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A METHODOLOGY AND A PRELIMINARY DATA BASE FOR EXAMINING THE HEALTH RISKS OF ELECTRICITY GENERATION FROM URANIUM AND COAL FUELS

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ABSTRACT

An analytical model was developed to assess and examine the health effects associated with the production of electricity from uranium and coal fuels. The model is based on a systematic methodology that is both simple and easy to check, and provides details about the various components of health risk.

A preliminary set of data that is needed to calculate the health risks was gathered, normalized to the model facilities, and presented in a concise manner. Additional data will become available as a result of other evaluations of both fuel cycles, and they should be included in the data base.

An iterative approach involving only a few steps is recommended for validating the model. After each validation step, the model is improved in the areas where new information or increased interest justifies such upgrading. Sensitivity analysis is proposed as the best method of using the model to its full potential.

Detailed quantification of the risks associated with the two fuel cycles is not presented in this report. The evaluation of risks from producing electricity by these two methods can be completed only after several steps that address difficult social and technical questions. Preliminary quantitative assessment showed that several factors not considered in detail in previous studies are potentially important.

EXECUTIVE SUMMARY

The importance of including the health effects of producing construction materials, etc. into an assessment of producing electricity from various energy sources was popularized as a result of Inhaber's work,[1] even though he may not have originated such considerations.[2,3] Nevertheless, the need to include the activities in the construction and decommissioning phases, as well as the energy and material requirements, in an assessment of the health risks of electricity generation from coal and uranium fuels has been clearly demonstrated.

A systematic methodology that is simple, clear, and easy to check is needed for such assessments. Such a methodology will assure an equitable treatment of the two cycles, provide a proper level of detail about the various risk components and the assumptions underlying their estimates, and permit comparisons of these estimates to identify significant risk contributors.

METHODOLOGY

A fuel cycle comprises four segments: fuel acquisition, fuel processing and upgrading, energy production, and waste disposal and fuel material recycle. Each segment includes one or more stages; each stage is characterized by a particular process involving the fuel material in some form, with typical transportation modes between stages.

Fuel cycle stages are represented by model facilities. Parameters of the model facility are chosen to reflect (1) current national production, (2) current state of technology, and (3) design of modern existing facilities or facilities planned or under construction. The model facility can be simple or composite. A simple model facility is characterized by a single dominant process for upgrading the fuel materials or generating energy. A composite facility combines several alternative processes, each fed with the same input and producing similar outputs.

The life cycle of each model facility is divided into construction, operation, and decommissioning phases. Each phase is analyzed to identify its typical activities and to determine the hazards associated with these activities. Activities, which include material production, equipment fabrication, normal operations, and transportation, are grouped into three basic activity categories: construction, operation, and decommissioning. Performing any activity in any category carries a certain level of risk to workers and the general public.

Risk can be quantified by developing a computational model that correlates each activity to its eventual health impact. The model uses three classes of variables: requirements (R), effluents (F), and health impact (P) variables. Requirements variables measure each activity's magnitude. For example, operational activities are measured primarily by the amounts of fuel (coal or uranium) involved in the annual operations of the model power plant. Fuel materials requirements depend on several secondary requirements, such as process materials, energy, and services (e.g., transportation and direct labor). Requirements variables tend to form a divergent chain (or tree), with a primary requirement variable being located in the first level of this tree. Each primary requirement variable requires several secondary variables, each of which is associated with several tertiary variables, and so on. Third- and higher-order variables are not considered in this study unless their impact is judged significant. Figure 1 shows the generic requirement tree for three typical primary variables: material requirement (RM), equipment requirement, (RQ), and transportation requirement (RT) variables. Typical secondary requirement variables--energy (RE), transportation (RT), and manpower (RL) (Figure 1.a)--required to produce the primary variable are also shown. These generic requirements trees serve as building blocks for structuring the analytic model.

Effluents are released as primary and secondary requirements variables are produced. Amounts of effluents released (FS variables) are used to define the effluent source terms in the model. These

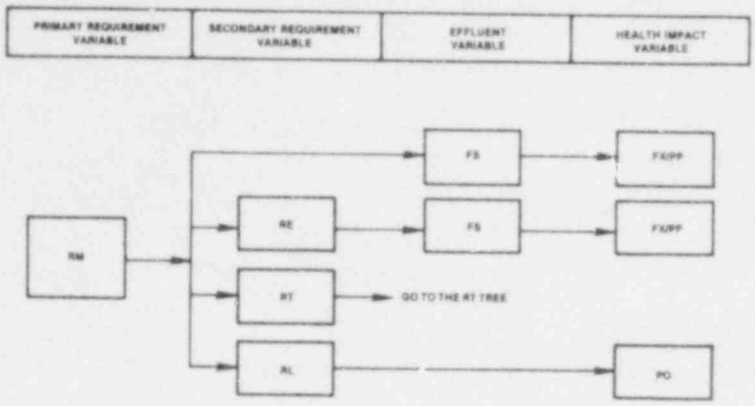

FIGURE 1-a. GENERIC MATERIAL REQUIREMENT TREE

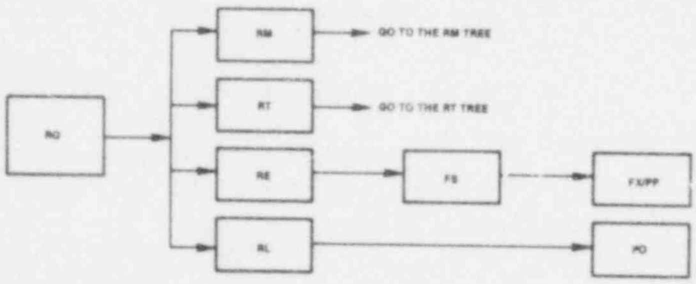

FIGURE 1-b. GENERIC EQUIPMENT REQUIREMENT TREE

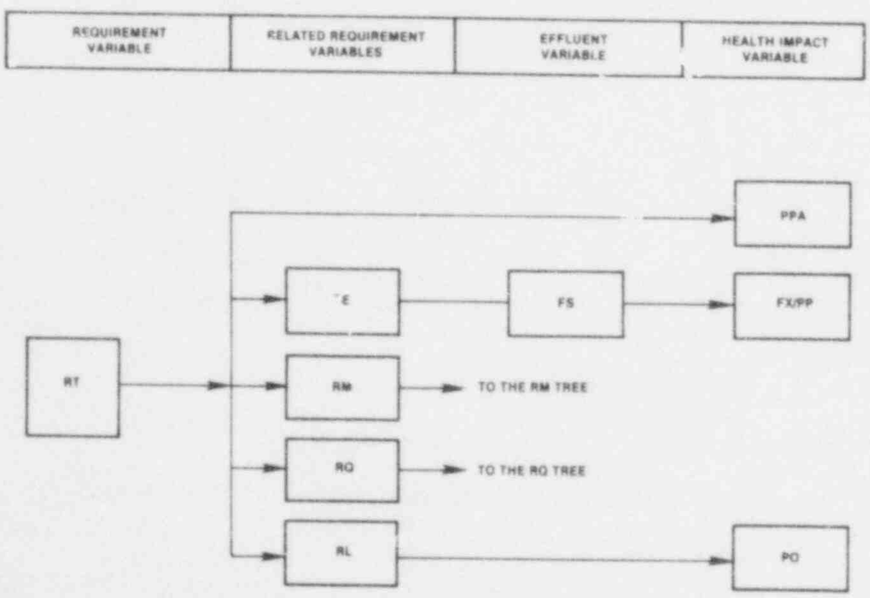

FIGURE 1-c. GENERIC TRANSPORTATION REQUIREMENT TREE

source terms, which include both normal and properly weighted accidental or uncontrolled release components, are inputs to the dispersion models used to compute effluent exposure (FX) variables. The health impact (P) variables have two major components: occupational (PO) and public health (PP) impacts. Occupational impact is directly related to the requirements variables, whereas public health impact depends to a larger extent on the effluent exposure variables.

Figure 2 shows variables used to calculate the health impact associated with each stage of the fuel cycle. The figure allows the analyst and the reader to assess the completeness of the model and clarifies the calculational chain involved in computing each health impact component.

Model facilities data and projected life times were used to estimate primary requirement variables and normal and accidental effluent source terms. Transfer coefficients linking primary requirements to higher-order variables and to their consequential effluents and health impact required extensive modeling. For example, the whole production cycle shown in Figure 3 was used to estimate occupational and public health effects associated with material, equipment, and nonelectric energy requirement variables for each model facility. Computations were complicated by the presence of imports in certain stages of the production cycle as well as in recycle of some metals (e.g., steel and aluminum). Similarly, a combination of transportation requirements changes with the geographic region served, and each mode has its cargo-related and non-cargo-related health impacts. The electric energy requirement variable can be supplied by a coal-fired or nuclear plant, a combination of both, or a combination with other plant types. National electric energy production data or future projections can be used to estimate the interaction terms, and a simple mathematical procedure was developed to estimate the health effects in the presence of this interaction. The coal and uranium cycles can operate under various options.

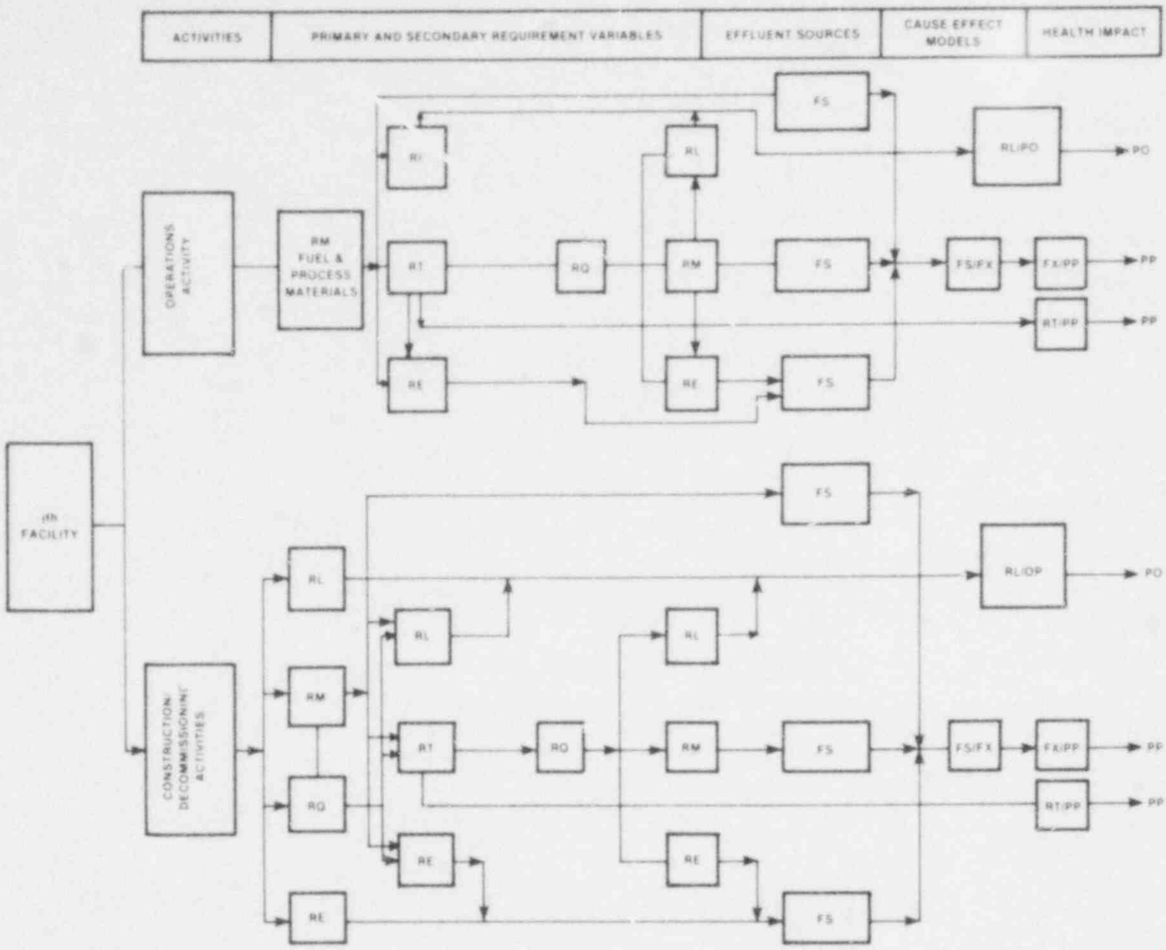

FIGURE 2. METHODOLOGY TREE.

