and have to be assembled from the parameter values for the ten originators  $\omega$  in Table E.6-1. They are given in Table E.6-5, together with their errors and the values for the baseline risks. Again, all values lie close to 1, reflecting the fact that the same activity is transported every year, regardless of treatment.

#### E.6.3.5 Cancer Risk To Public Driving In Same Direction As TRUPACT-II Transport

Longer exposure times occur for vehicles driving in the same direction as a TRUPACT-II transport. This leads to Risk Component 26. Using the symbols

$q_2^{(\kappa)}$	= Total activity per drum (Bq),
$n_d^{(\kappa)}$	= Number of drums per TRUPACT-II transport,
$n_1^{(\kappa)}$	= Number of shipments per year ( $\text{yr}^{-1}$ ),
$f_{21\omega}$	= Fraction of waste generated by originator $\omega$ ,
$L_{0\omega}^{(\lambda)}$	= Distance travelled as untreated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Distance travelled as treated waste from originator $\omega$ (m),
$L_{l\omega}^{(\lambda)}$	= Total distance travelled for originator $\omega$ and location option $\lambda$ (m),
$\Phi_{23}$	= TRUPACT-II shape function,
$K_0$	= Dose-Rate Conversion factor for point source ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),
$v_l$	= Transport speed in area $l$ ( $\text{m s}^{-1}$ ),
$f_{0l\omega}^{(\lambda)}$	= Fraction of travel as untreated waste from originator $\omega$ in area $l$ ,
$f_{1l\omega}^{(\lambda)}$	= Fraction of travel as treated waste from originator $\omega$ in area $l$ ,
$f_{25l\omega}$	= Fraction of freeway travel, area $l$ , originator $\omega$ ,
$g_{25l\omega}$	= Fraction of rush hour travel, area $l$ , originator $\omega$ ,
$h_{25l\omega}$	= Fraction of city street travel, originator $\omega$ ,
$x_l$	= Minimum exposure distance (m),

TABLE E.6-5

**RISK REDUCTION FACTORS FOR PUBLIC RISKS DUE  
TO CARS TRAVELING IN THE OPPOSITE DIRECTION**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{25 \text{ p} \kappa 1}$	$1.00 \pm 0.03$	
$P_{25 \text{ p} \kappa 2}$	$0.97 \pm 0.03$	
$P_{25 \text{ p} \kappa 3}$	$0.99 \pm 0.03$	
$P_{25 \text{ p} \kappa 4}$	$1.00 \pm 0.03$	
<b>Annual Baseline Risks:</b>		
$R_{25 \text{ p} 00}$	--	Not available in FSEIS

- $a_1$  = Cancer risk factor ( $\text{Sv}^{-1}$ ),  
 $\tau$  = Average time (2 sec) needed for vehicle to close the distance to TRUPACT-II transport (s),  
 $N_{p2}$  = Average number of persons in vehicle on the road,  
 $N_{251}$  = One-way vehicle count in area 1 ( $\text{s}^{-1}$ ),  
 $C_j$  = Constant parts of equations, and  
 $R_{26pk\lambda\omega}$  = Cancer risk for transportation for treatment/location option k and originator  $\omega$  per year of operation ( $\text{yr}^{-1}$ ), with  
 Index for rural areas  $i = 1$ ,  
 Index for suburban areas  $i = 2$ ,  
 Index for urban areas  $i = 3$ ,

it can be written as

$$R_{26pk\lambda\omega} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} f_{21\omega} \right\} K_0 \Phi_{23} N_{p2} a_1 \sum_{i=1}^3 \left[ f_{0i\omega}^{(\lambda)} L_{0\omega}^{(\lambda)} + f_{1i\omega}^{(\lambda)} L_{1\omega}^{(\lambda)} \right] (H_{26i\omega} + G_{26i\omega}), \quad (\text{E.6.21})$$

with the auxiliary functions defined by

$$H_{261\omega} = \frac{N_{251}}{V_1^3 \tau}, \quad (\text{E.6.22})$$

and

$$H_{262\omega} = N_{252} \left[ f_{252\omega} \left( \frac{16 g_{252\omega}}{\tau V_2^3} + \frac{1 - g_{252\omega}}{\tau V_1^3} \right) + (1 - f_{252\omega}) \frac{15 g_{252\omega} + 1}{\tau V_2^3} \right], \quad (\text{E.6.23})$$

and

$$H_{263\omega} = N_{253} \left[ (1 - h_{253\omega}) \left( \frac{16 g_{253\omega}}{\tau v_2^3} + \frac{1 - g_{253\omega}}{\tau v_1^3} \right) + (h_{253\omega}) \frac{15 g_{253\omega} + 1}{\tau v_3^3} \right]. \quad (\text{E.6.24})$$

Both auxiliary functions H and G have the dimension [s m<sup>-3</sup>]

$$G_{261\omega} = \frac{N_{251}}{2 v_1^2} \left( \frac{1}{x_1} - \frac{1}{\tau v_1} \right), \quad (\text{E.6.25})$$

and

$$G_{262\omega} = N_{252} \left\{ f_{252\omega} \left[ \frac{4 g_{252\omega}}{v_2^2} \left( \frac{1}{x_2} - \frac{2}{v_2 \tau} \right) + \frac{1 - g_{252\omega}}{2 v_1^2} \left( \frac{1}{x_2} - \frac{1}{v_1 \tau} \right) \right] \right. \\ \left. + (1 - f_{252\omega}) \left[ \frac{4 g_{252\omega}}{v_2^2} \left( \frac{1}{x_2} - \frac{2}{v_2 \tau} \right) + \frac{1 - g_{252\omega}}{2 v_2^2} \left( \frac{1}{x_2} - \frac{1}{v_2 \tau} \right) \right] \right\}, \quad (\text{E.6.26})$$

and

$$G_{263\omega} = N_{253} \left\{ (1 - h_{253\omega}) \left[ \frac{4 g_{253\omega}}{v_2^2} \left( \frac{1}{x_3} - \frac{2}{v_2 \tau} \right) + \frac{1 - g_{253\omega}}{2 v_1^2} \left( \frac{1}{x_3} - \frac{1}{v_1 \tau} \right) \right] \right. \\ \left. + h_{253\omega} \left[ \frac{4 g_{253\omega}}{v_3^2} \left( \frac{1}{x_3} - \frac{2}{v_3 \tau} \right) + \frac{1 - g_{253\omega}}{2 v_3^2} \left( \frac{1}{x_3} - \frac{1}{v_3 \tau} \right) \right] \right\}. \quad (\text{E.6.27})$$

Note that the source term is independent of treatment due to Equation (E.6.16) and so are the other factors on the first line of Equation (E.6.23). Thus this risk scales as

$$R_{26 p \kappa \lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21 \omega} \sum_{i=1}^3 \left[ f_{0i \omega}^{(\lambda)} L_{0 \omega}^{(\lambda)} + f_{1i \omega}^{(\lambda)} L_{1 \omega}^{(\lambda)} \right] (H_{26 i \omega} + G_{26 i \omega}), \quad (\text{E.6.28})$$

and the risk reduction factors are again independent of treatment

$$P_{26 p \kappa \lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21 \omega} \sum_{i=1}^3 f_{0i \omega}^{(0)} L_{i \omega}^{(0)} (H_{26 i \omega} + G_{26 i \omega})}{\sum_{\omega=1}^{\Omega} f_{21 \omega} \sum_{i=1}^3 \left[ f_{0i \omega}^{(\lambda)} L_{0 \omega}^{(\lambda)} + f_{1i \omega}^{(\lambda)} L_{1 \omega}^{(\lambda)} \right] (H_{26 i \omega} + G_{26 i \omega})}, \quad (\text{E.6.29})$$

with the standard errors estimated to be a few percent

$$\left( \frac{\Delta P_{26 p \kappa \lambda \omega}}{P_{26 p \kappa \lambda \omega}} \right) = 0.04, \quad (\text{E.6.30})$$

based on the same assumptions as those in the preceding sections. The risk reduction factors which have to be assembled from the parameter values for the 10 originators  $\omega$  are given in Table E.6-6, together with the value for the baseline risks. All factors cluster around unity, as expected, and are applied to a very small baseline risk.

#### E.6.3.6 Cancer Risk To Crew During Transport

The persons constantly in the radiation field of the TRUPACT-II containers are the members of the transport crew. Their exposure leads to Risk Component 27 with two subcomponents, cancer and genetic effects. Using the symbols:

- $q_2^{(k)}$  = Total activity per drum (Bq),
- $n_d^{(k)}$  = Number of drums per TRUPACT-II transport,
- $n_i^{(k)}$  = Number of shipments per year ( $\text{yr}^{-1}$ ),
- $\Omega$  = Number of originators,
- $f_{21 \omega}$  = Fraction of waste generated by originator  $\omega$ ,
- $f_{0i \omega}^{(\lambda)}$  = Fraction of travel as untreated waste from originator  $\omega$  in area  $i$ ,
- $f_{1i \omega}^{(\lambda)}$  = Fraction of travel as treated waste from originator  $\omega$  in area  $i$ ,
- $L_{0 \omega}^{(\lambda)}$  = Distance travelled as untreated waste from originator  $\omega$  (m),
- $L_{1 \omega}^{(\lambda)}$  = Distance travelled as treated waste from originator  $\omega$  (m),

TABLE E.6-6

**RISK REDUCTION FACTORS FOR PUBLIC DRIVING  
IN SAME DIRECTION AS TRUPACT-II**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{2\sigma, PK1}$	$1.00 \pm 0.04$	
$P_{2\sigma, PK2}$	$0.96 \pm 0.04$	
$P_{2\sigma, PK3}$	$0.99 \pm 0.04$	
$P_{2\sigma, PK4}$	$1.00 \pm 0.04$	
<b>Annual Baseline Risks:</b>		
$R_{2\sigma, P00}$	$3.6 \cdot 10^{-7}$	FSEIS (DOE, 1990a), Table D.3.14

- $L_{1\omega}^{(\lambda)}$  = Total distance travelled for originator  $\omega$  and location option  $\lambda$  (m),  
 $\Phi_{23}$  = TRUPACT-II shape function,  
 $K_0$  = Dose-Rate Conversion factor ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),  
 $v_i$  = Transport speed in area  $i$  ( $\text{m s}^{-1}$ ),  
 $\Phi_{271}$  = Dosimetry function (rms inverse distance, i.e.,  $\text{m}^{-2}$ ),  
 $N_{03}$  = Average number of crewmen aboard TRUPACT-II transport,  
 $a_1$  = Cancer risk factor ( $\text{Sv}^{-1}$ ),  
 $C_j$  = Constant parts of equations, and  
 $R_{270\kappa\lambda}$  = Cancer risk for crew exposures during transport for option  $\kappa$  per year of operation ( $\text{yr}^{-1}$ ), with  
 Index for rural areas  $i = 1$ ,  
 Index for suburban areas  $i = 2$ ,  
 Index for urban areas  $i = 3$ ,

the formula for this risk component is

$$R_{270\kappa\lambda} = \{q_2^{(0)} n_d^{(0)} n_i^{(0)}\} K_0 \Phi_{23} \Phi_{271} N_{03} a_1 \left[ \sum_{\omega=1}^{\Omega} f_{21\omega} \left( L_{0\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right) \right]. \quad (\text{E.6.31})$$

As the factors in the first row are all independent of the treatment/location options, the risk can be rewritten to scale according to

$$R_{270\kappa\lambda} = C_1 \left[ \sum_{\omega=1}^{\Omega} f_{21\omega} \left( L_{0\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right) \right]. \quad (\text{E.6.32})$$

The risk reduction coefficient is then again independent of the treatment option selected

$$P_{270\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{i\omega}^{(0)} \sum_{i=1}^3 \frac{f_{0i\omega}^{(0)}}{v_i}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \left( L_{0\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{0i\omega}^{(\lambda)}}{v_i} + L_{1\omega}^{(\lambda)} \sum_{i=1}^3 \frac{f_{1i\omega}^{(\lambda)}}{v_i} \right)}. \quad (\text{E.6.33})$$

The standard error is estimated to be

$$\left( \frac{\Delta P_{270k\lambda}}{P_{270k\lambda}} \right) = 0.03 ,$$

(E.6.34)

again under the assumptions made in the preceding sections.

The numerical values of the risk reduction factors are given in Table E.6-7, together with baseline risks. They cluster around one, being applied to a rather small baseline risk.

### E.6.3.7 Cancer Risk To Waste Handlers

In loading the TRUPACT-II transport, the work crew will be exposed in various drum geometries according to a particular time-motion profile. The exposure of handlers during the unloading at the WIPP is accounted for in Component 4 for external radiation and Components 1 and 2 for internal exposure. Putting the treatment facility at the site of the originator or at the WIPP does not affect the total dose to the loaders of the TRUPACT-II transport. Putting the facility somewhere in between, however, results in an additional loading and unloading operation. For the calculation of Risk Component 28, the symbols are:

- $q_2^{(k)}$  = Total activity per drum (Bq),
- $n_d^{(k)}$  = Number of drums per TRUPACT-II transport,
- $n_1^{(k)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $n_h$  = Number of handling operations per shipment,
- $f_{21\omega}$  = Fraction of waste generated by originator  $\omega$ ,
- $K_0$  = Dose-Rate Conversion factor for point source ( $Sv\ s^{-1}\ Bq^{-1}\ m^2$ ),
- $\Phi_{281}$  = Dosimetry function (rms inverse distance, i.e.,  $m^{-2}$ ),
- $\Phi_{282}$  = Time-averaged shape function of drum assemblies,
- $\Phi_{283\omega}^{(k\lambda)}$  = Location factor for Treatment Plant
- $N_{o4}$  = Average number of crewmen for the loading of TRUPACT-II,
- $\Delta t_h$  = Average handling time (s),
- $a_1$  = Cancer risk factor ( $Sv^{-1}$ ),
- $C_i$  = Constant parts of equations, and
- $R_{280k\lambda}$  = Annual cancer risk for exposures during handling for option k ( $yr^{-1}$ ),

TABLE E.6-7

## RISK REDUCTION FACTORS FOR CREW DURING TRANSPORT

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$P_{27pk1}$	$1.00 \pm 0.03$	
$P_{27pk2}$	$0.98 \pm 0.03$	
$P_{27pk3}$	$0.99 \pm 0.03$	
$P_{27pk4}$	$1.00 \pm 0.03$	
Annual Baseline Risks:		
$R_{27p00}$	$7.8 \cdot 10^{-5}$	FSEIS (DOE 1990a), Table D.3.14

the cancer risk per year of operation is

$$R_{280\kappa\lambda} = \{q_2^{(0)} n_d^{(0)} n_i^{(0)}\} K_0 \Phi_{281} \Phi_{282} \left[ \sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{283\omega}^{(\kappa\lambda)} \right] n_h \Delta t_h N_{04} a_1 \quad (E.6.35)$$

The product of all factors in the source term is independent of the measurement/location option due to Equation (E.6.4). Of the rest of the factors, only the sum is location dependent. Thus the scaling properties of the risk are

$$R_{280\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{283\omega}^{(\kappa\lambda)} \quad (E.6.36)$$

The values and standard errors for the function  $\Phi_{283\omega}^{(\kappa\lambda)}$  are given in Tables D.3-9 and D.3-10.

The risk reduction factor is then both location and treatment dependent and is given by

$$\begin{aligned} \rho_{280\kappa\lambda} &= \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{283\omega}^{(00)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{283\omega}^{(\kappa\lambda)}} \\ &= \frac{1}{\sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{283\omega}^{(\kappa\lambda)}} \equiv \frac{1}{V_{280\kappa\lambda}} \end{aligned} \quad (E.6.37)$$

The simplification in the numerator arises from the fact that all  $\Phi_{283\omega}^{(00)}$  are equal to 1, and that the sum of the fraction of the total waste is also equal to 1. Because  $\Phi_{283\omega}^{(\kappa\lambda)} \geq 1$ , the risk reduction factors are smaller than 1,  $\rho_{280\kappa\lambda} \leq 1$ , i.e., there is an increase in risk. Also, the standard error is small, arising only from the standard errors of the fractions  $\Phi_{283\omega}^{(\kappa\lambda)}$

$$\left( \frac{\Delta \rho_{280\kappa\lambda}}{\rho_{280\kappa\lambda}} \right)^2 = \sum_{\omega=1}^{\Omega} \left( \frac{f_{21\omega} \Delta \Phi_{283\omega}^{(\kappa\lambda)}}{V_{280\kappa\lambda}} \right)^2 \quad (E.6.38)$$

The risk reduction factors, calculated using data from Tables D.3-9 and D.3-10, are listed in Table E.6-8. Their values range from a risk increase by 50 percent to a risk reduction by a factor of almost 4. The relative standard errors are small, ranging from 2 to 8 percent.

#### E.6.3.8 Cancer Risk To Warehouse Personnel

The amount of time the warehouse crew is exposed is assumed to be a constant. During storage, a large number of drums at larger distances than during handling irradiate the warehouse crew. This leads to Risk Component 29, with one subcomponent. Using the notation

- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_d^{(\kappa)}$  = Number of barrels per TRUPACT-II container,
- $n_i^{(\kappa)}$  = Number of shipments per year ( $\text{yr}^{-1}$ ),
- $f_{21\omega}$  = Fraction of waste generated by originator  $\omega$ ,
- $\Omega$  = Number of waste originators,
- $\Delta t_s$  = Total storage time per shipment in baseline case (s),
- $K_0$  = Dose-Rate Conversion factor ( $\text{Sv s}^{-1} \text{Bq}^{-1} \text{m}^2$ ),
- $\Phi_{291}$  = Geometry-dosimetry function ( $\text{m}^2$ ),
- $\Phi_{292\omega}^{(\kappa\lambda)}$  = Time extension function due to location and treatment,
- $N_{05}^{(\kappa)}$  = Average number of personnel in warehouse,
- $a_1$  = Annual cancer risk factor ( $\text{Sv}^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{290\kappa\lambda}$  = Annual cancer risk for exposures during storage ( $\text{yr}^{-1}$ ),

the cancer risk per year of operation is

$$R_{290\kappa\lambda} = \{q_2^{(0)} n_d^{(0)} n_i^{(0)}\} K_0 \Phi_{291} \left( \sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{292\omega}^{(\kappa\lambda)} \right) \Delta t_s N_{05}^{(\kappa)} a_1. \quad (\text{E.6.39})$$

The source term is independent of treatment due to Equation (E.6.4). For different location/treatment options, only the quantities in the rounded brackets change. The risk can, therefore, be scaled as

$$R_{290\kappa\lambda} = C_1 \left( \sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{292\omega}^{(\kappa\lambda)} \right). \quad (\text{E.6.40})$$

TABLE E.6-8

## RISK REDUCTION FACTORS FOR WASTE HANDLERS

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
P <sub>28</sub> o 11	1	Identical risk component
P <sub>28</sub> o 12	0.689 ± 0.025	
P <sub>28</sub> o 13	0.726 ± 0.029	
P <sub>28</sub> o 14	0.712 ± 0.029	
P <sub>28</sub> o 21	1	Identical risk component
P <sub>28</sub> o 22	0.654 ± 0.022	
P <sub>28</sub> o 24	0.680 ± 0.025	
P <sub>28</sub> o 24	0.663 ± 0.024	
P <sub>28</sub> o 31	1	Identical risk component
P <sub>28</sub> o 32	0.970 ± 0.086	
P <sub>28</sub> o 33	1.14 ± 0.12	
P <sub>28</sub> o 34	1.19 ± 0.14	
P <sub>28</sub> o 41	1	Identical risk component
P <sub>28</sub> o 42	1.65 ± 0.03	
P <sub>28</sub> o 43	2.51 ± 0.06	
P <sub>28</sub> o 44	3.61 ± 0.13	
<b>Annual Baseline Risks:</b>		
R <sub>28</sub> o 00	---	Not given in FSEIS

The risk reduction factor can now be written as

$$\rho_{290\kappa\lambda} = \frac{1}{\sum_{\omega=1}^{\Omega} f_{21\omega} \Phi_{292\omega}^{(\kappa\lambda)}} = \frac{1}{V_{290\kappa\lambda}}, \quad (\text{E.6.41})$$

with a standard error

$$\left( \frac{\Delta \rho_{290\kappa\lambda}}{\rho_{290\kappa\lambda}} \right)^2 = \sum_{\omega=1}^{\Omega} \left( \frac{f_{21\omega}}{V_{290\kappa\lambda}} \Delta \Phi_{292\omega}^{(\kappa\lambda)} \right)^2. \quad (\text{E.6.42})$$

The function  $\Phi_{292\omega}^{(\kappa\lambda)}$  is modeled in Appendix I, Section D.3.11 and its numerical values are given in Tables D.3-11 and D.3-12. They range from unity up to risk reduction factors of 1.5, and down to values corresponding to risk increases by a factor of 4. The numerical values for the risk reduction factors are given in Table E.6-9.

#### E.6.4 Cancer Risks Due To Transportation Accident Exposures

##### E.6.4.1 Basic Considerations

The accidents discussed here are those considered in RADTRAN III. The amount of radioactive material released in an accident depends on the severity of the accident, the properties of the waste, and the characteristics of the shipping containment. The overall accident rate and the accident severity category are used to evaluate the risk. Accidents range in severity from categories one through eight (U.S. NRC, 1977b), defined by the crush force and fire duration of the accident. Nondispersal accidents are considered by using the source strength of penetrating external radiation only. External radiation is not assumed to attenuate in any structures between the center of the source and the exposed individual or population. Dispersal accident risks incorporate the resuspension and dissolution in addition to the source term's contribution to the risk. In this report, the probability of an accident is based on systemwide averages; the dispersal function is assumed to be a constant based on a systemwide average.

##### E.6.4.2 Risks Due To Nondispersal Accidents

###### E.6.4.2.1 Early Fatalities Due To Nondispersal Accidents

Nondispersal accidents are assumed to produce a closely distributed source of penetrating radiation at the accident site. For persons close by, this may lead to sizeable exposures to gammas and neutrons and in rare cases a potential for early health effects, such as radiation

TABLE E.6-9

## RISK REDUCTION FACTORS FOR RISK TO WAREHOUSE PERSONNEL

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
P <sub>29</sub> o 11	1	Identical to baseline
P <sub>29</sub> o 12	1.04 $\pm$ 0.03	
P <sub>29</sub> o 13	1.31 $\pm$ 0.05	
P <sub>29</sub> o 14	1.39 $\pm$ 0.05	
P <sub>29</sub> o 21	1	Identical to baseline
P <sub>29</sub> o 22	1.078 $\pm$ 0.024	
P <sub>29</sub> o 24	1.381 $\pm$ 0.044	
P <sub>29</sub> o 24	1.492 $\pm$ 0.052	
P <sub>29</sub> o 31	1	Identical to baseline
P <sub>29</sub> o 32	0.784 $\pm$ 0.077	
P <sub>29</sub> o 33	0.842 $\pm$ 0.097	
P <sub>29</sub> o 34	0.841 $\pm$ 0.099	
P <sub>29</sub> o 41	1	Identical to baseline
P <sub>29</sub> o 42	0.309 $\pm$ 0.016	
P <sub>29</sub> o 43	0.263 $\pm$ 0.013	
P <sub>29</sub> o 44	0.243 $\pm$ 0.011	
Annual Baseline Risks:		
R <sub>29</sub> o 00	---	Not available in FSEIS

sickness (bone marrow syndrome). The dose-effect function for fatalities is sigmoidal and can be described by a Weibull function (Scott et al., 1988). Due to the high doses required, the probabilities of these effects occurring are very low, resulting in a very small risk. This is Risk Component 30 with one subcomponent, and with the symbols:

- $p_{nd}$  = Linear probability density of a nondispersive accident ( $m^{-1}$ ),
- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,
- $n_i^{(\kappa)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Total distance travelled by waste from originator  $\omega$  (m),
- $\Omega$  = Number of originators  $\omega$ ,
- $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,
- $\Phi_{301}$  = Average geometry function due to released and enclosed activity,
- $\Phi_{302}$  = Dosimetry-effect function (nonlinear) for all exposed persons ( $Bq^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{30p\kappa\lambda}$  = Risk of bone-marrow lethality for exposures during accidents per year of operation ( $yr^{-1}$ ),

and applying Equation (E.1.5), it can be estimated from the expression

$$R_{30p\kappa\lambda} = \{q_2^{(0)} n_d^{(0)} n_i^{(0)}\} p_{nd} \quad (E.6.43)$$

$$\left( \sum_{\omega=1}^{\Omega} f_{21\omega} (L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)}) \right) \Phi_{301} \Phi_{302} .$$

With regard to a dependence on the alternative  $k = (\kappa, \lambda)$ , the top row of Equation (E.6.43) is constant and so are the last two factors. The risk scales as

$$R_{30p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(\lambda)} . \quad (E.6.44)$$

The reduction factors are then the same as those for Component 24,

$$\rho_{30\rho\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(\lambda)}} = \rho_{24\rho\kappa\lambda}, \quad (\text{E.6.45})$$

with the same standard errors

$$\Delta\rho_{30\rho\kappa\lambda} = \Delta\rho_{24\rho\kappa\lambda}. \quad (\text{E.6.46})$$

Thus the numerical values have already been assembled in Table E.6-4, together with the baseline risk.

#### E.6.4.2.2 Early Morbidity Due To Nondispersal Accidents

Another early effect of a high dose exposure is radiation sickness with a nonfatal outcome. Other effects of this type are radiation pneumonitis, damage to the gastrointestinal tract, hair loss, sterility in males, and the appearance of nodules in the thyroids in the intermediate term. Clearly, the same calculation can be made, except that the dose-effect function used is different. As dose increases, it rises, peaks, and decreases again. That decrease is due to the increase in fatalities at higher doses. Again, the doses required are high and the risks, therefore, very low. This nonfatal outcome results in Risk Component 31 with one subcomponent, and with the symbols:

- $\rho_{nd}$  = Linear probability density of a nondispersive accident ( $m^{-1}$ ),
- $q_2^{(k)}$  = Total activity per drum (Bq),
- $n_d^{(k)}$  = Number of drums per TRUPACT-II transport,
- $n_t^{(k)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Total distance traveled by waste from originator  $\omega$  (m),
- $\Omega$  = Number of originators  $\omega$ ,
- $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,
- $\Phi_{301}$  = Average geometry function for activity after accident,
- $\Phi_{311}$  = Dosimetry-effect function (nonlinear) for all exposed persons ( $Bq^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{31\rho\kappa\lambda}$  = Risk of bone-marrow lethality for exposures during accidents per year of operation ( $yr^{-1}$ ),

and again applying Equation (E.6.4), the risk component is

$$R_{31 p \kappa \lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} p_{nd} \left( \sum_{\omega=1}^{\Omega} f_{21 \omega} \left[ L_{0 \omega}^{(\lambda)} + L_{1 \omega}^{(\lambda)} \right] \right) \Phi_{301} \Phi_{311} \quad (\text{E.6.47})$$

With regard to a dependence on the alternative  $k = (\kappa, \lambda)$ , the risk can be scaled as

$$R_{31 p \kappa \lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i \omega}^{(\lambda)} \quad (\text{E.6.48})$$

which is the same as the risks for Component 24. The reduction factors are then also the same

$$p_{31 p \kappa \lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i \omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21 \omega} L_{i \omega}^{(\lambda)}} = p_{24 p \kappa \lambda} \quad (\text{E.6.49})$$

with the same standard errors

$$\Delta p_{31 p \kappa \lambda} = \Delta p_{24 p \kappa \lambda} \quad (\text{E.6.50})$$

Thus the values given in Table E.6-4 apply here as well.

#### E.6.4.2.3 Delayed Health Effects Due To Nondispersal Accidents

The delayed effects of radiation exposure are mainly cancer and genetic damage. Again, the same calculation is made, except that the dose-effect calculation is made differently in that the conservative, no-threshold linear model is used for both effects. The Risk Component 32 thus has two sub-components, and with the symbols:

$p_{nd}$	= Linear probability density of a nondispersive accident ( $m^{-1}$ ),
$L_{0 \omega}^{(\lambda)}$	= Distance traveled with untreated waste from originator $\omega$ (m),
$L_{1 \omega}^{(\lambda)}$	= Distance traveled with treated waste from originator $\omega$ (m),
$L_{i \omega}^{(\lambda)}$	= Total distance travelled by waste from originator $\omega$ (m),
$\Omega$	= Number of originators $\omega$ ,
$q_2^{(\kappa)}$	= Total activity per drum (Bq),
$n_d^{(\kappa)}$	= Number of drums per TRUPACT-II transport,
$n_i^{(\kappa)}$	= Number of shipments per year ( $yr^{-1}$ ),

- $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,  
 $\Phi_{301}$  = Average geometry function for activity after accident,  
 $\Phi_{321}$  = Dosimetry-effect function for all exposed persons (Sv Bq<sup>-1</sup>),  
 $a_1$  = Cancer risk coefficient (Sv<sup>-1</sup>),  
 $C_1$  = Constant parts of equations, and  
 $R_{32p\kappa\lambda}$  = Annual cancer risk for exposures during nondispersal accidents (yr<sup>-1</sup>),

and still using Equation (E.6.4), the risk component is

$$R_{32p\kappa\lambda} = \{q_2^{(\kappa)} n_d^{(\kappa)} n_i^{(\kappa)}\} p_{nd} \quad (E.6.51)$$

$$\left( \sum_{\omega=1}^{\Omega} f_{21\omega} [L_{0\omega}^{(\lambda)} + L_{1\omega}^{(\lambda)}] \right) \Phi_{301} \Phi_{321} a_1 .$$

Again, this risk scales as

$$R_{32p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} L_{i\omega}^{(\lambda)} , \quad (E.6.52)$$

which is the same as Equations (E.6.44) and (E.6.48). The reduction factors are then again

$$p_{32p\kappa\lambda} = p_{24p\kappa\lambda} , \quad (E.6.53)$$

with the same standard errors

$$\Delta p_{32p\kappa\lambda} = \Delta p_{24p\kappa\lambda} . \quad (E.6.54)$$

These values are tabulated in Table E.6-4 together with the baseline risk.

### E.6.4.3 Risks Due To Dispersal Accidents

#### E.6.4.3.1 Risk Of Early Fatalities Due To Inhalation

The FSEIS (DOE, 1990a) considers accidents with a breach of containment, suspension, and atmospheric dispersion of a mixture of radioisotopes, leading to inhalation exposures. This puts mainly the lung, but also other organs at risk. Again, the calculations made are similar to those in the preceding sections. The Risk Component 33 for early fatalities has one subcomponent,

using the symbols:

- $p_d$  = Linear probability density of a dispersive accident ( $m^{-1}$ ),
- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,
- $n_i^{(\kappa)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Total distance travelled by waste from originator  $\omega$  (m),
- $\Omega$  = Number of originators  $\omega$ ,
- $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,
- $f_{331}^{(\kappa)}$  = Fraction of activity suspended in average (systemwide) accident,
- $f_{332}^{(\kappa)}$  = Fraction of airborne particles in inhalable form,
- $S_{33\kappa}$  = Reduction factor for suspension in Inhalable form due to treatment  $\kappa$ ,
- $f_{333}$  = Fraction of airborne particles deposited in lung,
- $\Phi_{331}$  = Dosimetry-effect function for fatal effects in exposed persons ( $Bq^{-1}$ ),
- $a_1$  = Cancer risk coefficient ( $Sv^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{33p\kappa\lambda}$  = Risk of early fatalities for exposures during dispersal accidents per year of operation ( $yr^{-1}$ ),

and again applying Equation (E.6.4), is given by

$$R_{33p\kappa\lambda} = \{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \} p_d \quad (E.6.55)$$

$$\left( \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} f_{331}^{(0)} f_{332}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} f_{332}^{(\kappa)} \right] \right) f_{333} \Phi_{331} a_1 .$$

With regard to a dependence on the alternative  $k = (\kappa, \lambda)$ , the risk can be split into a constant and a variable part. The constant part consists of the first row and the last three factors. This risk component thus has the scaling property

$$R_{33p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} \phi_{33}^{(0)} + L_{1\omega}^{(\lambda)} \phi_{33}^{(\kappa)} \right] , \quad (E.6.56)$$

with the suspendability factor

$$\phi_{33}^{(\kappa)} \equiv f_{331}^{(\kappa)} f_{332}^{(\kappa)} . \quad (E.6.57)$$

Using the definition of the reduction factor

$$S_{33\kappa} \equiv \frac{\phi_{33}^{(0)}}{\phi_{33}^{(\kappa)}}, \quad (\text{E.6.58})$$

for the reduction in suspendability of waste in inhalable form in the average TRUPACT-II accident with breach of containment, the reduction factors are given by

$$p_{33\rho\kappa\lambda} = \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(0)}}{\sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} + \frac{L_{1\omega}^{(\lambda)}}{S_{33\kappa}} \right]} \equiv \frac{V_{3300}}{V_{33\kappa\lambda}}. \quad (\text{E.6.59})$$

The standard errors are given by the relatively large errors of the factors  $S_{33\kappa}$  and the relatively small errors of the road lengths and waste fractions; the latter are estimated at about two percent. Thus the errors are

$$\left( \frac{\Delta p_{33\rho\kappa\lambda}}{p_{33\rho\kappa\lambda}} \right)^2 = \left( \frac{\sum_{\omega=1}^{\Omega} f_{21\omega} L_{1\omega}^{(\lambda)}}{V_{33\kappa\lambda} S_{33\kappa}} \right)^2 \left( \frac{\Delta S_{33\kappa}}{S_{33\kappa}} \right)^2 + (0.02)^2. \quad (\text{E.6.60})$$

The first term with the large factor  $S_{33\kappa}$  in the denominator will usually be smaller than the second, even for large relative errors of  $S_{33\kappa}$ . The risk reduction factors do depend on  $\kappa$  and  $\lambda$  and their values are given in Table E.6-10. Inspection shows that the variability of the factors with the treatment alternative  $\kappa$  is minute. Table E.6-10, therefore, shows only the variability with location, which goes from 1 to about 15 with relative errors of 2 percent.

#### E.6.4.3.2 Risk Of Early Morbidity Due To Inhalation

All individuals that are exposed to a dose higher than the effect threshold but exhibit and survive the acute syndrome fall into the class of nonfatal early health effects. For this risk, the calculations are similar to those in the preceding section. Risk Component 34 for early nonfatal health effects has one subcomponent, using the symbols:

- $p_d$  = Linear probability density of a dispersive accident ( $m^{-1}$ ),
- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,
- $n_t^{(\kappa)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),
- $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),

**TABLE E.6-10**  
**RISK REDUCTION FACTORS AND BASELINE RISKS**  
**FOR COMPONENTS**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{33 \text{ p } \kappa 1}$	1	$P_{34 \text{ p } \kappa \lambda} = P_{33 \text{ p } \kappa \lambda}$
$P_{33 \text{ p } \kappa 2}$	2.94	$P_{35 \text{ p } \kappa \lambda} = P_{33 \text{ p } \kappa \lambda}$
$P_{33 \text{ p } \kappa 3}$	10.8	$P_{36 \text{ p } \kappa \lambda} = P_{33 \text{ p } \kappa \lambda}$
$P_{33 \text{ p } \kappa 4}$	14.7	$P_{37 \text{ p } \kappa \lambda} = P_{33 \text{ p } \kappa \lambda}$
		$P_{39 \text{ p } \kappa \lambda} = P_{33 \text{ p } \kappa \lambda}$
<b>Annual Baseline Risks:</b>		
$R_{33 \text{ p } 00}$	--	Not available in FSEIS (DOE, 1990a)
$R_{34 \text{ p } 00}$	--	
$R_{35 \text{ p } 00}$	--	
$R_{36 \text{ p } 00}$	--	
$R_{37 \text{ p } 00}$	--	
$R_{39 \text{ p } 00}$	--	

- $\Omega$  = Number of originators  $\omega$ ,  
 $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,  
 $f_{331}^{(\kappa)}$  = Fraction of activity released in average accident (systemwide),  
 $f_{332}^{(\kappa)}$  = Fraction of airborne particles in inhalable form,  
 $\Phi_{341}$  = Dosimetry-effect function (nonfatal effects for exposed persons) ( $Bq^{-1}$ ),  
 $a_1$  = Cancer risk coefficient ( $Sv^{-1}$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{34p\kappa\lambda}$  = Annual risk of early fatalities for exposures during dispersal accidents ( $yr^{-1}$ ),

and again applying Equations (E.6.4) and definition (E.6.57), is given by

$$R_{34p\kappa\lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} p_d \left( \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} f_{331}^{(0)} f_{332}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} f_{332}^{(\kappa)} \right] \right) \Phi_{341} a_1. \quad (E.6.61)$$

With regard to a dependence on the alternative  $k = (\kappa, \lambda)$ , the risk can be split into a constant and a variable part, yielding the scaling law

$$R_{34p\kappa\lambda} = C_1 \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} \Phi_{33}^{(0)} + L_{1\omega}^{(\lambda)} \Phi_{33}^{(\kappa)} \right], \quad (E.6.62)$$

which is the same as the equations in the preceding section for  $R_{33p\kappa\lambda}$ . The reduction factors are thus given in Table E.6-10, together with the baseline risk.