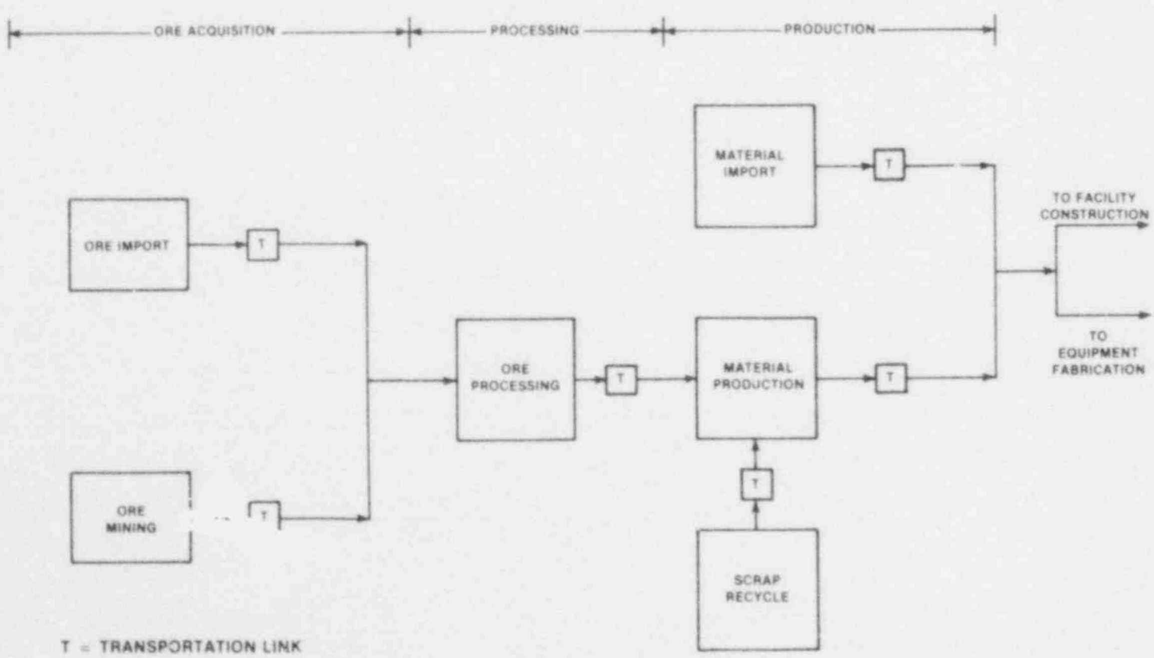

FIGURE 3. SIMPLIFIED MATERIAL PRODUCTION CYCLE

The coal cycle can be typical of the eastern U.S., using coal mined in the East and serving the dense populated Northeast, or it can be typical of the West with its long transportation routes. Because eastern and western cycles use coal with different characteristics and transportation modes, health effects estimates for the two options can ield valuable information. Similarly, the uranium cycle can operate on a once-through fuel mode, uranium recycle mode, or uranium and plutonium recycle. It can use the energy-intensive diffusion enrichment or centrifuge alternatives. The fuel cycle structure will vary from one option to another and the subsequent health risk will vary accordingly.

A simple mathematical model based on the methodology flow diagram in gure 2 was developed and used for hand calculations that led to the preliminary health effects estimates in this work. The proposed computerization of this model will have several advantages, among which is the ease of changing parameters and integrating newly acquired improved data and the simplicity of promoting the structure of the model segments where more sophistication may be eventually required. A computerized model will also add the capability for conducting sensitivity analysis, which is important because of the large uncertainties in the data base. This capability allows the analyst to identify and isolate those factors having the largest health impact.

DATA AND UNCERTAINTIES

Numerous data are required to assess the magnitude of the primary requirements and effluent variables and the functional dependence among the various variables. Ideally, a large pool of raw original data should be acquired, followed by consistent treatment of these data for optimum estimation of model parameters and parameter uncertainties. Unfortunately, all of the reported original data were not readily available, nor did the time and effort constraints on this study allow such a formidable task. The only available option was to rely on secondary sources of data. Data extracted from secondary sources are diverse, including elements based on experiments, design, accident statistics, expert opinion, and engineering judgment and extrapolations of secondary data. Reliance on secondary sources will result in errors and some biases in the health effects estimates and will introduce inconsistencies in the analysis. Other possible sources of uncertainties include the mathematical approximation involved in the modeling and the structure of the overall assessment model.

Nevertheless, valuable information can still be gained from this preliminary study phase by analyzing the health effect components constituting the fine structure of the overall results, using sensitivity analysis after the model computerization, and adopting an iterative approach to risk comparison for the coal and uranium cycles. Preliminary hand-calculated results produced by the model can be used for model validation, which can be achieved by two parallel methods: (1) comparison with previously published studies[4-12] and investigation of the discrepancies associated with new findings; and (2) peer review and exposure of the study to open criticism. This combination will enhance identification of pitfalls and new issues that can be used to direct the second iteration toward a higher level of effectiveness and confidence in the results.

OTHER ISSUES AND CONSIDERATIONS

Effluents from the coal and uranium cycles can have localized and short-term effects as well as long-term global or regional effects. Some effluents can induce climatic changes, and others can be released as long-lived effluents or daughters of long-lived effluents. Solid waste can be safely disposed of for long periods, but there is no guarantee that some mechanisms will not initiate future releases. Adverse health impacts can also result from human intrusion or illicit actions or indirectly result from resources depletion.

Climatic Changes

Climatic changes can be localized, as are those associated with heat and moisture releases from the model power plants, or they can be global and regional, e.g., "greenhouse" effects and "acid rain."

Carbon dioxide is the major gaseous effluent from coal combustion, and atmospheric measurements have indicated a steady increase in CO_2 concentrations.[12-15] CO_2 buildup in the atmosphere affects the climate through the greenhouse effect, i.e., entrapping heat in the earth's atmosphere. Doubling of CO_2 concentration in the atmosphere could raise the temperature at the middle latitudes by about 3°C and near the poles by 9 to 12°C.[13] Such postulated increases may result in changes in rainfall patterns or gradual melting of polar ice.

Sulfur and nitrogen oxides released from coal-fired plants interact with oxygen and moisture in the atmosphere to produce sulfuric and nitric acids. These acids are then scavenged from the atmosphere by precipitation to form acid rain.[12,14]

The relative contributions of the model coal-fired plant to the greenhouse effect or to acid rain is uncertain, and quantitative relationships correlating these effects to human health are even less certain, requiring further investigation.

Long-Term Effects

Untreated dry tailings from the uranium ore milling operation can affect human health by inhalation of wind-blown dust, inhalation of radon progeny, exposure to gamma radiation from radon and its progeny, and ingestion of surface water containing radionuclides leached from the pile.[16] Normal precautionary measures can diminish all these effects to an insignificant level. Mill tailings stabilization can minimize radon emanation for a long time; however the half-life (8×10^4 years) of Th-230, the radon precursor, means that pile stabilization is an interim, not a permanent, solution. Because radon releases can adversely affect the health of future generations, permanent solutions should be considered.

One solution is to dispose of the tailings in underground uranium mines as part of mine decommissioning. Open pit mines can be partially backfilled with mine waste from subsequent mine operations until the pit bottom is well above the underground water table; tailings can then be used as fill and covered with a thick layer of earth topped with vegetation or coarse rocks. Another solution is chemical separation of Th-230 and Ra-226 as a part of the milling process, followed by disposal in a high-level waste repository.

Estimations of the long-term effects of radon emanation from untreated tailings piles are controversial. Integrated health effect estimates range from insignificant to large values, depending on the dispersion and future population growth models used.[17,18,19]

Coal contains small quantities of U-238, U-235, Th-232, and their decay products. The uranium content in U.S. coal varies from 0.2 to greater than 25 ppm, with average content of about 1 ppm.[20] Because coal ash piles will emit radon, they present a problem similar to that of uranium mill tailings. However, unlike mill tailings, coal ash piles are close to population centers.

Another controversial issue is the possibility of future breach of the containment of a high-level waste geologic repository. Long-lived isotopes can be released to the biosphere after violent natural phenomena, human intrusion, or slow underground water transport. The consensus of previous studies in the U.S. and Europe[21,22,23] is that migration of nuclear waste in underground water is of greater concern than the possibility of sudden disruptive events. In underground aquatic transport, water enters the repository, dissolves the waste form, and the waste-bearing groundwater migrates to the biosphere. The potential for waste release is influenced by waste management practices, repository site and geology, repository design and waste form, the waste package, and other engineered release barriers selected. For reasonable site location and repository design, no plausible mechanisms can cause release earlier than a thousand years after waste disposal. By that time, fission products that dominate early risk will have decayed to insignificant levels (i.e., that of natural uranium ore). Although risk assessment studies are uniformly optimistic in their evaluation of long-term safety, there is not broad consensus that safety has been either demonstrated or proven.

Sabotage and Diversion

Sabotage can be accomplished by various hypothetical and generally complex scenarios. Motivations to commit such an act can be political or psychological or for coercion and monetary gain. Successful sabotage requires detailed knowledge about the target facility layout and design features. Diversion is the theft of nuclear material for the purpose of constructing a dispersal weapon. Detonation of such a device would result in limited to catastrophic impact.

Consequences of sabotage and diversion may be large, but highly uncertain. Relating these consequences to one power plant year operation will unavoidably involve some degree of arbitrariness and speculation.

CAUSE-EFFECT MODELS

In this study, the health effects of exposure to radiation are based on two models. The first, which deals with low-radiation exposure, is based on the linear (nonthreshold) models of the BEIR report[24] and GESMO.[7] This model expresses health effects in terms of cases per million person-rems. The estimated number of cases is latent and does not depend on the dose rate, which is a clear weakness in the model. However, the linear model is widely accepted and is generally thought to be conservative. The second model is related to acute exposure and is not used in this study phase.

Cause-effect relationships involving coal-fired plant effluents are in general lacking. The model developed by Hamilton and coworkers at BNL[25,26] was adopted. This model uses sulfates as an index and a cause-effect relationship relating sulfate exposure to increased annual mortality rate. Acute effects associated with air pollution episodes are not included in the model.

The models used so far are calculational and are based on extrapolations and other simplifying assumptions. Other health effects in the coal and uranium cycles are estimated from observed data. Among these are occupational injuries, deaths and illnesses, and some public hazard data. Occupational illnesses include black lung disease and lung cancers for coal and uranium mining. Present regulations have improved working conditions in the operating mines and the number of cases induced by present-day conditions are expected to differ from the latest published estimates. Occupational illness cannot be simply related to the latest production figures unless working conditions remain static for a long time.

PRELIMINARY RESULTS

The methodology and data base were applied to a case study involving the uranium cycle. Hand-calculated health effects estimates were computed for comparison with other published estimates as part of the model validation procedure. Resource limitations prevented similar calculations for the coal fuel cycle.

Occupational health effects in the operations phase of the model facilities of the uranium cycle were found to be comparable to previous estimates.[10] Occupational risks in the construction phase were found to be comparable to those of the operations phase for both the model enrichment facility and the model LWR. Decommissioning risks were found to be comparable to those of the operations phase for the model reprocessing facility, but were about an order of magnitude smaller than those for the model LWR. Corresponding risks for other model facilities remained insignificant.

Transportation requirements showed a significant increase when the construction and decommissioning requirements were considered, with the largest increase occurring for the model LWR. Accordingly, non-cargo-related transportation risks are increased, whereas the increase for cargo-related risks was less significant.

Materials requirements are dominated by those for the model LWR and the model enrichment facility. Occupational hazards associated with the materials production cycle were found to be relatively low when compared with other risks in the cycle.