#### E.6.4.3.3 Risk Of Delayed Health Effects Due To Inhalation

The inhalation of both the directly transmitted and the resuspended airborne particles contribute to the long-term exposure. With cancer and genetic effects as delayed action endpoints, Risk Component 35 has two subcomponents. The risks of incurring these consequences, using the symbols:

- $p_d$  = Linear probability density of a dispersive accident ( $m^{-1}$ ),  
 $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),  
 $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),  
 $\Omega$  = Number of originators  $\omega$ ,  
 $q_2^{(\kappa)}$  = Total activity per drum (Bq),  
 $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,  
 $n_i^{(\kappa)}$  = Number of shipments per year ( $yr^{-1}$ ),  
 $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,  
 $f_{331}^{(\kappa)}$  = Fraction of activity released in average accident (systemwide),

- $f_{332}^{(\kappa)}$  = Fraction of airborne particles in inhalable form,  
 $\Phi_{351}$  = Dosimetry function for all exposed persons (Sv Bq<sup>-1</sup>),  
 $a_1$  = Cancer risk coefficient (Sv<sup>-1</sup>),  
 $R_{35 p \kappa \lambda}$  = Annual cancer risk for inhalation exposures during dispersal accidents (yr<sup>-1</sup>),

and again applying Equation (E.6.4), is given by

$$R_{35 p \kappa \lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} p_d \quad (E.6.63)$$

$$\left( \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} f_{331}^{(0)} f_{332}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} f_{332}^{(\kappa)} \right] \right) \Phi_{351} a_1,$$

which again leads to cancer risk reduction factors and errors given in Table E.6-10.

#### E.6.4.3.4 Risks Of Delayed Health Effects Due To Cloudshine

This is a direct external exposure from a passing cloud of radioactive suspended particles. With cancer and genetic effects as delayed action endpoints, Risk Component 36 has two sub-components. The risks of these consequences, using the symbols:

- $p_d$  = Linear probability density of a dispersive accident (m<sup>-1</sup>),  
 $q_2^{(\kappa)}$  = Total activity per drum (Bq),  
 $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,  
 $n_i^{(\kappa)}$  = Number of shipments per year (yr<sup>-1</sup>),  
 $L_{0\omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),  
 $L_{1\omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),  
 $\Omega$  = Number of originators  $\omega$ ,  
 $f_{21\omega}$  = Fraction of total waste from originator  $\omega$ ,  
 $f_{331}^{(\kappa)}$  = Fraction of activity released in average accident (systemwide),  
 $f_{332}^{(\kappa)}$  = Fraction of airborne particles in inhalable form,  
 $\Phi_{361}$  = Cloudshine dosimetry function for all exposed persons (Sv Bq<sup>-1</sup>),  
 $a_1$  = Cancer risk coefficient (Sv<sup>-1</sup>),  
 $R_{36 p \kappa \lambda}$  = Cancer risk for exposures during dispersal accidents per year of operation (yr<sup>-1</sup>),

and again applying Equation (E.6.4), is given by

$$R_{36 p \kappa \lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} p_d \quad (E.6.64)$$

$$\left( \sum_{\omega=1}^{\Omega} f_{21 \omega} \left[ L_{0 \omega}^{(\lambda)} f_{331}^{(0)} + L_{1 \omega}^{(\lambda)} f_{331}^{(\kappa)} \right] \right) \Phi_{361} a_1 .$$

This equation has the same basic structure as Equation (E.6.63), except for the factors  $f_{332}^{(0)}$  and  $f_{332}^{(\kappa)}$ , respectively. The fraction of the suspended particles which is in inhalable form is assumed to be independent of the treatment  $\kappa$ . Thus the terms in the sum in Equation (E.6.64) can be multiplied by  $f_{332}^{(0)}$  and  $f_{332}^{(\kappa)}$ , respectively, and this again leads to the same cancer risk reduction factors as in the last section and errors given in Table E.6-10.

#### E.6.4.3.5 Risks Of Delayed Health Effects Due To Groundshine

Eventually, all the activity suspended in the accident is again deposited, leading to a surface contamination of the ground. The assumption is made here that this surface contamination level is proportional to the released radioactivity, i.e., the source term. The direct exposure to penetrating radiation from the fallout leads to Risk Component 37 with two sub-components. Using the symbols:

- $p_d$  = Linear probability density of a dispersive accident ( $m^{-1}$ ),
- $L_{0 \omega}^{(\lambda)}$  = Distance traveled with untreated waste from originator  $\omega$  (m),
- $L_{1 \omega}^{(\lambda)}$  = Distance traveled with treated waste from originator  $\omega$  (m),
- $L_{1 \omega}^{(\lambda)}$  = Total distance travelled by waste from originator  $\omega$  (m),
- $\Omega$  = Number of originators  $\omega$ ,
- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_d^{(\kappa)}$  = Number of drums per TRUPACT-II transport,
- $n_i^{(\kappa)}$  = Number of shipments per year ( $yr^{-1}$ ),
- $f_{21 \omega}$  = Fraction of total waste from originator  $\omega$ ,
- $f_{331}^{(\kappa)}$  = Fraction of activity released in average accident (systemwide),
- $f_{332}^{(\kappa)}$  = Fraction of activity released and suspended in inhalable form,
- $\Phi_{371}$  = Deposition function over exposure area ( $m^{-2}$ ),
- $\Phi_{372}$  = Groundshine dosimetry function for all exposed persons ( $Sv Bq^{-1} m^2$ ),
- $a_1$  = Cancer risk coefficient ( $Sv^{-1}$ ),
- $R_{37 p \kappa \lambda}$  = Annual cancer risk for exposures during dispersal accidents ( $yr^{-1}$ ),

and again applying Equation (E.6.4), the risk is given by:

$$R_{37p\kappa\lambda} = \left\{ q_2^{(0)} n_d^{(0)} n_i^{(0)} \right\} p_d \left( \sum_{\omega=1}^{\Omega} f_{21\omega} \left[ L_{0\omega}^{(\lambda)} f_{331}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)} \right] \right) \Phi_{371} \Phi_{372} a_1 \quad (\text{E.6.65})$$

With the general assumption that the particle size spectrum does not change with treatment, the quantity  $f_{331}^{(\kappa)}$  can be multiplied with the spectrum dependent factor  $f_{332}^{(\kappa)}$  for the calculation of the risk reduction factors. According to Equation (E.6.57) this is equal to  $\phi_{33}^{(\kappa)}$ . This brings Equation (E.6.65) into line with all the other risk equations for dispersal accidents, and the risk reduction factors and their errors are given in Table E.6-10.

#### E.6.5 Risk Of Monetary Losses Due To Decontamination Procedures

The largest potential financial losses treated in the RADTRAN-III code, but not in the FSEIS, are decontamination costs incurred in a dispersal accident. The assumption is made here that the only quantities sensitive to the treatment/location option are the accident probability and the source term. The risk is assumed to be linearly dependent on these parameters. While, for the general assumptions used here this is evident for the accident probability, it does not necessarily hold for the source term and the contamination caused by the accident. Assuming that the areas and number of people requiring a particular action scale with the quantity released, the financial Risk Component 39, with the symbols:

$p_d$	= Linear probability density of a dispersive accident ( $m^{-1}$ ),
$L_{0\omega}^{(\lambda)}$	= Distance traveled with untreated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Distance traveled with treated waste from originator $\omega$ (m),
$L_{1\omega}^{(\lambda)}$	= Total distance travelled by waste from originator $\omega$ (m),
$\Omega$	= Number of originators $\omega$ ,
$q_2^{(\kappa)}$	= Total activity per drum (Bq),
$n_d^{(\kappa)}$	= Number of drums per TRUPACT-II transport,
$n_i^{(\kappa)}$	= Number of shipments per year ( $yr^{-1}$ ),
$f_{21\omega}$	= Fraction of total waste from originator $\omega$ ,
$f_{331}^{(\kappa)}$	= Fraction of activity suspended in average accident (systemwide),
$\Phi_{371}$	= Deposition function over exposure area ( $m^{-2}$ ),
$\Phi_{392}$	= Cost function for all persons and areas contaminated ( $\$ Bq^{-1} m^2$ ),
$R_{39p\kappa\lambda}$	= Cost of decontamination incurred in dispersal accidents ( $\$ yr^{-1}$ ),

and again applying Equation (E.6.4), is given by

$$R_{39\rho\kappa\lambda} = \{q_2^{(0)} n_d^{(0)} n_i^{(0)}\} p_d \left( \sum_{\omega=1}^{\Omega} f_{21\omega} [L_{0\omega}^{(\lambda)} f_{331}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)}] \right) \Phi_{371} \Phi_{392} \quad (\text{E.6.66})$$

The variability of factors with alternative allows the risk component to be written as

$$R_{39\rho\kappa\lambda} = C_1 \left( \sum_{\omega=1}^{\Omega} f_{23\omega} [L_{0\omega}^{(\lambda)} f_{331}^{(0)} + L_{1\omega}^{(\lambda)} f_{331}^{(\kappa)}] \right), \quad (\text{E.6.67})$$

with the general assumption that the particle size spectrum does not change with treatment, the quantity  $f_{331}^{(\kappa)}$  can again be multiplied with the spectrum dependent factor  $f_{332}^{(\kappa)}$  for the calculation of the risk reduction factors, making Equation (E.6.67), the risk reduction factors and their errors, the same as those in the preceding sections which are listed in Table E.6-10.

## E.7 LATE OCCURRING RISKS

### E.7.1 Basic Considerations

For post-closure effects due to the presence of the repository, transportation options are irrelevant and the options are distinguished only by the treatment, i.e.,  $k = (\kappa, \lambda_0)$ . For the risk calculations, it is assumed that the total activity in the repository is independent of the waste treatment. The activity concentration in the repository is then given by

$$d_0^{(\kappa)} = \frac{Q_0}{A_0^{(\kappa)} h_0}, \quad (\text{E.7.1})$$

where the four quantities are

- $d_0^{(\kappa)}$  = Activity concentration in repository (Bq m<sup>-3</sup>),
- $Q_0$  = Total activity in repository (Bq),
- $A_0^{(\kappa)}$  = Footprint of wastes in repository (m<sup>2</sup>),
- $h_0$  = Height of wastes in repository panel (m).

In addition, the ratio of the footprints for different treatment options is related to the volume reduction factor  $F_{vk}$  due to the treatment of the wastes by

$$F_{vk} = \frac{A_0^{(0)}}{A_0^{(k)}} . \quad (\text{E.7.2})$$

With the symbols

$P_{1i}^{(k)}$  = Probability of a drill hole  $i$  through the wastes in scenario  $i$ , and  
 $\sigma_i$  = Probability density of type  $i$  drill hole in region of WIPP ( $\text{m}^{-2}$ ),

the probability of drilling a borehole through the wastes is

$$P_{1i}^{(k)} = \sigma_i A_0^{(k)} , \quad (\text{E.7.3})$$

and the product

$$d_0^{(k)} P_{1i}^{(k)} = \frac{\sigma_i Q_0}{h_0} = \text{const} , \quad (\text{E.7.4})$$

is a constant, assuming that the height  $h_0$  of the waste in the repository does not change due to treatment, i.e., remains at a stack height of three drums.

In drilling operations according to scenario  $i$ , the activity  $\{Q_i^{(k)}\}$  is brought to the surface. With its gamma component, it irradiates the drilling crew over the short term. The corresponding risk is, in the general terms of Equation (E.7.1), only treatment option-dependent through the source term  $Q_i^{(k)}$ . In this evaluation, it will be assumed that, for treated wastes, the mobilization is restricted to the drill hole, and is not changed thereafter until the hole is plugged. The activity brought to the surface is the same for each drill hole in each of the three intrusion scenarios.

Similarly, after the pond for the drilling mud has dried out, wind erosion will lead to a very low public inhalation risk, which is again only treatment option-dependent through the same source term according to Equation (E.7.2). Thus the public inhalation risk is subject to reduction factors which are identical to those of the occupational risks.

In the risk through the contamination of stock well water and, therefore, beef, the mobilization of the activity in the repository and its transport to the Culebra must be accounted for. From there to the stockwell, the activity transport is assumed to be linear in the source term at the drill hole. In the combined human intrusion Scenario E1E2, contaminations in groundwater and air can arise from different source locations. It is assumed here, that these effects superpose linearly. This

is particularly important in the groundwater contamination in the Culebra, as the water that carries the contamination also may carry salt at elevated concentrations.

## E.7.2 Post-Closure Occupational Radiation Risks From Drilling Operations

### E.7.2.1 Risk Of Drilling Operations In Scenario E1

In this scenario, a hole is drilled through the wastes and continued down into a portion of the Castile Formation containing a pressurized brine reservoir. The risk arises from direct external exposure to activity brought up in the drilling mud and the brine flowing to the surface. In addition to the waste in the borehole, the drilling mud and the brine will dissolve some of the waste around the borehole.

The mobilized material thus consists not only of drill cuttings but also includes material adjacent to the hole that becomes available for transport through processes such as dissolution or entrainment. The amount of the material in addition to drill cuttings depends upon the waste form and fluid flow environment. Cemented or vitrified waste will contribute less additional material than will a loose and unconsolidated waste form.

A two-step process is considered in this analysis: (1) a quantity of waste is "mobilized" in the vicinity of the hole penetrating the waste horizon, and (2) the mobilized quantity is transported to the surface. At any moment, the accumulated activity brought to the surface serves as source term for direct irradiation of the crew by penetrating gamma radiation. The assumption made here is that the increase in activity, and thus in the dose rate, is linear with time. The average surface activity and dose rate over the time interval of changing dose rate is, therefore, equal to the ultimately accumulated value for half the time it takes to drill through the waste. Afterward, the entire activity mobilized contributes to the dose to the drill crew. Any members of the public are assumed to be far enough away to incur only exposures that lie far below cosmic and terrestrial background.

Risk Component 40 then has two subcomponents, and with the symbols

- $P_{11}^{(k)}$  = Probability of a drill hole through the waste and into the Castile Formation,
- $P_{13}$  = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,
- $\Phi_{401}^{(k)}$  = Time average of total activity mobilized in scenario E1 (Bq),
- $\Phi_{402}^{(k)}$  = Transport function to surface,
- $\Phi_{403}^{(k)}$  = Global exposure function for drilling crew ( $\text{Sv Bq}^{-1}$ ),
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{40 \text{ or } \lambda}$  = Cancer risk of an E1 drilling operation,

the occupational cancer risk of an E1 drilling scenario is

$$R_{400\kappa\lambda} = [P_{11}^{(\kappa)} P_{13}] \{ \Phi_{401}^{(\kappa)} \Phi_{402}^{(\kappa)} \} \Phi_{403}^{(\kappa)} a_1. \quad (\text{E.7.5})$$

With no factor outside the source term and the probability being treatment option-dependent, only the footprint  $A_0^{(\kappa)}$  in  $P_{11}^{(\kappa)}$  [see equation (E.7.3)] and  $\Phi_{401}^{(\kappa)}$  change with treatment options, because the transport function to the surface is assumed to be treatment independent. The scaling of the risk can then be written as

$$R_{400\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{401}^{(\kappa)}, \quad (\text{E.7.6})$$

and the risk reduction factors are

$$\rho_{400\kappa\lambda} = \frac{A_0^{(0)} \Phi_{401}^{(0)}}{A_0^{(\kappa)} \Phi_{401}^{(\kappa)}} = F_{v\kappa} F_{s\kappa}, \quad (\text{E.7.7})$$

where the ratio of total mobilized activities is defined by

$$F_{s\kappa} = \frac{\Phi_{401}^{(0)}}{\Phi_{401}^{(\kappa)}}. \quad (\text{E.7.8})$$

Numerical values and errors estimated for the reduction factor for mobilized activities are given in Table D.5-1 of Attachment D. The standard errors of the risk reduction factors are

$$\left( \frac{\Delta \rho_{400\kappa\lambda}}{\rho_{400\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{s\kappa}}{F_{s\kappa}} \right)^2. \quad (\text{E.7.9})$$

The risk reduction factors for an E1 scenario are listed in Table E.7-1. They are grouped around a value of 5 but are applied to an exceedingly small baseline risk.

### E.7.2.2 Risk Of Drilling Operations In Scenario E2

In this scenario, a borehole is drilled into or through the waste without also penetrating a pressurized brine reservoir. Waste from the hole itself and dissolution of waste in regions adjacent to the hole again leads to a mobilized activity brought to the surface. Using the same

TABLE E.7-1

## RISK REDUCTION FACTORS FOR HUMAN INTRUSION SCENARIO E1

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{40\ 0\ 1\ \lambda}$	$4.7 \pm 0.7$	$P_{41\ 0\ \kappa\ \lambda} = P_{40\ 0\ \kappa\ \lambda}$
$P_{40\ 0\ 2\ \lambda}$	$4.8 \pm 0.7$	$P_{43\ p\ \kappa\ \lambda} = P_{40\ 0\ \kappa\ \lambda}$
$P_{40\ 0\ 3\ \lambda}$	$5.3 \pm 1.4$	$P_{44\ p\ \kappa\ \lambda} = P_{40\ 0\ \kappa\ \lambda}$
$P_{40\ 0\ 4\ \lambda}$	$4.5 \pm 0.7$	
<b>Annual Baseline Risks:</b>		
$R_{40\ 0\ 0\ 0}$	$3 \cdot 10^{-8}$	FSEIS (DOE 1990a), Table 5.61
$R_{41\ 0\ 0\ 0}$	--	Not available in FSEIS
$R_{43\ 0\ 0\ 0}$	--	Not available in FSEIS
$R_{44\ 0\ 0\ 0}$	--	Not available in FSEIS

assumptions as in the preceding section, this leads to a model for Risk Component 41 with two subcomponents. With the symbols:

- $P_{12}^{(k)}$  = Probability of drill hole into or through repository, no brine,
- $\Phi_{411}^{(k)}$  = Time average of total activity mobilized in scenario E2 (Bq),
- $\Phi_{412}^{(k)}$  = Transport function to surface in scenario E2,
- $\Phi_{413}^{(k)}$  = Global exposure function for crew in E2 scenario (Sv Bq<sup>-1</sup>),
- $a_1$  = Cancer risk coefficient (Sv<sup>-1</sup>),
- $C_1$  = Constant parts of equations, and
- $R_{41\sigma k\lambda}$  = Cancer risk from direct exposure in an E2 drilling operation,

this risk component is

$$R_{41\sigma k\lambda} = [P_{12}^{(k)}] \left\{ \Phi_{411}^{(k)} \Phi_{412}^{(k)} \right\} \Phi_{413}^{(k)} a_1. \quad (\text{E.7.10})$$

With Equation (E.7.3) and the fact that  $\Phi_{412}^{(k)}$  is assumed to be constant and the factors outside the source term and probability (in brackets) do not depend on the alternative, the risk can again be scaled as

$$R_{41\sigma k\lambda} = C_1 A_0^{(k)} \Phi_{411}^{(k)}. \quad (\text{E.7.11})$$

Again, reduction ratios can be defined for the mobilized activities which are the same as those in Scenario E1, due to the assumptions made in Sections D.5.1 and E.7.1,

$$\frac{\Phi_{411}^{(0)}}{\Phi_{411}^{(k)}} = F_{sk}. \quad (\text{E.7.12})$$

Numerical values for these reduction ratios are listed in Attachment D, Table D.5-1, together with their standard errors. The risk reduction factors are then given by

$$\rho_{41\sigma k\lambda} = \frac{A_0^{(0)} \Phi_{411}^{(0)}}{A_0^{(k)} \Phi_{411}^{(k)}} = F_{vk} F_{sk}, \quad (\text{E.7.13})$$

with the standard error

$$\left( \frac{\Delta \rho_{41\sigma k\lambda}}{\rho_{41\sigma k\lambda}} \right)^2 = \left( \frac{\Delta F_{vk}}{F_{vk}} \right)^2 + \left( \frac{\Delta F_{sk}}{F_{sk}} \right)^2. \quad (\text{E.7.14})$$

The numerical values are thus the same as those given in Table E.7-1.

### E.7.2.3 Risk Of Drilling Operations In Scenario E1E2

Scenario E1E2 consists of a sequence of an E1 and an E2 scenario. The first drilling leads to an E1 contribution to the risk which is equal to the component  $R_{40 \text{ o } \kappa \lambda}$  discussed in Section E.7.2.1 and thus leads to the risk reduction factors given in Table E.7-2. In addition, this scenario implies drilling into a pressurized repository in the E2 part, and results in the additional Risk Component 42. The repository consists of eight panels and a central zone, each of which is sealed. Therefore, Scenario E1E2 requires the E1 and E2 events to occur at least in the same sealed waste zone. Further, the consequence of Scenario E1E2 depends upon the time proximity and distance proximity of the two holes. E1E2 can involve a pressure gradient that causes collection and entrainment of larger quantities of material than does E1. Thus, the scenario depends not only upon the drilling of two holes, but also depends upon an interaction function between the two holes. Using the symbols

- $P_{11}^{(\kappa)}$  = Probability of first drill hole into repository and into the Castile Formation,
- $P_{13}$  = Probability of drilling into a brine reservoir in the Castile Formation,
- $P_{12}^{(\kappa)}$  = Probability of drill hole into or through repository,
- $\Phi_{421}^{(\kappa)}$  = Time average of total activity mobilized in E2 part of scenario (Bq),
- $\Phi_{422}^{(\kappa)}$  = Interaction function between the two drill holes,
- $\Phi_{423}^{(\kappa)}$  = Transport function to surface in E2 part of scenario,
- $\Phi_{424}^{(\kappa)}$  = Global exposure function for crew in E2 part of the scenario ( $\text{Sv Bq}^{-1}$ ),
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{42 \text{ o } \kappa \lambda}$  = Cancer risk from direct irradiation in the E2 part of an E1E2 drilling scenario,

The risk component for that part is

$$R_{42 \text{ o } \kappa \lambda} = [ P_{11}^{(\kappa)} P_{13} P_{12}^{(\kappa)} ] \{ \Phi_{421}^{(\kappa)} \Phi_{422}^{(\kappa)} \Phi_{423}^{(\kappa)} \} \Phi_{424}^{(\kappa)} a_1 . \quad (\text{E.7.15})$$

Using Equation (E.7.3) this risk contribution can be rewritten as scaling according to

$$R_{42 \text{ o } \kappa \lambda} = C_1 \left( A_0^{(\kappa)} \right)^2 \Phi_{421}^{(\kappa)} \Phi_{422}^{(\kappa)} . \quad (\text{E.7.16})$$

With the definition of the reduction factors

$$\frac{\Phi_{421}^{(0)}}{\Phi_{421}^{(\kappa)}} = F_{\text{sk}} , \quad (\text{E.7.17})$$

**TABLE E.7-2**  
**RISK REDUCTION FACTORS FOR DRILLING CREWS IN SCENARIO E1E2**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{42\ 0\ 1\ \lambda}$	$5.6 \pm 1.2$	$P_{45\ \rho\ \kappa\ \lambda} = P_{42\ 0\ \kappa\ \lambda}$
$P_{42\ 0\ 2\ \lambda}$	$5.7 \pm 1.2$	
$P_{42\ 0\ 3\ \lambda}$	$11.6 \pm 5.4$	
$P_{42\ 0\ 4\ \lambda}$	$41.5 \pm 9.5$	
<b>Annual Baseline Risks:</b>		
$R_{42\ 0\ 0\ 0}$	$3 \cdot 10^{-8}$	FSEIS (DOE 1990a), Table 5.61
$R_{45\ 0\ 0\ 0}$		Not available in FSEIS

given Table E.7-1, this leads to the risk reduction ratio of

$$P_{420\kappa\lambda} = F_{\text{sk}} \frac{(A_0^{(0)})^2}{(A_0^{(\kappa)})^2} = F_{\text{vk}}^2 F_{\text{sk}}, \quad (\text{E.7.18})$$

with standard error of

$$\left( \frac{\Delta P_{420\kappa\lambda}}{P_{420\kappa\lambda}} \right)^2 = 4 \left( \frac{\Delta F_{\text{vk}}}{F_{\text{vk}}} \right)^2 + \left( \frac{\Delta F_{\text{sk}}}{F_{\text{sk}}} \right)^2. \quad (\text{E.7.19})$$

The numerical values for the risk reduction factors are calculated using the values for  $F_{\text{sk}}$  in Table D.5-1 and those for  $F_{\text{vk}}$  in Table D.3-2, both in Attachment D. The aggregation of the contributions from the E1 and the E2 part of the E1E2 scenario is not carried out explicitly, because the E1 scenario is already included in the evaluation. The risk reduction factors are tabulated in Table E.7-2, ranging from a risk reduction factor of almost 6 for Level II treatments to risk reduction factors of 12 and 42 for Treatment Options 3 and 4, respectively.

### E.7.3 Post-Closure Public Radiation Risks From Drilling Operations

#### E.7.3.1 Basic Considerations

Whereas the direct public exposure from the drilling mud is negligible, the dried out pond may through wind erosion give rise to an inhalation hazard. As stated before, the superposition of exposures from two different drill sites is assumed to be linear. Another source of radiation exposure arises from the transport of the mobilized radioactive salt brine through the Culebra aquifer to a stock well, leading to a radioactive contamination of the beef produced on the surrounding land. Ingestion by man causes an internal exposure and a risk of cancer or genetic damage.

#### E.7.3.2 Inhalation Risks From Dried Up Ponds Of Drilling Mud

##### E.7.3.2.1 Public Inhalation Risk Due To Drilling In Scenario E1

The assumptions for this scenario are the same as those in Section E.7.2.1. After the drilling stops, the mud pond contains the total activity mobilized and brought to the surface in the E1 scenario. It is assumed to be eroded at a constant rate, leading to a constant time-averaged source term and activity concentrations in the air. Risk Component 43 then has two sub-components, and with the symbols

- $P_{11}^{(\kappa)}$  = Probability of a drill hole through the waste and into the Castile Formation,  
 $P_{13}$  = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,

- $\Phi_{431}^{(\kappa)}$  = Total activity brought to surface in Scenario E1 (Bq),  
 $\Phi_{432}^{(\kappa)}$  = Suspension and transport function from pond to receptors ( $m^{-3}$ ),  
 $\Phi_{433}^{(\kappa)}$  = Global dosimetry function for exposed persons ( $Sv\ m^3\ Bq^{-1}$ ),  
 $C_1$  = Constant parts of equations,  
 $a_1$  = Cancer risk coefficient ( $Sv^{-1}$ ), and  
 $R_{43p\kappa\lambda}$  = Public cancer risk by inhalation caused by an E1 drilling operation,

the inhalation pathway leads to a public cancer risk of an E1 drilling scenario of

$$R_{43p\kappa\lambda} = [P_{11}^{(\kappa)} P_{13}] \{ \Phi_{431}^{(\kappa)} \Phi_{432}^{(\kappa)} \} \Phi_{433}^{(\kappa)} a_1 . \quad (E.7.20)$$

With no factor outside the source term and the probability treatment option-dependent, only the footprint  $A_0^{(\kappa)}$  in  $P_{11}^{(\kappa)}$  [see Equation (E.7.3)] and  $\Phi_{431}^{(\kappa)}$  change with treatment options, because the suspension and transport function to the receptors is assumed to be independent. The risk can then be scaled as

$$R_{43p\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{431}^{(\kappa)} . \quad (E.7.21)$$

and the risk reduction factors are the same for the cancer and genetic risks,

$$p_{43p\kappa\lambda} = \frac{A_0^{(0)} \Phi_{431}^{(0)}}{A_0^{(\kappa)} \Phi_{431}^{(\kappa)}} = F_{vk} F_{sk} . \quad (E.7.22)$$

The standard errors of the reduction factors are given by

$$\left( \frac{\Delta p_{43p\kappa\lambda}}{p_{43p\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{vk}}{F_{vk}} \right)^2 + \left( \frac{\Delta F_{sk}}{F_{sk}} \right)^2 . \quad (E.7.23)$$

The numerical values of the reduction factors and thus also of their errors are the same as those given for  $p_{40p\kappa\lambda}$  in Section E.7.2.1 and Table E.7-1.

#### E.7.3.2.2 Public Inhalation Risk Due To Drilling In Scenario E2

This scenario is discussed in Section E.7.2.2 but also entails the suspension of the dried and eroded mud by wind. Using the same assumptions as in that section leads to a model for Risk Component 44 with two subcomponents. Defining the symbols

- $P_{12}^{(\kappa)}$  = Probability of drill hole into or through repository, no brine,  
 $\Phi_{441}^{(\kappa)}$  = Total activity brought to surface for Scenario E2 (Bq),

- $\Phi_{442}^{(\kappa)}$  = Suspension and transport function to receptor in Scenario E2 ( $m^{-3}$ ),  
 $\Phi_{443}$  = Global dosimetry function for public in Scenario E2 ( $Sv\ m^3\ Bq^{-1}$ ),  
 $C_1$  = Constant part of equations,  
 $a_1$  = Cancer risk coefficient ( $Sv^{-1}$ ), and  
 $R_{44p\kappa\lambda}$  = Cancer risk from direct irradiation in E2 drilling operation,

this risk component is

$$R_{44p\kappa\lambda} = [P_{12}^{(\kappa)}] \{ \Phi_{441}^{(\kappa)} \Phi_{442}^{(\kappa)} \} \Phi_{443} a_1 . \quad (E.7.24)$$

This expression has the same properties as Equation (E.7.10) in Section E.7.2.2 . Thus, the risk is again scaled according to

$$R_{44p\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{441}^{(\kappa)} . \quad (E.7.25)$$

Assuming again that the mobilized activity reduction factors  $F_{a\kappa}$  are the same as those in E2, the risk reduction factors are

$$\rho_{44p\kappa\lambda} = \frac{A_0^{(0)} \Phi_{441}^{(0)}}{A_0^{(\kappa)} \Phi_{441}^{(\kappa)}} = F_{v\kappa} F_{a\kappa} , \quad (E.7.26)$$

and, therefore, the same standard errors as those of  $\rho_{410\kappa\lambda}$  and thus  $\rho_{400\kappa\lambda}$ . Numerical values for these risk reduction factors have, therefore, already been given in Table E.7-1.

### E.7.3.2.3 Public Inhalation Risks Due To Drilling In Scenario E1E2

The assumptions about Scenario E1E2 are the same as those for the calculation of the risk reductions factors  $\rho_{420\kappa\lambda}$  in Section E.7.2.3. The first drilling leads to an E1 contribution to the public inhalation risk which is equal to the component  $R_{400\kappa\lambda}$  discussed in Section E.7.2.1 and thus leads to the risk reduction factors given in Table E.7-2. In addition, it means a second source of activity in the air from the E2 part of the scenario, and the addition of Risk Component 45. Using the symbols

- $P_{11}^{(\kappa)}$  = Probability of first drill hole into repository and into the Castile Formation,  
 $P_{13}$  = Probability of hitting a brine reservoir in the Castile Formation,  
 $P_{12}^{(\kappa)}$  = Probability of drill hole into or through repository,  
 $\Phi_{451}^{(\kappa)}$  = Time average of total activity mobilized and brought to surface in E2 part of scenario (Bq),  
 $\Phi_{452}^{(\kappa)}$  = Interaction function between the two holes,  
 $\Phi_{453}^{(\kappa)}$  = Suspension and transport function to receptor in E2 part of scenario ( $m^{-3}$ ) ,

- $\Phi_{454}^{(\kappa)}$  = Global exposure function for public in E2 scenario ( $\text{Sv m}^3 \text{Bq}^{-1}$ ),  
 $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{45\rho\kappa\lambda}$  = Cancer risk from inhalation in E2 part of E1E2 drilling operation,

the risk component for that part is

$$R_{45\rho\kappa\lambda} = [P_{11}^{(\kappa)} P_{13} P_{12}^{(\kappa)}] \{ \Phi_{451}^{(\kappa)} \Phi_{452}^{(\kappa)} \Phi_{453}^{(\kappa)} \} \Phi_{454}^{(\kappa)} a_1 . \quad (\text{E.7.27})$$

Using Equation (E.7.3) the risk can be scaled as

$$R_{45\rho\kappa\lambda} = C_1 (A_0^{(\kappa)})^2 \Phi_{451}^{(\kappa)} . \quad (\text{E.7.28})$$

As in Section E.7.2.3, this leads to a risk reduction ratio of

$$\rho_{45\rho\kappa\lambda} = \frac{\Phi_{451}^{(0)} (A_0^{(0)})^2}{\Phi_{451}^{(\kappa)} (A_0^{(\kappa)})^2} = F_{v\kappa}^2 F_{a\kappa} = \rho_{420\kappa\lambda} . \quad (\text{E.7.29})$$

with the same standard error as  $\rho_{420\kappa\lambda}$ . These values are thus the same as those in Section E.7.2.3 and are listed in Table E.7.2.

### E.7.3.3 Public Ingestion Risks Due To Drilling Operations

#### E.7.3.3.1 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water In Scenario E1

The assumptions for the E1 model are the same as before. Here, however, the pathway goes from the repository to an aquifer in the Culebra and from there to a stock well. This transport is assumed to be linear in the source term as are the subsequent transfer functions into beef and man. The activity concentrations in the water, in the beef, and, therefore, in the intake by man are assumed to be at an equilibrium value. This ingestion risk constitutes Risk Component 46 with two subcomponents for cancer and genetic risk. With the symbols

- $P_{11}^{(\kappa)}$  = Probability of a borehole through the repository and into the Castile Formation,  
 $P_{13}$  = Probability of hitting a brine reservoir in Castile Formation in area of WIPP,  
 $\Phi_{461}^{(\kappa)}$  = Long-term rate of activity mobilization and transport to the Culebra aquifer for Scenario E1 ( $\text{Bq s}^{-1}$ ),  
 $\Phi_{462}^{(\kappa)}$  = Transport function to stock well via Culebra ( $\text{s L}^{-1}$ ),  
 $\Phi_{463}^{(\kappa)}$  = Transfer-dosimetry function for water to beef to man ( $\text{Sv L Bq}^{-1}$ ),  
 $C_1$  = Constant parts of equations,

$a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),  
 $R_{48\rho\kappa\lambda}$  = Public cancer risk of an E1 drilling operation,

the expression for this component is

$$R_{48\rho\kappa\lambda} = [P_{11}^{(\kappa)} P_{13}] \{ \Phi_{481}^{(\kappa)} \Phi_{482}^{(\kappa)} \} \Phi_{483}^{(\kappa)} a_1. \quad (\text{E.7.30})$$

With only the product of the long-term rate of activity mobilization and the footprint in  $P_{11}^{(\kappa)}$  changing with treatment options, the risk has the scaling property

$$R_{48\rho\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{481}^{(\kappa)}, \quad (\text{E.7.31})$$

the risk reduction factors are

$$\rho_{48\rho\kappa\lambda} = \frac{A_0^{(0)} \Phi_{481}^{(0)}}{A_0^{(\kappa)} \Phi_{481}^{(\kappa)}} = F_{v\kappa} F_{b\kappa}, \quad (\text{E.7.32})$$

where

$$F_{b\kappa} = \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\kappa)}}, \quad (\text{E.7.33})$$

with values given in Table D.5-2 of Attachment D and with the assumption that the long-term rate of activity mobilization achieves equilibrium concentrations at the stock well by the time of the sampling. The errors of the model calculation of  $F_{b\kappa}$  are large, and lognormally distributed quantities are involved. The geometric standard deviations (see Section C.1.5) are

$$\sigma_g(\rho_{48\rho\kappa\lambda}) = \sigma_g(F_{b\kappa}), \quad (\text{E.7.34})$$

calculated in a simplified version made possible by the large difference in the geometrical standard deviations of the two factors. Numerical values for the risk reduction factors are listed in Table E.7-3. The means range from 10,000 to 100,000 with geometric standard errors of factors of 20 up and down from these values. The range of values, however, leads to risk reductions exclusively, applied to extremely low baseline risks.

**TABLE E.7-3**  
**RISK REDUCTION FACTORS FOR**  
**PUBLIC INGESTION IN SCENARIO E1**

QUANTITY	VALUE (GSD) *	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{46 p 1 \lambda}$	$1.14 \cdot 10^4$ (20)	$P_{50 p \kappa \lambda} = P_{46 p \kappa \lambda}$
$P_{46 p 2 \lambda}$	$1.14 \cdot 10^4$ (20)	
$P_{46 p 3 \lambda}$	$2.12 \cdot 10^4$ (20)	
$P_{46 p 4 \lambda}$	$9.95 \cdot 10^4$ (20)	
<b>Annual Baseline Risks:</b>		
$R_{46 p 0 0}$	$2.2 \cdot 10^{-13}$	FSEIS (DOE, 1990a), Table 5.70
$R_{50 p 0 0}$	--	Not available in FSEIS

\* GSD = Geometric standard deviation of a lognormal distribution.