As expected, the electrical energy requirements are dominated by the model diffusion facility and drop by more than 80% when the centrifuge enrichment is used. Most of the nonelectric energy requirement (about 60%) is projected to be consumed during decommissioning, while 30% is consumed during operations.

Impacts on public health are dominated by the model LWR and reprocessing facility. Radiological accidents were found to have a very small health impact, except for the LWR class 9 accidents, where calculations were based on very conservative assumptions.

Although these calculations are preliminary in nature, they yield valuable information about those factors that can change the value of risk estimates. The use of an improved data base and sensitivity analysis techniques will undoubtedly shed a new light on the relative health impact on the coal and uranium cycles.

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Their comments were very valuable and most appreciated. Their comments were carefully considered in the development of this final report; however, resource limitations did not permit a complete response at this time. The report does not necessarily reflect the opinions of these individuals, nor their organizations.

This project is one part of NRC research on methods available to determine acceptable risk. The other part is a study of approaches to acceptable risk and is being performed by B. Fischhoff, S. Lichtenstein, and P. Slovic of Decision Research, S. Derby of

Stanford University, and R. Keeney of Woodward-Clyde. Interaction with them provided the SAI staff with an appreciation of what we can expect to accomplish, what we should not attempt, and some perspective on the role of this type of quantitative methodology.

1.0 INTRODUCTION

1.1 BACKGROUND

The Nuclear Regulatory Commission (NRC) reviews the environmental impacts of proposed nuclear reactor power plants and prepares an environmental impact statement as required by the National Environmental Policy Act (NEPA). One important consideration in such a review is the assessment of alternatives to the proposed action, and a prime alternative to a proposed power plant is production of electricity by a coal plant. In making an analysis of the alternatives of producing electricity by a nuclear or a coal plant, one consideration is the health effects attributable to the entire fuel cycle of both alternatives. The nuclear fuel cycle consists of mining, milling, conversion, enrichment, fuel fabrication, power production, reprocessing, waste disposal, and transportation. The coal fuel cycle consists of mining, processing, power generation, waste disposal, and transportation.

Previous evaluations have considered these fuel cycle steps, but generally have emphasized the impacts of the operation phase of the various facilities. Recently, more attention has been focused on the other phases, such as decommissioning of nuclear facilities. Reports by Holdren[1] and coworkers at the University of California, by Inhaber[2] at the Canadian Atomic Energy Control Board, and others[3] indicated that, in addition to the construction, operation, and decommissioning of the different portions of the fuel cycle, the production of the materials and the energy required to construct and operate the fuel cycle facilities can be a major contributor to the overall risk. In response to this developing recognition of the importance of all phases of the fuel cycles, the effort documented here developed a methodology to integrate all risk-inducing phases of the two fuel cycles and developed a preliminary data base for use with the methodology.

In their review of nuclear plant safety the NRC makes judgments as to the acceptability of the risk of operating the plant. The criteria for these judgements generally have not been quantified, and the NRC is conducting research both on methods to quantify risk and methods to determine the acceptability of risk. One method of comparing alternatives is to compare the risks of the alternatives while assuming that both actions have the same benefit. Presumably, the alternative having the lower risk is judged preferable; however, both alternatives may have acceptably low risks. (The latter is the generally accepted view of the two alternatives considered in this report.) This report is part of NRC research on methods available to determine acceptable risk.

1.2 OBJECTIVES

The objectives of the research reported here are:

1. To investigate the health risks from the coal and nuclear fuel cycles by including the risk of constructing, decommissioning, and operating the facilities and the risk of producing the materials and the energy required during these phases.

2. To develop a consistent, systematic framework or methodology for future calculations of risk from alternative means of supplying electricity.

3. To identify those areas in which better data are needed to reduce the uncertainty of these risk calculations.

The approach has been to identify the occupational and public health risks of each step of the two fuel cycles by studying the available literature. Data needed to calculate the health risks were gathered, normalized to the model facilities, and presented in a concise manner. Variations and ranges in the data were indicated when they were found. More data was available in some areas than others, and this has resulted in some inconsistency in the presentation here. A number of NRC contractors (and contractors to other federal agencies) are evaluating in detail the various aspects of both fuel cycles. As these data become available, they should be included in the data base and be used to update numerical estimates.

Using the identification of risk-contributing elements, a multi-input, multi-output analytical model was developed for each fuel cycle step. This model started with a top-level evaluation and simulated the interrelationship among the steps. By using a top-down systems approach, the components can be modeled to an appropriate level of detail. Although data do exist to expand the level of detail of some component models, the systems approach resulted in a methodology that did not require this level of detail and is still consistent with the overall evaluation being developed.

This research has not resulted in determination of the risk of these two fuel cycles. Those answers can only come after a number of iterations, each having a thorough peer review. The main contributions of this research have been (1) to propose an analytical method to consistently and systematically evalute the overall risks of the two fuel cycles and (2) to gather relevant data on the construction, operation, and decommissioning phases of each cycle in a more complete form than previously reported.

The methodology and data base were applied to a case study involving the uranium cycle. Hand-calculated health effects estimates were computed for comparison with other published estimates as part of the model validation procedure. Resource limitations prevented similar calculations for the coal fuel cycle. Documentation of the results in detail would have required more explanation than resources permitted; therefore, to avoid unnecessary confusion, the results are not described in more detail in later sections. Recommendations to correct the situation are made in the next section.

Occupational health effects in the operations phase of the model facilities of the uranium cycle were found to be comparable to previous estimates.[4] Occupational risks in the construction phase were found to be comparable to those of the operations phase for both the model enrichment facility and the model LWR. Decommissioning risks were found to be comparable to those of the operations phase for the model reprocessing facility, but were about an order of magnitude smaller than those for the model LWR. Corresponding risks for other model facilities remained insignificant.

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Although these calculations are preliminary in nature, they yield valuable information about those factors that can change the value of risk estimates. The use of an improved data base and sensitivity analysis techniques will undoubtedly shed a new light on the relative health impact of the coal and uranium cycles.

1.3 RECOMMENDATIONS

The total task is formidable, and more work is needed in many sensitive areas. The report is being released for review and comment by the technical community to stimulate discussion. It is suggested that the hand calculation illustrating the methodology and the data base be completed and fully documented. The preliminary results could be used for comparison with other work. It is also recommended that the analytical model be programmed and that detailed risk calculations and sensitivity studies be made.

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2.0 METHODOLOGY

The main objective of this study is to provide a systematic methodology for assessing and comparing risks associated with the production of electricity from uranium and coal fuels. A systematic methodology assures uniform treatment of the two cycles and provides flexibility for integrating other energy cycles in future comparisons. Numerous comparisons of this type have been published, and recent work shows that including materials and energy used in the construction and operation of energy cycle facilities in the risk analysis significantly affects the total risk associated with the cycle, particularly for some of the materials-intensive, nonconventional energy cycles. As a consequence, this report considers the risks associated with construction, operation, and decommissioning of the cycle facilities.

Complete comparisons require the existence of an adequate data base, which is currently not available. Much of the information essential for the study is either completely absent or is associated with great uncertainty, which makes direct comparative analysis extremely difficult, if not impossible. This is especially true in the area of the health impact of nonradioactive effluents and in regard to the decommissioning of major facilities.

Factors such as resource depletion and conservation, damage to the environment, and the "greenhouse effect" have an indirect impact on health. In addition, acts of terrorism and sabotage and diversion of nuclear materials theoretically may have catastrophic consequences. The establishment of a link between these acts and nuclear power generation and the assessment of the magnitude of their consequences are extremely difficult tasks. These problem areas are briefly discussed in Section 5 of this report.

In this section, our concept of an energy production cycle is defined, and the study methodology is briefly outlined. Data related to the uranium and coal cycles are presented in the following sections in a format compatible with the proposed methodology.

2.1 FUEL CYCLE AND ENERGY PRODUCTION CYCLE

In general, a fuel cycle comprises four typical segments: (1) the fuel acquisition segment; (2) the fuel processing and upgrading segment; (3) the energy production segment; and (4) the waste disposal and fuel material recycle segment. Each segment includes one or more stages, each characterized by a particular process involving the fuel material. Figures 2.1 and 2.2 show the uranium and coal fuel cycles with their segments and stages within each segment. Transportation interconnects the different stages within each cycle and is considered as part of each stage.

Since one goal of this study is to provide detailed risk accounting, it is recognized that risks associated with fuel flow in an operating fuel cycle are significant, but by no means represent the overall risk associated with energy production. Pre- and post-operational activities are also associated with risk. For this reason, the energy production cycle concept is applied. An energy production cycle considers not only the operational phase of each stage in the fuel cycle, but also other phases, as shown in Figure 2.3. Included are the preconstruction, construction, operation, and decommissioning phases.

While the conventional fuel cycle is concerned with the mass flow of fuel materials, the energy production cycle considers each stage as a multi-input, multi-output stage. Typical input and output variables are shown in Figure 2.4.

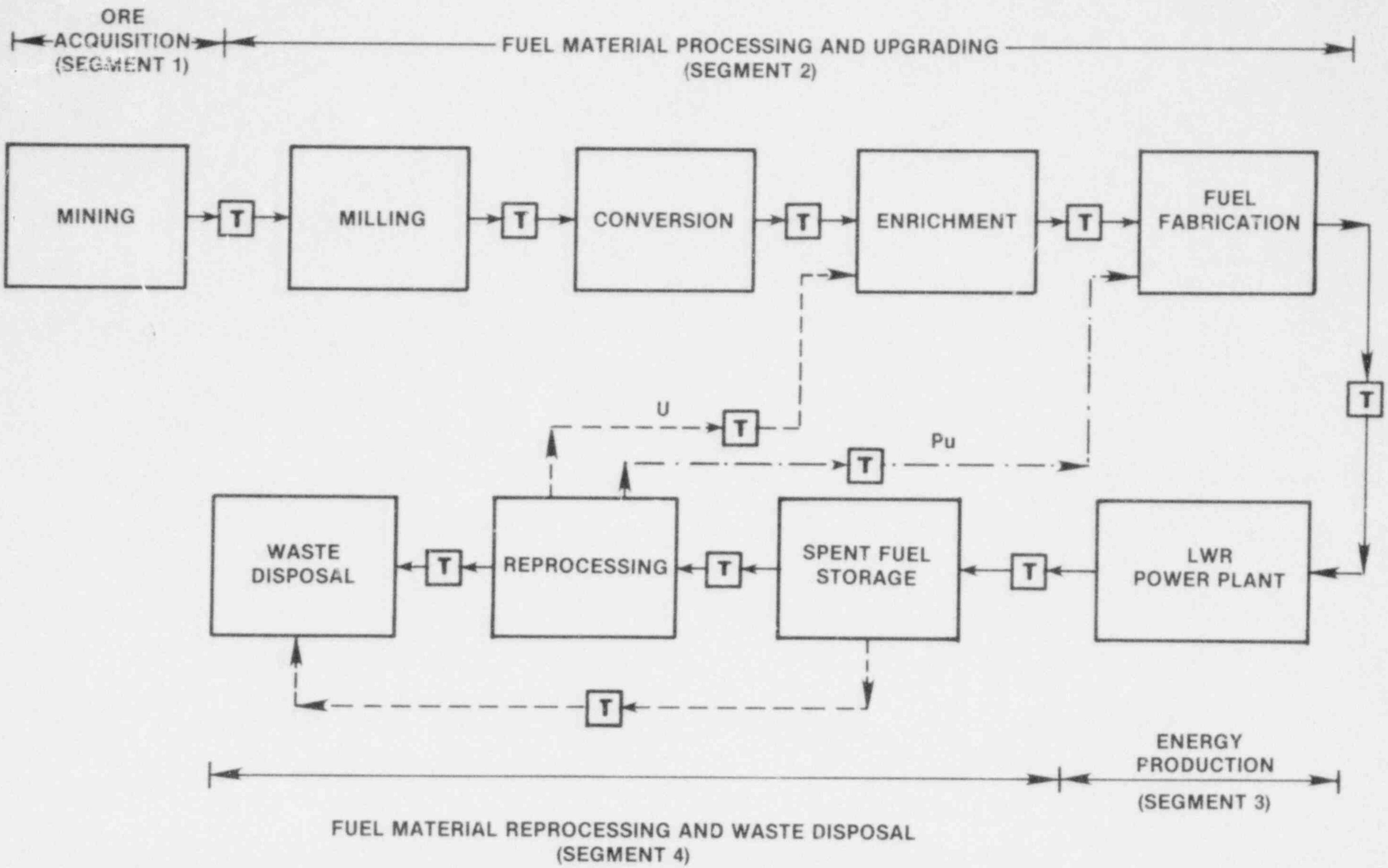

FIGURE 2.1. THE URANIUM FUEL CYCLE.

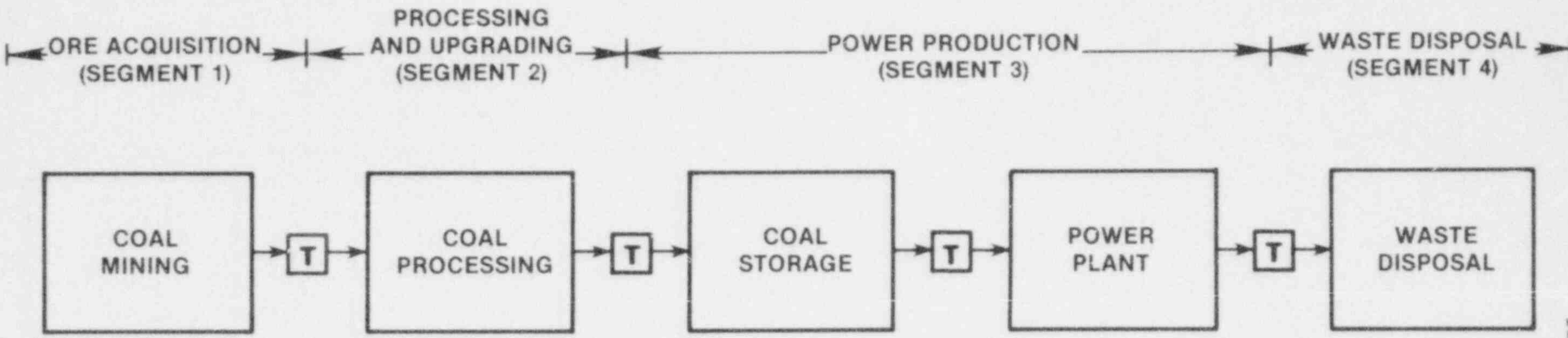

FIGURE 2.2. COAL FUEL CYCLE.

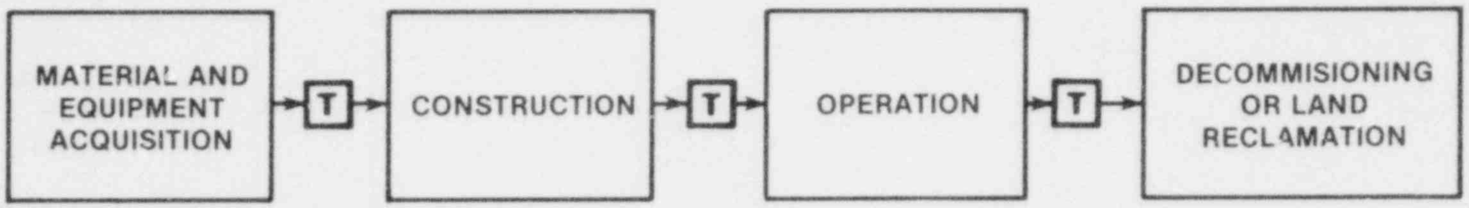

FIGURE 2.3. TYPICAL STAGE LIFE CYCLE.

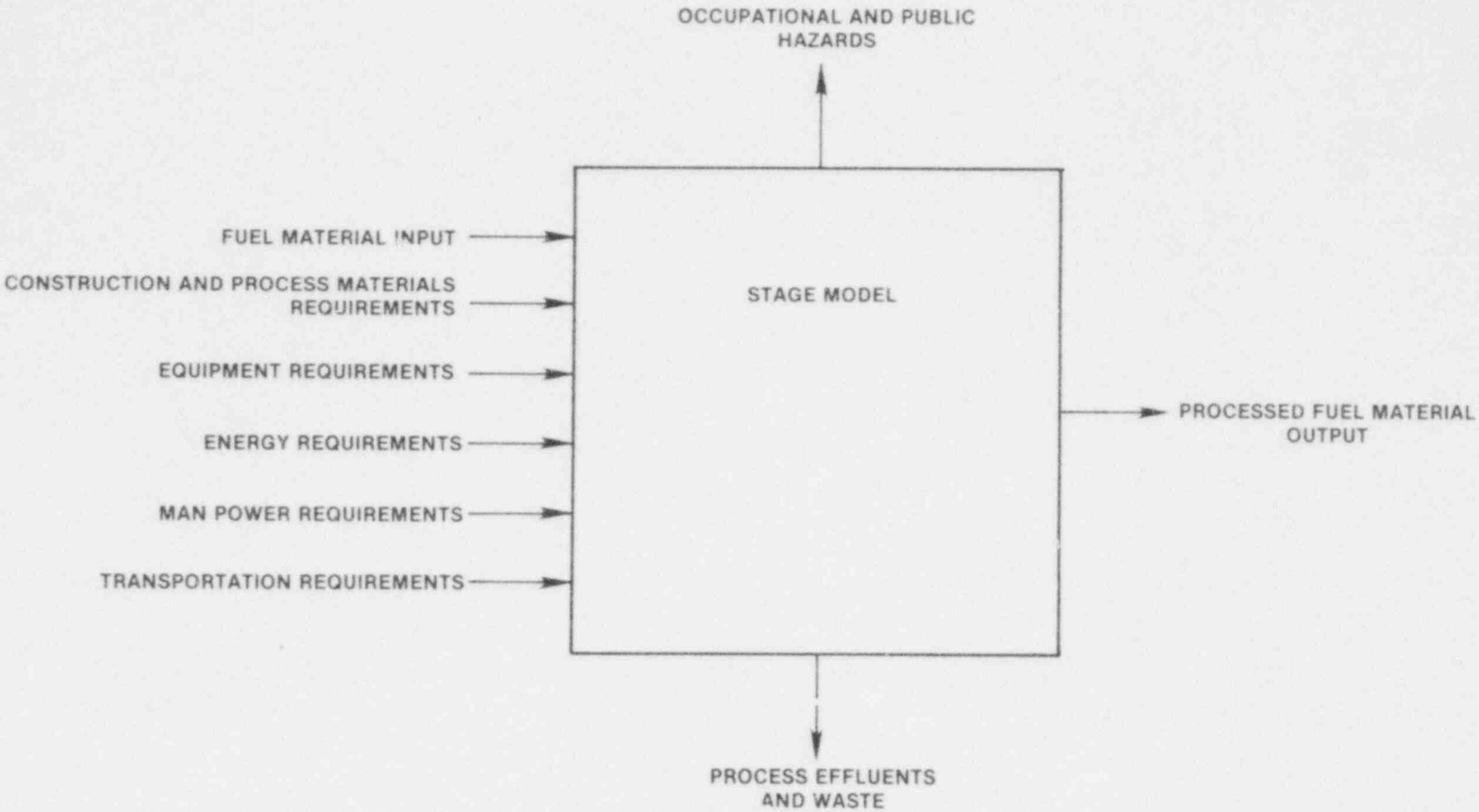

FIGURE 2.4. TYPICAL ENERGY PRODUCTION CYCLE STAGE INPUT AND OUTPUT INFORMATION

2.2 STAGE MODEL ACTIVITIES AND ASSOCIATED HAZARDS

In Section 2.1, the concept of an energy production cycle (EPC) was defined. Such a cycle can be divided into a number of sequential stages. The life cycle of each stage must be examined to identify and assess the magnitude of its contribution to the total health risk associated with the production of a unit of energy. To accomplish this task, a simple three-step procedure is followed. This procedure takes advantage of common features among the cycle stages and provides a systematic approach to this study.

In the first step, a comprehensive survey of previous studies in the area of comparative risk analysis is conducted, with particular emphasis on those aspects related to coal and uranium. Typical activities conducted during the life cycle phases of the two EPCs are identified. Hazards and other features common to these activities are investigated also.

In the second step, the data base is examined and used to develop a general analytical methodology (Sections 3 and 4 include such data). The third step involves using this information to establish an analytical model that can be used to estimate and compare the health effects of the two EPCs. The systematic framework that results is the main goal of this investigation. The health impact associated with each hazard type is estimated (1) first for each component, (2) for the sum of all components in each stage, and (3) for the sum of the whole energy production cycle.

The major activities associated with a typical model facility are:

1. Production of construction and process materials.
2. Fabrication of major equipment.
3. Construction of facility.

4. Supply of facility energy requirements.

5. Operation of facility.

6. Transportation activities.

7. Decommissioning of facility.

Each of these activities is associated with hazards that may impact public and/or employee health. The following subsections outline specifics that characterize the stage model and activities listed above.

2.2.1 Model Facility

Energy production cycle stages are either simple or composite. A simple stage is characterized by one dominant type of facility; a composite stage may include a number of alternative facilities fed with the same input and producing a similar output. An example of a simple stage is the power production stage in the coal cycle. Most modern coal-powered plants have the same basic design, and differences among plants are minor, with respect to the scope of this study. However, the power production stage in the uranium cycle (LWR) can be a pressurized water reactor (PWR) or a boiling water reactor (BWR), with significant differences in design. A composite model, referred to as the model facility, is provided to avoid biasing the study toward one type of facility.

The model facility is based on the design and capacity of the newer. existing facilities or facilities under construction and on current operating data. Thus, the model reflects the current national production and the current state of technology and design of the component facilities. The model facility lifetime may vary from one facility to another. However, lifetimes were selected to be consistent with those in published literature in order to simplify the model validation procedure. Figure 2.5 shows the modeling of a typical composite facility.

2.2.2 Construction and Process Materials Production Activities

Amounts of materials required for the construction and operation of each model facility are estimated. Risks to the public and to workers producing and handling these materials are associated with their acquisition and production. These risks are evaluated based on the estimated material requirements.

2.2.3 Major Equipment Fabrication

Model facilities include a variety of equipment of varying degrees of sophistication. The manufacturing and handling of this equipment consume significant amounts of time (man-hours) and energy. Manufacturing activities involve hazards to the workers as well as to the general public.

2.2.4 Energy Generation

Energy is needed to produce the construction and equipment materials used in the model facility, to manufacture its equipment, and for construction, operation, decommissioning and transportation activities. Energy is supplied by either electricity or fossil fuel combustion. Electric energy requirements are supplied by coal-fired power plants, LWRs, or a combination of both. Generation of this electrical energy or direct use of fossil fuel creates a hazard that affects the workers and the public.