### E.7.3.3.2 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water In Scenario E2

Risk Component 47 with two subcomponents is calculated using the same assumptions for this scenario as before. Using the symbols

- $P_{12}^{(k)}$  = Probability of drill hole into or through repository, no brine,
- $\Phi_{471}^{(k)}$  = Long-term rate of activity mobilization and transport to the Culebra ( $\text{Bq s}^{-1}$ ),
- $\Phi_{472}^{(k)}$  = Transport function to stock well via Culebra in Scenario E2 ( $\text{L}^{-1} \text{s}$ ),
- $\Phi_{473}^{(k)}$  = Transfer-dosimetry function for contaminated beef ( $\text{Sv Bq}^{-1} \text{L}$ ),
- $C_1$  = Constant parts of equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ), and
- $R_{47pk\lambda}$  = Public risk due to an E2 drilling scenario,

the expression for the public ingestion risk is

$$R_{47pk\lambda} = [P_{12}^{(k)}] \{ \Phi_{471}^{(k)} \Phi_{472}^{(k)} \} \Phi_{473}^{(k)} a_1 . \quad (\text{E.7.35})$$

With the constant parts eliminated, the scaling of risks is given by

$$R_{47pk\lambda} = C_1 A_0^{(k)} \Phi_{471}^{(k)} . \quad (\text{E.7.36})$$

and the risk reduction factors are

$$p_{47pk\lambda} = F_{vk} F_{ck} , \quad (\text{E.7.37})$$

with the definition of the factor  $F_{ck}$  as

$$F_{ck} \equiv \frac{\Phi_{471}^{(0)}}{\Phi_{471}^{(k)}} . \quad (\text{E.7.38})$$

$F_{ck}$  is the reduction factor for the activity mobilized to be transported to the stock well. Numerical values are listed in Table D.5-2 in Attachment D. The errors are calculated under the assumption that the standard errors of  $F_{ck}$  are much larger than those of all other contributions. Thus the geometric standard deviations are

$$\sigma_g (p_{47pk\lambda}) = \sigma_g (F_{ck}) . \quad (\text{E.7.39})$$

Numerical values for the risk reduction factors are given in Table E.7-4, grouped closely to 1 for Treatments 1 and 2, with geometrical standard deviations corresponding to a factor of 3 up and down for Level II treatments, rising to a factor of 1.8 for Treatment 3 and 64 for Treatment 4. This

**TABLE E.7-4**  
**RISK REDUCTION FACTORS FOR**  
**PUBLIC INGESTION IN SCENARIO E2**

QUANTITY	VALUE	(GSD) *	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>			
$P_{47 p 1 \lambda}$	1.2	(3)	$P_{51 p \kappa \lambda} = P_{47 p \kappa \lambda}$
$P_{47 p 2 \lambda}$	1.3	(3)	
$P_{47 p 3 \lambda}$	1.8	(5)	
$P_{47 p 4 \lambda}$	64	(50)	
<b>Annual Baseline Risks:</b>			
$R_{47 p 0 0}$	$5.9 \cdot 10^{-11}$		FSEIS (DOE 1990a), Table 5.70
$R_{51 p 0 0}$	--		Not available in FSEIS

\* GSD = Geometric standard deviation of a lognormal distribution.

may result in either considerable risk reductions. These reduction factors are applied to an exceedingly small baseline risk.

### E.7.3.3.3 Public Ingestion Risks Due To Beef Contaminated By Stock Well Water in Scenario E1E2

Using the same model assumptions as in Section E.7.2.3, the ingestion of contaminated beef leads to a risk contribution which is the same as that of Scenario E1, so that the risk reduction factors, errors, and numerical values for the E1 part of the operation apply [Equations (E.7.32) and (E.7.34)]. In addition, there is the Risk Component 48 for the E2 part of Scenario E1E2. With the symbols

- $P_{11}^{(\kappa)}$  = Probability of first drill hole into repository and into Castile Formation,
- $P_{13}$  = Probability of hitting a brine reservoir in the Castile Formation,
- $P_{12}^{(\kappa)}$  = Probability of drill hole into or through repository,
- $\Phi_{481}^{(\kappa)}$  = Long-term rate of activity mobilization and transport to the Culebra for E2 part of Scenario E1E2 ( $\text{Bq s}^{-1}$ ),
- $\Phi_{482}^{(\kappa)}$  = Interaction function between the two drill holes,
- $\Phi_{483}^{(\kappa)}$  = Transport function to surface via Culebra in E2 part of Scenario E1E2 ( $\text{s L}^{-1}$ ),
- $\Phi_{484}^{(\kappa)}$  = Transfer-dosimetry function for residents eating beef ( $\text{Sv Bq}^{-1} \text{L}$ ),
- $C_1$  = Constant parts of all equations,
- $a_1$  = Cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $R_{48p\kappa\lambda}$  = Public cancer risk due to an E1E2 scenario,

this risk component is

$$R_{48p\kappa\lambda} = [P_{11}^{(\kappa)} P_{13} P_{12}^{(\kappa)}] \{ \Phi_{481}^{(\kappa)} \Phi_{482}^{(\kappa)} \Phi_{483}^{(\kappa)} \} \Phi_{484}^{(\kappa)} a_1 . \quad (\text{E.7.40})$$

As in Section E.7.2.3, the component is proportional to the product of the square of the footprint and the rate of activity mobilization

$$F_{d\kappa} \equiv \frac{\Phi_{481}^{(0)} \Phi_{482}^{(0)} \Phi_{484}^{(0)}}{\Phi_{481}^{(\kappa)} \Phi_{482}^{(\kappa)} \Phi_{484}^{(\kappa)}} . \quad (\text{E.7.41})$$

The risk reduction is, therefore,

$$R_{48p\kappa\lambda} = F_{d\kappa} \frac{(A_0^{(0)})^2}{(A_0^{(\kappa)})^2} = F_{d\kappa} F_{v\kappa}^2 . \quad (\text{E.7.42})$$

Under the assumption that the last three factors in the numerator and denominator of Equation (E.7.41) do not depend on the waste treatment and, therefore, cancel, the ratio of activity mobilization factors reduces to

$$F_{dk} \equiv \frac{\Phi_{481}^{(0)}}{\Phi_{481}^{(\kappa)}} \quad (\text{E.7.43})$$

The ratio of activities  $F_{dk}$ , mobilized for each waste treatment are listed in Table D-5.2 of Attachment D. Despite the factor  $F_{v\kappa}^2$ , the geometrical standard deviations remain at

$$\sigma_g(\rho_{48p\kappa\lambda}) = \sigma_g(F_{dk}) \quad (\text{E.7.44})$$

because the uncertainties in  $F_{v\kappa}$  are much smaller than those of  $F_{dk}$ . The numerical values for the risk reduction factors given in Table E.7-5 show considerable variation from about one million to 10 billion. The geometric standard deviations range from 40 to 80, adding one to two orders of magnitude to the range of risk reduction factors. Note that these factors are applied to a very small baseline risk.

#### E.7.4 Post-Closure Public Risks Due To Chemical Agents

##### E.7.4.1 Basic Considerations

The FSEIS (DOE, 1990a) calculates one post-closure chemical risk. It is due to the presence of lead, and it is assumed for the risk calculations that the total amount of lead in the repository is independent of the waste treatment, except in Treatment Option 4 in which metals are largely decontaminated and removed. The lead concentration in the repository is then given by

$$d_1^{(\kappa)} = \frac{M_0}{A_0^{(\kappa)} h_0} \quad (\text{E.7.45})$$

for  $1 \leq \kappa \leq 3$ , where the quantities

- $d_1^{(\kappa)}$  = Lead concentration in repository ( $\text{kg m}^{-3}$ ),
- $M_0$  = Total mass of lead in repository (kg),
- $A_0^{(\kappa)}$  = Footprint of wastes in repository ( $\text{m}^2$ ),
- $h_0$  = Height of wastes in repository panel (m).

For Treatment Option 4 the melting process leads to a reduction in the total lead mass by a factor  $f_{\text{red}}$ . This factor is assumed to be one here. In the groundwater, lead is assumed to be attached to colloidal matter and to move with the water. In combined human intrusion scenarios, the contaminations in groundwater can arise from different sources. It is again assumed here that

**TABLE E.7-5**  
**RISK REDUCTION FACTORS FOR**  
**PUBLIC INGESTION IN AN E1E2 SCENARIO**

QUANTITY	VALUE	(GSD) *	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>			
$P_{48 p 1 \lambda}$	$8.3 \cdot 10^5$	(80)	$P_{52 p \kappa \lambda} = P_{48 p \kappa \lambda}$
$P_{48 p 2 \lambda}$	$1.2 \cdot 10^6$	(60)	
$P_{48 p 3 \lambda}$	$9.5 \cdot 10^6$	(80)	
$P_{48 p 4 \lambda}$	$1.3 \cdot 10^{10}$	(40)	
<b>Annual Baseline Risks:</b>			
$P_{48 p 0 0}$	$7.8 \cdot 10^{-6}$		FSEIS (DOE, 1990a), Table 5.70
$P_{52 p 0 0}$	--		Not available in FSEIS

\* GSD = Geometric standard deviation of a lognormal distribution.

these effects superpose linearly, implying in particular that the salt content in the Culebra does not saturate.

#### E.7.4.2 Ingestion Risk Caused By Lead In Contaminated Beef

##### E.7.4.2.1 Risks Due To Beef Contaminated By Stock Well Water In Scenario E1

The assumptions for the E1 model are the same as before, and the transport is assumed to be linear in the source term as are the subsequent transfer functions into beef and man. The lead concentrations in the water, in the beef, and, therefore, in the intake by man are assumed to be at an equilibrium value. This ingestion risk constitutes Risk Component 50. With the symbols

- $P_{11}^{(\kappa)}$  = Probability of a borehole through the repository into the Castile Formation,
- $P_{13}$  = Probability of hitting a brine reservoir in the Castile Formation,
- $\Phi_{501}^{(\kappa)}$  = Long-term lead mobilization and transport rate to the Culebra ( $\text{mg s}^{-1}$ ),
- $\Phi_{502}^{(\kappa)}$  = Transport function to stock well via Culebra ( $\text{s L}^{-1}$ ),
- $\Phi_{503}$  = Transfer/daily-intake function for contaminated beef ( $\text{L day}^{-1}$ ),
- $N_{p4}$  = Number of persons exposed by ingestion,
- $L_{pb}^{(\text{ref})}$  = Reference level for lead ( $\text{mg Pb kg}^{-1} \text{day}^{-1}$ ),
- $M_1$  = Mass of reference man (kg),
- $f_1$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),
- $C_1$  = Constant parts of equations,
- $r_0$  = Risk associated with reference level,
- $R_{50p\kappa\lambda}$  = Morbidity risk due to lead ingestion ( $\text{yr}^{-1}$ ),

the lead ingestion risk from an E1 event is

$$R_{50p\kappa\lambda} = [P_{11}^{(\kappa)} P_{13}] \{ \Phi_{501}^{(\kappa)} \Phi_{502}^{(\kappa)} \} \Phi_{503} \frac{N_{p4} r_0 f_1}{M_1 L_{pb}^{(\text{ref})}} \quad (\text{E.7.46})$$

With only the product of the long-term rate of lead mobilization and the footprint in  $P_{11}^{(\kappa)}$  changing with treatment options, the risk is found to scale according to

$$R_{50p\kappa\lambda} = C_1 A_0^{(\kappa)} \Phi_{501}^{(\kappa)} \quad (\text{E.7.47})$$

The risk reduction factors for this scenario are

$$P_{50p\kappa\lambda} = \frac{A_0^{(0)} \Phi_{501}^{(0)}}{A_0^{(\kappa)} \Phi_{501}^{(\kappa)}} = F_{v\kappa} F_{Pbb\kappa} \quad (\text{E.7.48})$$

with the definition,

$$F_{Pbb\kappa} \equiv \frac{\Phi_{501}^{(0)}}{\Phi_{501}^{(\kappa)}} \quad (E.7.49)$$

for the reduction factor in the long-term rate of lead mobilization. The geometrical standard deviations of the risk reduction factors are the determining contribution,

$$\sigma_g(\rho_{50p\kappa\lambda}) = \sigma_g(F_{Pbb\kappa\lambda}) \quad (E.7.50)$$

If it is assumed that the dissolution of radioisotopes and lead is impeded by treatment in the same way, then  $F_{Pbb\kappa} = F_{b\kappa}$  and the last two equations are the same as those calculated for Scenario E1 as  $\rho_{46p\kappa\lambda}$ . The numerical values for the risk reduction factors are given in Table E.7-3.

#### E.7.4.2.2 Risks Due To Beef Contaminated By Stock Well Water In Scenario E2

Risk Component 51 is calculated using the same assumptions for this scenario as before. With the symbols

- $P_{12}^{(\kappa)}$  = Probability of a borehole into or through the repository, no brine,
- $\Phi_{511}^{(\kappa)}$  = Long-term lead mobilization and transport rate to the Culebra ( $\text{mg s}^{-1}$ ),
- $\Phi_{512}^{(\kappa)}$  = Transport function to stock well via Culebra ( $\text{s L}^{-1}$ ),
- $\Phi_{513}^{(\kappa)}$  = Transfer/daily-intake function for contaminated beef ( $\text{L day}^{-1}$ ),
- $N_{p4}$  = Number of persons exposed by ingestion,
- $L_{Pb}^{(ref)}$  = Reference level for lead ( $\text{mg Pb kg}^{-1} \text{ day}^{-1}$ ),
- $M_1$  = Mass of reference man (kg),
- $r_o$  = Risk associated with reference level,
- $f_t$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),
- $C_1$  = Constant parts of equations,
- $R_{51p\kappa\lambda}$  = Morbidity risk due to lead ingestion ( $\text{yr}^{-1}$ ),

the lead ingestion risk from an E2 event is

$$R_{51p\kappa\lambda} = [P_{12}^{(\kappa)}] \{ \Phi_{511}^{(\kappa)} \Phi_{512}^{(\kappa)} \} \Phi_{513}^{(\kappa)} \frac{N_{p4} r_o f_t}{M_1 L_{Pb}^{(ref)}} \quad (E.7.51)$$

With only the product of the long-term rate of lead mobilization and the footprint in  $P_1^{(k)}$  changing with treatment options, the risk scales as

$$R_{51\rho\kappa\lambda} = C_1 A_0^{(k)} \Phi_{511}^{(k)}, \quad (\text{E.7.52})$$

and the risk reduction factors are

$$\rho_{51\rho\kappa\lambda} = \frac{A_0^{(0)} \Phi_{511}^{(0)}}{A_0^{(k)} \Phi_{511}^{(k)}} = F_{v\kappa} F_{pbc\kappa} = F_{v\kappa} F_{c\kappa}, \quad (\text{E.7.53})$$

where

$$F_{pbc\kappa} = \frac{\Phi_{511}^{(0)}}{\Phi_{511}^{(k)}}. \quad (\text{E.7.54})$$

This assumes just as in the case of radioactivity that while the mobilization rates for lead and radioisotopes may differ, the reduction ratios due to treatment are the same. The geometrical standard deviations of the risk reduction factors are again assumed to be

$$\sigma_g(\rho_{51\rho\kappa\lambda}) = \sigma_g(F_{pbc\kappa}) = \sigma_g(F_{c\kappa}). \quad (\text{E.7.55})$$

This is the same result as that for the component  $\rho_{47\rho\kappa\lambda}$  and the values are again those of Table E.7-4.

#### E.7.4.2.3 Risks Due To Beef Contaminated By Stock Well Water In Scenario E1E2

The use of the same model assumptions as in Section E.7.2.3 leads to a risk contribution which is the same as that of the E1 scenario, so that the risk reduction factors, errors, and numerical values for the E1 part of the operation apply, as described by Equations (E.7.48) and (E.7.50). In addition, there is Risk Component 52 for the E2 part of the drilling scenario E1E2. With the symbols

- $P_{11}^{(k)}$  = Probability of first drill hole into repository and into the Castile Formation,
- $P_{13}^{(k)}$  = Probability of drilling into a brine reservoir in the Castile Formation,
- $P_{12}^{(k)}$  = Probability of drill hole into or through repository,
- $\Phi_{521}^{(k)}$  = Long-term rate of lead mobilization and transport to the Culebra ( $\text{mg s}^{-1}$ ),
- $\Phi_{522}^{(k)}$  = Interaction term between drills holes,
- $\Phi_{523}^{(k)}$  = Transport function to stock well via Culebra ( $\text{s L}^{-1}$ ),
- $\Phi_{524}^{(k)}$  = Transfer/daily-intake function for contaminated beef ( $\text{L day}^{-1}$ ),
- $N_{p4}$  = Number of persons exposed by ingestion,
- $L_{Pb}^{(\text{ref})}$  = Reference level for lead ( $\text{mg Pb kg}^{-1} \text{ day}^{-1}$ ),
- $M_1$  = Mass of reference man (kg),

- $f_1$  = Exposure time correction factor for one year ( $\text{yr}^{-1}$ ),  
 $C_1$  = Constant parts of equations,  
 $r_o$  = Risk associated with reference level,  
 $R_{52pk\lambda}$  = Morbidity risk due to lead ingestion ( $\text{yr}^{-1}$ ),

this risk component is given by

$$R_{52pk\lambda} = [P_{11}^{(k)} P_{13} P_{12}^{(k)}] \{ \Phi_{521}^{(k)} \Phi_{522}^{(k)} \Phi_{523}^{(k)} \} \Phi_{524}^{(k)} \frac{N_{p4} r_o f_1}{M_1 L_{Pb}^{(ref)}}. \quad (\text{E.7.56})$$

As in Section E.7.2.3, the component is proportional to the product of the square of the footprint and the rate of lead mobilization, assuming all functions  $\Phi_{jv}^{(k)}$  independent of treatment except  $\Phi_{521}^{(k)}$ . The risk reduction is, therefore,

$$\rho_{52pk\lambda} = \frac{\Phi_{521}^{(0)} (A_0^{(0)})^2}{\Phi_{521}^{(k)} (A_0^{(k)})^2} = F_{Pbdk} F_{vk}^2, \quad (\text{E.7.57})$$

with the definition

$$F_{Pbdk} \equiv \frac{\Phi_{521}^{(0)}}{\Phi_{521}^{(k)}}. \quad (\text{E.7.58})$$

With the assumption that the ratio of lead mobilization  $F_{Pbdk}$  is the same as that for the radioactivity,

$$\rho_{52pk\lambda} = F_{vk}^2 F_{dk} = \rho_{48pk\lambda}. \quad (\text{E.7.59})$$

The geometrical standard deviation is again

$$\sigma_g(\rho_{52pk\lambda}) = \sigma_g(F_{dk}). \quad (\text{E.7.60})$$

The numerical values have already been given in Table E.7-5.

## ATTACHMENT F

### RISKS OF TREATMENT OPTIONS

#### F.1 BASIC CONSIDERATIONS

##### F.1.1 Scope for Assessment of Treatment Risks

Scope and limitations of the model for the Treatment Facility have already been described in Appendix I and in more detail in Attachment D. The description here will be limited to aspects which are important to the approach to risk assessment.

The simplifying assumptions of the modular form without taking credit for economies of scale for larger units makes most evaluations location-independent. Each module is assumed to contain all two, four, or six devices, or multiples thereof, according to the treatment level chosen. There are seven modules with the appropriate capabilities that are moved along the path from the WIPP to the originators of the waste according to the location scenario selected.

The risks chosen as baseline risks are those of the assay and certification process in the WHB in the currently proposed sequence of activities. An exception is the general occupational risks for fatalities and injuries. These are not considered in the FSEIS but play a more important role in a risk comparison. For these risk components, the occupational risks of the assay and certification process are calculated and used as baseline. Apart from these general accidents, no accidents particular to the treatment of radioactive waste are considered, in order to limit the scope of this study. Only routine exposures to radioactivity and to volatile organic chemicals (VOCs) are taken into account.

All treatment devices are assumed to be operating in airtight enclosures with access through air locks until the treated wastes are enclosed in drums again. Shielding is used to lower penetrating radiation to levels compatible with the ALARA concept and DOE's health and safety goals.

In both routine and maintenance operations, internal exposures to radioisotopes occur. In this assessment, only inhalation exposures are evaluated. Ingestion, wound, and skin exposures are not considered because in routine and maintenance scenarios they tend to be much lower than inhalation exposures and the corresponding doses.

## **F.1.2 Treatment of the Engineered Waste Forms**

### **F.1.2.1 Treatment Options 1 and 2**

In Treatment Option 1, after the assay and certify operation, the solidified sludges are left as they are. Without sorting, combustibles, metals, glasses, and the drum are shredded and then cemented. This Level II treatment is the least work-intensive treatment option considered here. As discussed in Attachment D, this process leads to a decrease of void space and an increase in the weight of the drum. In Treatment Option 2, the only change is that the sludges are cemented as well.

### **F.1.2.2 Treatment Option 3**

Treatment Option 3 is a Level III treatment. After assay and certification, the sludges are cemented and the rest of the waste is sorted. Shredding is done separately for combustibles and for metals and glasses. Combustibles are then incinerated and the ashes transported to the cementing area for inclusion in the process. Metals and glass, on the other hand, are cemented directly.

### **F.1.2.3 Treatment Option 4**

This is the most ambitious Level III treatment considered here. After the assay and certify procedure, the sludges are vitrified, possibly in a microwave oven. Separate shredding is used for combustibles and for metals and glasses. Combustibles are incinerated and their ashes vitrified. Shredded metals and glasses are melted with frit, taking advantage of the disproportionation of radioisotopes between slag and metal. The metals are disposed of as low level waste and only the slag is emplaced in the WIPP.

## **F.2 GENERAL OCCUPATIONAL ACCIDENTS**

Normal occupational accidents are not addressed in the FSEIS. Here they are needed because they increase as the complexity of the treatment increases. Directly relevant incidence data are not available, but data for similar industries were used in Attachment D, Section D.4.1, to estimate the relevant risk coefficients.

### **F.2.1 Industrywide Occupational Accidents**

#### **F.2.1.1 Fatal Occupational Accidents**

Fatal occupational accidents are addressed here, excluding forklift accidents with fatal outcome. Those are evaluated separately. This class of accidents leads to Risk Component 53. Using the symbols:

$N_{01}^{(k)}$	=	Number of persons in WHB and TF,
$P_{14}$	=	Annual occupational fatality rate per worker in accidents not involving forklifts ( $\text{yr}^{-1}$ ),
$C_1$	=	Constant parts of equations,
$P_{of}$	=	Annual probability rate for occupational accidents with fatal outcome,
$f_{531}$	=	Fraction of forklift accidents in all occupational accidents, and
$R_{530k\lambda}$	=	Risk of occupational fatality per year ( $\text{yr}^{-1}$ ),

the general expression for this risk is given by

$$R_{530k\lambda} = N_{01}^{(k)} P_{14} . \quad (\text{F.2.1})$$

The data given in Attachment D, Section D.4.1, gives the probability rate  $P_{14}$  in terms of the annual probability rate  $P_{of}$

$$P_{14} = P_{of} (1 - f_{531}) , \quad (\text{F.2.2})$$

where  $f_{531} = 10^{-2}$ . Thus the baseline risk is  $R_{53000} = (1.6 \pm 0.4) \cdot 10^{-3}$ , and the risk is

$$R_{530k\lambda} = N_{01}^{(k)} P_{of} (1 - f_{531}) . \quad (\text{F.2.3})$$

The risk equation has the scaling property

$$R_{530k\lambda} = C_1 N_{01}^{(k)} . \quad (\text{F.2.4})$$

The risk reduction ratios are, therefore

$$P_{530k\lambda} = \frac{N_{01}^{(0)}}{N_{01}^{(k)}} = F_{mk} , \quad (\text{F.2.5})$$

with the standard errors of

$$\Delta P_{530k\lambda} = \Delta F_{mk} . \quad (\text{F.2.6})$$

The numerical values are given in Table F.2-1 with values for the factor  $F_{mk}$  and its errors taken from Table D.3-2. The risk reduction factors decrease with more treatment, indicating an increase in risk due to an increasing crew in the Treatment Facility. The baseline risks are derived from the risk coefficients in D.4.1 for a crew of 12.

TABLE F.2-1

**RISK REDUCTION FACTORS FOR GENERAL OCCUPATIONAL  
ACCIDENT FATALITIES AND INJURIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{5301\lambda}$	$0.276 \pm 0.016$	$P_{540\kappa\lambda} = P_{530\kappa\lambda}$
$P_{5302\lambda}$	$0.260 \pm 0.015$	
$P_{5303\lambda}$	$0.170 \pm 0.010$	
$P_{5304\lambda}$	$0.076 \pm 0.004$	
<b>Annual Baseline Risk:</b>		
$R_{53000}$	$(1.6 \pm 0.4) \cdot 10^{-3}$	U.S. Dept. of Labor, Bulletin 2366, 1990
$R_{54000}$	$0.70 \pm 0.03$	

### F.2.1.2 Nonfatal Injuries

The model for general occupational injuries in Attachment D, Section D.4.1, derives an estimate for nonfatal accidents with workdays lost. One percent of those are the forklift accidents not considered in this section. These accidents form Risk Component 54. Using the symbols

- $N_{01}^{(k)}$  = Number of persons in WHB and TF,
- $P_{15}$  = Annual occupational injury rate per worker in accidents not involving forklifts ( $\text{yr}^{-1}$ ),
- $C_1$  = Constant parts of equations,
- $P_{01}$  = Annual probability of general occupational injury,
- $f_{541}$  = Fraction of injuries caused by forklift in all occupations, and
- $R_{540k\lambda}$  = Risk of occupational injuries per year of operation ( $\text{yr}^{-1}$ ),

the general risk expression is for every year of operation is

$$R_{540k\lambda} = N_{01}^{(k)} P_{15} . \quad (\text{F.2.7})$$

In Section D.4.1, Attachment D, the value for  $P_{01}$  is given. It is related to  $P_{15}$  by

$$P_{15} = P_{01} (1 - f_{541}) , \quad (\text{F.2.8})$$

where  $f_{541} = 0.01$ . For a crew of 12, the baseline risk is  $R_{54000} = 0.70 \pm 0.03$ . Thus the risk can be written as

$$R_{540k\lambda} = N_{01}^{(k)} P_{01} (1 - f_{541}) , \quad (\text{F.2.9})$$

and hence the scaling property of this risk component depends only on the numbers of persons handling the waste, not including forklift operations,

$$R_{540k\lambda} = C_1 N_{01}^{(k)} . \quad (\text{F.2.10})$$

The risk reduction ratios are again

$$\rho_{540k\lambda} = \frac{N_{01}^{(o)}}{N_{01}^{(k)}} = F_{mk} , \quad (\text{F.2.11})$$

which is the same as for the fatalities with the same standard errors

$$\Delta \rho_{540k\lambda} = \Delta F_{mk} . \quad (\text{F.2.12})$$

The values for both risk reduction factors are given in Table F.2-1.

**F.2.2 Forklift Accidents****F.2.2.1 Fatal Forklift Accidents**

This scenario is a subset of the occupational accidents considered in Section F.2.1. However, it is an important component and will be considered separately. It is assumed that the number of forklift accidents is independent of drum weight, although accidents involving heavier vehicles may lead to increased severity of consequences. Fatal forklift accidents form Risk Component 55. Using the symbols

- $n_r^{(k)}$  = Number of drums handled per year ( $\text{yr}^{-1}$ ),
- $n_f^{(k)}$  = Number of forklift operations per drum handled,
- $P_{of}$  = General annual occupational fatality rate,
- $C_1$  = Constant parts of equations,
- $f_{531}$  = Fraction of fatal forklift accidents in all fatal occupational accidents,
- $\Phi_{551}$  = Conversion function to baseline risk per forklift operation,
- $P_{16}$  = Probability of a fatal accident per forklift operation, and
- $R_{550k\lambda}$  = Risk of a fatal forklift accident per year of operation ( $\text{yr}^{-1}$ ),

the risk of a fatal forklift accident per year of operation can be stated as

$$R_{550k\lambda} = n_r^{(k)} n_f^{(k)} P_{16} . \quad (\text{F.2.13})$$

The probability of a forklift fatality per forklift operation  $P_{16}$  derives from the total probability rate of occupational fatalities by the expression

$$P_{16} = P_{of} f_{531} \Phi_{551} . \quad (\text{F.2.14})$$

Thus the risk can be rewritten as

$$R_{550k\lambda} = n_r^{(k)} n_f^{(k)} P_{of} f_{531} \Phi_{551} . \quad (\text{F.2.15})$$

and the baseline risk is given by 10 percent of the total occupational fatalities according to Section D.4.1. The baseline risk is thus  $R_{55000} = 0.00016 \pm 0.00006$ .

The scaling property of Risk Component 55 is derived from the fact that only the product of the number of drums handled per year and the number of forklift operations per drum handled is treatment dependent,

$$R_{550k\lambda} = C_1 n_r^{(k)} n_f^{(k)} . \quad (\text{F.2.16})$$

The risk reduction ratios are thus

$$P_{550\kappa\lambda} = \frac{n_r^{(0)} n_f^{(0)}}{n_r^{(\kappa)} n_f^{(\kappa)}} = F_{v\kappa} F_{f\kappa}, \quad (\text{F.2.17})$$

with standard errors

$$\left( \frac{\Delta P_{550\kappa\lambda}}{P_{550\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{v\kappa}}{F_{v\kappa}} \right)^2 + \left( \frac{\Delta F_{f\kappa}}{F_{f\kappa}} \right)^2. \quad (\text{F.2.18})$$

The risk reduction factors for the forklift fatalities and the standard errors are given in Table F.2-2. The risk reduction factors correspond to increases in risk that vary from about 4 to about 14. The relative errors lie near 5 percent.

#### F.2.2.2 Nonfatal Forklift Injuries

This component is again a subset of occupational injuries. It is important because 1 percent of the industrial accidents cause 10 percent of the workdays lost. Again, it is assumed that the frequency of forklift accidents does not depend on the drum weight. This is achieved by utilizing forklifts appropriate to the weight. These accidents comprise Risk Component 56. Using the symbols

- $n_r^{(\kappa)}$  = Number of drums handled per year ( $\text{yr}^{-1}$ ),
- $n_f^{(\kappa)}$  = Number of forklift operations per drum handled,
- $P_{01}$  = General annual occupational injury rate,
- $f_{541}$  = Fraction of all occupational injuries caused in forklift accidents,
- $\Phi_{561}$  = Conversion function to baseline risk per forklift operation,
- $C_1$  = Constant parts of the equations,
- $P_{17}$  = Probability of an injury per forklift operation, and
- $R_{560\kappa\lambda}$  = Risk of a forklift injury per year of operation ( $\text{yr}^{-1}$ ),

the risk of nonfatal forklift injury per year of operation can be stated as

$$R_{560\kappa\lambda} = n_r^{(\kappa)} n_f^{(\kappa)} P_{17}. \quad (\text{F.2.19})$$

Again, there is a relationship between probabilities analogous to those in the previous sections,

$$P_{17} = P_{01} f_{541} \Phi_{561}. \quad (\text{F.2.20})$$

TABLE F.2-2

**RISK REDUCTION FACTORS FOR FORKLIFT ACCIDENT  
FATALITIES AND INJURIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{5501\lambda}$	$0.276 \pm 0.016$	$P_{580\lambda} = P_{550\lambda}$
$P_{5502\lambda}$	$0.260 \pm 0.015$	
$P_{5503\lambda}$	$0.170 \pm 0.010$	
$P_{5504\lambda}$	$0.076 \pm 0.004$	
<b>Annual Baseline Risk:</b>		
$R_{55000}$	$(1.6 \pm 0.6) \cdot 10^{-4}$	U.S. Dept. of Labor, Bulletin 2257, 1986
$R_{58000}$	$0.070 \pm 0.003$	

The risk of a nonfatal forklift injury is then

$$R_{560\kappa\lambda} = n_r^{(\kappa)} n_f^{(\kappa)} P_{of} f_{541} \Phi_{561} \quad (F.2.21)$$

and the baseline risk is one tenth of the general injury risk  $R_{56000} = 0.070 \pm 0.003$ . Thus, as in the previous scenario, the scaling property of Risk Component 56 is dependent only on the product of the number of drums handled per year and the number of forklift operations per drum handled

$$R_{560\kappa\lambda} = C_1 n_r^{(\kappa)} n_f^{(\kappa)} \quad (F.2.22)$$

The risk reduction ratios are the same as those for  $p_{550\kappa\lambda}$  with the same standard errors listed in Table F.2-2.

### F.3 RISK OF RADIATION EXPOSURES

#### F.3.1 External Exposures

External exposures are the result of irradiation by penetrating radiations, both gammas and neutrons. For routine operations, shielding is provided and for maintenance operations little or only partial shielding is available. Because waste handling facilities are at large distances from the public, public exposures are much smaller than the background levels and can, therefore, be ignored.

##### F.3.1.1 Routine Operations: External Exposure

External exposure of the work crew depends on the shielding, which is dictated by health and safety concerns as well as the ALARA concept. It is also dependent on the type of waste and on the time-motion parameters and the time spent at each particular choice. This leads to Risk Component 57 with two subcomponents, cancer and genetic. With the symbols

- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_r^{(\kappa)}$  = Number of drums handled annually ( $\text{yr}^{-1}$ ),
- $\eta_w$  = Fraction of waste in form w.
- $N_{06}^{(v)}$  = Number of persons needed for treatment v,
- $\Phi_{571}^{(wv)}$  = Shielding-geometry function of facility v to treat waste w,
- $\Phi_{572}^{(wv)}$  = Dosimetry function of average exposed person ( $\text{Sv s}^{-1} \text{Bq}^{-1}$ ),
- $t_{57}^{(v)}$  = Exposure time for treatment v of one drum of waste form w (s),
- $a_1$  = Lifetime cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $C_1$  = Constant parts of equation, and
- $R_{570\kappa\lambda}^{(wv)}$  = Occupational risk of cancer due to treatment v of waste form w in alternative  $\kappa$  per year of operation ( $\text{yr}^{-1}$ ),

the general occupational risk equation used is

$$R_{570\kappa\lambda}^{(wv)} = \{q_2^{(\kappa)} n_r^{(\kappa)} \eta_w\} N_{08}^{(v)} \Phi_{571}^{(wv)} \Phi_{572}^{(wv)} t_{57}^{(v)} a_1. \quad (\text{F.3.1})$$

The dependence on alternative  $\kappa$  is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the variability of the first two factors, and the assumption that operational health and safety standards will provide at least the same level of shielding protection at every plant. The second condition leads to the requirement that for the drum being processed in different devices  $v$  the residual radiation level outside the containment is the same

$$q_2^{(0)} \Phi_{571}^{(wv)} = C_1. \quad (\text{F.3.2})$$

In addition, in the absence of time-motion studies in the type of treatment plants needed here, it will be assumed that the dosimetry function  $\Phi_{572}^{(wv)}$  is the same for all devices. Under these conditions, the risk can be rewritten as

$$R_{570\kappa\lambda}^{(wv)} = C_2 \eta_w N_{08}^{(v)} t_{57}^{(v)} = C_2 \phi_{57\kappa}^{(wv)}. \quad (\text{F.3.3})$$

where the quantity  $\phi_{57\kappa}^{(wv)}$  is the effort (in man-hours) expended for the treatment of one drum of waste form  $w$  in device  $v$ ,

$$\phi_{57\kappa}^{(wv)} \equiv \eta_w N_{08}^{(v)} t_{57}^{(v)}. \quad (\text{F.3.4})$$

Assuming that the device  $v$  can accommodate all types of wastes sent to it, the total risk of alternative  $\kappa$  is

$$R_{570\kappa\lambda} = C_2 \sum_{w=1}^W \sum_{v=1}^T \phi_{57\kappa}^{(wv)}, \quad (\text{F.3.5})$$

where  $W$  is the number of waste forms (three), and  $T$  the number of different treatment devices in the treatment facility (two, four, or six). The summation over  $v$  starts with  $v = 1$  because the term with  $v = 0$  is already included in a component of the baseline risk which consists of that term only. The risk reduction factors are then

$$P_{570\kappa\lambda} = \frac{\sum_{w=1}^W \phi_{570}^{(w0)}}{\sum_{w=1}^W \sum_{v=1}^T \phi_{57\kappa}^{(wv)}} \equiv \frac{V_{5700}}{V_{570\kappa}}, \quad (\text{F.3.6})$$

with standard errors calculated under the assumption that no appreciable contributions come from the abundances  $\eta_w$

$$\left( \frac{\Delta \rho_{570\kappa\lambda}}{\rho_{570\kappa\lambda}} \right)^2 = \sum_{w=1}^W \left[ \left( \frac{\Delta \phi_{570}^{(w0)}}{V_{5700}} \right)^2 + \sum_{v=1}^T \left( \frac{\Delta \phi_{57\kappa}^{(wv)}}{V_{570\kappa}} \right)^2 \right], \quad (\text{F.3.7})$$

with the error given by the approximation

$$\frac{\Delta \phi_{57\kappa}^{(wv)}}{\phi_{57\kappa}^{(wv)}} = \frac{\Delta t_{57}^{(v)}}{t_{57}^{(v)}}. \quad (\text{F.3.8})$$

The numerical values for the effort factors  $\phi_{57\kappa}^{(wv)}$  needed here are given in Table D.4-1. The numerical values of the risk reduction factors  $\rho_{570\kappa\lambda}$  and their errors are given in Table F.3-1. They are smaller than 1, indicating risk increases of factors between 2 and about 10, increasing with more complex treatment. The baseline risk data in the FSEIS for the assay and certify process are not detailed enough to provide a value.