2.2.5 Facility Construction, Operation, and Decommissioning Activities

Construction and decommissioning activities involve the use of heavy machinery; a variety of risk-inducing factors characterize these activities. All facilities are designed to operate safely, with the

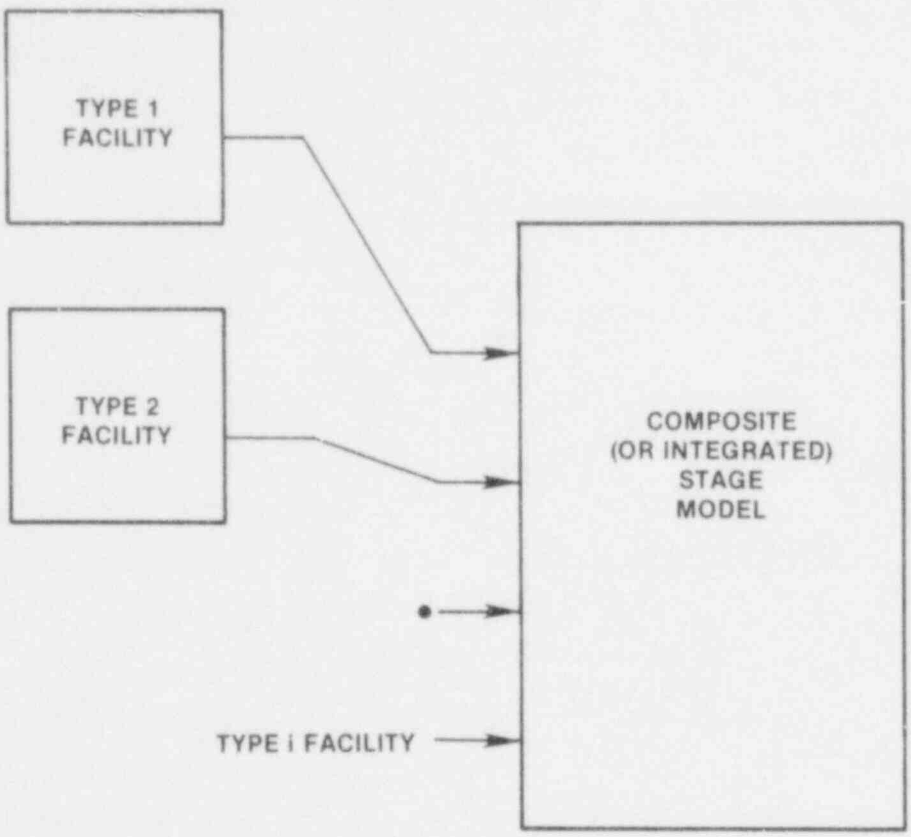

FIGURE 2.5. ENERGY CYCLE STAGE COMPOSITE MODEL.

least possible adverse impact on the health of the workers or the general public. However, risk-inducing factors cannot be eliminated completely.

2.2.6 Transportation-Related Activities

Construction and operation materials, facility equipment, fuel materials, and fuel material waste products require transportation. Traffic accidents, loading and unloading accidents, and release of transportation vehicle exhaust or accidental releases of toxic cargo materials represent some of the transportation-related risks.

2.2.7 Hazards and Types of Hazards

Any activity involves some associated hazards and, hence, some degree of risk. As shown in Figure 2.6, risk can be either public-related or occupation-related, depending on the group of people affected. Risk can also be normal or catastrophic. Normal risks are associated with day-to-day activities in an environment affected by the cycle. Catastrophic risks are associated with violent phenomena, such as fires or explosions; with the existence of a serious combination of failures in the facility equipment; and/or with operational errors. Risks may be either radiological or nonradiological, depending on the nature of the release source.

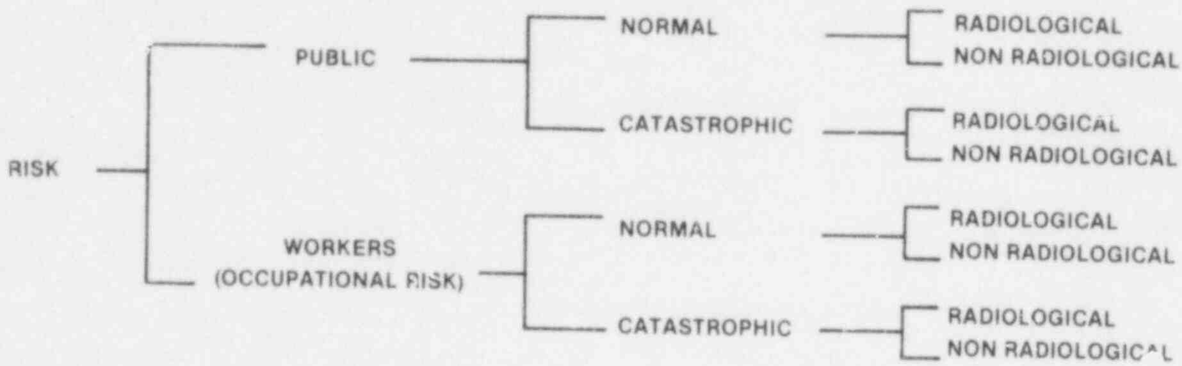

FIGURE 2.6. RISK CATEGORIES.

2.3 MAGNITUDE OF ACTIVITIES AND THEIR RELATED RISKS

A vast amount of information is needed for adequate assessment of the risks associated with a fuel cycle. This information ranges from construction, design, and process details and production data, to manpower and accident history statistics. The amount of information supplied should be sufficient to assess the magnitude of each of the activities detailed in Section 2.2.

As an example, knowledge of the amounts of metals, concrete, and insulating materials required for constructing the existing facilities can be used to define the amounts of construction materials for the model facility. These amounts can then be normalized to a unit energy production requirement by using the typical life span and annual production data for the facility. Assuming the data exist and are sufficient to determine the magnitude of the different activities, industrial occupational statistics can then be used to determine occupational risk components for each of these activities.

It is recognized that one of the major impacts of energy production on public health is associated with effluents emitted during the performance of each activity. As shown in Figure 2.7, effluents are emitted during normal operations, usually in a diluted form or in small-to-substantial quantities during the course of accidents. Material effluents also can be categorized according to their nature (radiological or nonradiological) and their physical form (gaseous, liquid, or solid).

Proper treatment of accidental releases requires the listing of all accidents with potential impact on workers or on public health for each model facility in the two cycles. A range of possible consequences associated with each accident must be identified. Postulated serious accidents also are listed in spite of their low likelihood of occurrence. A frequency range for each type of accident can aid in establishing a more realistic range of health impact.

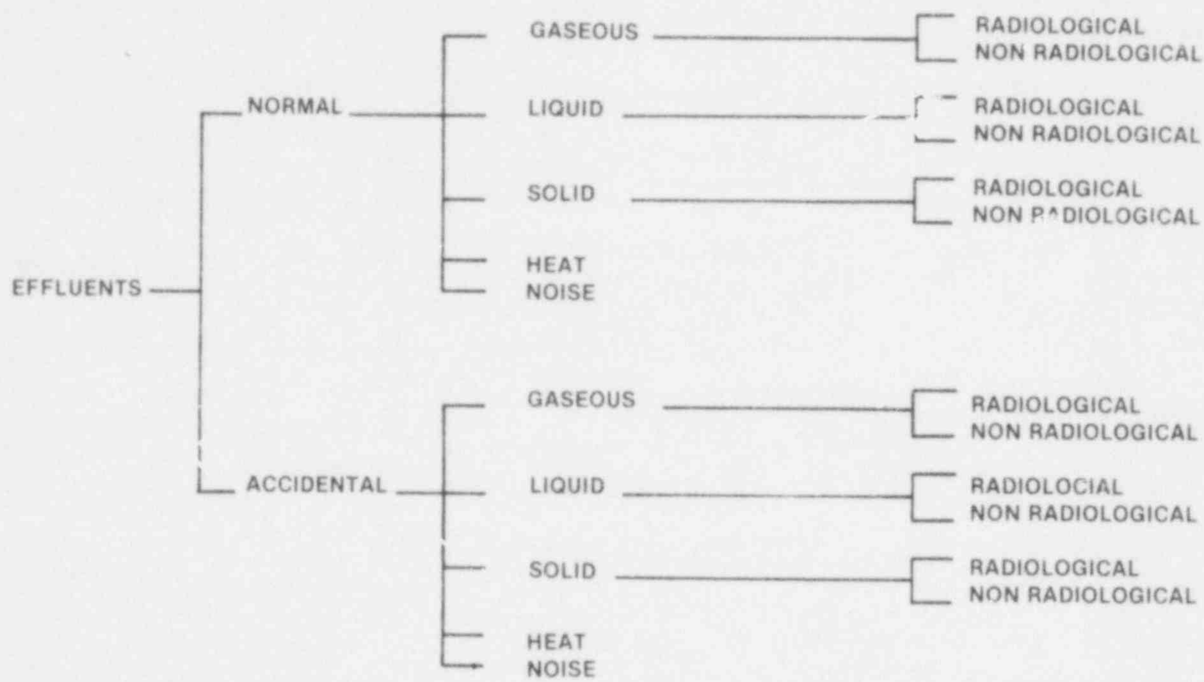

FIGURE 2.7. CATEGORIES OF EFFLUENTS.

2.4 TREATMENT OF ACCIDENTS

This section discusses the generic approach to accidents and the specific applications for the two EPCs considered. Previous investigators have put forth a great deal of effort in uranium EPC accident analysis, especially in the case of the LWR stage; the major emphasis in the coal EPC has been on the mining stage. Therefore, the level of information varies considerably.

The conventional approach to accident treatment is to provide a list of postulated accidents for each EPC stage. These accidents may be expected to occur once or a few times during the model facility lifetime or may not be expected to occur at all. In this sense, lists of postulated accidents conceived for an EPC model facility emphasize completeness rather than credibility. Moreover, estimation of the amounts of effluents released during the course of any particular accident (consequential release source terms) depends on many factors, among which are model facility design features, initial inventory of the pollutants, and specifics of the accident scenario.

To put the complete list of accidents into perspective, the probabilistic approach must be adopted and used to estimate the expected accidental release source terms during a year of operation of an EPC facility. These source terms are computed by combining the estimated frequencies (likelihood) of accident occurrence and the amount of effluents expected to be released during the course of each accident.

In general, estimation of accident frequencies relies on component and equipment failure data, published literature, and historic data from previous experience. On the other hand, consequential source terms are estimated using analytical codes. In this investigation, the uranium EPC accident data rely mainly on the Reactor Safety Study (RSS)[1], criticism of the RSS by the Union of Concerned Scientists[2,3], the American Physical Society Report,[4] the Lewis Report,[5] and other sources[6,7,8,9]. Unfortunately, the coal EPC accident data used[10,11,12,13] were not of comparable analytical depth.

It is important to note that while diversification of data sources has its merits, it prevents the modeling of a uniform, consistent methodology that assures lack of bias in the estimation of source terms.

Accidents identified for the two EPCs under investigation were found to belong to seven categories. These are:

A. Failure of radiological release controls or release barriers incidents.
B. Failure of nonradiological release controls or release barriers incidents.
C. Criticality incidents.
D. Natural phenomena.
E. Explosions.
F. Fires.
G. Industrial accidents.

Depending on the EPC stage, each category may include a number of severity classes, with a number of postulated accidents in each class. It is recognized that some degree of overlap exists among these categories; however, their main use is to assure completeness of analysis and to identify areas where a lack of data may exist.

LWR accidents, with their nine classes (from proposed Annex to Appendix D, 10CFR, Part 50), are typical of Category A. Failure of acid tanks (e.g. in the uranium conversion and fuel reprocessing facilities) or failure of coal sludge dikes belongs to Category B. Criticality incidents in the uranium cycle fuel fabrication or reprocessing facilities are typical of Category C. Natural phenomena include seismic events, tornados, lightening, etc. Explosions and fires (Categories E and F) can occur in underground coal mines, in facilities using petroleum derivatives as solvents, or in facilities using pressurized containers, etc. Industrial accidents include falls or injury induced by machinery and equipment, regular traffic accidents (with no toxic releases), etc.

Sections 3 and 4 include a selected listing of accidents fo: each EPC stage. Because the calculation of accident frequencies and consequential source terms is beyond the scope of this study, publ'shed literature will be used to define the contribution of acci ent categories or individual accidents to the overall facility effl ent source terms.

2.5 HEALTH IMPACT ASSESSMENT

Health impact can be determined partially from industrial occupational hazards data as well as from accident statistics. However, quantification of health impacts of exposure to different types of effluents is rather difficult. For radiological releases, extensive studies have been conducted and have lead to well-defined procedures for calculating effluent/dose relationships for many radioisotopes. Calculated dosage can be used to estimate health effects under a variety of assumptions. It is important to note that radiation effects on human health have not been observed at or below the allowable limits specified by national and international regulatory bodies (5 rem/yr for workers and 170 mrem/yr for the general public). Low-level radiation effects are calculated using linear extrapolation (from high levels of exposure). This linear (nonthreshold) hypothesis is generally believed to be conservative because of the repair capability of damaged cells.

Analogous procedures for chemical effluents are generally lacking, and several simplifying assumptions have to be used in place of the well-studied, well-established models for radiological effluents. Detailed discussion of effluent-dose models and dose-health effect models is provided in Appendices IV and V.

2.6 FORMAL METHODOLOGY

Most published work in the area of comparative health effects of coal and uranium cycles address the power production stage operations or the operation of the whole fuel cycle. The latter is generally referred to as first-cut (or first-order) analysis. Recently,[14,15,16] an improved approach to the problem was developed, which considers the impact of material production, equipment fabrication, construction, etc. Such an approach is thus a second-cut (second-order) approach. Inclusion of second-cut variables in the analysis proved to have a significant impact on the study results, especially in the case of nonconventional energy production cycles. Some simplicity of methodology has to be sacrificed in order to compare the study results with those of the previously published first- and second-cut studies.

The various model facilities in the two EPCs under study were examined to identify typical activities conducted in each and common features in each. As mentioned, performance of these activities is associated with some risk to the facility workers and to the general public. A calculational model should provide a quantitative measure to these activities and the means of correlating them to their eventual health impact. Three basic sets of variables were selected to accomplish this task. These are:

1. Requirement (R) variables.
2. Effluent (F) variables.
3. Health Impact (P) variables.

The following subsections introduce these variables and establish the conceptual relationships among them and the activities and their interrelationships.

2.6.1 Activities

Typical activities undergone during the life cycle phases of any EPC stage are material production activities, equipment fabrication activities, normal operations activities, transportation activities, etc. As indicated above, it is more advantageous to develop activities categories using the first-cut and second-cut approaches. Therefore, activities related to the operations of an EPC stage will be classified as first-order activities (A1) whereas those related to construction and decommissioning will be classified under second-order activities (A2-1, A2-2). Third- and higher-order activities generally will be omitted from this study. This omission means that the health risk contribution of manufacturing machines used in the production of a major component in an EPC stage is not accounted for.

2.6.2 Requirement Variables

Requirement variables are provided to measure the magnitudes of various activities. For example, operations activities are primarily measured by the amounts of fuel materials (coal or uranium) involved in the operations. These amounts are properly weighted to reflect the annual operations requirement (per power plant) or, alternatively, the requirements per unit of energy generated.

To provide the fuel material requirements, a number of additional (secondary) requirements have to be supplied, among which are other process materials, energy, as well as services such as transportation and labor. In this sense, requirement variables are not simple in nature, and they tend to form a divergent chain (or tree), with a primary variable in the first level of this tree. This primary requirement variable generally requires a number of secondary requirement variables. In turn, each one of these secondary variables is associated with a number of tertiary requirements, etc. Third- and higher-order requirement variables will not be accounted for unless their impact is judged to be significant.

Figures 2.8, 2.9, and 2.10 show three typical primary requirement variables: material requirement (RM); equipment requirement (RQ); and transportation requirement (RT). Secondary requirement variables (energy (RE), transportation (RT), and manpower (RL) in case of Figure 2.8) required to produce the primary variable also are shown. The three trees in Figures 2.8, 2.9, and 2.10 will be used as building blocks to structure the analytical models for the two EPCs. The energy requirement variable is supplied partly as electricity and partly by fossil fuel combustion in the model facilities. The electric energy requirements are supplied by coal-fired plants, LWRs, a combination of both, or a combination including other electric energy sources. Thus, the coal and nuclear cycles interact through the electric energy requirement variable. This interaction is mathematically treated in Section 6.

Non-electric energy requirements are supplied by the combustion of coal, natural gas, diesel fuel, and other petroleum products. Assessment of risks associated with supplying this component of the energy requirement variable is conceptually similar to risk assessment for the material requirement. Risk associated with materials is evaluated by analyzing the material production cycle which includes ore aquisition, processing, and production. As discussed in Appendix II, material production cycles are complicated by the presence of imports, exports and recycle. Occupational data for the material cycles are not generally reported in the level of detail adequate for this study.

2.6.3 Effluent Variables

In general, effluents are released during the process of producing the primary and secondary requirement variables. Amounts of effluents are referred to as the FS variables and are used to define the effluent source terms in the calculational model. These source terms include normal as well as properly weighted accidental or uncontrolled release components. The FS variables are used to compute the effluent

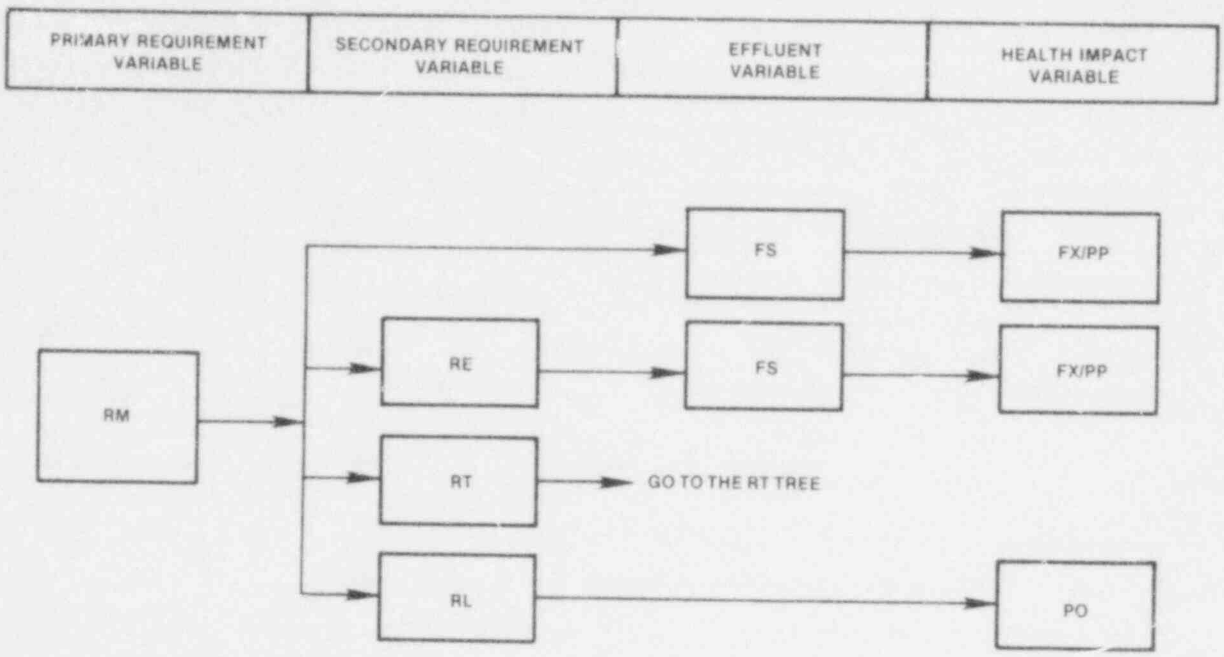

FIGURE 2.8. MATERIAL REQUIREMENT TREE.

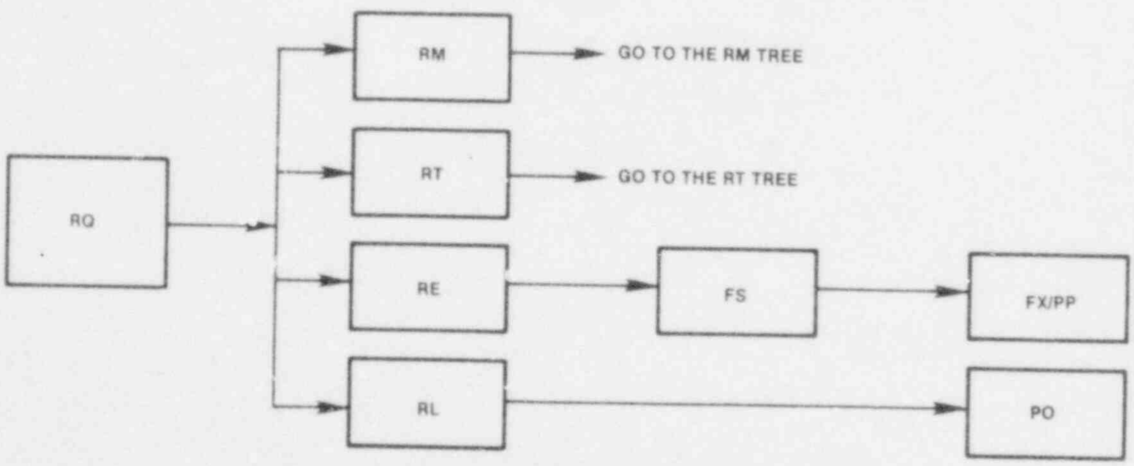

FIGURE 2.9. EQUIPMENT REQUIREMENT TREE.

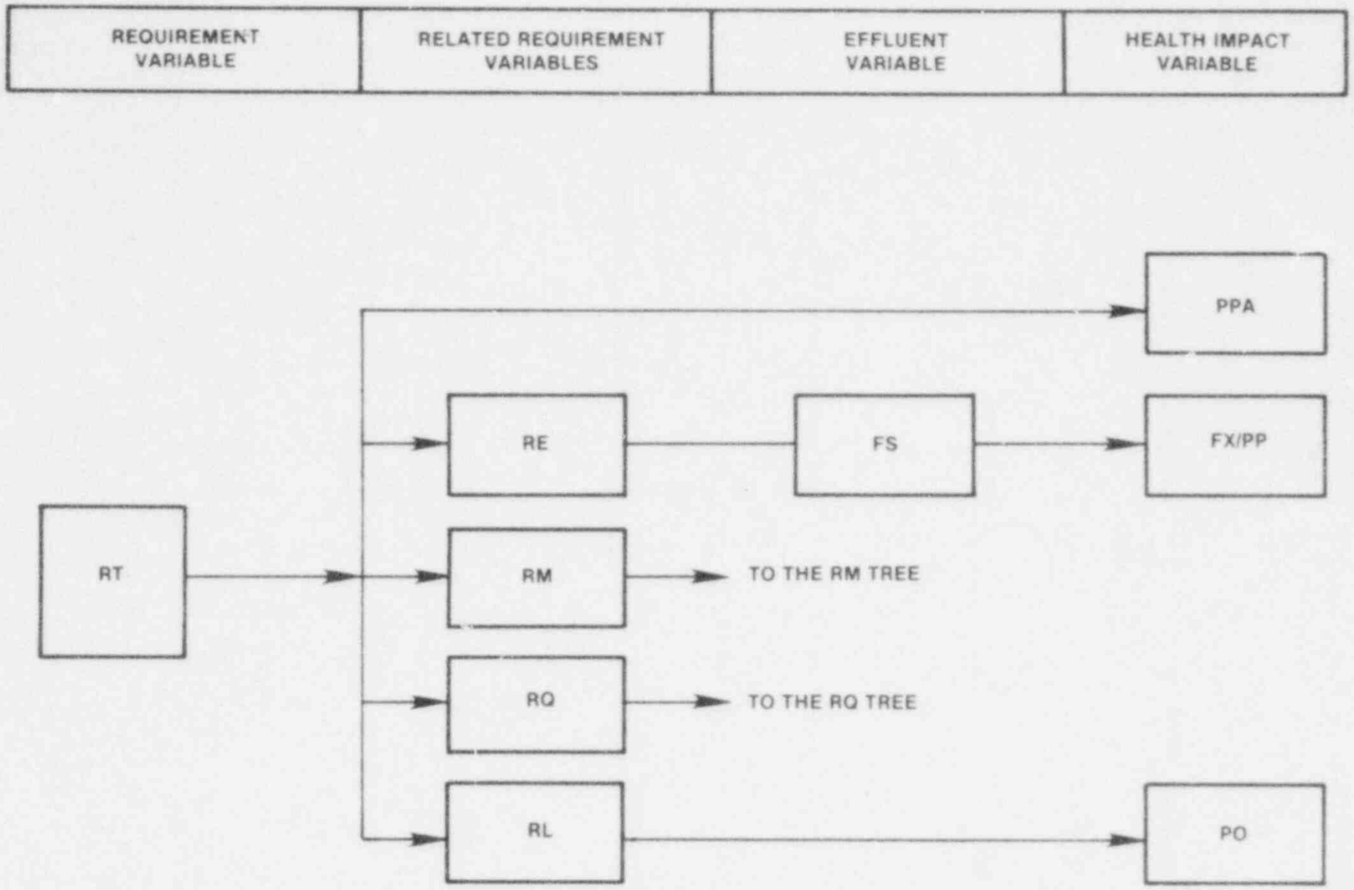

FIGURE 2.10. TRANSPORTATION REQUIREMENTS TREE.

exposure (FX) variables. The FX variables are computed only for those effluents with known adverse health impact.