### F.3.1.2 Routine Maintenance: External Exposure

External exposure to penetrating radiation during maintenance operations is particularly important. Depending on the type of waste and the device, different times must be spent in the contaminated area. This leads to Risk Component 58 with two subcomponents. With the symbols

- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_r^{(\kappa)}$  = Number of drums handled annually ( $\text{yr}^{-1}$ ),
- $\eta_w$  = Fraction of waste in form  $w$ ,
- $f_{582}^{(wv)}$  = Fraction of waste in form  $w$  released into containment of device  $v$ ,
- $N_{07}^{(v)}$  = Number of persons needed for maintenance of device  $v$ ,
- $\Phi_{581}$  = Dosimetry function of average exposed person ( $\text{Sv s}^{-1} \text{Bq}^{-1}$ ),
- $\Phi_{58\kappa}^{(v)}$  = Maintenance function (annual number of operations) for device  $v$ ,
- $t_{58}^{(v)}$  = Exposure time for maintenance of device  $v$  (s),
- $a_1$  = Lifetime cancer risk coefficient ( $\text{Sv}^{-1}$ ),
- $C_i$  = Constant parts of equations, and
- $R_{580\kappa\lambda}^{(wv)}$  = Occupational risk of cancer due to device  $v$  treating waste form  $w$  in alternative  $\kappa$ ,

the general occupational risk equation is

$$R_{580\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)} n_r^{(\kappa)} \eta_w f_{582}^{(wv)} \right\} N_{07}^{(v)} \Phi_{581} \Phi_{58\kappa}^{(v)} t_{58}^{(v)} a_1. \quad (\text{F.3.9})$$

TABLE F.3-1

## RISK REDUCTION FACTORS FOR ROUTINE EXTERNAL EXPOSURES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
P <sub>5701λ</sub>	0.469 ± 0.033	
P <sub>5702λ</sub>	0.429 ± 0.030	
P <sub>5703λ</sub>	0.234 ± 0.017	
P <sub>5704λ</sub>	0.104 ± 0.008	
Annual Baseline Risks:		
R <sub>57000</sub>	--	Not available in FSEIS

The dependence on alternative  $\kappa$  is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the product of the first two factors as a variable. Again, because of the lack of time-motion studies, it will be assumed that the dosimetry function  $\Phi_{581}$  is the same for all treatment plants. Under these conditions, the risk can be rewritten as scaling according to

$$\begin{aligned} R_{580\kappa\lambda}^{(wv)} &= C_1 \eta_w f_{582}^{(wv)} N_{07}^{(v)} \Phi_{58\kappa}^{(v)} t_{58}^{(v)} \\ &= C_1 f_{582}^{(wv)} \phi_{58\kappa}^{(wv)}, \end{aligned} \quad (\text{F.3.10})$$

with the definition of the manpower factor

$$\phi_{58\kappa}^{(wv)} \equiv \eta_w N_{07}^{(v)} \Phi_{58\kappa}^{(v)} t_{58}^{(v)}. \quad (\text{F.3.11})$$

The total risk of alternative  $\kappa$  is then

$$R_{580\kappa\lambda} = C_1 \sum_{v=1}^T \sum_{w=1}^W \phi_{58\kappa}^{(wv)} f_{582}^{(wv)}, \quad (\text{F.3.12})$$

where  $W$  is the number of waste forms and  $T$  the number of treatment devices. The risk reduction factors are then

$$P_{580\kappa\lambda} = \frac{\sum_{w=1}^W \phi_{580}^{(w0)} f_{582}^{(w0)}}{\sum_{v=1}^T \sum_{w=1}^W \phi_{58\kappa}^{(wv)} f_{582}^{(wv)}} \equiv \frac{V_{5800}}{V_{580\kappa}}, \quad (\text{F.3.13})$$

with standard errors derived under the assumption that the errors  $\Delta\eta_w$ ,  $\Delta t_{58}^{(v)}$ , and  $\Delta\Phi_{58\kappa}^{(v)}$  are considerably smaller than the errors of the suspension factors  $\Delta f_{582}^{(wv)}$ . The error of  $N_{07}^{(v)}$  is included in that of  $\Delta t_{58}^{(v)}$ . Error propagation is thus calculated for these factors only,

$$\left( \frac{\Delta P_{580\kappa\lambda}}{P_{580\kappa\lambda}} \right)^2 = \sum_{w=1}^W \left[ \left( \frac{\phi_{580}^{(w0)} \Delta f_{582}^{(w0)}}{V_{5800}} \right)^2 + \sum_{v=1}^T \left( \frac{\phi_{58\kappa}^{(wv)} \Delta f_{582}^{(wv)}}{V_{580\kappa}} \right)^2 \right]. \quad (\text{F.3.14})$$

The numerical values for the manpower factor  $\phi_{58\kappa}^{(wv)}$  are available in Table D.4-2 of Attachment D. Using the values in Tables D.4-3 for  $f_{582}^{(wv)}$  leads to the numerical values of the risk reduction factors

in Table F.3-2. They show effective increases in risk by factors between 250 and 1400 with standard errors of about 25 percent.

### F.3.2 Internal Exposures

#### F.3.2.1 Routine Operations; Internal Exposure

##### F.3.2.1.1 Occupational Risks Due to Internal Routine Exposures

In this routine scenario a certain fraction of waste form  $w$  treated in device  $v$  escapes from containment and fills the treatment module concerned to equilibrium air concentrations without tripping the alarm setting on continuous air monitors. The crews, therefore, do not leave the area and do not don respirators. These conditions give rise to a chronic inhalation exposure to alpha-, beta-, and gamma-emitters, and thus the two subcomponents of Risk Component 59. Using the symbols

- $q_2^{(k)}$  = Total activity per drum (Bq),
- $n_r^{(k)}$  = Number of drums handled annually ( $yr^{-1}$ ),
- $\eta_w$  = Fraction of waste in form  $w$ ,
- $f_{59\kappa}^{(v)}$  = Fraction of waste in form  $w$  suspended and released from containment in inhalable form due to treatment  $v$  in alternative  $\kappa$ ,
- $N_{o1}^{(k)}$  = Number of persons in treatment plant,
- $f_{15}$  = Fraction of personnel exposed,
- $L_1$  = Annual ventilation volume ( $m^3$ ),
- $V_1$  = Annual breathing volume ( $m^3$ ),
- $f_{593}$  = Deposited fraction of suspended particles,
- $\Phi_{591}$  = Overall dosimetry function of average exposed person ( $Sv\ Bq^{-1}$ ),
- $a_1$  = Lifetime cancer risk coefficient ( $Sv^{-1}$ ),
- $C_1$  = Constant parts of equations, and
- $R_{59\circ\kappa\lambda}^{(wv)}$  = Occupational risk of cancer due to treatment  $v$  of waste form  $w$  in alternative  $\kappa$  ( $yr^{-1}$ ),

the general risk equation is

$$R_{59\circ\kappa\lambda}^{(wv)} = \left\{ q_2^{(k)} n_r^{(k)} \eta_w f_{59\kappa}^{(v)} \right\} f_{15} N_{o1}^{(k)} \frac{V_1}{L_1} f_{593} \Phi_{591} a_1 . \quad (F.3.15)$$

The dependence on alternative  $\kappa$  is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the variability of the first two factors. Upon elimination of the other constant terms, the risk can be scaled as

$$R_{59\circ\kappa\lambda}^{(wv)} = C_1 \eta_w f_{59\kappa}^{(v)} N_{o1}^{(k)} . \quad (F.3.16)$$

TABLE F.3-2

**RISK REDUCTION FACTORS FOR EXTERNAL EXPOSURE DURING  
ROUTINE MAINTENANCE**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{58\ 01\lambda}$	$(4.0 \pm 1.0) \cdot 10^{-3}$	
$P_{58\ 02\lambda}$	$(3.9 \pm 1.0) \cdot 10^{-3}$	
$P_{58\ 03\lambda}$	$(2.9 \pm 0.7) \cdot 10^{-3}$	
$P_{58\ 04\lambda}$	$(7.2 \pm 2.1) \cdot 10^{-4}$	
<b>Annual Baseline Risks:</b>		
$R_{58\ 000}$	--	Not available in FSEIS

The total risk of alternative  $\kappa$  is then scaled according to

$$R_{59\ 0\ \kappa\ \lambda} = C_1 N_{01}^{(\kappa)} \sum_{v=1}^T f_{59\ \kappa}^{(v)}. \quad (\text{F.3.17})$$

No sum over  $w$  appears, because the sum over  $v$  is independent of  $w$ , and the sum over the normalized waste fractions  $\eta_w$  leads to a factor of 1. The risk reduction factors are then

$$p_{59\ 0\ \kappa\ \lambda} = F_{m\ \kappa} \frac{f_{59\ 0}^{(0)}}{\sum_{v=1}^T f_{59\ \kappa}^{(v)}} \equiv F_{m\ \kappa} \frac{V_{59\ 0\ 0}}{V_{59\ 0\ \kappa}}, \quad (\text{F.3.18})$$

with standard errors

$$\left( \frac{\Delta p_{59\ 0\ \kappa\ \lambda}}{p_{59\ 0\ \kappa\ \lambda}} \right)^2 = \left( \frac{\Delta F_{m\ \kappa}}{F_{m\ \kappa}} \right)^2 + \left( \frac{\Delta f_{59\ 0}^{(0)}}{V_{59\ 0\ 0}} \right)^2 + \sum_{v=1}^T \left( \frac{\Delta f_{59\ \kappa}^{(v)}}{V_{59\ 0\ \kappa}} \right)^2. \quad (\text{F.3.19})$$

Numerical values for the factors  $f_{59\ \kappa}^{(v)}$  are listed in Table D.4-4 of Attachment D, and values of the risk reduction factors are listed in Table F.3-3. Risk reductions indicate decreases in occupational risk by factors varying from 290 to 1730 with relative errors of about 33 to 40 percent.

#### F.3.2.1.2 Public Risks Due to Internal Routine Exposures

This scenario employs the same source term as in the previous scenario. It is assumed that there is a release of radioactivity from containment which exits through the HEPA filters and is dispersed on the outside. The actual dispersion function is not dependent on the treatment option, but the number of persons exposed and their location may be. Using the symbols

- $q_2^{(\kappa)}$  = Total activity per drum (Bq),
- $n_r^{(\kappa)}$  = Number of drums handled annually ( $\text{yr}^{-1}$ ),
- $\eta_w$  = Fraction of waste in form  $w$ ,
- $f_{59\ \kappa}^{(v)}$  = Fraction of waste in form  $w$  suspended and released from containment in inhalable form due to treatment  $v$  in alternative  $\kappa$ ,
- $f_{\text{dep}}^{(\kappa)}$  = Fraction of equilibrium concentration not deposited before filters,
- $f_{\text{rem}}^{(\kappa)}$  = Fraction of concentration penetrating HEPA filters,
- $\Phi_{59\ \text{dd}}^{(\kappa)}$  = Dispersion-dosimetry function ( $\text{Sv Bq}^{-1}$ ),
- $a_1$  = Lifetime cancer risk coefficient ( $\text{Sv}^{-1}$ ),

TABLE F.3-3

**RISK REDUCTION FACTORS FOR OCCUPATIONAL RISKS DUE TO  
ROUTINE INTERNAL EXPOSURES DURING WASTE TREATMENT**

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
P <sub>59012</sub>	$(1.73 \pm 0.70) \cdot 10^3$	
P <sub>59022</sub>	$(1.44 \pm 0.56) \cdot 10^3$	
P <sub>59032</sub>	$(7.1 \pm 2.5) \cdot 10^2$	
P <sub>59042</sub>	$(2.9 \pm 1.0) \cdot 10^2$	
<b>Annual Baseline Risks:</b>		
R <sub>59000</sub>	--	Not available in FSEIS

$C_1$  = Constant parts of equation, and  
 $R_{59\rho\kappa\lambda}^{(wv)}$  = Public cancer risk due to treatment v of waste w in alternative  $\kappa$  (yr<sup>-1</sup>),

the general type of risk equation is

$$R_{59\rho\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)} n_r^{(\kappa)} \eta_w f_{59\kappa}^{(v)} \right\} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{59dd}^{(\kappa)} a_1. \quad (F.3.20)$$

As always, the dependence on alternative  $\kappa$  is simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)]. Upon elimination of the other constant terms, the risk can be rewritten to scale as

$$R_{59\rho\kappa\lambda}^{(wv)} = C_1 \Phi_{59dd}^{(\kappa)} \eta_w f_{59\kappa}^{(v)}. \quad (F.3.21)$$

The total risk is, therefore, scaling according to

$$R_{59\rho\kappa\lambda} = C_1 \Phi_{59dd}^{(\kappa)} \sum_{v=1}^T f_{59\kappa}^{(v)}, \quad (F.3.22)$$

which has the same basic structure as the expression for the occupational risk in Equation (F.3.17). Summation over all waste forms and treatment leads to the same risk reduction factors as Equation (F.3.18), except for the number of persons involved. Thus the risk reduction factors are

$$\rho_{59\rho\kappa\lambda} = F_{\rho\kappa} \frac{f_{590}^{(0)}}{\sum_{v=1}^T f_{59\kappa}^{(v)}} \equiv F_{\rho\kappa} \frac{V_{5900}}{V_{59\kappa}}, \quad (F.3.23)$$

with the standard errors

$$\left( \frac{\Delta \rho_{59\rho\kappa\lambda}}{\rho_{59\rho\kappa\lambda}} \right)^2 = \left( \frac{\Delta F_{\rho\kappa}}{F_{\rho\kappa}} \right)^2 + \left( \frac{\Delta f_{590}^{(0)}}{V_{5900}} \right)^2 + \sum_{v=1}^T \left( \frac{\Delta f_{59\kappa}^{(v)}}{V_{59\kappa}} \right)^2. \quad (F.3.24)$$

Note that the second and third terms are identical to those in Equation (F.3.19); only the first term is different. Numerical values of the reduction factors  $\rho$  and their errors are listed in Table F.3-4. Again, substantial decreases in risk are indicated, with reduction factors ranging from 1900 to 3100 with errors near 40 percent. Baseline risks in the FSEIS are not detailed enough to give the component associated with the assay and certification procedure.

TABLE F.3-4

## RISK REDUCTION FACTORS FOR PUBLIC RISKS DUE TO INTERNAL EXPOSURES

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Risk Reduction Factors:		
$P_{50p12}$	$(3.1 \pm 1.4) \cdot 10^3$	
$P_{50p22}$	$(2.8 \pm 1.2) \cdot 10^3$	
$P_{50p32}$	$(2.1 \pm 0.8) \cdot 10^3$	
$P_{50p42}$	$(1.9 \pm 0.7) \cdot 10^3$	
Annual Baseline Risks:		
$R_{50p00}$	--	Not available in FSEIS

### F.3.2.2 Routine Maintenance: Internal Exposure

#### F.3.2.2.1 Occupational Risk Due to Internal Maintenance Exposures

During maintenance, respiratory protection is assumed to be mandatory for the cleanup crew. Protection is not total, however, but depends again on health and safety as well as ALARA concerns. This leads to inhalation exposures and thus a risk of cancer and genetic damage, both in occupational and public settings. There are four subcomponents of Risk Component 60. Using the symbols

$q_2^{(k)}$	= Total activity per drum (Bq),
$n_r^{(k)}$	= Number of drums handled annually ( $\text{yr}^{-1}$ ),
$\eta_w$	= Fraction of waste in form $w$ ,
$f_{582}^{(wv)}$	= Fraction of waste in form $w$ released into containment of device $v$ ,
$f_{603}^{(wv)}$	= Fraction of waste resuspended during cleanup of device $v$ ,
$\Phi_{601}^{(v)}$	= Activity concentration function ( $\text{L}^{-1}$ ),
$v_6$	= Inhalation rate of workers ( $\text{L s}^{-1}$ ),
$P_{60}$	= Transmission factor of respiratory protection,
$N_{07}^{(v)}$	= Number of persons needed for maintenance of device $v$ ,
$f_{13}$	= Fraction of airborne particles deposited in lung,
$\Phi_{602}$	= Internal dosimetry function of average exposed person ( $\text{Sv Bq}^{-1}$ ),
$\Phi_{58\kappa}^{(v)}$	= Maintenance function (annual maintenance operations for device $v$ ),
$t_{58}^{(v)}$	= Exposure time for maintenance of device $v$ (s),
$a_1$	= Lifetime cancer risk coefficient ( $\text{Sv}^{-1}$ ),
$C_1$	= Constant parts of equation, and
$R_{60\sigma\kappa\lambda}^{(wv)}$	= Occupational risk of cancer due to maintenance of device $v$ ( $\text{yr}^{-1}$ ),

the general risk equation is

$$R_{60\sigma\kappa\lambda}^{(wv)} = \left\{ q_2^{(k)} n_r^{(k)} \eta_w f_{582}^{(wv)} f_{603}^{(wv)} \right\} \Phi_{601}^{(v)} v_6 t_{58}^{(v)} P_{60} f_{13} \Phi_{602} \Phi_{58\kappa}^{(v)} N_{07}^{(v)} a_1 . \quad (\text{F.3.25})$$

The assumption of a constant amount of activity treated annually [Equation (E.1.5)] is again used to eliminate the product of the first two factors as a variable. The risk can then be determined to scale as

$$R_{60\sigma\kappa\lambda}^{(wv)} = C_1 \eta_w f_{582}^{(wv)} f_{603}^{(wv)} N_{07}^{(v)} \Phi_{58\kappa}^{(v)} t_{58}^{(v)} \quad (\text{F.3.26})$$

$$= C_1 \phi_{58\kappa}^{(wv)} f_{603}^{(wv)} ,$$

where

$$\phi_{58\kappa}^{(wv)} = \eta_w N_{07}^{(v)} \Phi_{58\kappa}^{(v)} t_{58}^{(v)} . \quad (\text{F.3.27})$$

The total risk of alternative  $\kappa$  is then scaling as

$$R_{60\sigma\kappa\lambda}^{(wv)} = C_1 \sum_{v=1}^T \sum_{w=1}^W \phi_{58\kappa}^{(wv)} f_{582}^{(wv)} f_{603}^{(wv)}. \quad (\text{F.3.28})$$

Consequently the risk reduction factors are

$$P_{60\sigma\kappa\lambda} = \frac{\sum_{w=1}^W \phi_{580}^{(w0)} f_{582}^{(w0)} f_{603}^{(w0)}}{\sum_{v=1}^T \sum_{w=1}^W \phi_{58\kappa}^{(wv)} f_{582}^{(wv)} f_{603}^{(wv)}} \equiv \frac{V_{60\sigma 0}}{V_{60\sigma\kappa}}, \quad (\text{F.3.29})$$

with standard errors which are derived under the assumption that the errors  $\Delta\phi_{58\kappa}^{(wv)}$  are considerably smaller than the others. Error propagation is thus calculated for the remaining two factors only,

$$\left( \frac{\Delta P_{60\sigma\kappa\lambda}}{P_{60\sigma\kappa\lambda}} \right)^2 = \frac{1}{V_{60\sigma 0}^2} \sum_{w=1}^W \left[ \left( f_{603}^{(w0)} \Delta f_{582}^{(w0)} \right)^2 + \left( f_{582}^{(w0)} \Delta f_{603}^{(w0)} \right)^2 \right] \left( \phi_{580}^{(w0)} \right)^2 \quad (\text{F.3.30})$$

$$+ \frac{1}{V_{60\sigma\kappa}^2} \sum_{v=1}^T \sum_{w=1}^W \left[ \left( f_{603}^{(wv)} \Delta f_{582}^{(wv)} \right)^2 + \left( f_{582}^{(wv)} \Delta f_{603}^{(wv)} \right)^2 \right] \left( \phi_{58\kappa}^{(wv)} \right)^2.$$

The numerical values of the parameters  $f_{603}^{(wv)}$  which are needed in the following are given in Table D.4-5 of Attachment D. Using these values and those in Tables D.4-2 and D.4-3 leads to the numerical values for the risk reduction factors listed in Table F.3-5. These factors are rather closely grouped around values that signify large increases in risk by factors of about 20,000 to about 120,000 with relative standard errors of about 40 percent. Information on risk components in WHB operations are not detailed enough in the FSEIS to yield a baseline risk for this scenario.

#### F.3.2.2.2 Public Risk Due to Internal Exposures Caused by Maintenance

This scenario is similar to the previous one in that the source term is the same, but it differs by considering in addition the transmission of radioactivity to the outside atmosphere. Dispersion is the same for all alternatives but number and location of the exposed population may not be. Inhalation exposure leads to the two public subcomponents of Risk Component 60. The symbols

$q_2^{(k)}$	= Total activity per drum (Bq),
$n_r^{(k)}$	= Number of drums handled annually (yr <sup>-1</sup> ),
$\eta_w$	= Fraction of waste in form w,
$f_{582}^{(wv)}$	= Fraction of waste in form w released into containment of device v,
$f_{603}^{(wv)}$	= Fraction of waste resuspended during cleanup of device v,
$\Phi_{60\kappa}^{(v)}$	= Fraction of year spent on maintenance of device v,

TABLE F.3-5

**RISK REDUCTION FACTORS FOR OCCUPATIONAL RISKS DUE TO  
INTERNAL EXPOSURE DURING ROUTINE MAINTENANCE**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{8001\lambda}$	$(4.0 \pm 1.5) \cdot 10^{-5}$	
$P_{8002\lambda}$	$(3.9 \pm 1.4) \cdot 10^{-5}$	
$P_{8003\lambda}$	$(4.2 \pm 1.4) \cdot 10^{-5}$	
$P_{8004\lambda}$	$(8.5 \pm 3.8) \cdot 10^{-5}$	
<b>Annual Baseline Risks:</b>		
$R_{80000}$	--	Not available in FSEIS

- $\Phi_{601}$  = Activity-concentration function ( $L^{-1}$ ),  
 $f_{dep}^{(\kappa)}$  = Fraction of equilibrium concentration not deposited before filters,  
 $f_{rem}^{(\kappa)}$  = Fraction of concentration penetrating HEPA filters,  
 $\Phi_{60dd}^{(\kappa)}$  = Dispersion-dosimetry function ( $Sv Bq^{-1} L$ ),  
 $a_1$  = Lifetime cancer risk coefficient ( $Sv^{-1}$ ),  
 $C_i$  = Constant parts of equations, and  
 $R_{60p\kappa\lambda}^{(wv)}$  = Occupational risk of cancer due to maintenance of device  $v$  ( $yr^{-1}$ )

are used for the general risk equation

$$R_{60p\kappa\lambda}^{(wv)} = \left\{ q_2^{(\kappa)} n_r^{(\kappa)} \eta_w f_{582}^{(wv)} f_{603}^{(wv)} \Phi_{60\kappa}^{(v)} \right\} \Phi_{601} f_{dep}^{(\kappa)} f_{rem}^{(\kappa)} \Phi_{60dd}^{(\kappa)} a_1. \quad (F.3.31)$$

The study of the dependence on alternative  $\kappa$  is again simplified by the assumption of a constant amount of activity treated annually [Equation (E.1.5)] which eliminates the product of the first two factors as a variable. With all factors outside the source term which are independent of alternative aggregated into a constant, the risk can be written to scale as

$$R_{60p\kappa\lambda}^{(wv)} = C_1 \eta_w f_{582}^{(wv)} f_{603}^{(wv)} \Phi_{60\kappa}^{(v)}. \quad (F.3.32)$$

The total risk of alternative  $k = (\kappa, \lambda)$  then has the scaling property

$$R_{60p\kappa\lambda} = C_1 \sum_{v=1}^T \Phi_{60\kappa}^{(v)} \sum_{w=1}^W \eta_w f_{582}^{(wv)} f_{603}^{(wv)}, \quad (F.3.33)$$

where  $W$  is the number of waste forms and  $T$  the number of treatments in the treatment facility

$$p_{60p\kappa\lambda} = \frac{\Phi_{600}^{(0)} \sum_{w=1}^W \eta_w f_{582}^{(w0)} f_{603}^{(w0)}}{\sum_{v=1}^T \Phi_{60\kappa}^{(v)} \sum_{w=1}^W \eta_w f_{582}^{(wv)} f_{603}^{(wv)}} \equiv \frac{V_{60p0}}{V_{60p\kappa}}, \quad (F.3.34)$$

with standard errors which are derived under the assumption that the errors  $\Delta\eta_w$  and  $\Delta\Phi_{60\kappa}^{(v)}$  are considerably smaller than those of the other two factors  $f_{582}^{(wv)}$  and  $f_{603}^{(wv)}$ . The error calculation for

the remaining factors then yields

$$\left( \frac{\Delta \rho_{60 \rho \kappa \lambda}}{\rho_{60 \rho \kappa \lambda}} \right)^2 = \left( \frac{\Phi_{600}^{(0)}}{V_{6000}} \right)^2 \sum_{w=1}^W \eta_w^2 \left\{ \left( f_{603}^{(w0)} \Delta f_{582}^{(w0)} \right)^2 + \left( f_{582}^{(w0)} \Delta f_{603}^{(w0)} \right)^2 \right\} \\ + \frac{1}{V_{600\kappa}^2} \sum_{w=1}^W \eta_w^2 \sum_{v=1}^T \left( \Phi_{60\kappa}^{(v)} \right)^2 \left\{ \left( f_{603}^{(wv)} \Delta f_{582}^{(wv)} \right)^2 + \left( f_{582}^{(wv)} \Delta f_{603}^{(wv)} \right)^2 \right\}. \quad (\text{F.3.35})$$

The numerical values of the factors  $f_{603}^{(wv)}$  have been given in Table D.4-5; those for factors  $f_{582}^{(wv)}$  in Table D.4-3; those for  $\Phi_{60\kappa}^{(v)}$  are given in Table D.2-2 of Attachment D. The risk reduction factors and their errors are listed in Table F.3-6. Again, a large increase in risk is seen with factors ranging from 40,000 to 260,000 with relative standard errors of about 30 percent.

#### F.4 RISK OF EXPOSURES TO VOLATILE ORGANIC COMPOUNDS

The chemical agents of concern in the waste are VOCs; three of them are carcinogens, two are not. During treatment, some of the VOCs are released. For Level II treatments, the gases are allowed to escape during shredding. For Level III treatments, sorting and shredding leads to the release of VOCs from all void spaces upon opening liners and bags.

Occupational risks are minimized by respiratory protection by the use of bubble suits during sorting or of glove boxes covering conveyor belts. Low-level releases, however, lead to a residual risk. The baseline risk is given by the routine emissions of the drums through their carbon filters during the assay and certify procedure.

##### F.4.1 Risk of Cancer by Exposure to VOCs

###### F.4.1.1 Routine Operations: Occupational Exposures

In this scenario, gases escaping from the wastes are absorbed in filters or vented outside the facility. A small fraction will escape and concentrations of agent  $j$  build up against the ventilation system until they reach equilibrium value. The released quantity of carcinogenic VOCs is assumed to be the entire void volume from the drums, all of which is released upon opening the liners and bags in the TF. Using the symbols:

- $q_{18j}^{(0)}$  = Total mass of gas  $j$  per "as received" drum (mg),  
 $n_r^{(0)}$  = Number of "as received" drums handled annually ( $\text{yr}^{-1}$ ),

TABLE F.3-6

**RISK REDUCTION FACTORS FOR PUBLIC RISKS  
DUE TO ROUTINE MAINTENANCE**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{60p1\lambda}$	$(2.53 \pm 0.72) \cdot 10^{-5}$	
$P_{60p2\lambda}$	$(2.16 \pm 0.60) \cdot 10^{-5}$	
$P_{60p3\lambda}$	$(1.31 \pm 0.34) \cdot 10^{-5}$	
$P_{60p4\lambda}$	$(3.91 \pm 1.03) \cdot 10^{-6}$	
<b>Annual Baseline Risk:</b>		
$R_{60p00}$	--	Not available in FSEIS

- $N_{o1}^{(k)}$  = Number of persons in WHB and treatment plant,  
 $f_{15}$  = Fraction of crew exposed,  
 $\Phi_{61j}^{(k)}$  = Gas release function for agent  $j$  and alternative  $k$ ,  
 $L_1$  = Annual ventilation volume ( $m^3$ ),  
 $V_1$  = Annual occupational respiratory volume ( $m^3$ ),  
 $M$  = Body mass of receptor (kg),  
 $f_{12j}$  = Probability of absorption into body for chemical  $j$ ,  
 $f_t$  = Exposure time correction factor for one year,  
 $c_j$  = Lifetime cancer risk coefficient for chemical  $j$  ( $mg^{-1} kg day$ ),  
 $C_1$  = Constant parts of equations, and  
 $R_{61o\kappa\lambda j}$  = Occupational risk of cancer due to chemical  $j$  per year of operation ( $yr^{-1}$ ),

are used in the general occupational risk equation

$$R_{61o\kappa\lambda j} = \{q_{16j}^{(0)} n_r^{(0)} \Phi_{61j}^{(\kappa)}\} f_{15} N_{o1}^{(\kappa)} \frac{V_1}{L_1 M} f_{12j} f_t c_j. \quad (F.4.1)$$

Considering the dependence on alternatives, the risk can be scaled as

$$R_{61o\kappa\lambda j} = C_1 \Phi_{61j}^{(\kappa)} N_{o1}^{(\kappa)}. \quad (F.4.2)$$

The risk reduction factors are then

$$p_{61o\kappa\lambda j} = \frac{\Phi_{61j}^{(0)} N_{o1}^{(0)}}{\Phi_{61j}^{(\kappa)} N_{o1}^{(\kappa)}} = F_{m\kappa} \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}} = F_{m\kappa} F_{r\kappa j}, \quad (F.4.3)$$

using the definition

$$F_{r\kappa j} \equiv \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(\kappa)}}, \quad (F.4.4)$$

and the standard errors

$$\left( \frac{\Delta p_{61o\kappa\lambda j}}{p_{61o\kappa\lambda j}} \right)^2 = \left( \frac{\Delta F_{m\kappa}}{F_{m\kappa}} \right)^2 + \left( \frac{\Delta F_{r\kappa j}}{F_{r\kappa j}} \right)^2. \quad (F.4.5)$$

The reduction factors  $F_{r\kappa j}$  are listed in Table D.4-7 where it is also shown that the release reduction factors and, thus, the risk reduction factors are independent of the chemical considered. No aggregation is, therefore, needed. The values of the risk reduction factors  $p_{61o\kappa\lambda j}$  and their errors are given in Table F.4-1. These values show the same large increases as those found for the radiation risks. Increases of risk over baseline values of factors between 50,000 and 200,000 are found with relative errors of about 13 percent.

TABLE F.4-1

**REDUCTION OF OCCUPATIONAL RISK DUE TO ROUTINE GAS  
RELEASES OF CARCINOGENIC CHEMICALS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{6101\lambda}$	$(2.21 \pm 0.28) \cdot 10^{-5}$	For all chemicals $j$ , $P_{620k\lambda} = P_{610k\lambda}$
$P_{6102\lambda}$	$(1.66 \pm 0.21) \cdot 10^{-5}$	
$P_{6103\lambda}$	$(1.09 \pm 0.14) \cdot 10^{-5}$	
$P_{6104\lambda}$	$(4.86 \pm 0.60) \cdot 10^{-6}$	
<b>Annual Baseline Risks:</b>		
$R_{61000}$	--	Not available in FSEIS
$R_{62000}$	--	Not available in FSEIS

#### F.4.1.2 Routine Operations: Public Exposures to VOCs

This scenario is the same as the previous one, except that cancer risks are calculated for the public when the vapors escape to the outside. The symbols

$q_{18j}^{(0)}$	= Total mass of gas j per "as received" drum (mg),
$n_r^{(0)}$	= Number of "as received" drums handled annually ( $\text{yr}^{-1}$ ),
$\Phi_{81j}^{(\kappa)}$	= Gas release function for alternative $\kappa$ ,
$f_{out}^{(\kappa)}$	= Penetration to outside of treatment plant,
$\Phi_{81dd}^{(\kappa)}$	= Dispersion-dosimetry function of all exposed persons ( $\text{day}^{-1}$ ),
M	= Body mass of receptor (kg),
$f_{12j}$	= Probability of absorption into body for chemical j,
$c_j$	= Lifetime cancer risk coefficient for chemical j ( $\text{mg}^{-1} \text{kg day}$ ),
$f_t$	= Exposure time correction factor for one year,
$C_1$	= Constant parts of equations, and
$R_{81p\kappa\lambda j}$	= Public risk of cancer due to chemical j per year of operation ( $\text{yr}^{-1}$ ),

are used in the general public risk equation

$$R_{81p\kappa\lambda j} = \left\{ q_{18j}^{(0)} n_r^{(0)} \Phi_{81j}^{(\kappa)} \right\} f_{out}^{(\kappa)} \Phi_{81dd}^{(\kappa)} f_{12j} \frac{1}{M} f_t c_j \quad (\text{F.4.6})$$

Considering the dependence on treatment options in the usual manner, the risk can be shown to scale according to

$$R_{81p\kappa\lambda j} = C_1 \Phi_{81j}^{(\kappa)} \quad (\text{F.4.7})$$

The risk reduction factors are then

$$\rho_{81p\kappa\lambda j} = \frac{\Phi_{81j}^{(0)}}{\Phi_{81j}^{(\kappa)}} = F_{r\kappa j} \quad (\text{F.4.8})$$

again independent of the chemical agent j. Their standard errors are

$$\Delta \rho_{81p\kappa\lambda j} = \Delta F_{r\kappa j} \quad (\text{F.4.9})$$

The values of the risk reduction factors  $\rho_{81p\kappa\lambda}$  and their errors are given in Table F.4-2. All of them lie near risk increases of factors of about 15,000 to 20,000 with relative standard errors of 11 percent.

TABLE F.4-2

**REDUCTION FACTORS FOR PUBLIC RISKS DUE TO  
ROUTINE RELEASES OF CARCINOGENIC CHEMICALS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Risk Reduction Factors:</b>		
$P_{61p1\lambda j}$	$(8.00 \pm 0.90) \cdot 10^{-5}$	$P_{62p\kappa j} = P_{61p\kappa j}$
$P_{61p2\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
$P_{61p3\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
$P_{61p4\lambda j}$	$(6.40 \pm 0.70) \cdot 10^{-5}$	
<b>Annual Baseline Risk:</b>		
$R_{61p00}$	--	Not available in FSEIS
$R_{62p00}$	--	Not available in FSEIS

## F.4.2 Risk of Noncancer Health Effects

### F.4.2.1 Routine Operations: Occupational Exposures

Again, as in Section F.4.1.1, workers are exposed to concentrations of agent  $j$  that build up against the ventilation system to equilibrium value. This time, however, the noncancer health effects risk is calculated. With the symbols

$q_{18j}^{(0)}$	= Total mass of gas $j$ per "as received" drum (mg),
$n_r^{(0)}$	= Number of "as received" drums handled annually ( $\text{yr}^{-1}$ ),
$N_{o1}^{(\kappa)}$	= Number of persons in WHB and Treatment Facility,
$\Phi_{81j}^{(\kappa)}$	= Gas release function for alternative $\kappa$ ,
$f_{15}$	= Fraction of personnel exposed to chemicals,
$L_1$	= Annual ventilation volume ( $\text{m}^3$ ),
$V_2$	= Daily occupational respiratory volume ( $\text{m}^3 \text{ day}^{-1}$ ),
$M$	= Body mass of receptor (kg),
$f_{12j}$	= Probability of absorption into body for chemical $j$ ,
$L_j^{(\text{ref})}$	= Reference level for chemical $j$ [ $\text{mg} (\text{kg day})^{-1}$ ],
$r_{o1}$	= Risk of reference level $L_j^{(\text{ref})}$ ,
$C_1$	= Constant parts of equations, and
$R_{82o\kappa\lambda j}$	= Occupational noncancer risk due to chemical $j$ per year of operation ( $\text{yr}^{-1}$ ),

the general occupational risk equation can be written as

$$R_{82o\kappa\lambda j} = \left\{ q_{18j}^{(0)} n_r^{(0)} \Phi_{81j}^{(\kappa)} \right\} N_{o1}^{(\kappa)} f_{15} \frac{V_2}{L_1 M L_j^{(\text{ref})}} f_{12j} r_{o1} \quad (\text{F.4.10})$$

Considering the dependence on treatment options as before, the risk can be scaled as

$$R_{82o\kappa\lambda j} = C_1 N_{o1}^{(\kappa)} \Phi_{81j}^{(\kappa)}, \quad (\text{F.4.11})$$

which is the same result as that for the occupational exposures to carcinogens. The risk reduction factors are then

$$\rho_{82o\kappa\lambda} = \frac{\Phi_{81j}^{(0)} N_{o1}^{(0)}}{\Phi_{81j}^{(\kappa)} N_{o1}^{(\kappa)}} = F_{m\kappa} F_{r\kappa j} = \rho_{81o\kappa\lambda}, \quad (\text{F.4.12})$$

which is independent of agent  $j$  and has standard errors

$$\Delta \rho_{82o\kappa\lambda} = \Delta \rho_{81o\kappa\lambda}. \quad (\text{F.4.13})$$

The values of the risk reduction factors  $\rho_{82o\kappa\lambda}$  and their errors are thus given in Table F.4-1. No aggregation is needed because there is no difference between the different chemical agents.

#### F.4.2.2 Routine Operations: Public Exposures to VOCs

Again, as in F.4.1.2, the public is exposed to VOCs when concentrations of agent  $j$  build up against the ventilation system to equilibrium value and are vented to the outside. Noncancer health effects risks are calculated for this scenario. Using the symbols

$q_{16j}^{(0)}$	= Total mass of gas $j$ per "as received" drum (mg),
$n_r^{(0)}$	= Number of "as received" drums handled annually ( $\text{yr}^{-1}$ ),
$\Phi_{61j}^{(k)}$	= Gas release function for alternative $k$ ,
$f_{out}^{(k)}$	= Penetration to outside of treatment plant,
$\Phi_{62dd}^{(k)}$	= Dispersion-dosimetry function ( $\text{day}^{-1}$ ),
$M$	= Body mass of receptor (kg),
$f_{12j}$	= Probability of absorption into body for chemical $j$ ,
$r_{oj}$	= Risk of reference level $L_j^{(ref)}$ ,
$L_j^{(ref)}$	= Reference level for chemical $j$ [ $\text{mg (kg day)}^{-1}$ ],
$C_1$	= Constant parts of equations, and
$R_{62pk\lambda j}$	= Public noncancer risk due to chemical $j$ per year of operation ( $\text{yr}^{-1}$ ),

the general public risk expression can be stated as

$$R_{62pk\lambda j} = \left\{ q_{16j}^{(0)} n_r^{(0)} \Phi_{61j}^{(k)} \right\} f_{out}^{(k)} \Phi_{62dd}^{(k)} \frac{1}{M L_j^{(ref)}} f_{12j} r_{oj} \quad (\text{F.4.14})$$

The dependence on alternatives again leads to a scaling law

$$R_{62pk\lambda j} = C_1 \Phi_{61j}^{(k)}, \quad (\text{F.4.15})$$

which is the same result as for the public risk in the last section. The risk reduction factors are then

$$p_{62pk\lambda j} = \frac{\Phi_{61j}^{(0)}}{\Phi_{61j}^{(k)}} = p_{61pk\lambda j}, \quad (\text{F.4.16})$$

with the same standard errors

$$\Delta p_{62pk\lambda j} = \Delta p_{61pk\lambda j} \quad (\text{F.4.17})$$

The values of the risk reduction factors  $p_{62pk\lambda j}$  and their errors are given in Table F.4-2. Again, no aggregation over all chemicals is necessary.

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## ATTACHMENT G

### RISK COMPARISON

#### G.1 AGGREGATION OF CONSEQUENCE REDUCTION FACTORS

##### G.1.1 Set Of Consequence Reduction Factors

The discussion in the preceding sections leads to a total of 124 reduction factors for risk components, including all subcomponents. This is too large a number for the assignment of individual societal weights, even if all baseline risk components and subcomponents were known. One way to reduce the number of subcomponents is to discard risk reduction factors that would not influence the result appreciably and aggregate others into appropriate categories.

Genetic damages are subcomponents with risks that are smaller than the corresponding risks of cancer. (National Research Council, 1980, 1988, 1990). For internal exposures, they are also less well defined. These 45 subcomponents are consequently not included in the aggregation process (National Research Council, 1980, 1988, 1990). Similarly, public noncancer risks due to exposures to chemical toxicants are extremely low (DOE, 1990a) and the health consequences of no great influence. These six subcomponents, too, will be dropped from consideration for aggregation (Table G.1-1).

The rest of the risk reduction factors are sorted into eight supercomponents:

1. Transportation fatalities
2. Transportation injuries
3. Occupational fatalities
4. Occupational injuries
5. Occupational cancers
6. Public cancers
7. Late occupational cancers
8. Late public cancers.

Six of these supercomponents are listed in the FSEIS (DOE, 1990a), but numbers 3 and 4, the occupational accident fatalities and injuries, are not. In a comparison of risks involving waste treatment, however, they are important and have thus been included. These eight supercomponents arise from the aggregation of 73 components and subcomponents.

A problem in the aggregation of these subcomponents arises from the fact that the FSEIS does not give explicit values for a number of component and subcomponent risks, but gives some values for more aggregated risks. These baseline risks will be denoted by the symbol  $R_{1990}$ .

TABLE G.1-1

## COMPONENTS AND SUBCOMPONENTS FOR THE EIGHT SUPERCOMPONENTS

SUPERCOMPONENT	ALL SUBCOMPONENTS	AGGREGATED IN SUPERCOMPONENTS
1 Transportation fatalities	3	3
2 Transportation injuries	3	3
3 Occupational fatalities	2	2
4 Occupational injuries	11	11
5 Occupational cancers	40	22
6 Public cancers	41	22
7 Late occupational cancers	6	3
8 Late public cancers	<u>12</u>	<u>6</u>
	Total classified	<u>118</u>
	Not classified *	<u>6</u>
	Total	<u>124</u>

- \* P 14 p κ λ
- P 15 p κ λ
- P 50 p κ λ
- P 51 p κ λ
- P 52 p κ λ
- P 62 p κ λ

where the index  $j$  denotes the risk component,  $\xi$  the receptor type (public or occupational), and  $\tau$  the index of the subaggregate. This will only be needed for supercomponents 5 and 6, which need subaggregates explicitly. If aggregation proceeds in one step, as for all other supercomponents, then the baseline risks are denoted by  $R_{j\chi o o}$ , where  $\chi$  is either 'o' or 'p'.

The aggregation of risk reduction factors that do not have numerical values associated with them, presents a major problem in this evaluation. A large risk reduction factor for a very small risk may bias the aggregation because it cannot be weighted with an appropriately small weight. In this situation, aggregating by means of geometrical average minimizes the bias that may be caused by widely different risk reduction factors. However, there will be a residual bias that cannot be removed unless the baseline risks are known. The related problems and assumptions are discussed in each case.

## G.1.2 Aggregation of the Eight Components

### G.1.2.1 Supercomponent 1: Fatal Transportation Accidents

In Supercomponent 1, the fatal transportation accidents in the three components listed in Table G.1-2 are aggregated. Direct traffic fatalities are by far the largest risk component, dominating the other two components. The aggregate consequence reduction factor for the first supercomponent is

$$\Gamma_{1\kappa\lambda} = \prod_{\tau \in \{n_1\}} (\rho_{\tau p \kappa \lambda})^{g_{1\tau}}, \quad (\text{G.1.1})$$

with the set  $\{n_1\} = \{21, 30, 33\}$ , and the weights

$$g_{1\tau} = \frac{R_{\tau p 00}}{\sigma_1}, \quad (\text{G.1.2})$$

with the sum  $\sigma_1$  given by

$$\sigma_1 = \sum_{\delta \in \{n_1\}} R_{\delta p 00}. \quad (\text{G.1.3})$$

If the relationship

$$R_{21p00} > 10^5 R_{3\chi p 00}, \text{ for } \chi = 0, 3 \quad (\text{G.1.4})$$

TABLE G.1-2

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 1:  
TRANSPORTATION FATALITIES**

COMPONENT	DESCRIPTION	COMMENTS
$P_{21} p_{\lambda}$	Fatalities caused directly by impact	Large baseline risk
$P_{30} p_{\lambda}$	Fatalities caused by early radiation effects in nondispersal accidents	Very small baseline risk
$P_{33} p_{\lambda}$	Fatalities caused by early radiation effects in atmospheric dispersal accidents	Very small baseline risk

holds, then the weights can without significant loss of accuracy be set at

$$g_{30} = g_{33} = 0, \quad g_{21} = 1. \quad (\text{G.1.5})$$

The aggregated risk reduction factor is then simply

$$\Gamma_{1\kappa\lambda} = \rho_{21\rho\kappa\lambda}, \quad (\text{G.1.6})$$

and its standard error is

$$\Delta\Gamma_{1\kappa\lambda} = \Delta\rho_{21\rho\kappa\lambda}. \quad (\text{G.1.7})$$

Numerical values for the  $\lambda$  and  $\kappa$  dependent quantities are given in Table G.1-3 for Level II treatments, aggregated consequence reduction factors  $\Gamma_{1\kappa\lambda}$  indicate an increase in this supercomponent by factors between 1.0 and 1.5 with a weak dependence on location. The relative errors of these factors 7 to 8 percent. For Treatment Option 3, this component shows no increases within the errors for different locations; for Treatment Option 4, there is a decrease of this risk component by factors of 1 to 3.5 with relative errors of up to 7 percent. Here, a moderate location dependence is found.

The corresponding baseline risk or consequence  $\Gamma_{1,0,0}$  is of a significant amount so that even modest risk increases or decreases are of importance. The treatment dependence of these consequence reduction factors is shown in Figure G.1-1 for Location 3. It demonstrates the change from a consequence increase for Level II treatments to a consequence reduction for Level III treatments. For Location 1, the factors are identical to 1; for Treatment Options 1, 2 and 3 and Locations 2, 3 and 4, there are no significant differences from those shown in Figure G.1-1. For Treatment Options 4, however, the value goes from 1 to 3.5, increasing with decentralized location. These reduction factors are applied to a low baseline risk of 0.2 traffic fatalities per year.

#### G.1.2.2 Supercomponent 2: Transportation Accident Injuries

In Supercomponent 2 injuries in transportation accidents are combined. Three components are aggregated in Table G.1-4. Direct traffic injuries are by far the largest risk component in this aggregate.

$$\Gamma_{2\kappa\lambda} = \prod_{\tau \in \{n_2\}} (\rho_{\tau\rho\kappa\lambda})^{g_{2\tau}}, \quad (\text{G.1.8})$$

with the set  $\{n_2\} = \{22, 31, 34\}$ . With the same argument as in last section, the weights can be set at

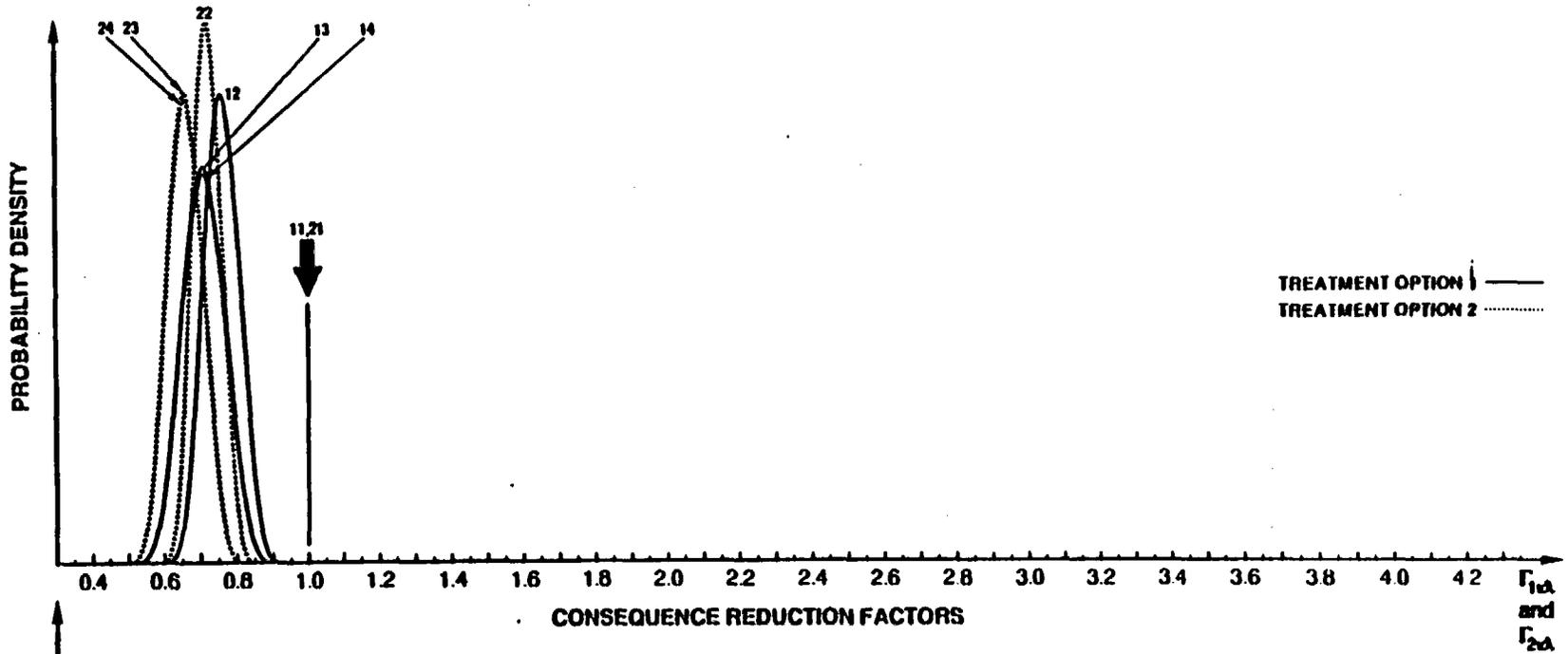
$$g_{22} = 1; \quad g_{31} = g_{34} = 0. \quad (\text{G.1.9})$$

TABLE G.1-3

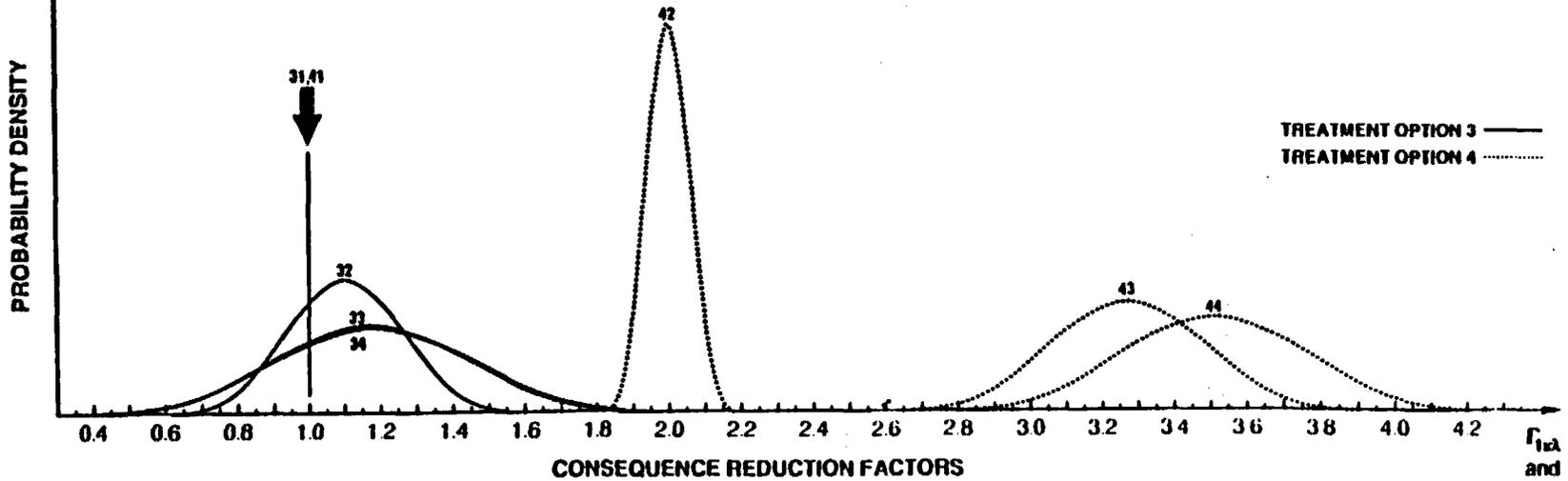
**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{1,k,l}$  FOR SUPERCOMPONENT 1:  
FATALITIES IN TRANSPORTATION ACCIDENTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{1,1,1}$	1	
$\Gamma_{1,1,2}$	0.760 $\pm$ 0.48	
$\Gamma_{1,1,3}$	0.713 $\pm$ 0.57	
$\Gamma_{1,1,4}$	0.715 $\pm$ 0.58	
$\Gamma_{1,2,1}$	1	
$\Gamma_{1,2,2}$	0.720 $\pm$ 0.42	
$\Gamma_{1,2,3}$	0.666 $\pm$ 0.48	
$\Gamma_{1,2,4}$	0.666 $\pm$ 0.49	
$\Gamma_{1,3,1}$	1	
$\Gamma_{1,3,2}$	1.10 $\pm$ 0.17	
$\Gamma_{1,3,3}$	1.17 $\pm$ 0.26	
$\Gamma_{1,3,4}$	1.18 $\pm$ 0.27	
$\Gamma_{1,4,1}$	1	
$\Gamma_{1,4,2}$	2.00 $\pm$ 0.06	
$\Gamma_{1,4,3}$	3.27 $\pm$ 0.21	
$\Gamma_{1,4,4}$	3.51 $\pm$ 0.25	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{1,0,0}$	0.2	FSEIS (DOE, 1990a),

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Appendix I, Attachment G

FIGURE G 1-1 CONSEQUENCE REDUCTION FACTORS  $\Gamma_{1kA}$  AND  $\Gamma_{2kA}$  FOR PUBLIC FATALITIES AND INJURIES IN TRAFFIC ACCIDENTS. THE LARGER VALUES FOR TREATMENT OPTION 4 ARE DUE TO A DECREASE IN THE NUMBER OF TRANSPORTS.

TABLE G.1-4

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 2:  
TRANSPORTATION INJURIES**

COMPONENT	DESCRIPTION	COMMENTS
P <sub>22PKλ</sub>	Injuries caused directly by accident impact	Significant baseline risk
P <sub>31PKλ</sub>	Injuries caused by early radiation in nondispersal accidents	Very low baseline risk
P <sub>34PKλ</sub>	Injuries caused by early radiation effects in atmospheric dispersal accidents	Very low baseline risk

The aggregated consequence reduction factor is then

$$\Gamma_{2\kappa\lambda} = \rho_{22\rho\kappa\lambda} , \quad (\text{G.1.10})$$

with a standard error of

$$\Delta\Gamma_{2\kappa\lambda} = \Delta\rho_{22\rho\kappa\lambda} . \quad (\text{G.1.11})$$

All consequence reduction factors explicitly depend on both the treatment  $\kappa$  and the location  $\lambda$ . Numerical values for the  $\kappa$  and  $\lambda$  quantities are given in Table G.1-5. The values are the same as those in Table G.1-3 due to the assumptions (G.1.5) and (G.1.9). Thus Figure G.1-1 and the corresponding discussion in the last section applies here as well. The consequence reduction factors apply to an acceptable number of about 3 traffic injuries sustained annually.

### G.1.2.3 Supercomponent 3: Occupational Fatalities

In Supercomponent 3, two components are aggregated (Table G.1-6).

The aggregation of two components yields

$$\Gamma_{3\kappa\lambda} = \prod_{\tau \in \{n_3\}} (\rho_{\tau o\kappa\lambda})^{g_{3\tau}} , \quad (\text{G.1.12})$$

with the set  $\{n_3\} = \{53, 55\}$ . The weights are

$$g_{3\tau} = \frac{R_{\tau o00}}{\sigma_3} , \quad (\text{G.1.13})$$

where

$$\sigma_3 = \sum_{\tau=1}^2 R_{\tau o00} . \quad (\text{G.1.14})$$

Note that the risks are given in Sections F.2.1.1 and F.2.2.1 by

$$R_{53 o\kappa\lambda} = N_{o1}^{(\kappa)} P_{of} (1 - f_{531}) , \quad (\text{G.1.15})$$

TABLE G.1-5

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{2\kappa\lambda}$  FOR SUPERCOMPONENT 2:  
INJURIES IN TRANSPORTATION ACCIDENTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{211}$	1	
$\Gamma_{212}$	0.760 $\pm$ 0.048	
$\Gamma_{213}$	0.713 $\pm$ 0.057	
$\Gamma_{214}$	0.715 $\pm$ 0.058	
$\Gamma_{221}$	1	
$\Gamma_{222}$	0.720 $\pm$ 0.042	
$\Gamma_{223}$	0.666 $\pm$ 0.048	
$\Gamma_{224}$	0.666 $\pm$ 0.049	
$\Gamma_{231}$	1	
$\Gamma_{232}$	1.10 $\pm$ 0.17	
$\Gamma_{233}$	1.17 $\pm$ 0.26	
$\Gamma_{234}$	1.18 $\pm$ 0.27	
$\Gamma_{241}$	1	
$\Gamma_{242}$	2.00 $\pm$ 0.06	
$\Gamma_{243}$	3.27 $\pm$ 0.21	
$\Gamma_{244}$	3.51 $\pm$ 0.25	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{200}$	3.0	FSEIS (DOE, 1990a), Executive Summary

TABLE G.1-6

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 3:  
OCCUPATIONAL FATALITIES**

COMPONENT	DESCRIPTION	COMMENTS
P 530 κλ	General industrial accidents	
P 550 κλ	Forklift accidents	

and

$$R_{550\kappa\lambda} = n_f^{(\kappa)} n_f^{(\kappa)} P_{of} f_{531} \Phi_{551}, \quad (G.1.16)$$

where  $P_{of}$  is a mere scale factor and drops out for error calculations; and the relative abundance of forklift accidents  $f_{531}$  is contravariant in the two equations. Thus it can be assumed that, in weight calculations, uncertainties are highly correlated. Taking into account that both components have the same risk reduction factor, the standard error of  $\Gamma_{3\kappa\lambda}$  is thus

$$\Delta \Gamma_{3\kappa\lambda} = \Delta \rho_{530\kappa\lambda}. \quad (G.1.17)$$

The numerical values are given in Table G.1-7. Although  $\lambda$  is carried as an index, these risk reduction factors all are smaller than 1 and depend only on treatment  $\kappa$  but not on the location parameter  $\lambda$ . They actually indicate an increase in consequence by 3.6 to 13 with relative errors of 5 to 7 percent.

In Figure G.1-2 the inverse of the consequence reduction  $\Gamma_{3\kappa\lambda}$  is plotted for the four values  $\kappa = 1, 4$ . The data show the increase in risk with more complex treatment, due to the increase in manpower required. These consequence augmentation factors apply to a relatively low baseline risk of 0.0016 occupational fatalities annually.

#### G.1.2.4 Supercomponent 4: Occupational Injuries

In Supercomponent 4, occupational injuries, the components aggregated are listed in Table G.1-8. Most important in this aggregation are the injuries from general industrial and forklift accidents; morbidity from exposure to chemical agents are very small. Generally, the aggregated risk reduction factor is

$$\Gamma_{4\kappa\lambda} = (\rho_{540\kappa\lambda})^{g_{54}} (\rho_{560\kappa\lambda})^{g_{56}} \left( \prod_{\tau=14}^{20} \rho_{\tau0\kappa\lambda} \rho_{15a\kappa\lambda} \rho_{620\kappa\lambda} \right)^{g_{chem}/9}, \quad (G.1.18)$$

where in this particular case

$$g_{54} = \frac{R_{54000}}{\sigma_4} \quad ; \quad g_{56} = \frac{R_{56000}}{\sigma_4} \quad ; \quad g_{chem} = 0, \quad (G.1.19)$$

TABLE G.1-7

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{3 \times 1}$  FOR  
SUPERCOMPONENT 3: OCCUPATIONAL FATALITIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{31 \lambda}$	$0.276 \pm 0.016$	
$\Gamma_{32 \lambda}$	$0.260 \pm 0.015$	
$\Gamma_{33 \lambda}$	$0.170 \pm 0.010$	
$\Gamma_{34 \lambda}$	$0.076 \pm 0.004$	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{300}$	$1.6 \cdot 10^{-3}$	U.S. Dept. of Labor, Bulletin 2366, 1990

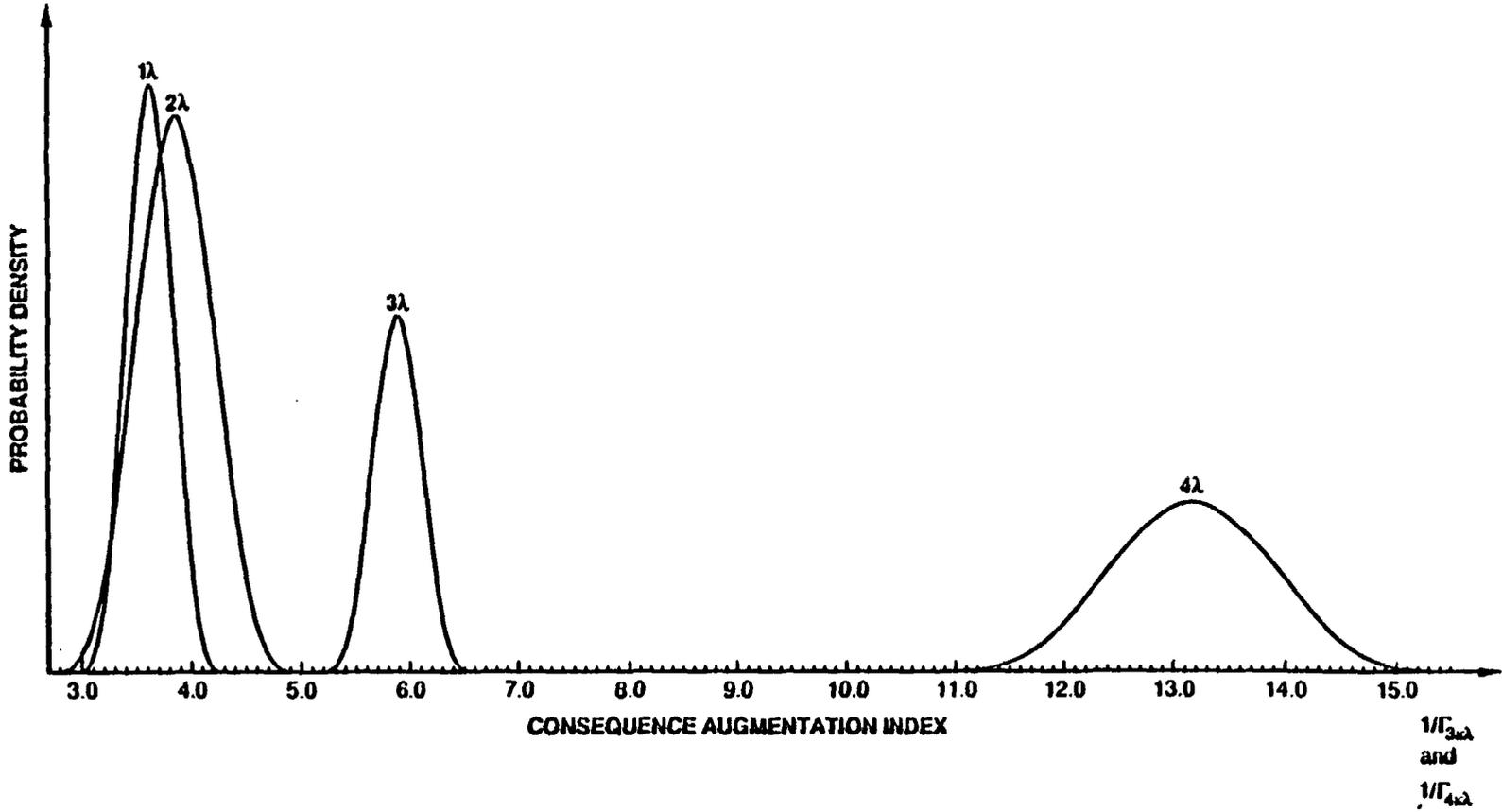


FIGURE G.1-2 CONSEQUENCE AUGMENTATION FACTORS  $1/\Gamma_{3\lambda}$  AND  $1/\Gamma_{4\lambda}$  FOR OCCUPATIONAL FATALITIES AND INJURIES INVOLVING ACCIDENTS. THE INVERSE OF RISK REDUCTION FACTORS, THE CONSEQUENCE AUGMENTATION FACTORS, ARE PLOTTED HERE TO GIVE A BETTER IMPRESSION OF THE INCREASE IN THESE COMPONENTS DUE TO TREATMENT

TABLE G.1-8

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 4:  
OCCUPATIONAL INJURIES**

COMPONENT	DESCRIPTION	COMMENTS
P 140 κλ	Routine, chemical, noncancer effects	Exceedingly small risk
P 150 κλ	Routine, chemical, noncancer effects	Exceedingly small risk
P 158 κλ	Routine, chemical, noncancer effects	Exceedingly small risk
P 160 κλ	Accident, chemical, noncancer effects	Exceedingly small risk
P 170 κλ	Accident, chemical, noncancer effects	Exceedingly small risk
P 180 κλ	Accident, chemical, noncancer effects	Exceedingly small risk
P 190 κλ	Accident, chemical, noncancer effects	Exceedingly small risk
P 200 κλ	Accident, chemical, noncancer effects	Exceedingly small risk
P 540 κλ	General industrial accidents	Sizeable risk
P 560 κλ	Forklift accidents	Small risks
P 620 κλ	VOC, routine, releases, noncancer effects	Exceedingly small risk

and

$$\sigma_4 = R_{54000} + R_{58000} \cdot \quad (G.1.20)$$

As no data are available to weight the very small risks of morbidity due to exposure to chemicals, all have to be aggregated in an unweighted geometrical average. As exceedingly small contributions they are neglected here.

In the evaluation of the standard errors, the two components finally aggregated are not independent. In this particular case

$$\Delta \Gamma_{4\kappa\lambda} = \Delta \rho_{540\kappa\lambda} \cdot \quad (G.1.21)$$

Numerical values are given in Table G.1-9; they are the same as those for supercomponent  $\Gamma_{3\kappa\lambda}$ , varying from an equivalent consequence increase by a factor of 3.6 to a factor of 13. The consequence augmentation factors are given in Figure G.1-2 and are applied to an annual occupational risk of 0.7 injuries with workdays lost.

#### G.1.2.5 Supercomponent 5: Occupational Cancer

In this supercomponent, the 22 components listed in Table G.1-10 are aggregated. For these components, four aggregated partial risk values are available. The choice made here is to aggregate the appropriate components that make up the partial risk values at equal weight and then, as soon as the partial baseline risks are known, aggregate further with a properly weighted geometric average. This implies the assumption that the components of the partial risks are of about equal risk.

The partial aggregations according to the list in Table G.1-11 are

$$\Xi_{5\kappa\lambda\tau} = \left( \prod_{\chi=\{n_i\}} \rho_{\chi o \kappa \lambda} \right)^{\frac{1}{m_\tau}}, \quad (G.1.22)$$

with standard errors

$$(\Delta \Xi_{5\kappa\lambda\tau})^2 = \left( \frac{1}{m_\tau} \right)^2 \sum_{\chi=\{n_i\}} \left( \frac{\Delta \rho_{\chi o \kappa \lambda}}{\rho_{\chi o \kappa \lambda}} \right)^2 \cdot \quad (G.1.23)$$

TABLE G.1-9

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{4 \times 1}$  FOR SUPERCOMPONENT 4:  
OCCUPATIONAL INJURIES**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{41 \lambda}$	0.276 $\pm$ 0.016	
$\Gamma_{42 \lambda}$	0.260 $\pm$ 0.015	
$\Gamma_{43 \lambda}$	0.170 $\pm$ 0.010	
$\Gamma_{44 \lambda}$	0.076 $\pm$ 0.004	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{400}$	0.7 $\pm$ 0.03	U.S. Dept. of Labor, Bulletin 2366, 1990

TABLE G.1-10

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 5:  
OCCUPATIONAL CANCER**

COMPONENT	DESCRIPTION	COMMENTS
P 1 0 κ	Routine, internal radiation	
P 2 0 κ	Routine, internal radiation	
P 3 0 κ	Routine, internal radiation	
P 4 0 κ	Routine, external radiation	
P 5 0 κ	Routine, external radiation	
P 6 0 κ	Accident, internal radiation	
P 7 0 κ	Accident, internal radiation	
P 8 0 κ	Accident, internal radiation	
P 9 0 κ	Accident, internal radiation	
P 1 0 0 κ	Accident, internal radiation	
P 1 1 0 κ	Accident, internal radiation	
P 1 2 0 κ	Routine, chemical exposure	
P 1 3 0 κ	Routine, chemical exposure	
P 1 3 a κ	Routine, chemical exposure	
P 2 7 0 κ λ	Routine transport, external radiation	
P 2 8 0 κ λ	Routine transport, external radiation	
P 2 9 0 κ λ	Routine transport, external radiation	
P 5 7 0 κ	Routine, treatment, external radiation	
P 5 8 a κ	Routine, treatment, external radiation	
P 5 9 0 κ	Routine, treatment, internal radiation	
P 6 0 0 κ	Routine, treatment, internal radiation	
P 6 1 0 κ	Routine, treatment, VOC releases	

TABLE G.1-11

**SETS FOR PARTIAL AGGREGATIONS  $\Xi$  FOR SUPERCOMPONENT 5:  
OCCUPATIONAL CANCER FATALITIES**

$\tau$	$m_{\tau}$	$\{n_{\tau}\}$	COMMENTS
1	7	4, 5, 27, 28, 29, 57, 58	Radiation, routine external exposures
2	5	1, 2, 3, 59, 60	Radiation, routine internal exposures
3	6	6, 7, 8, 9, 10 11	Accidents, internal exposures
4	4	12, 13, 13a, 61	Chemicals, routine exposure
Total	22		

In this aggregation, Component 11, the C10 accident, is dropped from consideration. The risk is excessively low and the risk reduction factor very high. This contribution, not listed in the FSEIS (DOE, 1990a), is therefore not allowed to influence the result.

There is an additional obstacle to the weighting of the partial aggregations: for Components 57 to 61, all components of the risks of waste treatment, no baseline risks have been estimated. It is assumed here that the same health and safety concerns that govern all WIPP operations are evident in the Treatment Facility as well, leading essentially to the same risks. Thus it is appropriate to assume that, if the baseline risk is  $R_{j\ 0\ 0\ 0\ \tau}$ , where  $j$  stands for the risk component, 'o' is the index for occupational risk,  $\tau$  is the index of the partial aggregation applied to a set of  $m_\tau$  risk reduction factors, the baseline risk for a combined set of  $\{M_\zeta\} = \{m_\tau\} + \{n_\tau\}$  factor is given by

$$R_{j\ 0\ 0\ 0\ \zeta} = \frac{M_\zeta}{m_\tau} R_{j\ 0\ 0\ 0\ \tau} . \quad (G.1.24)$$

This extension of health and safety practices can be applied to the partial aggregations  $\tau = 1, 2,$  and  $4$  in Table G.1-11.

The final, properly weighted aggregation of occupational cancer then yields a consequence reduction factor

$$\Gamma_{5\ \kappa\ \lambda} = \prod_{\tau=1}^4 (\Xi_{5\ \kappa\ \lambda\ \tau})^{g_{5\tau}} , \quad (G.1.25)$$

with the weights

$$g_{5\tau} = \frac{R_{5\ 0\ 0\ 0\ \tau}}{\sum_{\chi=1}^4 R_{5\ 0\ 0\ 0\ \chi}} , \quad (G.1.26)$$

and standard errors given by

$$\left( \frac{\Delta \Gamma_{5\ \kappa\ \lambda}}{\Gamma_{5\ \kappa\ \lambda}} \right)^2 = \sum_{\tau=1}^4 \left( g_{5\tau} \frac{\Delta \Xi_{5\ \kappa\ \lambda\ \tau}}{\Xi_{5\ \kappa\ \lambda\ \tau}} \right)^2 . \quad (G.1.27)$$

Here again the weights have been normalized and are calculated using the aggregated baseline risks in Table G.1-12. Numerical values for the final aggregation are listed in Table G.1-13.

TABLE G.1-12

## AGGREGATED BASELINE RISKS FOR THE SETS IN TABLE G.1-11

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Aggregated Baseline Risks $R_{50,001}$ :		
$R_{50,001}$	0.025	Compiled from data in FSEIS (DOE, 1990a)
$R_{50,002}$	0.0012	*
$R_{50,003}$	0.0011	*
$R_{50,004}$	$2.9 \cdot 10^{-7}$	*

TABLE G.1-13

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{s,k}$  FOR SUPERCOMPONENT 5:  
OCCUPATIONAL CANCERS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENT/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{51,1}$	0.853 $\pm$ 0.031	
$\Gamma_{51,2}$	0.814 $\pm$ 0.030	
$\Gamma_{51,3}$	0.846 $\pm$ 0.031	
$\Gamma_{51,4}$	0.852 $\pm$ 0.032	
$\Gamma_{52,1}$	0.841 $\pm$ 0.030	
$\Gamma_{52,2}$	0.801 $\pm$ 0.029	
$\Gamma_{52,3}$	0.833 $\pm$ 0.030	
$\Gamma_{52,4}$	0.840 $\pm$ 0.031	
$\Gamma_{53,1}$	0.704 $\pm$ 0.023	
$\Gamma_{53,2}$	0.677 $\pm$ 0.025	
$\Gamma_{53,3}$	0.699 $\pm$ 0.027	
$\Gamma_{53,4}$	0.704 $\pm$ 0.028	
$\Gamma_{54,1}$	0.460 $\pm$ 0.019	
$\Gamma_{54,2}$	0.420 $\pm$ 0.017	
$\Gamma_{54,3}$	0.435 $\pm$ 0.018	
$\Gamma_{54,4}$	0.452 $\pm$ 0.019	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{500}$	5 $\cdot$ 10 <sup>-3</sup>	FSEIS (DOE, 1990a)

Within the error, the consequence reduction factors are independent of the location index  $\lambda$ . For Level II treatments, they range from 7 to 8; for Treatment Option 3, they are grouped around 11; for Treatment Option 4, the consequence reduction factors are down to 8 again. The factors show very little dependence on location, and a mixed influence on Treatment Option. Relative standard errors are about 12 percent.

In Figure G.1-3, the consequence reduction factors  $\Gamma_{s\kappa\lambda}$  are shown, demonstrating the grouping around 8 for Level II treatments and the grouping of the Level III treatments around 11 for Treatment Option 3 and around 8 for Treatment Option 4. These risk consequence reduction factors are applied baseline or consequence of 0.005 cancers per year of option.

#### G.1.2.6 Supercomponent 6: Public Cancers

In Supercomponent 6, public cancers from 22 components are aggregated. They are listed in Table G.1-14. For these 22 contributions, numerical values for only four subaggregates are available. Again the choice is made to aggregate by unweighted geometrical averaging, before final properly weighted aggregation.

The partial aggregations according to Table G.1-15 are

$$\Xi_{6\kappa\lambda\tau} = \left( \prod_{\chi=\{n_i\}} \rho_{\chi\rho\kappa\lambda} \right)^{\frac{1}{m_\tau}}, \quad (\text{G.1.28})$$

with standard errors

$$\left( \frac{\Delta \Xi_{6\kappa\lambda}}{\Xi_{6\kappa\lambda}} \right)^2 = \left( \frac{1}{m_\tau} \right)^2 \sum_{\chi=\{n_i\}} \left( \frac{\Delta \rho_{\chi\rho\kappa\lambda}}{\rho_{\chi\rho\kappa\lambda}} \right)^2. \quad (\text{G.1.29})$$

In this aggregation, the C10 accident in Component 11 is not used because the risk is excessively low and the risk reduction factor very high. Even though the risk is considered in the FSEIS, it will not be allowed to dominate the averaging.