2.6.4 Health Impact Variables

The health impact variables have two major components. The first is occupational (PO) and is directly related to the requirement variables. The second component impacts public health (PP) and is mainly derived from the effluent exposure variables (FX) by using a number of exposure-health impact models.

2.6.5 Summary

The general approach is based on defining various activities during the life cycle of each stage of the two EPCs under study. Activities are measured by requirement variables which form a divergent two- or three-level tree in this study. Requirement variables have either direct impact on health, as in the case of occupational hazards and traffic accidents, or an indirect impact through polluting the biosphere with effluents that have a potential adverse effect to human health.

Figure 2.11 is a schematic diagram showing the role played by various variables. Each activity is measured by a set of requirement variables; each requirement variable is associated with some direct health impact which is either occupational (PO) or nonoccupational (PP). The process of supplying a requirement variable is also associated with releases ($F_{S1} \ldots F_{SM}$) that are referred to as release source terms. A release source term is used to calculate its corresponding exposure variable FX which in turn is fed into an exposure-health effect model to assess its health impact.

Figure 2.12 represents a detailed version of Figure 2.11 and shows a typical number of variables that will be calculated for each stage in the two EPCs.

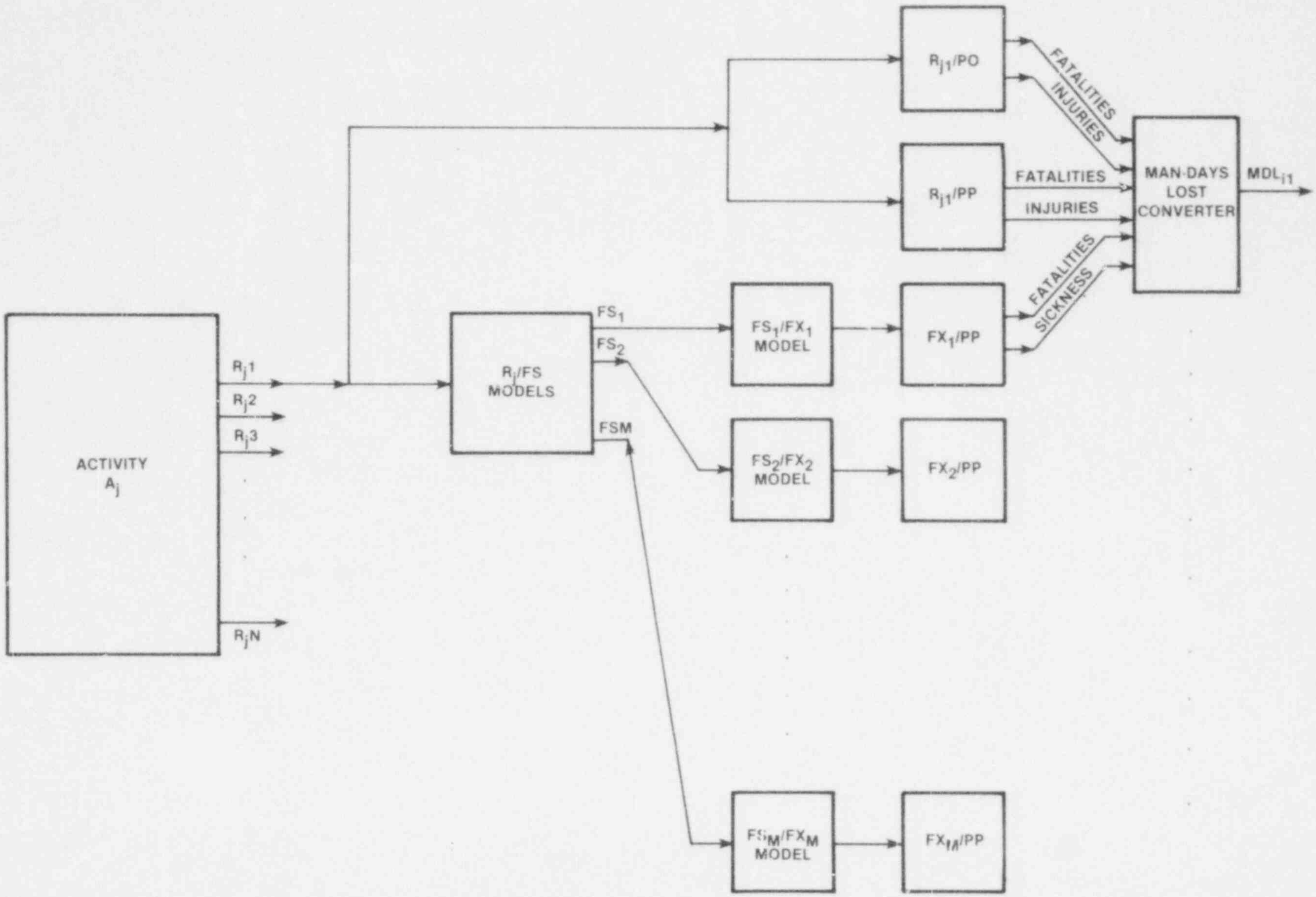

FIGURE 2.11. GENERAL APPROACH

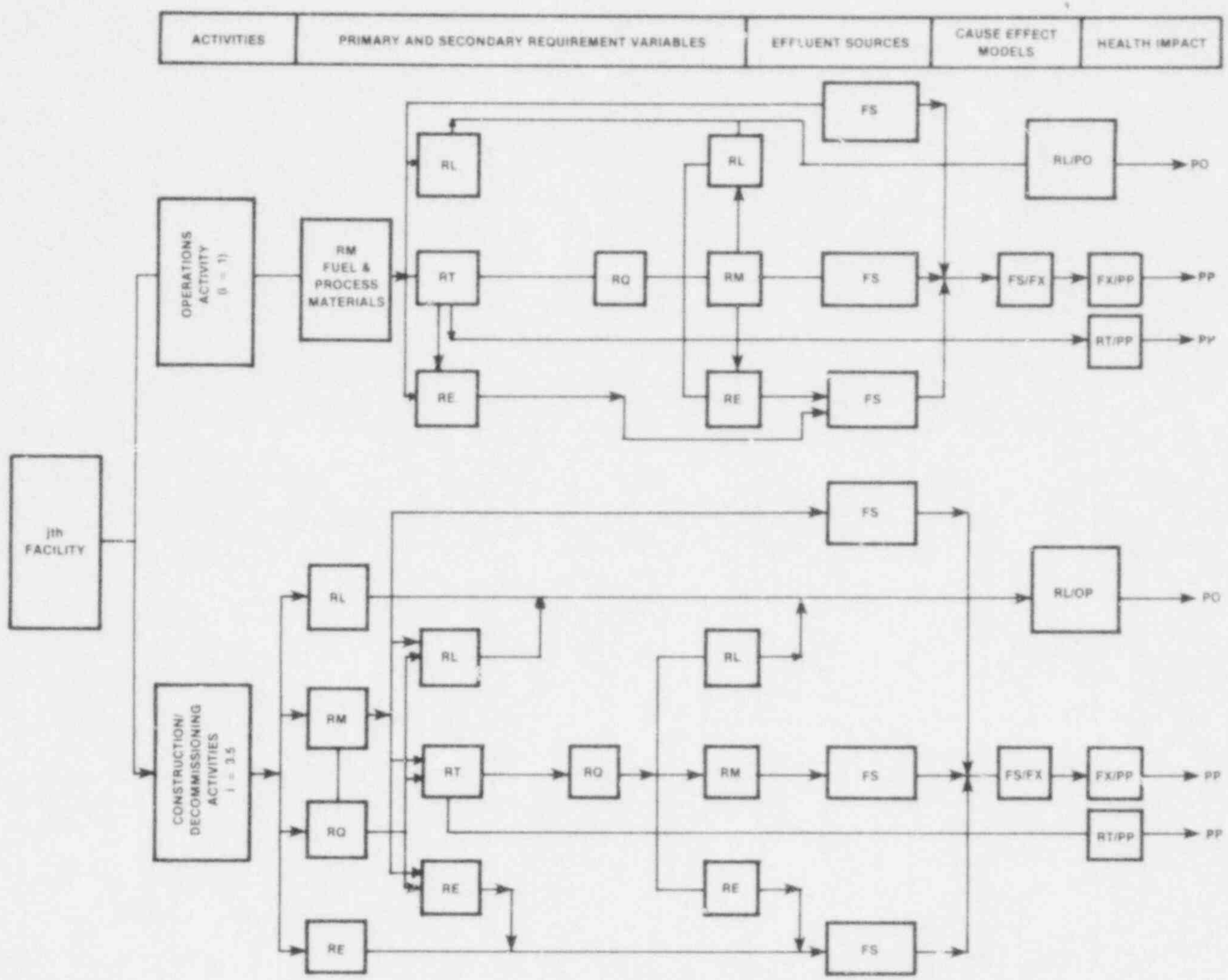

FIGURE 2.12. METHODOLOGY TREE

The large number of requirement, effluent and health impact variables will require an overwhelming amount of data to determine quantitative health effects. To assure consistency of the data base, first hand data from original sources has to be extracted. Unfortunately, time and resource constraints did not permit such a task. The only option that was available was to rely on secondary sources of information. Data in these sources were based on experiments, accident statistics, engineering judgement, expert opinion, design, and in some cases extrapolations of the above. Thus, the data base presented here is not fully consistent. Inhomogeneity of this data base however, is not likely to limit the usefulness of this study.

Th ultimate objectives of this study are served best by an iterative approach. Preliminary hand-calculated results produced by the model can be used for model validation, which can be accomplished by two parallel methods: (1) comparison with previously published studies and investigation of the discrepancies associated with new findings; and (2) peer review and exposure of the study to open criticism. This combination will enhance identification of pitfalls and issues that can be used to direct the second iteration. The second iteration will have narrower data uncertainties, smaller computational and model structural uncertainties, and better mathematical approximations.

A computerized calculational model based on this methodology has many advantages including, ease of modification, integration of improved or newly acquired data, ease of integration of other energy cycles in the study, and a capability to conduct sensitivity analysis. Sensitivity analysis, even when conducted at this stage of the study, will provide the user with valuable information about those factors or parameters having the largest risk contribution.

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3.0 THE URANIUM ENERGY PRODUCTION CYCLE

Stages in the uranium energy production cycle are:

1. Mining.
2. Milling.
3. Conversion.
4. Enrichment.
5. Fuel fabrication.
6. Power plant (LWR).
7. Reprocessing.
8. Waste disposal.

The fuel cycle for light water reactors can be operated in one of three optional modes. In Option 1, no recycling is considered (hence, no fuel reprocessing), and the waste storage stage handles spent fuel assemblies. In Option 2, uranium recycling is considered; reprocessing is included in the cycle; and the waste disposal stage handles Pu and radioactive waste (high-, intermediate-, and low-level). Option 3 includes U and Pu recycling and, hence, mixed oxide fuels. Option 3 will not be considered in this study.

Preconstruction, construction, operation, and decommissioning activities for the different stages in the cycle require consumption of electricity. This electricity is assumed to be produced by nuclear or coal-fired power plants. Through electricity consumption, the two energy cycles (uranium and coal) interact.