The situation with new treatment risks is the same as that in the last supercomponent: for Components 59, 60, and 61, no baseline risks are available. Again, the assumption of the same health and safety standards, this time for the public, leads to the formulation

$$R_{j\rho 00\zeta} = \frac{M_\zeta}{m_\tau} R_{j\rho 00\tau}, \quad (\text{G.1.30})$$

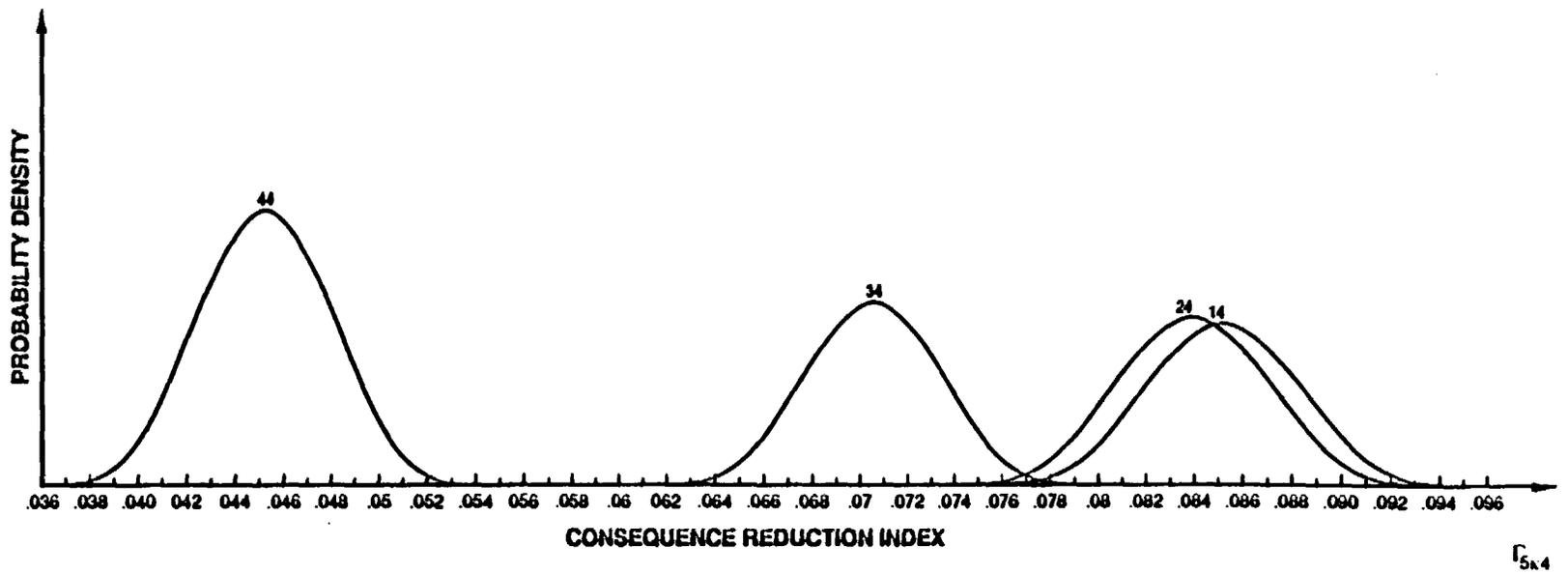


FIGURE G.1-3 CONSEQUENCE REDUCTION INDICES  $\Gamma_{5 \times 4}$  FOR OCCUPATIONAL CANCERS DUE TO RADIATION AND CHEMICAL AGENTS. BECAUSE OF THE NEAR INDEPENDENCE FROM LOCATION, ONLY THE CURVES FOR LOCATION  $\lambda = 4$  ARE SHOWN.

TABLE G.1-14

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 6:  
PUBLIC CANCERS**

COMPONENT	DESCRIPTION	COMMENTS
P 1 p κ	Routine internal	
P 2 p κ	Routine internal	
P 3 p κ	Routine internal	
P 6 p κ	Internal accident	
P 7 p κ	Internal accident	
P 8 p κ	Internal accident	
P 9 p κ	Internal accident	
P 10 p κ	Internal accident	
P 11 p κ	Internal accident	
P 12 p κ	Routine chemical	
P 13 p κ	Routine chemical	
P 23 p κ λ	Routine transportation	
P 24 p κ λ	Routine transportation	
P 25 p κ λ	Routine transportation	
P 26 p κ λ	Routine transportation	
P 32 p κ λ	Transportation accident, nondispersal	
P 35 p κ λ	Transportation accident, dispersal	
P 36 p κ λ	Transportation accident, cloudshine	
P 37 p κ λ	Transportation accident, groundshine	
P 59 p κ	Treatment routine internal radiation	
P 60 p κ	Treatment routine internal radiation	
P 61 p κ	Treatment routine VOC releases	

**TABLE G.1-15**  
**SETS FOR PARTIAL AGGREGATIONS  $\Xi$  FOR SUPERCOMPONENT 6:**  
**PUBLIC CANCER FATALITIES**

$\tau$	$m_{\tau}$	$\{n_{\tau}\}$	COMMENTS
1	4	23, 24, 25, 26	Radiation, routine external exposures
2	4	32, 35, 36, 37	Radiation, accidental external exposures
3	11	1, 2, 3, 6, 7, 8, 9, 10, 11, 59, 60	Radiation, internal exposures
4	3	12, 13, 61	Chemicals, routine exposure
<b>Total</b>	<b>22</b>		

for the baseline risk of the set  $\{M_\tau\} = \{m_\tau\} + \{n_\tau\}$  where the set  $\{m_\tau\}$  forms the subaggregate public risk  $R_{j p 0 0 \tau}$  and the set  $\{n_\tau\}$  comprises the components for which there are no baseline risk estimates. This extrapolation is needed for the partial aggregations  $\tau = 3$  and 4 in Table G.1-15.

The final aggregation of occupational cancer risks then yields consequence reduction factors

$$\Gamma_{6 \kappa \lambda} = \prod_{\tau=1}^4 (\Xi_{6 \kappa \lambda \tau})^{g_{6\tau}}, \quad (\text{G.1.31})$$

with the normalized weights

$$g_{6\tau} = \frac{R_{6 p 0 0 \tau}}{\sum_{\chi=1}^4 R_{6 p 0 0 \chi}}. \quad (\text{G.1.32})$$

The standard errors are given by

$$\left( \frac{\Delta \Gamma_{6 \kappa \lambda}}{\Gamma_{6 \kappa \lambda}} \right)^2 = \sum_{\tau=1}^4 \left( g_{6\tau} \frac{\Delta \Xi_{6 \kappa \lambda \tau}}{\Xi_{6 \kappa \lambda \tau}} \right)^2. \quad (\text{G.1.33})$$

Here again the weights have normalized to 1. The aggregated baseline risks  $R_{6 p 0 0 \tau}$  needed for the final aggregation are listed in Table G.1-16. The resulting numerical values for the consequence reduction factors are given in Table G.1-17. They range from about 1 to about 10, almost independent of the Treatment Option. The location dependence is illustrated in Figure G.1-4 for Treatment Option 3, showing widely separated narrow probability distributions.

#### G.1.2.7 Supercomponent 7: Occupational Cancer (Late Effects)

In supercomponent 7, the three components listed in Table G.1-18 are aggregated. In this aggregation it is assumed that for all of them the event probability is 1 and that the risk is evaluated for the one year during which the event occurs. As the baseline risks are not known, the risk reductions are geometrically averaged with equal weight.

The consequence reduction factors are then

$$\Gamma_{7 \kappa \lambda} = \prod_{\tau=40}^{42} (\rho_{\tau o \kappa \lambda})^{1/3}, \quad (\text{G.1.34})$$

TABLE G.1-16

## AGGREGATED BASELINE RISKS FOR THE SETS IN TABLE G.1-15

QUANTITY	VALUE ± STANDARD ERROR	COMMENTS/REFERENCES
Aggregated Baseline Risks $R_{8000i}$ :		
$R_{80001}$	$7.5 \cdot 10^{-8}$	Compiled from data in the FSEIS (DOE, 1990a)
$R_{80002}$	$3.8 \cdot 10^{-2}$	*
$R_{80003}$	$9.0 \cdot 10^{-5}$	*
$R_{80004}$	$6.9 \cdot 10^{-12}$	*

TABLE G.1-17

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{6r\lambda}$  FOR SUPERCOMPONENT 6:  
PUBLIC CANCERS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{611}$	1.13 $\pm$ 0.00	
$\Gamma_{612}$	2.64 $\pm$ 0.01	
$\Gamma_{613}$	7.44 $\pm$ 0.02	
$\Gamma_{614}$	9.47 $\pm$ 0.02	
$\Gamma_{621}$	1.13 $\pm$ 0.00	
$\Gamma_{622}$	2.65 $\pm$ 0.01	
$\Gamma_{623}$	7.46 $\pm$ 0.02	
$\Gamma_{624}$	9.49 $\pm$ 0.02	
$\Gamma_{631}$	1.13 $\pm$ 0.00	
$\Gamma_{632}$	2.65 $\pm$ 0.01	
$\Gamma_{633}$	7.46 $\pm$ 0.02	
$\Gamma_{634}$	9.49 $\pm$ 0.02	
$\Gamma_{641}$	1.13 $\pm$ 0.00	
$\Gamma_{642}$	2.65 $\pm$ 0.01	
$\Gamma_{643}$	7.47 $\pm$ 0.02	
$\Gamma_{644}$	9.50 $\pm$ 0.02	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{600}$	0.02	FSEIS (DOE, 1990a), Executive Summary

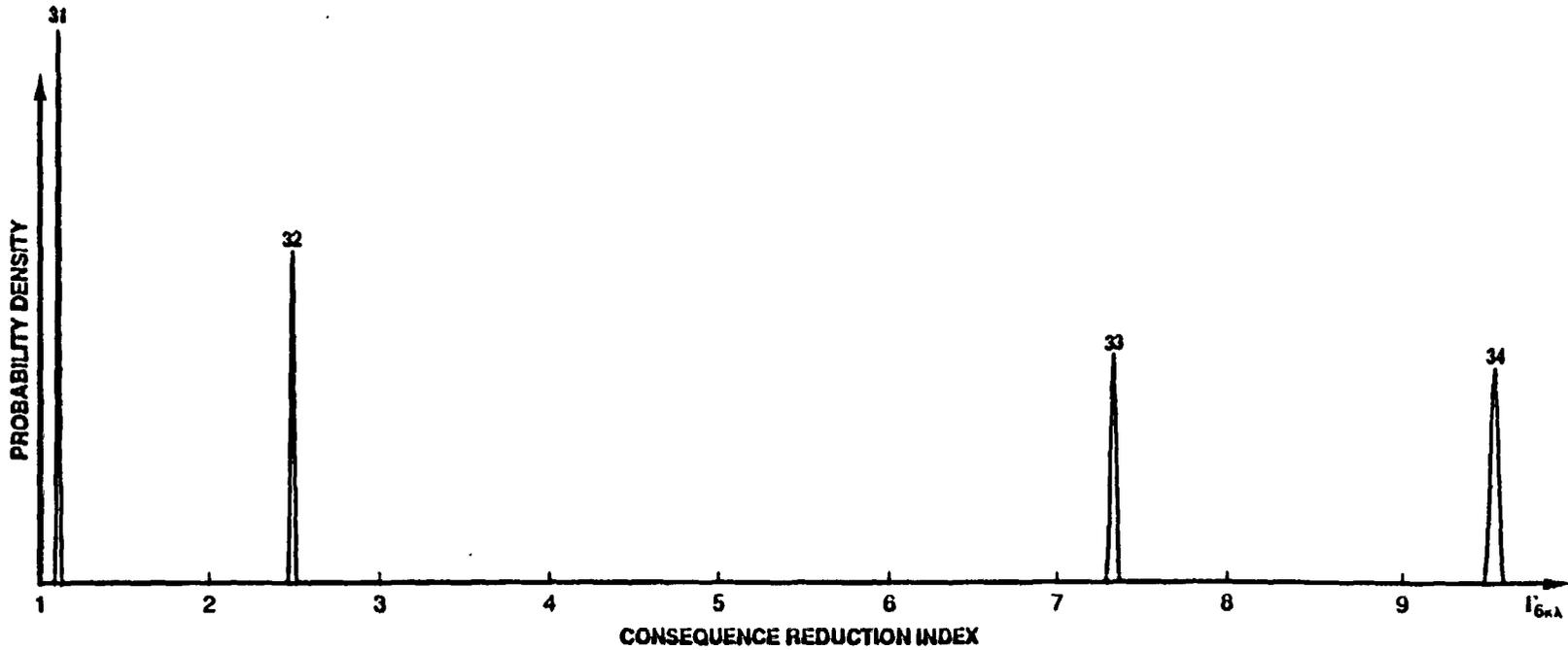


FIGURE G.1-4 CONSEQUENCE REDUCTION INDICES  $I_{6\alpha}$  FOR PUBLIC CANCERS CAUSED BY EXPOSURE TO RADIATION AND CHEMICAL AGENTS. BECAUSE OF THE NEAR INDEPENDENCE ON TREATMENT, ONLY THE VALUES FOR TREATMENT OPTION 3 ARE SHOWN, VARYING FROM 1 TO ALMOST TEN.

TABLE G.1-18

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 7:  
POST-CLOSURE OCCUPATIONAL CANCERS**

COMPONENT	DESCRIPTION	COMMENTS/REFERENCES
$p_{40 \text{ ex } 1}$	E1 scenario, direct exposure	Drilling crew
$p_{41 \text{ ex } 1}$	E2 scenario, direct exposure	Drilling crew
$p_{42 \text{ ex } 1}$	E1E2 scenario, direct exposure	Drilling crew

with standard errors given by

$$\left( \frac{\Delta \Gamma_{7\kappa\lambda}}{\Gamma_{7\kappa\lambda}} \right)^2 = \left( \frac{1}{9} \right) \sum_{\tau=40}^{42} \left( \frac{\Delta \rho_{\tau\sigma\kappa\lambda}}{\rho_{\tau\sigma\kappa\lambda}} \right)^2 \quad (\text{G.1.35})$$

Numerical values for the consequence reduction factors are given in Table G.1-19. The values are independent of the location parameter  $\lambda$ , as expected for a late post-closure effect. They range from about 5 to 9, with relative standard errors between 10 and 20 percent. Both Level II treatments yield consequence reduction factors close to 5, whereas for Level III treatments the values are 7 and 9, respectively. This is illustrated in Figure G.1-5, showing separate but overlapping values of the consequence reduction factors. They are, however, applied to an exceedingly small consequence in the  $10^{-8}$  range.

#### G.1.2.8 Supercomponent 8: Public Cancer (Late Effects)

In this supercomponent, the six components in Table G.1-20 are aggregated. Again, no risk values are available for the individual components, and the aggregate is formed by unweighted geometric averaging.

The consequence risk reduction factor is thus given by

$$\Gamma_{8\kappa\lambda} = \prod_{\tau=43}^{48} (\rho_{\tau\sigma\kappa\lambda})^{1/6}, \quad (\text{G.1.36})$$

with geometric standard errors given by Equations (C.1.20) and (C.1.22)

$$\begin{aligned} [\log_a \sigma_g (\Gamma_{8\kappa\lambda})]^2 &= [S (\Gamma_{8\kappa\lambda})]^2 \\ &= \sum_{\tau=43}^{48} [\log_a \sigma_g (\rho_{\tau\sigma\kappa\lambda})]^2, \end{aligned} \quad (\text{G.1.37})$$

and thus for the GSD

$$\sigma_g (\Gamma_{8\kappa\lambda}) = a^{S(\Gamma_{8\kappa\lambda})}. \quad (\text{G.1.38})$$

Again, as expected for a late post-closure effect, the factors  $\Gamma_{8\kappa\lambda}$  are location independent, with geometric standard errors given by the definitions given in Attachment C, Section C.1.3. The values for the consequence reduction factors range over one order of magnitude from 100 to 2,000 with geometric standard deviations between 2 and 3 (Table G.1-21). This situation is

TABLE G.1-19

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{7k1}$  FOR SUPERCOMPONENT 7:  
OCCUPATIONAL CANCERS, POST-CLOSURE EFFECTS**

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{711}$	5.0 $\pm$ 0.48	
$\Gamma_{721}$	5.0 $\pm$ 0.49	
$\Gamma_{731}$	6.9 $\pm$ 1.4	
$\Gamma_{741}$	9.4 $\pm$ 1.0	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{700}$	3 $\cdot$ 10 <sup>-8</sup>	FSEIS (DOE, 1990a), Executive Summary

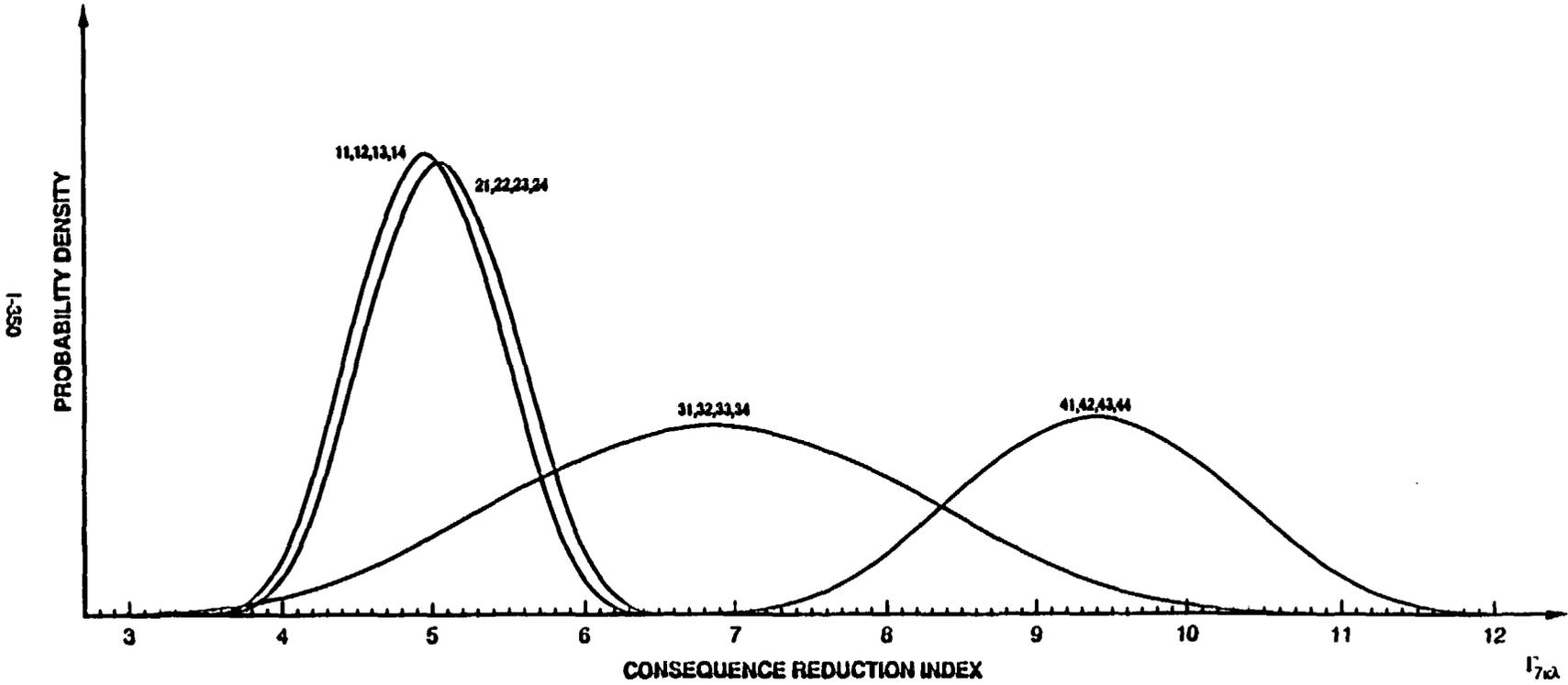


FIGURE G.1-5 CONSEQUENCE REDUCTION INDICES  $I_{7ca}$  FOR OCCUPATIONAL CANCERS IN THE LATE POST-CLOSURE PERIOD. THE INDICES ARE INDEPENDENT OF LOCA AND SHOW THE EFFECT OF TREATMENT ONLY.

TABLE G.1-20

**RISK REDUCTION FACTORS AGGREGATED IN SUPERCOMPONENT 8:  
POST-CLOSURE PUBLIC CANCER**

COMPONENT	DESCRIPTION	COMMENTS
P 43 p κ λ	Scenario E1 inhalation	Receptors: 5 persons at ranch 5 km from site
P 44 p κ λ	Scenario E2 inhalation	
P 45 p κ λ	Scenario E1E2 inhalation	
P 46 p κ λ	Scenario E1 ingestion	
P 47 p κ λ	Scenario E2 ingestion	
P 48 p κ λ	Scenario E1E2 ingestion	

TABLE G.1-21

**CONSEQUENCE REDUCTION FACTORS  $\Gamma_{s, \lambda}$  FOR SUPERCOMPONENT 8:  
PUBLIC CANCER**

QUANTITY	VALUE (GSD)	COMMENTS/REFERENCES
<b>Consequence Reduction Factors:</b>		
$\Gamma_{s, 1, \lambda}$	106 (2.3)	
$\Gamma_{s, 2, \lambda}$	115 (2.2)	
$\Gamma_{s, 3, \lambda}$	221 (2.4)	
$\Gamma_{s, 4, \lambda}$	2030 (2.7)	
<b>Annual Baseline Risk or Consequence:</b>		
$\Gamma_{s, 0, \lambda}$	$7 \cdot 10^{-5}$	FSEIS (DOE, 1990a) Executive Summary

GSD = Geometrical Standard Deviation.

illustrated in Figure G.1-6, which shows the factors on a logarithmic scale. There is little difference between the two Level II treatments but a substantial spread between the two Level III treatments. These consequence reduction factors are, in this case, applied to a very small baseline in the range below  $10^{-4}$ .

## G.2 CALCULATIONS OF CONSEQUENCE REDUCTION INDICES $\Theta_{\kappa\lambda}$ AND CONSEQUENCE AUGMENTATION INDICES $\Psi_{\kappa\lambda}$

Although the consequence reduction and augmentation indices,  $\Theta_{\kappa\lambda}$  and  $\Psi_{\kappa\lambda}$ , can be calculated directly from Equations (B.3.19 and B.3.20), the indirect route via single and multi-attribute utility indices  $\theta_{j\kappa\lambda}$  and  $U_{\kappa\lambda}$  and Equations (B.3.13) and (B.3.18) is chosen in order to accommodate quantities with both normal and lognormal distributions. The weighted sum leading to the utility indices  $U_{\kappa\lambda}$  provides the vehicle to again apply the Central Limit Theorem and assume a normal distribution for the utility indices and, therefore, a lognormal distribution for the consequence reduction or augmentation indices.

### G.2.1 Single Attribute Utility Indices $\theta_{\kappa\lambda}$

#### G.2.1.1 Consequence Reduction Factors with Assumed Normal Distribution

Assuming a normal distribution by virtue of the Central Limit Theorem discussed before (see Attachment B.4.4), the risk reduction factors  $\Gamma_{j\kappa\lambda}$  and their standard errors  $\Delta \Gamma_{j\kappa\lambda}$  yield the single attribute utility functions

$$\theta_{j\kappa\lambda} = \log_{10} (\Gamma_{j\kappa\lambda}) , \quad (\text{G.2.1})$$

with standard errors of

$$\Delta \theta_{j\kappa\lambda} = Q \frac{\Delta \Gamma_{j\kappa\lambda}}{\Gamma_{j\kappa\lambda}} \quad \text{with} \quad Q = \frac{1}{\ln 10} = 0.434294... \quad (\text{G.2.2})$$

The distribution of the stochastic variable  $\theta_{j\kappa\lambda}$  with standard error  $\Delta \theta_{j\kappa\lambda}$  is no longer normal.

#### G.2.1.2 Consequence Reduction Factors with Assumed Lognormal Distribution

For quantities with large error intervals such as Supercomponent 8, the assumption of a lognormal distribution is a convenient choice. Given the geometric mean  $\Gamma_{j\kappa\lambda}$  and a geometric standard deviation  $\sigma_g (\Gamma_{j\kappa\lambda})$ , and taking the logarithm of the lognormally distributed argument will result in a normally distributed quantity

$$\theta_{j\kappa\lambda} = \log_{10} (\Gamma_{j\kappa\lambda}) , \quad (\text{G.2.3})$$

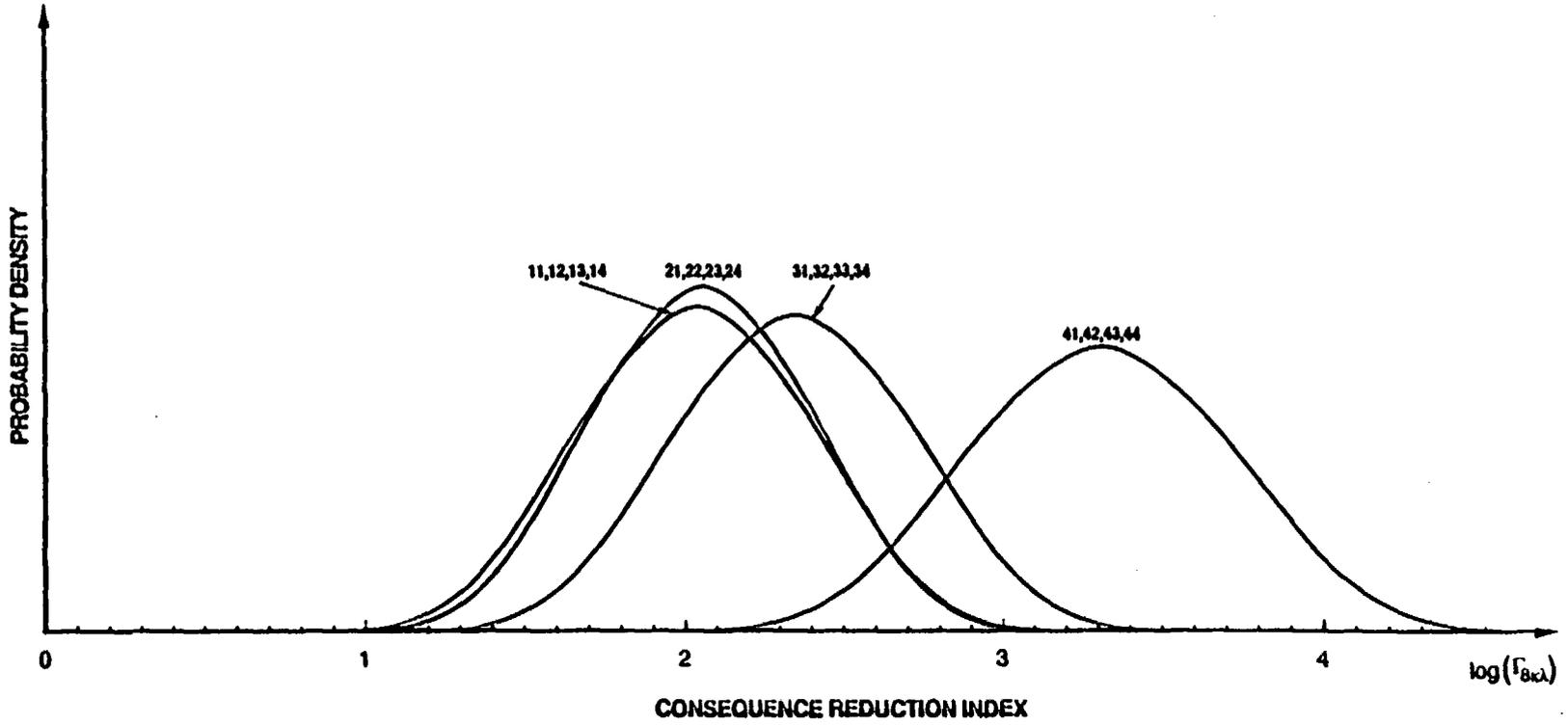


FIGURE G.1-6 CONSEQUENCE REDUCTION INDICES  $\Gamma_{Bc\lambda}$  FOR PUBLIC CANCERS IN THE LATE POST-CLOSURE PERIOD PLOTTED ON A LOGARITHMIC SCALE. THE INDICES SHOW THE DEPENDENCE ON TREATMENT OPTION, BEING INDEPENDENT OF LOCATION.

with a standard deviation of

$$\Delta \theta_{j\kappa\lambda} = \log_{10} \sigma_g (\Gamma_{j\kappa\lambda}) . \quad (\text{G.2.4})$$

## G.2.2 Calculation of Multiattribute Utility Indices

### G.2.2.1 Societal Valuations

The elicitation of the societal weights for various components of the total risk relative to each other is based on premises that are somewhat unusual as compared to those usually elicited in a Multi-Attribute Utility Theory:

- It is not the actual components that are being valued, but reductions and increases in those components.
- Only relatively small increases and decreases (for the small risks discussed here increases and decreases by a factor of two) are being considered.
- It is recognized that for the small size of these risks, the rough order of magnitude of the risk influences the valuation of a risk reduction or risk enhancement.

The first condition arises from the fact that at issue is a risk comparison, i.e., a risk reduction or a risk augmentation. The second is based on the fact that the law of diminishing marginal utility of economics is applied here to risk comparison. It is taken into account by using the logarithm of a particular risk reduction factor as the utility for that component. It is shown in Attachment B that, in risk assessment, the law of diminishing marginal utility describes the fact that a unit increase in risk reduction is most valuable for a risk reduction of one, less valuable for a risk reduction of 10 and even less for 100, and so on. The third condition accounts for the fact that a risk reduction of 2 is most valuable for a risk of immediate concern, say for  $10^{-2} < p < 1$ , much less so for a risk of lesser concern with a value of  $10^{-3}$  to  $10^{-4}$ , and almost irrelevant for a risk smaller than  $10^{-6}$ .

The societal valuations or weights needed here, are a measure of the preference for one risk reduction over another by the same factor. Thus, these relative weights have little or nothing to do with the dollar value of a human life. This valuation is squeezed rather tightly into a very narrowly scoped question to every person participating in the valuation procedure:

"How do I rate an increase or decrease by a factor of two in one component (say occupational fatalities) relative to the same change in another component (say cancer deaths in 10 years)?"

As mentioned above, the absolute magnitude of the components being compared is clearly of some import. A pair-wise comparison, however, should not be influenced by the magnitude of any other component.

In the time schedule of this work, it was not possible to acquaint the necessary number of experts with this new valuation procedure. A more technical viewpoint, represented by one person in the role of a decision maker, but supported by the views of several others, will be presented here.

The considerations that enter the relative weighting of the first four supercomponents is discussed in the main text of this appendix in Section 5.1.1. Consideration of the value of a consequence reduction or augmentation, given the magnitude of the baseline risk, led to the absolute weights 10, 7, 5, and 4 given in Table G.2-1. The absolute weights of the occupational and public cancers relative to all other components are 1 and 3, respectively, taking into account their small size and the fact that for occupational cancers the latency adds 5 to 20 years of useful life after exposure. The last two components finally are set at 0.1 and 0.2, taking into account that in 5,000 years cancer is not likely to be a problem but that these exposures may be indicative of an environmental problem caused by our generation. In order to forestall this, the weights are assumed to be much higher than cancer itself would justify. The resulting societal weights, with a sum normalized to 1, are given in Table G.2-1.

The weights given in Table G.2-1 are based on the opinions of three leading experts in risk assessment and management and three more technically oriented persons. The final selection, however, was made by one person (the project leader) in the role of decision maker. The weights are based on the input received from the six advisors but reflect his own informed valuations.

### G.2.2.2 General Considerations

The Multi-Attribute Utility Index, the basic quantity for the risk comparison used here, is given by

$$U_{k\lambda} = \sum_{j=1}^8 \gamma_j \theta_{jk\lambda} \quad (\text{G.2.5})$$

with the normalized weights defined in the previous section

$$\sum_j \gamma_j = 1. \quad (\text{G.2.6})$$

The standard error of the index is

$$(\Delta U_{k\lambda})^2 = \sum_{j=1}^8 (\gamma_j \Delta \theta_{jk\lambda})^2 + (\theta_{jk\lambda} \Delta \gamma_j)^2. \quad (\text{G.2.7})$$

**TABLE G.2-1**  
**SOCIETAL VALUATIONS AND WEIGHTS,  $\gamma_j$**

RISK SUPERCOMPONENT	ANNUAL BASELINE RISK	ABSOLUTE WEIGHTS	NORMALIZED WEIGHT $\gamma_j$
1 Transportation fatalities	0.2	10	0.33
2 Transportation injuries	3	7	0.23
3 Occupational fatalities	0.002	5	0.17
4 Occupational injuries	0.7	4	0.13
5 Occupational cancers	0.005	1	0.033
6 Public cancers	0.02	3	0.10
7 Late occupational cancers	$3 \cdot 10^{-8}$	0.1	0.003
8 Late public cancers	$7 \cdot 10^{-8}$	0.2	0.007

The single attribute utilities  $\theta_{j_{k\lambda}}$  are not normally distributed, except in those cases in which the consequence reduction factors were lognormally distributed. However, with the eight super components in a sum, application of the central limit theorem allows the statement that the multiattribute utility indices should be approximately normally distributed.

The transformation back to linear space yields the two derived quantities of interest, the consequence reduction indices  $\Theta_{k\lambda}$  and their inverse quantities, the consequence augmentation indices  $\Psi_{k\lambda}$ . Due to the use of the Central Limit Theorem, the utility indices  $U_{k\lambda}$  can be assumed to be normally distributed, allowing the use of the Gaussian approximation for error propagation. The resulting values of the consequence reduction indices  $\Theta_{k\lambda}$  are given in Table G.2-2. Sometimes it is more convenient to discuss the inverse indices, the consequence augmentation indices  $\Psi_{k\lambda}$  given in Table 5-2 of the main text and the values are discussed in Section 5.2.1.

Using the definition of the consequence reduction index

$$\Theta_{k\lambda} = 10^{U_{k\lambda}}, \quad (\text{G.2.8})$$

and with  $U_{k\lambda}$  being a normally distributed quantity, the risk reduction index is lognormally distributed. As the errors are small, however, a normal distribution is a sufficient approximation with

$$\frac{\Delta \Theta_{k\lambda}}{\Theta_{k\lambda}} = \ln 10 \cdot \Delta U_{k\lambda}. \quad (\text{G.2.9})$$

For the consequence augmentation index, the definition,

$$\Psi_{k\lambda} = 10^{-U_{k\lambda}}, \quad (\text{G.2.10})$$

results again in a narrow lognormal distribution, approximated by a normal distribution with a standard error given by the same equation,

$$\frac{\Delta \Psi_{k\lambda}}{\Psi_{k\lambda}} = \ln 10 \cdot \Delta U_{k\lambda} = \frac{\Delta \Theta_{k\lambda}}{\Theta_{k\lambda}} \quad (\text{G.2.11})$$

If a more exact approximation is desired, the geometric standard deviation of the lognormal distribution is given by

$$\sigma_g(\Psi_{k\lambda}) = \sigma_g(\Theta_{k\lambda}) = 10^{\Delta U_{k\lambda}}, \quad (\text{G.2.12})$$

with the mean values given by equations (G.2.8) and (G.2.10).

TABLE G.2-2

## CONSEQUENCE REDUCTION INDICES FOR 16 TREATMENT/LOCATION OPTIONS

QUANTITY	VALUE $\pm$ STANDARD ERROR	COMMENTS/REFERENCES
$\Theta_{11}$	0.712 $\pm$ 0.010	
$\Theta_{12}$	0.663 $\pm$ 0.019	
$\Theta_{13}$	0.710 $\pm$ 0.025	
$\Theta_{14}$	0.728 $\pm$ 0.026	
$\Theta_{21}$	0.700 $\pm$ 0.010	
$\Theta_{22}$	0.632 $\pm$ 0.017	
$\Theta_{23}$	0.671 $\pm$ 0.021	
$\Theta_{24}$	0.688 $\pm$ 0.022	
$\Theta_{31}$	0.617 $\pm$ 0.008	
$\Theta_{32}$	0.707 $\pm$ 0.046	
$\Theta_{33}$	0.811 $\pm$ 0.074	
$\Theta_{34}$	0.837 $\pm$ 0.078	
$\Theta_{41}$	0.486 $\pm$ 0.006	
$\Theta_{42}$	0.779 $\pm$ 0.014	
$\Theta_{43}$	1.138 $\pm$ 0.033	Actual risk reductions
$\Theta_{44}$	1.213 $\pm$ 0.038	Actual risk reductions

The values for the consequence reduction indices in Table G.2-2 lie mostly below 1, indicating increases of the societally weighted geometric average over the eight risk reduction factors. Only the last two treatment/location options show actual decreases in risk. Relative standard errors range from 0 to 10 percent. The values for treatments 1 and 2 (Level II treatment) lie closely together, often little more than a standard error apart. Treatment 3 indices, except for location option 1, decrease with location option  $\lambda$ , beginning to approach the baseline risk. Treatment 4 indices go from the lowest value in the array to the highest (see also Figure 5.1).

### G.3 CLASSES OF INDIFFERENCE AND RISK COMPARISON

#### G.3.1 Approach To Establishing Indifference

For the case of strongly overlapping probability distributions, the criteria of Goodman (see Section B.4.3) can be used to determine whether two risk reduction or augmentation indices are significantly different or not (Goodman, 1986). Both criteria are based on comparing the main bodies of two distributions rather than their tails. The first criterion is an information theoretical measure called the divergence between two distributions. It is in essence proportional to the absolute value of the difference between the two distributions [see Equation (B.4.5)]. The second criterion determines for a given confidence level how much of the second distribution lies between the confidence limits of the first one, and vice-versa. From these two numbers, the second criterion is fashioned.

##### G.3.1.1 Use of the Criteria

Compare two distributions with the means defined as

$$\mu_1 = \Theta_{\kappa, \lambda_1} \quad (G.3.1)$$

$$\mu_2 = \Theta_{\kappa, \lambda_2} ,$$

and with standard errors defined as

$$\sigma_1 = \Delta \Theta_{\kappa, \lambda_1} \quad (G.3.2)$$

$$\sigma_2 = \Delta \Theta_{\kappa, \lambda_2} ,$$

With the additional definitions

$$\sigma_s = \max\{\sigma_1, \sigma_2\} , \quad (G.3.3)$$

and

$$\sigma_z = \min\{\sigma_1, \sigma_2\}, \quad (\text{G.3.4})$$

and

$$\rho = \frac{\sigma_y}{\sigma_z}, \quad (\text{G.3.5})$$

the test quantity

$$T = \frac{|\mu_1 - \mu_2|}{\sigma_z}, \quad (\text{G.3.6})$$

can be evaluated. For rejection of the hypothesis of different risks, Goodman's "confidence" criterion derived from Equation (B.4.10) according to Goodman (1986) is

$$T \leq T_{cr}(\rho, \epsilon_o) \quad (\text{G.3.7})$$

where

$$T_{cr}(\rho, \epsilon_o) = 2.306 \sqrt{\epsilon_o - 0.385(\rho - 1)}. \quad (\text{G.3.8})$$

For acceptance of the hypothesis of different risks, on the other hand, Goodman's "informational" criterion, derived from Equation (B.4.6) can be applied

$$T > T_{ca}(\rho, D_o), \quad (\text{G.3.9})$$

where

$$T_{ca}(\rho, D_o) = \sqrt{\frac{1 + J_o - (\rho^2 + \rho^{-2})}{0.5(1 + \rho^{-2})}} \quad (G.3.10)$$

with

$$D_o = 5.318 \varepsilon_o \quad (G.3.11)$$

The numerical constants are valid for a confidence level of  $C_o = 0.9$ . For the calculations in this paper, a significance level of  $\varepsilon_o = 0.05$  is used.

In the region between the two criteria, i.e., for

$$T_{cr}(\rho, \varepsilon_o) < T \leq T_{ca}(\rho, D_o) \quad (G.3.12)$$

the "informational criterion" rejects the hypothesis of different indices, whereas the 'confidence' criterion does not yet reject it. The assignment of indifference or difference is consequently uncertain. In Figure G.3-1, this situation is shown on a plot of the critical curves, Equations (G.3.8) and (G.3.10), in the  $(T, \rho)$  - plane. The two curves divide the plane into three domains: one of different utility indices (D), one of indifferent utility indices (I), and one of questionable status (Q). In the last case, a decision may be reached on the basis of the location of questionable points in this plane relative to the limiting curves.

### G.3.1.2 Discussion of Results

The comparison of all pairs (a,b) of the 16 indices is best thought of in terms of a 16 by 16 matrix with 256 elements. Of these, the 16 diagonal pairs (a,a) are irrelevant and all off-diagonal pairs are symmetrical,  $(a,b) = (b,a)$ . These properties result in  $(256-16) / 2 = 120$  independent pairs. The analysis of all these comparisons yields information on the significance of differences between indices. The results of the analysis in terms of the Goodmann criteria are given in Table G.3-1 and Figure G.3-1, five pairs of indices are indifferent, five are questionable and three lie close enough outside the outer limit to be included due to possible residual systematic errors. This is due to the fact that biases may change the  $(T, \rho)$ -combination sufficiently to include them in the difference domain.

The same information is shown graphically in Figure G.3-2. Nine of the 120 combinations of consequence reduction or augmentation indices overlap sufficiently to be shown here. Only one combination clearly lies within the indifference domain and one within the domain of questionable overlap. Three other points lie relatively close to the outer limiting curve. Both limiting curves

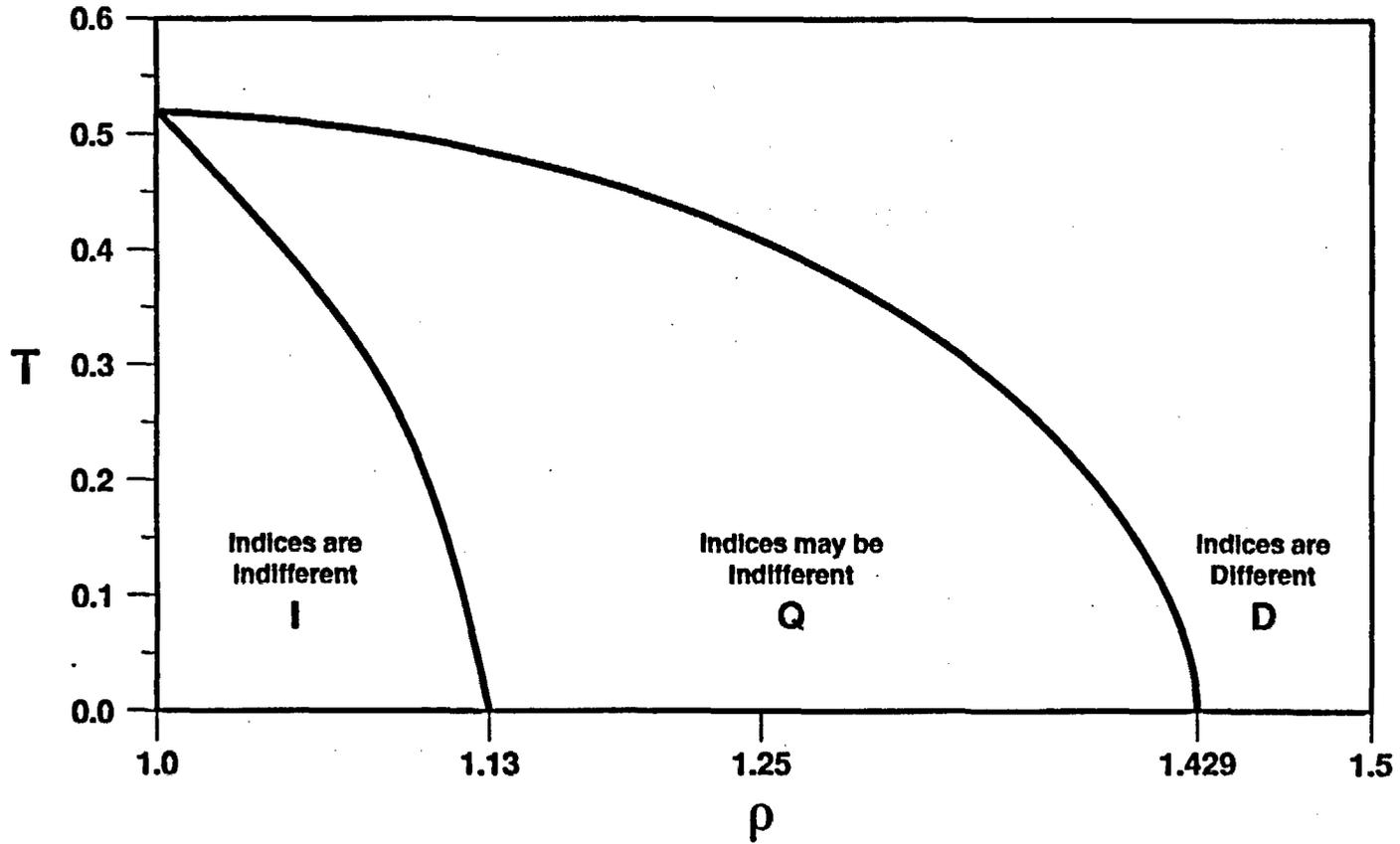


FIGURE G.3-1 DOMAINS OF DIFFERENCE, INDIFFERENCE AND QUESTIONABLE OUTCOME OF A COMPARISON

TABLE G.3-1

## DIFFERENCES AND INDIFFERENCES FOR UTILITY INDICES

k			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	$\kappa$	$\lambda$	11	12	13	14	21	22	23	24	31	32	33	34	41	42	43	44
1	1	1	-	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D
2	1	2	-	-	D	D	D	D	Q	D	D	D	D	D	D	D	D	D
3	1	3	-	-	-	C	D	D	D	D	D	C	D	D	D	D	D	D
4	1	4	-	-	-	-	D	D	D	D	D	D	D	D	D	D	D	D
5	2	1	-	-	-	-	-	D	D	D	D	D	D	D	D	D	D	D
6	2	2	-	-	-	-	-	-	D	D	D	D	D	D	D	D	D	D
7	2	3	-	-	-	-	-	-	-	C	D	D	D	D	D	D	D	D
8	2	4	-	-	-	-	-	-	-	-	D	D	D	D	D	D	D	D
9	3	1	-	-	-	-	-	-	-	-	-	D	D	D	D	D	D	D
10	3	2	-	-	-	-	-	-	-	-	-	-	D	D	D	D	D	D
11	3	3	-	-	-	-	-	-	-	-	-	-	-	I	D	D	D	D
12	3	4	-	-	-	-	-	-	-	-	-	-	-	-	D	D	D	D
13	4	1	-	-	-	-	-	-	-	-	-	-	-	-	-	D	D	D
14	4	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	D	D
15	4	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	D
16	4	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

I = Combination of significantly different indices.

D = Combination of different indices.

Q = Combination of questionable status.

C = Combination included due to proximity to limits.

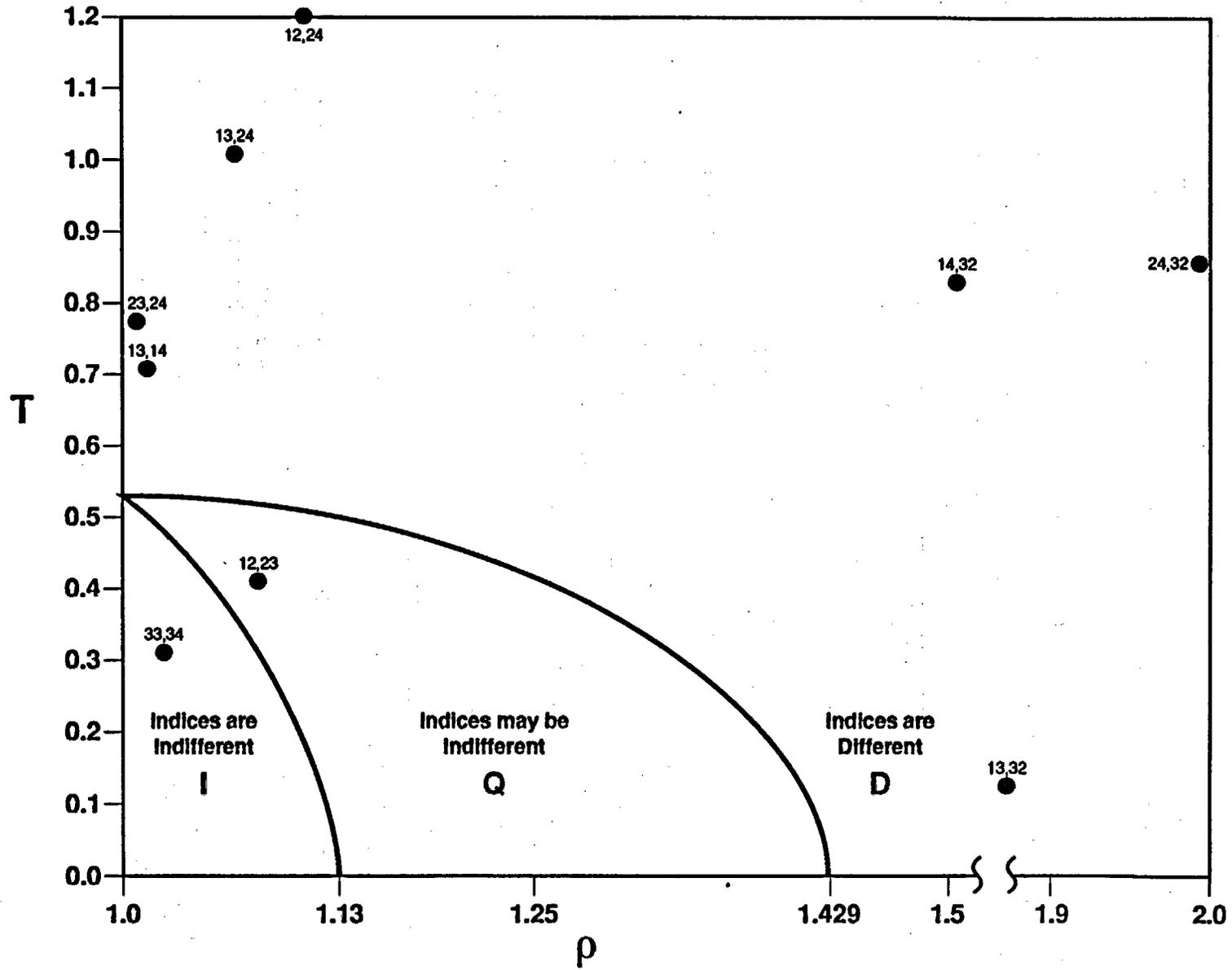


FIGURE G.3-2 CRITICAL COMPARISON FOR RISK REDUCTION INDICES

are functions of quantities defined in Attachment B, Section B.4.3, such as the confidence level  $C_0 = 0.9$ , the significance level  $\epsilon_0 = 0.05$ , and the divergence limit  $D_0$  given by Equation (G.3.11). The selections made here are conventional but otherwise as arbitrary as all such choices. The three points lying closest to the outer limit are included, because changes in the limits could shift the curves so as to engulf these points.

From these discussions, it is obvious that 115 of the 120 possible pairings are clearly different from each other; only 2 show sufficient overlap to be considered indifferent. This is shown clearly in Figure 5-1. There, other groupings are evident, that can be used in the process of reaching conclusions. It is important at this juncture to realize that the errors quoted for the consequence reduction or augmentation indices are generally somewhat too small. As already discussed in Section 3.1.3 of the Introduction, this situation arises both from incomplete information and from the decision not to include the partial effects of systematic errors on the final result. With this fact in mind, the small differences between the indices of the Level II treatments are even less significant, supporting an interpretation as a group.

#### G.4 ANALYSIS OF THE CONSEQUENCE REDUCTION INDICES

Risk comparisons are usually used in further evaluations of the alternatives being compared. In the present case, the results of this comparison are part of the selection procedure of the Engineered Alternatives for the treatment of wastes to be emplaced at the WIPP. In order to arrive at an appropriate weighting in that process, a detailed analysis of the influence of the different supercomponents on the final values of the consequence reduction indices is needed. It will serve as an additional input for the decision maker at the higher level. Indeed, it is quite likely that the interaction between the two decision makers will result in an iterative process of reweighting at both levels until a consensus is reached. In the present study, this interaction was discussed between the two decision makers, but could not be carried out due to the external constraints of the work.

##### G.4.1 Contributions of Traditional and Radiological Effects

One of the major concerns about the WIPP is centered on the health effects due to the radioactivity of the wastes. As an inspection of the baseline risk numbers in Table G.2-1 shows, the consequences in supercomponents 5 and 6 are among the smallest expected health effects of the entire operation. Transportation fatalities and injuries, although well within acceptable limits, are much larger. This is a direct consequence of the public and administrative concerns over radiological effects and of the successful efforts by health physicists to keep these effects at low levels.

#### G.4.1.1 Consequence Reduction Indices Without Transportation Health Effects

Although Supercomponents 1 and 2 contain some radiological risk contributions, their influence was set to zero by the assumptions for Equations (G.1.5) and (G.1.9). The influence of the nonradiological transportation accidents can thus be studied easily by setting their absolute weights in Table G.2-1 to zero. After renormalization, the relative weights listed in the second column of Table G.4-1 are obtained.

An evaluation of the consequence augmentation indices yields the values given in Figure G.4-1. For Level II treatments, the consequences decrease with increasing decentralization of the treatment from indices around 2 down to indices near 1.4. For Level III treatments the indices for Location Option 1 (WIPP) increase to values near 3 for Treatment Option 3 and near 5 for Treatment Option 4. Here too, the indices decrease with decentralization, but only to values near 2 and near 3 for Treatment Options 3 and 4, respectively. The shading of the cells indicates these values, with the lightest shade for the largest increases in the index, i.e., for group 1 with values between 4 and 5, the next darker shade for the group of values near 3, even darker for group 3 with values near 2, and darkest for the lowest consequence augmentation indices near 1.4.

This pattern reflects the increase of the now dominant occupational accident risk with more complex treatment. All treatment/location options show an increase in consequences due to the treatment activities. This trend is overlaid with a decrease in accidental public cancer risk during transportation. In evaluating these data, two facts should be borne in mind: (1) an inspection of the remaining baseline risks in Table G.2-1 shows them to be small and (2) the increases in consequences indicated by the augmentation indices in Figure G.4-1 are not linearly related to these baseline risks. Thus, it would be absolutely false to state that the remaining baseline risks are higher by a factor equal to the consequence augmentation index.

#### G.4.1.2 Consequence Reduction Indices Without Occupational Health Effects

Supercomponent 4 also has a contribution of a chemical noncancer health risk, whereas supercomponent 3 is a pure consequence of occupational accidents. The chemical health risks are exceedingly small, however, and that contribution was set to zero in Equation (G.1.19). Thus setting the absolute weights of supercomponents 3 and 4 to zero (Table G.2-1) results in the relative weights given in column 3 of Table G.4-1, and shows the consequence reduction indices with the influence of conventional occupational accidents removed.

The consequence reduction indices  $\Theta_{\kappa, \lambda}$  are mostly larger than 1, so they are listed in Figure G.4-2. For Level II treatments, the values of the indices cluster closely around unity, showing that it is the occupational risk components that are responsible for the increase in the index for all Level II treatments in the fully weighted case. The group of treatment/location options with consequence reduction indices around 1 is shown with the lightest shading of the cells. For Level

TABLE G.4-1

## CONTRIBUTIONS OF TRADITIONAL AND RADIOLOGICAL EFFECTS

RISK SUPERCOMPONENT	NORMALIZED WEIGHTS $\gamma_i$		
	NO TRAFFIC ACCIDENTS	NO OCCUPATIONAL ACCIDENTS	NO TRAFFIC OR OCCUPATIONAL ACCIDENTS
1 Transportation fatalities	0	0.47	0
2 Transportation injuries	0	0.33	0
3 Occupational fatalities	0.38	0	0
4 Occupational injuries	0.30	0	0
5 Occupational cancers	0.075	0.047	0.23
6 Public cancers	0.23	0.14	0.70
7 Late occupational cancers	0.0075	0.0047	0.023
8 Late public cancers	0.015	0.0094	0.047

**Location Option**

		1	2	3	4
Treatment Option	1	$2.17 \pm 0.07$	$1.80 \pm 0.06$	$1.42 \pm 0.04$	$1.34 \pm 0.04$
	2	$2.26 \pm 0.07$	$1.87 \pm 0.06$	$1.47 \pm 0.04$	$1.40 \pm 0.04$
	3	$3.01 \pm 0.09$	$2.49 \pm 0.08$	$1.97 \pm 0.06$	$1.86 \pm 0.06$
	4	$5.16 \pm 0.16$	$4.30 \pm 0.13$	$3.39 \pm 0.10$	$3.20 \pm 0.10$

 Group 1   
  Group 2   
  Group 3   
  Group 4

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FIGURE G.4-1 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT TRANSPORTATION RISKS. AS ALL CONSEQUENCE REDUCTION FACTORS ARE SMALLER THAN 1, VALUES FOR THEIR INVERSES ARE SHOWN HERE.

		Location Option			
		1	2	3	4
Treatment Option	1	$1.06 \pm 0.01$	$0.96 \pm 0.04$	$1.06 \pm 0.05$	$1.10 \pm 0.05$
	2	$1.06 \pm 0.01$	$0.92 \pm 0.03$	$1.00 \pm 0.04$	$1.04 \pm 0.04$
	3	$1.06 \pm 0.01$	$1.29 \pm 0.12$	$1.57 \pm 0.20$	$1.64 \pm 0.22$
	4	$1.07 \pm 0.01$	$2.08 \pm 0.04$	$3.57 \pm 0.14$	$3.91 \pm 0.16$



FIGURE G.4-2 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT OCCUPATIONAL ACCIDENT RISKS

III treatments, the reduction indices increase to values near 1.3 to 1.6 (group 2 shading) for Treatment Option 3 carried out in decentralized facilities, and values of 2 (group 3 shading) up to indices near 4 (group 4 with darkest shading) for Treatment Option 4 and treatment near the originators of the waste. This demonstrates the influence of the transportation risk components in the location dependence of Level III treatments in the fully weighted case.

#### G.4.1.3 Indices Without Transportation or Occupational Health Effects

For the last sensitivity study, both the transportation and the occupational accident risks are weighted with zero. This will remove the influence of the largest baseline risk components and will show the influence of the radiological risk contributions with a small addition for the risks due to the exposure to chemical agents. Using the relative weights given in the last column of Table G.4-1, the consequence reduction indices calculated are all larger than 1, indicating a uniform reduction in consequences (Figure G.4-3). This can be understood from the fact that all direct external radiation doses are essentially independent of treatment because they depend on the total activity transported and handled per year. This quantity is assumed to be constant in this study [see Equation (E.1.5)].

The consequence reduction here is thus almost exclusively due to transportation and handling accidents, which are responsible for relatively small contributions to the baseline risks for supercomponents 5 and 6 in Table G.2-1. This results in large relative decreases for all baseline risks for almost any form of treatment, leading to the nearly treatment-independent consequence reduction indices in Figure G.4-3. The lightest patterns are reserved for cells with indices around 1.35, the group 2 pattern for values around 2.4, the darker group 3 pattern for indices around 5, and the darkest pattern for the highest reduction indices near 6. It should be noted in this context that the accidents contributing to these indices all had to be weighted with equal weights because their baseline risks are not available. A considerable amount of bias may, therefore, be expected. The general location trend is too strong, however, and is probably independent of this bias.

#### G.4.2 Contribution of Each Supercomponent to the Final Indices

##### G.4.2.1 Contribution of Each Component to All Indices

The factors defined in Equation (B.3.22) will be given in the 4 x 4 matrices used before for the display of values for the 16 treatment/location options even though the treatment or location dependence does not exist in some cases and is too small to matter in others.

##### G.4.2.1.1 Supercomponent 1: Fatal Transportation Accidents

By definition, these factors  $\Phi_{1, \kappa \lambda}$  are equal to 1 for treatment at the WIPP, after all the transportation is done (Figure G.4-4). For Level II treatments, consequence increases of around 10 percent are effected, due to the volume increase in the treated wastes, resulting in an

		Location Option			
		1	2	3	4
Treatment Option	1	$1.35 \pm 0.06$	$2.42 \pm 0.10$	$5.03 \pm 0.20$	$5.96 \pm 0.24$
	2	$1.36 \pm 0.05$	$2.42 \pm 0.10$	$5.03 \pm 0.20$	$5.97 \pm 0.23$
	3	$1.35 \pm 0.06$	$2.42 \pm 0.10$	$5.02 \pm 0.21$	$5.95 \pm 0.25$
	4	$1.37 \pm 0.06$	$2.42 \pm 0.11$	$5.03 \pm 0.23$	$6.00 \pm 0.28$

 Group 1  
  Group 2  
  Group 3  
  Group 4

FIGURE G.4-3 CONSEQUENCE AUGMENTATION INDICES FOR ALL TREATMENT AND LOCATION OPTIONS IN THE SENSITIVITY STUDY WITHOUT TRANSPORTATION AND OCCUPATIONAL ACCIDENT RISKS

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		Location Option			
		1	2	3	4
Treatment Option	1	1	$0.91 \pm 0.02$	$0.89 \pm 0.02$	$0.90 \pm 0.02$
	2	1	$0.90 \pm 0.02$	$0.87 \pm 0.02$	$0.87 \pm 0.02$
	3	1	$1.03 \pm 0.05$	$1.05 \pm 0.08$	$1.06 \pm 0.08$
	4	1	$1.26 \pm 0.01$	$1.48 \pm 0.03$	$1.51 \pm 0.04$

 Group 1   
  Group 2   
  Group 3   
  Group 4

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FIGURE G.4-4 CONTRIBUTING FACTORS  $\Phi_{1k\lambda}$  FOR SUPERCOMPONENT 1: TRAFFIC ACCIDENT FATALITIES

increased number of transports. For Level III treatments, relative contributions to the consequence reduction indices of a few percent occur for Treatment Option 3, and more substantial relative increases of 20 to 50 percent for option 4. Both Level III treatments show a distinct trend to higher factors for decentralized treatment facilities.

#### G.4.2.1.2 Supercomponent 2: Injuries in Transportation Accidents

By definition, these factors are also equal to 1 for treatment at the WIPP; again because all the transportation is already done. The corresponding factors  $\Phi_{2\kappa\lambda}$  are shown in Figure G.4-5. The situation is essentially the same as that for the factors  $\Phi_{1\kappa\lambda}$ , but with smaller deviations from 1. For Level II treatments, this component contributes increases of up to 10 percent, again due to the volume increase in the treated wastes and an increase in the number of transports needed. For Level III treatments, contributions of 2 to 4 percent are found for Treatment Option 3, and more substantial relative increases of 20 to 30 percent for Treatment Option 4. Again, both show a trend to higher factors for decentralized treatment facilities.

#### G.4.2.1.3 Supercomponent 3: Fatalities Due to Occupational Accidents

The factors  $\Phi_{3\kappa\lambda}$  for the contribution of the occupational fatalities are listed in Figure G.4-6. Here, due to the assumption of a modular treatment plant, the factors do not depend on location. For Level II treatments, the factors practically all the same, decreasing the index by about 20 percent. For Treatment Option 3, the decrease amounts to about 25 percent, for Treatment Option 4, to about 35 percent. This is the expression of the higher contribution of occupational fatalities for more complex treatments to the index.

#### G.4.2.1.4 Supercomponent 4: Injuries Due to Occupational Accidents

The factors  $\Phi_{4\kappa\lambda}$  for the contribution of the occupational injuries are shown in Figure G.4-7. Again, due to the assumption of a modular treatment plant, the factors do not depend on location, but generally deviate less from 1 than the corresponding factors for the third supercomponent. For Level II treatments, the factors practically all decrease the index by about 16 percent. For Treatment Option 3, the decrease amounts to about 20 percent, and for Treatment Option 4 to nearly 30 percent. Again, this can be interpreted as the expression of the higher contribution of occupational injuries for more complex treatments to the index.

#### G.4.2.1.5 Supercomponent 5: Cancer Cases Due to Occupational Exposures

The factors  $\Phi_{5\kappa\lambda}$  for the contribution of the occupational cancer fatalities are listed in Figure G.4-8. These factors all deviate only by a few percent from 1, contributing little to the index. This is largely due to the fact that the occupational cancer risk is almost exclusively due to routine exposures which are independent of treatment, contributing nothing to the consequence reduction.

		Location Option			
		1	2	3	4
Treatment Option	1	1	$0.94 \pm 0.01$	$0.93 \pm 0.02$	$0.93 \pm 0.02$
	2	1	$0.93 \pm 0.01$	$0.91 \pm 0.02$	$0.91 \pm 0.02$
	3	1	$1.02 \pm 0.04$	$1.04 \pm 0.05$	$1.04 \pm 0.06$
	4	1	$1.17 \pm 0.01$	$1.32 \pm 0.02$	$1.34 \pm 0.02$

 Group 1   
  Group 2   
  Group 3   
  Group 4

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FIGURE G.4-5 CONTRIBUTING FACTORS  $\Phi_{2k\lambda}$  FOR SUPERCOMPONENT 2: TRAFFIC ACCIDENT INJURIES

		Location Option			
		1	2	3	4
Treatment Option	1	$0.81 \pm 0.01$	$0.81 \pm 0.01$	$0.81 \pm 0.01$	$0.81 \pm 0.01$
	2	$0.81 \pm 0.01$	$0.81 \pm 0.01$	$0.81 \pm 0.01$	$0.81 \pm 0.01$
	3	$0.75 \pm 0.01$	$0.75 \pm 0.01$	$0.75 \pm 0.01$	$0.75 \pm 0.01$
	4	$0.65 \pm 0.01$	$0.65 \pm 0.01$	$0.65 \pm 0.01$	$0.65 \pm 0.01$

 Group 1  
  Group 2  
  Group 3

FIGURE G.4-6 CONTRIBUTING FACTORS  $\Phi_{3k\lambda}$  FOR PERCOMPONENT 3: OCCUPATIONAL ACCIDENT FATALITIES

		Location Option			
		1	2	3	4
Treatment Option	1	$0.85 \pm 0.01$	$0.85 \pm 0.01$	$0.85 \pm 0.01$	$0.85 \pm 0.01$
	2	$0.84 \pm 0.01$	$0.84 \pm 0.01$	$0.84 \pm 0.01$	$0.84 \pm 0.01$
	3	$0.79 \pm 0.01$	$0.79 \pm 0.01$	$0.79 \pm 0.01$	$0.79 \pm 0.01$
	4	$0.71 \pm 0.01$	$0.71 \pm 0.01$	$0.71 \pm 0.01$	$0.71 \pm 0.01$

 Group 1   
  Group 2   
  Group 3   
  Group 4

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FIGURE G.4-7 CONTRIBUTING FACTORS  $\Phi_{4k\lambda}$  FOR SUPERCOMPONENT 4: OCCUPATIONAL ACCIDENT INJURIES

		Location Option			
		1	2	3	4
Treatment Option	1	$0.995 \pm 0.001$	$0.993 \pm 0.001$	$0.995 \pm 0.001$	$0.995 \pm 0.001$
	2	$0.994 \pm 0.001$	$0.993 \pm 0.001$	$0.994 \pm 0.001$	$0.994 \pm 0.001$
	3	$0.988 \pm 0.001$	$0.987 \pm 0.001$	$0.988 \pm 0.001$	$0.988 \pm 0.001$
	4	$0.974 \pm 0.001$	$0.972 \pm 0.001$	$0.973 \pm 0.001$	$0.974 \pm 0.001$

 Group 1   
  Group 2   
  Group 3   
  Group 4

FIGURE G.4-8 CONTRIBUTING FACTORS  $\Phi_{5K}$  FOR SUPERCOMPONENT 5: OCCUPATIONAL CANCERS

**G.4.2.1.6 Supercomponent 6: Cancer Cases Due to Public Exposures**

The factors  $\Phi_{6\kappa\lambda}$  for the contribution of the public cancer fatalities are shown in Figure G.4-9. These factors display a minute dependence on treatment, and practically depend on location only. The deviations from 1 are substantial, ranging from increases of about 1 to 25 percent. These contributions to the index are largely due to the fact that the public cancer risk is almost exclusively due to accidental exposures which are, apart from the fact of treatment, almost independent of the method of treatment.

**G.4.2.1.7 Supercomponent 7: Occupational Cancer Cases Due to Post-Closure Exposures**

The factors  $\Phi_{7\kappa\lambda}$  for the contribution of late occupational cancer fatalities due to human intrusion scenarios are listed in Figure G.4-10. These factors deviate only a fraction of a percent from 1, show as expected no location dependence and only a minute dependence on treatment. These tiny contributions to the index are largely due to the fact that the baseline cancer risk is exceedingly small and thus rank very low in societal valuation.

**G.4.2.1.8 Supercomponent 8: Public Cancer Cases Due to Post-Closure Exposures**

The factors  $\Phi_{8\kappa\lambda}$  for the contribution of late occurring public cancer fatalities due to human intrusion scenarios are listed in Figure G.4-11. These factors also deviate only a few percent from 1, show as expected no location dependence and only a weak dependence on treatment. Again, the small size of the contributions to the index are largely due to the fact that the baseline cancer risk is very small and thus ranks low in societal valuation.

**G.4.2.2 Contributions of All Components to Some Indices**

Another way to analyze the contributions  $\Phi_{j\kappa\lambda}$  to each consequence reduction index is to list all eight factors together as in Table G.4-2 for Level II treatments and G.4-3 for Level III treatments. The small variation in the indices  $\Theta_{\kappa\lambda}$  is explained by the fact that most supercomponents do not change with treatment/location options. Only supercomponent 6 shows a moderate increase with location, offset by smaller changes in supercomponents 1 and 2. The overall values of the indices are determined by the small values of the factors for supercomponents 1 to 4. For Level III treatments, however, only supercomponents 3 and 4 yield constant, values below 1. Components 1, 2, and 6 are all increasing considerably with more decentralized treatment while components 5, 7, and 8 are constant, hovering near 1. The driving force in the increase are, therefore, components 1, 2, and 6 for traffic accidents and public cancers, which overcome the low values from the occupational effects and lead to actual consequence reductions.

		Location Option			
		1	2	3	4
Treatment Option	1	$1.012 \pm 0.001$	$1.101 \pm 0.001$	$1.220 \pm 0.001$	$1.250 \pm 0.001$
	2	$1.012 \pm 0.001$	$1.101 \pm 0.001$	$1.220 \pm 0.001$	$1.250 \pm 0.001$
	3	$1.012 \pm 0.001$	$1.101 \pm 0.001$	$1.220 \pm 0.001$	$1.250 \pm 0.001$
	4	$1.012 \pm 0.001$	$1.101 \pm 0.001$	$1.220 \pm 0.001$	$1.250 \pm 0.001$



FIGURE G.4-9 CONTRIBUTING FACTORS FOR SUPERCOMPONENT 6: PUBLIC CANCERS

		Location Option			
		1	2	3	4
Treatment Option	1	1.005 ± 0.001	1.005 ± 0.001	1.005 ± 0.001	1.005 ± 0.001
	2	1.005 ± 0.001	1.005 ± 0.001	1.005 ± 0.001	1.005 ± 0.001
	3	1.006 ± 0.001	1.006 ± 0.001	1.006 ± 0.001	1.006 ± 0.001
	4	1.007 ± 0.001	1.007 ± 0.001	1.007 ± 0.001	1.007 ± 0.001

 Group 1   
  Group 2   
  Group 3

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FIGURE G.4-10 CONTRIBUTING FACTORS  $\Phi_{7k\lambda}$  FOR SUPERCOMPONENT 7: LATE OCCUPATIONAL CANCERS

		Location Option			
		1	2	3	4
Treatment Option	1	$1.031 \pm 0.006$	$1.031 \pm 0.006$	$1.031 \pm 0.006$	$1.031 \pm 0.006$
	2	$1.032 \pm 0.005$	$1.032 \pm 0.005$	$1.032 \pm 0.005$	$1.032 \pm 0.005$
	3	$1.036 \pm 0.006$	$1.036 \pm 0.006$	$1.036 \pm 0.006$	$1.036 \pm 0.006$
	4	$1.052 \pm 0.007$	$1.052 \pm 0.007$	$1.052 \pm 0.007$	$1.052 \pm 0.007$

 Group 1
  Group 2

FIGURE G.4-11 CONTRIBUTING FACTORS  $\phi_B$  FOR SUPERCOMPONENT 8: LATE PUBLIC CANCERS

TABLE G.4-2

FACTORS  $\Phi_{j, \kappa \lambda}$  FOR THE CONTRIBUTION OF SUPERCOMPONENT J TO THE  
CONSEQUENCE REDUCTION INDEX  $\Theta_{\kappa \lambda}$  OF LEVEL II TREATMENTS

SUPER COMPONENT	1 1	1 2	1 3	1 4	2 1	2 2	2 3	2 4
1	1	0.914	0.895	0.895	1	0.897	0.874	0.874
2	1	0.939	0.925	0.925	1	0.927	0.910	0.910
3	0.809	0.809	0.809	0.809	0.801	0.801	0.801	0.801
4	0.844	0.844	0.844	0.844	0.837	0.837	0.837	0.837
5	0.995	0.993	0.995	0.995	0.994	0.993	0.994	0.994
6	1.012	1.101	1.220	1.249	1.012	1.101	1.220	1.250
7	1.005	1.005	1.005	1.005	1.005	1.005	1.005	1.005
8	<u>1.031</u>	<u>1.031</u>	<u>1.031</u>	<u>1.031</u>	<u>1.032</u>	<u>1.032</u>	<u>1.032</u>	<u>1.032</u>
$\Phi_{\kappa \lambda}$	0.712	0.663	0.710	0.728	0.700	0.632	0.671	0.688

TABLE G.4-3

FACTORS  $\Phi_{j,r}$  FOR THE CONTRIBUTION OF SUPERCOMPONENT J TO THE  
CONSEQUENCE REDUCTION INDEX  $\Theta_{r,1}$  OF LEVEL III TREATMENTS

SUPER COMPONENT	3 1	3 2	3 3	3 4	4 1	4 2	4 3	4 4
1	1	1.032	1.053	1.057	1	1.258	1.479	1.513
2	1	1.022	1.037	1.040	1	1.174	1.315	1.337
3	0.746	0.746	0.746	0.746	0.654	0.654	0.654	0.654
4	0.791	0.791	0.791	0.791	0.8	0.8	0.8	0.8
5	0.988	0.987	0.988	0.988	0.975	0.972	0.973	0.974
6	1.012	1.101	1.220	1.250	1.013	1.101	1.220	1.250
7	1.006	1.006	1.006	1.006	1.007	1.007	1.007	1.007
8	<u>1.036</u>	<u>1.036</u>	<u>1.036</u>	<u>1.036</u>	<u>1.051</u>	<u>1.051</u>	<u>1.051</u>	<u>1.051</u>
$\Phi_{r,1}$	0.617	0.707	0.811	0.837	0.486	0.779	1.138	1.213

### G.4.3 Discussion of the Analysis

The analysis given here reveals the dominant contributions to the consequence reduction factors of the 16 treatment/location options discussed in this study. The main driving force derives from the valuations society puts on the different sources of health effects. It should not come as a surprise that radiological health effects are among the smaller contributions to the total consequences of the entire WIPP operation. After all, there is a type of health and safety professional, the health physicist, whose sole job it is to keep any radiological risks small. Indeed, the entire WIPP effort is dedicated to the purpose of disposing TRU wastes under these conditions. Thus it is only one supercomponent, the public cancer risk in component 6, that influences the consequence reduction indices in an appreciable way. Even that refers to a small, acceptable annual baseline risk (Table G.2-1).

Less weight is given by society to keep non-radiation occupational accidents low, even though occupational health and safety professionals do a creditable job in many industries. However, less time and effort is expended to lower these risks. This leads to the location-independent factors for components 3 and 4 which are lower than 1 and signal progressively increasing consequences with more complex treatment activities.

The dominant influence in the location-dependence of the consequence reduction indices are the traffic accidents in components 1 and 2. They reflect the almost cavalier attitude that our society takes toward the prevention of traffic accidents, with little time and effort expended to curb the number of fatalities on our roads. It, therefore, comes as no surprise that the largest consequences in fatalities and injuries due to the operation of the WIPP are also deemed acceptable (Table G.2-1).

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**APPENDIX J**

**DEVELOPMENT OF COST ESTIMATES  
FOR WASTE TREATMENT FACILITIES  
AND FOR TRANSPORTATION**

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## **1.0 METHODOLOGY FOR COST ESTIMATION OF WASTE TREATMENT FACILITIES**

### **1.1 INTRODUCTION**

The Intent of Appendix J is to provide supporting calculations for cost estimates associated with the waste treatment which is discussed in Section 6.3.4 of Volume I of this report. Specifically, Appendix J presents cost estimation calculations for:

- Capital costs for waste treatment facilities
- Annual operating costs for waste treatment facilities
- Life cycle costs
- Transportation costs (Section 2.0).

### **1.2 GENERAL ASSUMPTIONS FOR COST ESTIMATION OF FACILITIES**

The EATF cost estimation methodology relies on published reports for treatment operation costs. As noted in Section 6.3.4 of Volume I, the scope of EATF work does not permit "bottom-up" cost estimation. If treatment becomes necessary, detailed costs may be estimated for required facilities. Assumptions associated with EATF cost estimates include:

- Treatment operation costs may be scaled and combined with a modified version of the "point six rule" (Baasel, 1990).
- Treatment operation costs may be factored to a common basis year of 1990.
- Life cycle operations costs are calculated based on a cost escalation factor of 3.4 percent (Smedley, 1991) and a discount factor of 10 percent (Bozik, 1991), both on an annual basis.
- Life cycle costs are based on an assumption of waste treatment operations beginning in the year 2000.
- Annual operations costs (labor and materials) may be estimated as a percentage of capital cost (Ross et al., 1982; McKee et al., 1986).
- Batch treatment facilities of a certain minimum size are necessary at sites with small quantities of waste.
- Continuous operation is defined as 24 hours per day, 240 days per year. The remainder of time is used for routine maintenance and periodic down-time.

- Batch operation is defined as 8 hours per day, 240 days per year minimum and will vary up to the definition of continuous operation.

### **1.3 COST ESTIMATION FOR WASTE TREATMENT FACILITY**

#### **1.3.1 Capital Cost Estimation Procedure**

Capital cost estimation for waste treatment consists of the following steps:

- Define treatment need by generic waste form (solid organics, solid inorganics, sludges) (Section 1.3.1.1).
- Define treatment operations necessary to meet treatment need. In other words, define the sequence of operations necessary to generate a specified waste form (Section 1.3.1.2).
- Define facility capacity; this is a function of the number of facilities and work-off period (Section 1.3.1.3).
- Calculate capital cost (Section 1.3.1.4).

##### **1.3.1.1 Treatment Need**

The various treatment alternatives considered by the EATF are provided in Table 1-2 in Volume I of this report. The combination alternatives defined in Table 1-2 form the basis for determination of the effectiveness and feasibility of engineered alternatives.

##### **1.3.1.2 Treatment Operations**

The intent of this section is to define the treatment operations necessary for the combination alternatives of Table 1-2. Prior to defining the sequence of treatment operations required for each waste type and combination alternative, input data specified in Table J-1 presents all the treatment operations used in the fourteen combination alternatives, cost (in a reference year), and cost in 1990 dollars. Cost in 1990 dollars is computed using consumer price indices as follows:

$$Cost_{1990} = \frac{CPI_{1990}}{CPI_n} Cost_n \quad (J.1-1)$$

where:

- $CPI_{1990}$  = Consumer Price Index for 1990
- $CPI_n$  = Consumer Price Index for a reference year, and
- $Cost_n$  = Cost of treatment operation in reference year.

TABLE J-1

## TREATMENT OPERATION CAPITAL COST ESTIMATES

Treatment Operation	Capital <sup>(1)</sup> Cost (millions)	Basis Capacity	Basis Year	Reference for Basis	Basis <sup>(2)</sup> CPI	1990 <sup>(3)</sup> (millions)
Basic Facility	\$46.0	18,000 drums/yr	1989	Kaiser, 1989	345.2	\$47.6
Cementation	\$14.7	367 lb/hr	1981	PNL, 1982 <sup>(4)</sup>	297.0	\$18.0
Incineration	\$17.6	100 lb/hr	1984	PNL, 1986 <sup>(5)</sup>	322.7	\$20.0
Metal Decon.	\$19.0	81 lb/hr	1984	PNL, 1986 <sup>(5)</sup>	322.7	\$21.6
Metal Melting	\$23.0	220 lb/hr	1984	PNL, 1986 <sup>(5)</sup>	322.7	\$26.0
Shredding	\$4.0	3750 lb/hr	1984	PNL, 1986 <sup>(5)</sup>	322.7	\$4.5
Supercompaction	\$6.0	3145 lb/hr	1990	Barthel, 1990	366.9	\$6.0
Vitrification	\$16.1	100 lb/hr	1981	PNL, 1982 <sup>(4)</sup>	297.0	\$20.0

<sup>(1)</sup> Capital costs estimated from references on the basis of applicable equipment.

<sup>(2)</sup> Cost Price Index (CPI) obtained from Baasel (1990) for Chemical Engineering Plant Cost Indices.

<sup>(3)</sup> 1990 CPI assumed to be 366.9

<sup>(4)</sup> Same reference as Ross et al. (1982)

<sup>(5)</sup> Same reference as McKee et al. (1986)

These base costs are used to estimate capital cost of facilities as described in Section 1.3.1.4.

Table J-2 illustrates how each of the fourteen combination alternatives can actually consist of more than one treatment operation for each generic waste form. This list of treatment operations must be scaled and then cost is estimated based on number of facilities and work-off period. The sum of costs for treatment operations and support facilities (described in Section 6.3, Volume I) represents the rough cost presented in Tables 6-8a, b, and c.

#### **1.3.1.3 Waste Treatment Facility Capacity**

Table J-3 presents total waste (sum of retrievably stored and newly generated waste) by waste type in retrievable storage and/or newly generated at each DOE site. The information in Table J-3 is adapted from DOE (1988b). The values in this table indicate the percent of all waste destined for the WIPP.

Table J-4 builds on the information in Table J-3 by first identifying the EATF choices for waste treatment locations for one through seven facilities. It should be noted that other choices can easily be made. The choices made by the EATF place emphasis on selecting sites based on the amount of waste in retrievable storage in addition to the newly generated waste rate at the sites. The WIPP is an EATF choice for waste treatment facility for logistical reasons: current transportation planning can still be used and no further transportation will be required for waste potentially treated at the WIPP.

The second choice presented in Table J-4 involves transportation. The decision of where waste will be shipped for treatment is based on selecting treatment locations in close proximity to waste storage/generators in order to minimize transportation requirements. It should be noted that system capacity is constant. Thus, whether one or multiple facilities are used, processing capacity is always 13,640 cubic meters of waste per year, assuming the work-off period is ten years for treating all waste. The capacity may be adjusted according to the work-off period.

#### **1.3.1.4 Capital Cost Calculation**

The information in Tables J-1 through J-4 provide all input parameters necessary for estimation of capital costs. These input parameters are:

- Treatment operation costs and capacity scaled to 1990 dollars
- Capacity required for a given number of facilities
- Sequence of treatment operations required for each waste form for all combination alternatives.

TABLE J-2

## TREATMENT OPERATIONS REQUIRED TO PRODUCE FINAL WASTE FORM

Combination <sup>(1)</sup> Alternative	Unprocessed Waste Form	Sequence of Treatment Operations	Final Waste Form
1	Solid Organics Solid Inorganics Sludges	Shred→Cement Shred→Cement NA	Cement Monolith Cement Monolith Unprocessed
2,3	Solid Organics Solid Inorganics Sludges	Shred→Cement Shred→Cement Cement	Cement Monolith Cement Monolith Cement Monolith
4,5	Solid Organics Solid Inorganics Sludges	Shred→Incinerate→Cement Shred→Incinerate→Cement Cement	Cement Monolith Cement Monolith Cement Monolith
6,7	Solid Organics Solid Inorganics Sludges	Shred→Incinerate→Vitrify Shred→Incinerate→Melt <sup>(2)</sup> Vitrify	Glass Monolith Metal Ingot Glass Monolith
8,9,13	Solid Organics Solid Inorganics Sludges	Shred→Incinerate→Vitrify Shred→Incinerate→Melt→Vitrify <sup>(3)</sup> Vitrify	Glass Monolith Glass Monolith Glass Monolith
10	Solid Organics Solid Inorganics Sludges	NA Decontaminate→Cement NA	Unprocessed Cement Monolith Unprocessed
11,12,14	Solid Organics Solid Inorganics Sludges	Supercompacted Supercompacted NA	Compacted Compacted Unprocessed

<sup>(1)</sup> See Table 1-2 in Volume I for complete description of Alternatives.

<sup>(2)</sup> Metals are melted into TRU waste ingots.

<sup>(3)</sup> Metals are melted with glass/glass frit; radionuclides partition into slag, and metals are eliminated from the WIPP inventory.

**TABLE J-3**  
**TOTAL CH-TRU WASTE STORED/GENERATED<sup>(1)</sup>**

DOE-Site	Solid Organics (m <sup>3</sup> )	Solid Inorganics (m <sup>3</sup> )	Sludges (m <sup>3</sup> )	Site Total (m <sup>3</sup> )	Total Inventory (%)
ANL-E	31	19	44	94	0.07
INEL	14859	12990	9672	37521	27.51
LANL	4407	6724	4403	15534	11.39
LLNL	2367	433	87	2887	2.12
Mound	60	120	1017	1197	0.88
NTS	353	254	12	619	0.45
ORNL	927	603	15	1545	1.13
Hanford	8736	11591	1217	21544	15.79
RFP	17017	9828	9550	36395	26.68
SRS	14297	4098	667	19062	13.98
<b>TOTALS</b>	<b>63054</b>	<b>46660</b>	<b>26684</b>	<b>136398</b>	<b>100.00</b>

<sup>(1)</sup> Values adapted from DOE, 1988b

TABLE J-4

## TEN-YEAR WORK-OFF CAPACITIES FOR EATF WASTE TREATMENT FACILITIES

Number of Facilities	Assumed Treatment Location	Assumed Feed Locations	Required Capacity (10-Year Work-off)				
			Solid Organics (lbs/hr)	Solid Inorganics (lbs/hr)	Sludges (lbs/hr)	Total (lbs/hr)	Total (drums/yr)
1	WIPP	All Sites	559	1212	831	2601	60892
2	INEL	Hanford, INEL, LANL, LLNL, NTS, RFP	469	1017	697	2183	51088
	SRS	ANL-E, Mound, ORNL, SRS	90	195	134	419	9804
			559	1212	831	2601	60892
3	INEL	Hanford, INEL	242	525	360	1126	26366
	RFP	RFP	149	324	222	695	16258
	WIPP	All other Sites	168	363	249	780	18268
			559	1212	831	2601	60892
4	INEL	INEL, LANL, LLNL, NTS	232	503	345	1080	25270
	RFP	RFP	149	324	222	695	16258
	SRS	ANL-E, Mound, ORNL, SRS	89	194	133	416	9743
	Hanford	Hanford	88	191	131	410	9621
			559	1212	831	2601	60892
5	INEL	INEL	154	333	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	ANL-E, Mound, ORNL, SRS	89	194	133	416	9743
	Hanford	Hanford	88	191	131	411	9621
	WIPP	LANL, LLNL, NTS	78	170	116	364	8525
			559	1212	831	2601	60892

TABLE J-4, Continued

## TEN-YEAR WORK-OFF CAPACITIES FOR EATF WASTE TREATMENT FACILITIES

Number of Facilities	Assumed Treatment Location	Assumed Feed Locations	Required Capacity (10-Year Work-off)				
			Solid Organics (lbs/hr)	Solid Inorganics (lbs/hr)	Sludges (lbs/hr)	Total (lbs/hr)	Total (drums/yr)
6	INEL	INEL	154	133	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	ORNL, SRS	84	183	125	393	9195
	Hanford	Hanford	88	191	131	411	9621
	LANL	LANL	64	138	95	297	6942
	WIPP	ANL-E LLNL, Mound, NTS	20	42	29	91	2131
			<u>559</u>	<u>1212</u>	<u>831</u>	<u>2601</u>	<u>60892</u>
7	INEL	INEL	154	333	229	715	16745
	RFP	RFP	149	324	222	695	16258
	SRS	SRS	78	170	116	364	8525
	Hanford	Hanford	88	191	131	411	9621
	LANL	LANL	64	138	95	297	6942
	ORNL	ORNL	6	13	9	29	670
	WIPP	ANL-E LLNL, Mound, NTS	20	42	29	91	2131
			<u>559</u>	<u>1212</u>	<u>831</u>	<u>2601</u>	<u>60892</u>

The following general expression is used to determine cost, first on a facility basis, and then on a system basis (sum of all facility costs):

$$\text{Capital Cost} = \sum_{k=1}^I \sum_{j=1}^P \sum_{m=1}^n \left[ C_i \left( \frac{Q_{i,j,k} + \mu}{q_i} \right)^m \right] \quad (\text{J.1-2})$$

where:

- $C_i$  = Cost in 1990 dollars of input treatment operation, Table J-1,
- $q_i$  = Capacity of reference input treatment operation, Table J-1,
- $Q_{i,j,k}$  = Capacity as a function of total waste, for each treatment operation  $i$ , given number of facilities  $j$ , and generic waste form  $k$ ,
- $\mu$  = Quantity of secondary waste generated, e.g., incinerator ash which must be vitrified,
- $m$  = 0.88. [It should be noted that Equation J.1-2 in its most basic form is referred to as the point six rule, with point six indicating  $m = 0.6$ . The EATF chose a more conservative approach by using  $m = 0.88$  (Baasel, 1990), which predicts higher costs than  $m = 0.6$ .]

Equation J.1-2 may be applied to any choice of combination alternative, work-off period, and number of facilities. This expression is easily amenable to application in spreadsheet form.

Table J-5 presents a sample calculation using:

- 1990 treatment operation cost,  $C_i$ , and base capacity,  $q_i$ , from Table J-1
- Necessary treatment operations (for each unprocessed waste form) from Table J-2
- Waste treatment capacity by waste form for a ten-year work-off period, developed from Table J-3 and presented in Table J-4.

While the applications of costing equations are presented for a particular case of ten-year work-off and Combination Alternatives 2 and 3, minor modifications allow application to all different cases. The data presented in Tables 6-8a, b, and c in Volume I of this report were similarly generated.

TABLE J-5

**CAPITAL COST SAMPLE CALCULATIONS:  
TEN-YEAR WORK-OFF OPTION  
ALTERNATIVES 2, 3**

NUMBER OF FACILITIES	% OF WASTE PROCESSED	TREATMENT: SHRED APPLICABLE WASTE FORMS:		TREATMENT: CEMENTATION APPLICABLE WASTE FORMS:			BASIC FACILITY COST (MILLIONS)	TOTAL (MILLIONS)
		SOLID ORGANICS	SOLID INORGANICS	SOLID ORGANICS	SOLID INORGANICS	SLUDGES		
1(j=1)	100%	$\$4.5 \times \left( \frac{559 + 1212}{3750} \right)^{0.88}$		$+ \$18 \times \left( \frac{559 + 1212 + 831}{367} \right)^{0.88}$			$+ \$47.6 \times \left( \frac{60892}{18000} \right)^{0.88} = 241$	241
4(j=4)								
1	41.5%	$\$4.5 \times \left( \frac{232 + 503}{3750} \right)^{0.88}$		$+ \$18 \times \left( \frac{232 + 503 + 345}{367} \right)^{0.88}$			$+ \$47.6 \times \left( \frac{25270}{18000} \right)^{0.88} = 111$	
2	26.7%	$\$4.5 \times \left( \frac{149 + 324}{3750} \right)^{0.88}$		$+ \$18 \times \left( \frac{149 + 324 + 222}{367} \right)^{0.88}$			$+ \$47.6 \times \left( \frac{16258}{18000} \right)^{0.88} = 75$	
3	16.0%	$\$4.5 \times \left( \frac{89 + 194}{3750} \right)^{0.88}$		$+ \$18 \times \left( \frac{89 + 194 + 133}{367} \right)^{0.88}$			$+ \$47.6 \times \left( \frac{9743}{18000} \right)^{0.88} = 48$	
4	15.8%	$\$4.5 \times \left( \frac{88 + 191}{3750} \right)^{0.88}$		$+ \$18 \times \left( \frac{88 + 191 + 131}{367} \right)^{0.88}$			$+ \$47.6 \times \left( \frac{9621}{18000} \right)^{0.88} = 48$	282

**NOTE:** Equation J.1-2 must be used with caution for small capacity facilities. There is potential for predicting unreasonably low costs. The EATF defined a minimum-size facility for all combination alternatives. This minimum cost is compared to all calculated values. If minimum cost is greater than a facility cost predicted by Equation J.1-2, the minimum facility cost is substituted and becomes part of total capital cost for the particular option.

### **1.3.2 Operating Costs**

#### **1.3.2.1 Costs for Continuous Operation Facilities**

Operating costs are estimated based on literature (Ross et al., 1982; McKee et al., 1986) which report operating costs as a function of capital costs. On this basis, the EATF estimates operating costs as 12 percent of capital costs, which represents continuous operation of 24 hours per day and 240 days per year.

#### **1.3.2.2 Batch Facility Operating Costs**

As noted in Section 1.3.1.4, care must be taken in estimating cost for small facilities. The same can be said for operating costs of small facilities. In practice, small facilities are operated in batch mode instead of continuous operation. Operating costs for batch facilities are assumed to be a minimum of four percent (1/3 of continuous operation) of capital, which represents a one-shift (eight hours per day) operation for 240 days per year. A sliding scale was developed to account for facilities which may operate between a single shift and 24 hours per day. It should be noted that for the treatment options considered, few facilities required batch operations.

### **1.3.3 Life Cycle Costs**

#### **1.3.3.1 Life Cycle Operating Costs**

Operating costs may be computed on a life cycle basis. Application of appropriate factors allows computation of costs on a common basis of 1990 dollars. A number of assumptions are necessary for calculation of life cycle operating costs:

- EATF assumes waste processing begins in 2000 and continues for the duration of the work-off period.
- 1990 costs may be escalated at an average rate of 3.4 percent. This figure is adapted from DOE cost estimation literature (Smedley, 1991).
- Future costs may be discounted to a common basis of 1990 dollars using a discount factor of ten percent (Bozik, 1991).

### 1.3.3.2 Life Cycle Operating Cost Estimation

Life cycle operation cost estimation is a four-step process, as outlined below:

- 1990 annual operating cost is escalated to year 2000 cost
- A future value of an annuity (for operating cost) is calculated based on the length of the work-off period
- A gradient term is computed to account for the fact that costs rise by 3.4 percent each year. The gradient factor is approximated by annual operating costs in the last year of the work-off period less annual operating cost in the first year (year 2000). This amount is divided by the work-off period  $n$ , as illustrated in Equation J.1-3.
- The sum of the annuity and gradient terms are then discounted back to 1990 dollars.

The expression used by the EATF to estimate life cycle operating cost is presented below:

$$\begin{aligned}
 LCOC = & AOC_{1990} \times (1+i)^{10} \times \left[ \frac{(1+i)^n - 1}{i} \right] \times \left[ \frac{1}{(1+k)^{(n+10)}} \right] \\
 & + \frac{G}{T} \left[ \frac{(1+i)^n - 1}{i} - n \right] \times \left[ \frac{1}{(1+k)^{(n+10)}} \right]
 \end{aligned}
 \tag{J.1-3}$$

where

- LCOC =Life cycle operating cost  
 AOC<sub>1990</sub> =Annual operating cost in 1990 dollars (see Tables 6-8a, b, and c of Volume I)  
 i =Escalation factor, 3.4 percent  
 n =Work-off period: 5, 10, or 20 years  
 k =Discount factor, 10 percent  
 G =An approximation of a gradient computed as follows:

$$\frac{(AOC_n - AOC_{2000})}{n}$$

and

$$\begin{aligned}
 AOC_n &= AOC_{1990} (1+i)^{(n+10)} \text{ operating cost at the end of work-off} \\
 AOC_{2000} &= AOC_{1990} (1+i)^{10} \text{ operating cost in the year 2000}
 \end{aligned}$$

Table J-6 presents life cycle operation cost estimates for combination alternatives 2 and 3, based on a ten-year work-off period ( $n = 10$ ), and for one through seven facilities.

### 1.3.3.3 Total Project Cost

The final calculation is a summation of capital costs described in Section 1.3.1.4 and life cycle costs developed in Section 1.3.3.2. This calculation is possible because capital cost and life cycle operating costs are both in 1990 dollars.

**TABLE J-6**  
**LIFECYCLE OPERATING COST ESTIMATES<sup>1</sup>**

NUMBER OF FACILITIES OPTION	ANNUAL OPERATING COST, (IN MILLIONS) <sup>2</sup>	LIFE CYCLE OPERATING COST (IN MILLIONS)
1	29	82
2	31	87
3	33	93
4	34	96
5	35	99
6	35	100
7	36	102

<sup>1</sup>Computed by applying Equation J.1-3, ten-year work-off period.

<sup>2</sup>Annual operating costs from Table 6-6b for combination alternatives 2 and 3.

<sup>3</sup>As an example, substituting into Equation J.1-3:

$$\begin{aligned}
 LCOC &= (29) \times (1 + 0.034)^{10} \times \left[ \frac{(1 + 0.034)^{10} - 1}{0.034} \right] \times \left[ \frac{1}{(1 + 0.10)^{(10-10)}} \right] + \\
 &\quad \left[ \frac{29 (1 + 0.034)^{(10-10)} - 29 (1 + 0.034)^{10}}{10} \right] \times \left[ \frac{1}{0.034} \right] \times \\
 &\quad \left[ \frac{(1 + 0.034)^{10} - 1}{0.034} - 10 \right] \times \left[ \frac{1}{(1 + 0.10)^{(10-10)}} \right] = \$82
 \end{aligned}$$

Note: Due to round-off of AOC for example purposes, slightly higher values for LCOC will be produced by hand calculation.

## 2.0 METHODOLOGY FOR ESTIMATION OF TRANSPORTATION COSTS

### 2.1 INTRODUCTION

The estimation of costs for transporting waste to the WIPP is based on the following general assumptions:

- TRUPACT-II trailers that originate from a particular shipping site will return to the same shipping site after unloading waste at the processing site.
- TRUPACT-II trailers used for transporting waste from the processing site to the WIPP will return empty to the processing site after unloading treated waste at the WIPP.

In case of options where WIPP itself is selected as the processing site, it is assumed that the TRUPACT-II trailers load waste at the shipping site, transport the waste to the WIPP and unload it there for subsequent treatment, and then return empty to the shipping sites.

Based on the above assumptions, the cost for transportation of waste from the sites to the WIPP consists of the following components:

- Cost of loading TRUPACT-II trailers with untreated waste at the shipping site
- Cost of trucking waste from the shipping site to the waste treatment facility at the processing site, and the cost of trucking empty TRUPACT-II trailers back to the shipping site
- Cost of unloading untreated waste from the TRUPACT-II trailers at the processing site
- Cost of loading TRUPACT-II trailers with treated waste after processing at the waste treatment facility
- Cost of trucking treated waste from the processing site to the WIPP site and the cost of trucking empty TRUPACT-II trailers back to the processing site
- Cost of unloading treated waste from the TRUPACT-II trailers at the WIPP site.

These costs are discussed in Sections 2.2 to 2.7, and a sample calculation is presented later in Section 2.8.

## 2.2 COST OF LOADING AT THE SHIPPING SITE

The cost of loading untreated waste at the shipping sites has been based on information about operations cost obtained from Westinghouse Electric Corporation (Gregory, 1991). The information provided to the EATF includes estimates of labor hours required for performing the various operations associated with loading one trailer with three TRUPACT-II containers of waste. According to these estimates, it will take 12.8 labor hours per trip for loading waste into a trailer with three TRUPACT-II containers. Thus, the total cost for loading waste at the shipping sites is estimated by the following equation:

$$\begin{aligned} \text{Cost of loading} &= (\text{Labor hours per trip}) \times (\# \text{ of trips required}) \times (\text{Labor cost per hour}) \\ &= (12.8) \times (\# \text{ of trips required}) \times (\text{Labor cost per hour}) \end{aligned}$$

The number of trips required for transporting the amount of waste from each site, has been based on the estimate that approximately 10 m<sup>3</sup> of untreated waste is equivalent to the payload for one trailer (Batchelder, 1990). Based on this assumption, the total volume of waste at each site (from Table 6-1 in Volume I) has been divided by 10 to estimate the number of trips required for each site. Finally, a rate of \$50 an hour has been assumed for labor costs. Thus, the equation for estimating the loading costs at the shipping sites is then given by:

$$\text{Cost of loading} = (12.8) \times (\text{Volume of waste in m}^3/10) \times (50 \text{ dollars})$$

Once the loading costs for each shipping site are calculated using the above equation, these costs are then added together to arrive at a total loading cost for each option.

## 2.3 COST OF TRUCKING BETWEEN SHIPPING SITES AND PROCESSING SITES

As mentioned earlier, each TRUPACT-II trailer that transports untreated waste from a particular site to a given shipping site is assumed to return to the same shipping site with empty TRUPACT-II containers. The trucking costs are based on the estimation that the cost for transporting one TRUPACT-II trailer (i.e., three TRUPACT-II containers) through a distance of one mile is approximately \$1.70 (Gregory, 1991). This quantity is also referred to as a "TRUPACT-II mile." Thus, the trucking costs are given by the following equation:

$$\begin{aligned} &\text{Cost of trucking between shipping and processing sites} \\ &= (\text{Number of TRUPACT-II miles}) \times (\text{Cost per TRUPACT-II mile}) \\ &= (\# \text{ of trips}) \times (2 \times \text{distance between shipping and processing sites}) \times (1.70) \end{aligned}$$

The distance between the shipping and the processing sites is multiplied by two to account for the round trip of a trailer between the two sites. The number of trips required can be estimated using the same procedure that has been outlined earlier in Section 2.2. The total trucking costs are estimated by adding together the cost for each combination of shipping and processing sites considered for a given number of facilities.

#### 2.4 COST OF UNLOADING AT THE PROCESSING SITE

The cost of unloading waste at the processing site has been based on similar estimates of unloading waste at the WIPP site that have been obtained from Gregory (1991). According to these estimates, it takes approximately 11.5 labor hours to unload waste from one TRUPACT-II trailer and to replace the empty TRUPACT-II containers on the trailer after the unloading process has been completed. Therefore, the cost of unloading untreated waste at the processing site is given by the following equation:

$$\begin{aligned} & \text{Cost of unloading untreated waste at the processing site} \\ & = (\# \text{ of trips}) \times (\text{Labor hours per trip}) \times (\text{Cost per labor hour}) \\ & = (\# \text{ of trips}) \times (11.5 \times 50 \text{ dollars}) \end{aligned}$$

The number of trips can be estimated using the methodology outlined earlier in Section 2.2. The total unloading costs at the processing site are then obtained by adding the costs of unloading waste from each shipping site.

#### 2.5 COST OF LOADING TREATED WASTE AT THE PROCESSING SITE

The cost of loading treated waste can be estimated in a manner similar to the method outlined earlier in Section 2.2. The only exception in this case is that some of the untreated waste will undergo volume reduction due to the waste processing. Consequently, the volume of waste will decrease after treatment, and so will the number of trips required to transport the treated waste to the WIPP. Thus, the number of trips required need to be recalculated using the estimated amount of waste after the volume reduction.

The number of trips required from the processing site to the WIPP site has been estimated using the following methodology:

- Estimation of the volume of waste after treatment, by dividing the untreated waste volumes by the volume reduction factors that were discussed in Section 3.0 of Volume I of this document. This has been done for all three waste forms (i.e., sludges, solid organics, and solid inorganics).

- Estimation of the weight of the processed waste by multiplying the volume of processed waste by the density of processed waste for each option.
- Estimation of the number of trips required based on the information that the maximum allowable waste payload per TRUPACT-II trailer is 13,595 lb. (Gregory, 1991).

Once the required number of trips has been estimated, the loading costs are estimated as follows:

Cost of loading treated waste at the processing site

$$= (\# \text{ of trips}) \times (\text{Labor hours per trip}) \times (\text{Cost per labor hour})$$

$$= (\# \text{ of trips}) \times (12.8) \times (50 \text{ dollars})$$

The total cost for each option can then be obtained as the sum total of the loading costs for processed waste from all shipping sites.

## 2.6 COST OF TRUCKING BETWEEN PROCESSING SITES AND THE WIPP SITE

The cost of trucking for carrying treated waste from the processing site to the WIPP site has been calculated using the same methodology outlined earlier in Section 2.3. Therefore, once the number of trips required has been calculated using the methodology described in the previous section, the trucking costs are estimated by the following equation:

Cost of trucking between processing sites and the WIPP site

$$= (\text{Number of TRUPACT-II miles}) \times (\text{Cost per TRUPACT-II mile})$$

$$= (\# \text{ of trips}) \times (2 \times \text{distance between processing sites and WIPP}) \times (1.70)$$

The distance between the sites is multiplied by a factor of two to account for the round trip required for bringing trailers with empty TRUPACT-II containers back to the processing site.

## 2.7 COST OF UNLOADING WASTE AT THE WIPP SITE

The cost of unloading waste at the WIPP site has been calculated using the same methodology presented earlier in Section 2.4. Thus, the unloading costs are estimated by the following equation:

Cost of unloading waste at the WIPP site

$$= (\# \text{ of trips}) \times (\text{Labor hours per trip}) \times (\text{Cost per labor hour})$$

$$= (\# \text{ of trips}) \times (11.5 \times 50 \text{ dollars})$$

The number of trips required from the processing site to the WIPP site is obtained using the same methodology outlined in Section 2.5. Once the unloading costs for waste from each processing site have been calculated, these costs can be added to obtain an estimate for the total unloading costs for each option.

## 2.8 SAMPLE CALCULATION FOR ESTIMATION OF TRANSPORTATION COSTS

The methodology for estimation of transportation costs is illustrated using the case of two processing facilities from Table J-4 as an example. The following sample calculation uses the example of Hanford as the shipping site and INEL as the processing site, followed by disposal at the WIPP site. It is also assumed that Alternative 2 (or 3) is the selected treatment option.

### 2.8.1 Cost of Loading Untreated Waste at the Hanford Site

The volume of waste at the Hanford site is given in Table J-3 as follows:

Sludges	1217 m <sup>3</sup>
Solid Organic	8736
Solid Inorganics	<u>11591</u>
	21544 m <sup>3</sup>

The cost of loading waste at Hanford is then calculated by using the equation provided in Section 2.2 as follows:

Cost of loading untreated waste at the Hanford site

$$= (12.8) \times (\text{Volume of waste in m}^3/10) \times (50 \text{ dollars})$$

$$= \$ 1,380,000$$

### 2.8.2 Cost of Trucking Between Hanford and INEL

The trucking costs are calculated by the equation given in Section 2.3 as follows:

**Cost of trucking between Hanford and INEL**

$$\begin{aligned} &= (\# \text{ of trips}) \times (2 \times \text{distance between Hanford and INEL}) \times (1.70) \\ &= (\text{Volume of waste in m}^3/10) \times (2 \times 581) \times (1.70) \\ &= (21544/10) \times (2 \times 581) \times (1.70) \\ &= \$ 4,260,000 \end{aligned}$$

**2.8.3 Cost of Unloading Waste at INEL**

The unloading costs at the INEL site can be calculated using the equation presented in Section 2.4 as follows:

**Cost of unloading untreated waste at the INEL site**

$$\begin{aligned} &= (\# \text{ of trips}) \times (11.5) \times (50 \text{ dollars}) \\ &= (21544/10) \times (11.5) \times (50 \text{ dollars}) \\ &= \$ 1,240,000 \end{aligned}$$

**2.8.4 Cost of Loading Treated Waste at the INEL Site**

The costs for loading treated waste at the INEL site is estimated using the step-by-step methodology described in Section 2.5. The volume and weight of the waste after treatment are calculated using volume reduction factors for each of the three waste forms using Alternative 2, and the densities of these processed waste forms. For Alternative 2, these factors are listed on Table J-7. Using these values, the total weight of processed waste can be calculated as follows:

**Total volume of sludges after processing**

$$\begin{aligned} &= 1217/1.0 \\ &= 1217 \end{aligned}$$

**Total weight of sludges after processing**

$$\begin{aligned} &= (1217 \text{ m}^3) \times (0.0510 \text{ lb/in}^3) \times (61023.37 \text{ in}^3/\text{m}^3) \\ &= 3,788,000 \text{ lb.} \end{aligned}$$

TABLE J-7

**VOLUME REDUCTION FACTORS AND PROCESSED WASTE DENSITIES  
FOR ALTERNATIVE 2**

<b>WASTE FORM</b>	<b>VOLUME REDUCTION FACTOR</b>	<b>DENSITY (lb/in<sup>3</sup>)</b>
Sludges	1:1	.0510
Solid Organics	1.173:1	.0637
Solid Inorganics	1.173:1	.0726

**Total volume of solid organics after processing**

$$= 8736/1.173$$

$$= 7448 \text{ m}^3$$

**Total weight of solid organics after processing**

$$= (7448 \text{ m}^3) \times (0.0637 \text{ lb/in}^3) \times (61023.37 \text{ in}^3/\text{m}^3)$$

$$= 28,952,000 \text{ lb.}$$

**Total volume of solid inorganics after processing**

$$= 11591/1.173$$

$$= 9881 \text{ m}^3$$

**Total weight of solid inorganics after processing**

$$= (9881 \text{ m}^3) \times (0.0726 \text{ lb/in}^3) \times (61023.37 \text{ in}^3/\text{m}^3)$$

$$= 43,776,000 \text{ lb.}$$

**Therefore, the total weight of treated waste to be shipped to WIPP is:**

$$= 3,788,000 + 28,952,000 + 43,776,000$$

$$= 76,516,000 \text{ lb.}$$

Once the total weight to be shipped is known, the number of trips required is calculated as follows:

**Number of trips required**

$$= 76,516,000 \text{ lb.} / 13,595 \text{ lb. per trip}$$

$$= 5628 \text{ trips}$$

The loading costs at the processing site for 5628 trips is calculated by the equation given in Section 2.5 as follows:

$$\begin{aligned}
 & \text{Cost of loading treated waste at INEL} \\
 &= (\# \text{ of trips}) \times (\text{Labor hours per trip}) \times (\text{Cost per labor hour}) \\
 &= (5628) \times (12.8) \times (50 \text{ dollars}) \\
 &= \$ 3,600,000
 \end{aligned}$$

#### 2.8.5 Cost of Trucking Between INEL and the WIPP Site

The trucking costs are estimated by the equation given Section 2.6 as follows:

$$\begin{aligned}
 & \text{Cost of trucking between INEL and the WIPP site} \\
 &= (\# \text{ of trips}) \times (2 \times \text{distance between INEL and WIPP}) \times (1.70) \\
 &= (5628) \times (2 \times 1484) \times (1.70) \\
 &= \$ 28,400,000
 \end{aligned}$$

#### 2.8.6 Cost of Unloading at the WIPP Site

The cost of unloading waste at the WIPP site is estimated by the equation given in Section 2.7 as follows:

$$\begin{aligned}
 & \text{Cost of unloading waste at the WIPP site} \\
 &= (\# \text{ of trips}) \times (11.5) \times (50 \text{ dollars}) \\
 &= (5628 \times (11.5)) \times (50 \text{ dollars}) \\
 &= \$ 3,240,000
 \end{aligned}$$

### **2.8.7 Total Transportation Costs for Two Facilities Using Alternative 2**

The estimates presented above can be added together to obtain the total transportation costs for shipping all the waste from the Hanford site to INEL for processing and then transporting the processed waste to the WIPP site. The approach used for Hanford and INEL above can be repeated for all other shipping/processing site combinations and the resulting costs can be added to obtain a total transportation cost using two facilities and Alternative 2 (or 3) as the treatment option.

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