The model plant assumed for this study is a 1000 MWe facility. The average annual fuel requirement and enrichment for typical and model LWRs ar[illegible]n Table 3.1. The fuel material requirement of the cycle s[illegible]eceding the LWR are shown in Table 3.2. This annual requirement represents an average of the first core fuel material (uranium) requirement and the yearly reload requirement over the re-

TABLE 3.1

LWR MODEL CHARACTERISTICS

	Vendor[a]				
	B&W (PWR)	C-E (PWR)	W (PWR)	GE (BWR)	2/1 (PWR/BWR) (Model)
Initial Core Requirement (MTU)	106.6	116.8	100.5	160.4	125.4
Reload Requirement (MTU)	35.4	38.8	33.3	35.7	35.8
Reload Enrichment	----------3.2%----------			2.6%	3%
Burnup (MWD/MTU)	--------27,500----------			27,500	27,500
Initial Core Enrichment	----------2.6%----------			2.6%	2.6%

[a] U.S. Nuclear Regulatory Commission, Draft, "Generic Environmental Impact Statement on Handling and Storage of Spent Light Water Power Reactor Fuel," NUREG-0404, Vol. 2, March 1978.

TABLE 3.2

FUEL BALANCE ARRAY FOR THE URANIUM CYCLE ANNUAL MODEL LWR REQUIREMENT AND UNIT ENERGY PRODUCTION

Facility	Material Quantity and Characteristics	Initial Core		Reload Requirement		Average Annual Fuel Material Requirement	
		Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
Power Plant	MTU	125.4	125.4	35.8	35.8	38.8	38.8
	Enrichment	2.6%	2.6%	3%	3%	3%	3%
Fuel Fabrication	MT UO_2 (a)	143.7	143.7	41.0	41.0	44.4	44.4
Enrichment	MT enriched UF_6	187.3	187.3	53.5	53.5	58	58
	Enrichment	2.6%	2.6%	3%	3%	3%	3%
	MT SWU	568.2	397/513 (b)	203.7	161.6/198 (b)	215.8	169/208 (b)
Conversion	MT Natural Enrichment UF_6	955	636.7	319	253	340	265.8
Milling	MT U_3O_8	761.5	507.7	254.4	201.7	271.1	211.8
Uranium Mining	MT Ore (c)	553×10^3	368.7×10^3	184.2×10^3	146.5×10^3	196.9×10^3	148.7×10^3

(a) Fabrication loss is assumed to be one percent.

(b) The first number represents the separative work related to natural UF^6; the second includes the overall SWUs including reprocessed uranium.

(c) Mill efficiency is assumed to be 0.918 and average ore grade 0.15%.

maining 29 years of the projected lifetime of the model power plant. The average is estimated for Options 1 (no recycle) and 2 (uranium recycle). It is recognized that at the end of 30 years' operation, the model reactor core will include spent fuel as well as partially burned fuel. The average enrichment of the discharged fuel is estimated to be so low that the last core will have a minor impact on Option 2 columns of Table 3.2.

3.1 URANIUM MINING

3.1.1 General Description

Uranium minerals generally occur in diluted, localized ore bodies. Choice of an extraction technique depends on (1) size and grade of the deposit, (2) geotechnical considerations, and (3) hydrologic properties. Contemporary extraction methods include open-pit mining, underground mining, and in situ leach mining. Recent statistical data (see Footnote a, Table 3.3) for the uranium industry indicate that in situ leaching and by-product operations (combined) accounted for only 4 percent of the total U.S. uranium production in 1977. Since in situ leaching and other nonconventional techniques are not expected to contribute major supplies of uranium, these minor technologies are not addressed in this study. Emphasis is on the conventional techniques of underground and open-pit mining.

3.1.2 Model Description

The mine model is based on one open-pit mine and one underground mine, together serving the model uranium mill. The extreme variation in the uranium mine sizes is reflected in the range of capacity values given in Table 3.3. During 1977, underground mines had an average ore grade of 0 172 percent U_3O_8; open-pit mines had an average ore grade of 0.127 percent U_3O_8; and the average mill operated with a feed grade of 0.15 percent U_3O_8. Using these figures, the model assumes that the total U_3O_8 production is split on a 52 percent-48 percent basis between the underground and open-pit mines. Table 3.3 summarizes the basic data for the model mine. Trends in the uranium mining industry point to a decrease in ore grade as the richer deposits are depleted. Projected ore and feed grades in the years 1984 to 2000, are 0.10 percent, 0.07 percent, and 0.09 percent for the underground mines, open-pit mines, and mills, respectively. Such decreases will require vast expansion of mining activity to meet the demand for uranium.

TABLE 3.3

URANIUM MINING DATA

	Underground Mine[a]	Open-Pit Mine[a]
Capacity range (MT ore/day)	90-1350	90-2700
Average ore grade (%U_3O_8)	0.172	0.127
Percentage of model U_3O_8 production	52	48
Ore requirement per 1000-MWe plant:		
Option 1	87.4×10^3	109.5×10^3
Option 2	66×10^3	82.7×10^3
MT of overburden per MT of ore	1	15[b]

(a) U.S. Department of Energy, "Statistical Data of the Uranium Industry," GJO-100(70), January 1978.

(b) Twenty percent of the overburden is assumed to be stored outside the pit.

3.1.3 Material and Equipment Requirements

The materia: requirement informat. .n available for this study is expressed on an industry-wide basis. These data, normalized to the annual reactor requirement, appear in Tables 3.4 and 3.5. The material requirements (Table 3.4) were derived from the equipment requirements (Table 3.5). The effective lifetime of the mining equipment is assumed to coincide with the estimated 10 year lifetime of the model mine.

3.1.4 Energy Requirements

The energy requirements for the uranium mining model are listed in Table 3.6. Most of the energy used in mining is consumed in excavation and removal of overburden materials. Decreasing ore grades results in an increase in overburden removal and increased energy consumption per unit of uranium produced.

3.1.5 Effluents

Uranium mines display extremely diverse geologic and environmental conditions. The emissions factors in Table 3.7 are a composite of reported data from existing mines. The entries under liquids and suspended solid effluents express the range of compositions found for mines studied. Local conditions will cause great variation in the actual water quality of liquid effluents. For the purposes of this study, the reported emissions represent a typical, if not conservative, estimate.

Effluents such as dust and exhaust from mining equipment are directly related to the quantity of ore or overburden removed. Mine drainage and radon releases are functions of site geology, mine configuration. surface area of ore and sub-ore grade materials, chemical and physical properties of the ore, and numerous other local conditions. Therefore, emission from these sources are more or less continuous and nearly independent of any short-term change in mining activity or ore

TABLE 3.4

URANIUM MINING ESTIMATED MATERIAL PER ANNUAL MODEL LWR ORE REQUIREMENT

	Material Requirement (MT)[a,b]	
Material	Option 1	Option 2
Aluminum	3.13	2.44
Antimony	0.15	0.12
Asbestos	0.03	0.024
Boron	0.004	0.003
Cadmium	0.01	0.007
Chromium	2.74	2.14
Cobalt	0.006	0.004
Concrete	76.58	59.84
Copper	6.54	5.11
Dynamite	66.15	51.68
Iron	562.64	439.57
Lead	1.98	1.47
Manganese	5.87	4.59
Molybdenum	0.17	0.13
Nickel	2.80	2.18
Niobium	0.006	0.004
Nitrate	15.07	11.77
Silver	0.003	0.003
Tin	0.08	0.06
Titanium	0.05	0.04
Vanadium	0.006	0.004
Zinc	0.90	0.76

(a) "Demand and Supply of Non-Fuel Minerals and Materials for the United States Energy Industry, 1975-90--A Preliminary Report," Geological Survey Professional Paper 1006-A, B, 1976.

(b) Data include some uranium milling materials.

TABLE 3.5

COMPOSITE MINE AND MILL EQUIPMENT

Item	Quantity[a,b,c]
Roof bolts	120×10^3
Drill steel	95×10^3 ft
Bits	20×10^3
Pumps (20 gal/min)	109
Pumps (1000 gal/min)	33
Hoists (100-HP)	5
Hoists (1000-HP)	2
Slusher	36
Slusher cable	3.2×10^6 ft
Three-ton rail car	64
Rail (60-lb)	20×10^3
Loaders	18
Cars (five-ton diesel)	88
Jack hammers	438
Water pipe	110×10^3 ft
Ventilation line	110×10^3 ft
Compressor (250 ft^3/min)	41
Compressor (1000 ft^3/min)	18
Road grader	13
Maintenance trucks	20
75-Ton trucks	31
20-Ton trucks	61
Forklifts	4
30-Ton trucks	102
Pickup trucks	62
Small drill rig	36
Heavy bulldozer	42
Scrapers (30-yd)	14
Backhoes	31

TABLE 3.5 (Continued)

Item	Quantity
Power shovel (15-yd^3)	3
Generator (500-kw)	6
Generator (1500-kw)	3
Mechanical shop	5
Drill rig (blast hole)	22
Trucks for small drilling	36
Quonset-type huts	18
Primary crusher[(d)]	1
Secondary crusher[(d)]	2
Grinders (rod for ball mill)[(d)]	1
Steel autoclaves[(d)]	1
T tanium-Clad, lead-lined autoclaves[(d)]	2
Gear reducers[(d)]	16
Drill mobiles	4
C ntinuous miners	5
Wire line and hoist x 3/8 cable	36
Trammer	13
Power line (heavy duty)	110×10^3 ft

[(a)]"Demand and Supply of Non-Fuel Minerals and Materials for the United States Energy Industry, 1975-90--A Preliminary Report," Geological Survey Professional Paper 1006-A, B, 1976.

[(b)]Calculations based on composite mine-mill facility (1500 MT/day, ten-year life) and equipment data for production of 671,000 MT of U_3O_8 over 13 years.

[(c)]Over its lifetime (ten years) the mine-mill facility would produce 7540 MT of uranium, sufficient for 253 annual requirements without recycle or 335 requirements with recycle.

[(d)]Milling equipment.

TABLE 3.6

URANIUM MINING ENERGY REQUIREMENTS
(CONSTRUCTION AND OPERATION)

Source	Energy Per Annual Model LWR Requirement[a,b,c]		
	Per MTU[c]	Option 1	Option 2
Construction			
Electricity (MWH)	1.59	3.7×10^2	2.9×10^2
Fossil Fuel (BTU)	1.1×10^8	2.6×10^{10}	2.0×10^{10}
Operation			
Process Material Energy:			
Electricity (MWH)	2.64	6.1×10^2	4.7×10^2
Fossil Fuel (BTU)	1.6×10^8	3.7×10^{10}	2.9×10^{10}
Direct Energy:			
Electricity (MWH)	12.1	2.8×10^3	2.2×10^3
Fossil Fuel (BTU)	2.6×10^8	5.9×10^{10}	4.6×10^{10}

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.

(b) Model annual LWR requirement is assumed to be 271 MT of U_3O_8 for Option 1 and 211.8 MT of U_3O_8 for Option 2.

(c) Rate per MT of U_3O_8 leaving the uranium mill.

TABLE 3.7

URANIUM MINING EFFLUENTS
(CONSTRUCTION AND OPERATION PHASES)

	Release Per MT of Ore		Release per Annual Model LWR Ore Requirement[c]	
Effluent[a,b]	Underground Mine	Open-Pit Mine	Option 1	Option 2
Airborne Gases and Particulates				
Non Radioactive:				
SO_x	3.7 g	55 g	6,380 kg	4,820 kg
NO_x	55.0 g	760 g	88,000 kg	66,400 kg
HC	5.1 g	27 g	8,900 kg	6,700 kg
CO	33.0 g	462 g	53,500 kg	40,400 kg
Particulates	1.5 g	18 g	2,100 kg	1,600 kg
Radioactive:				
Rn-222	0.015 Ci	0.0048 Ci	1.84×10^3 Ci	1.39×10^3 Ci
Particulates	60 g	60 g	11,800 kg	8,900 kg
Liquids and Suspended Solids[d]				
Non Radioactive:				
$SO_4^{=}$	0-10 kg	5.8-98 kg	1,204 MT	910 MT
$NO_3^{=}$	0-120 g	10 g	7.1 MT	5.5 MT
F^-				

TABLE 3.7 (Continued)

Effluent	Release Per MT of Ore		Release per Annual Model LWR Ore Requirement(c)	
	Underground Mine	Open Pit Mine	Option 1	Option 2
Ca^{++}				
Cl^{-}	0.01-16 kg	0.93 kg	710 MT	536 MT
Na^{+}	0.9-13 kg		~500 MT	~460 MT
NH_3	0-190 g	2-16 g	9.7 MT	7.3 MT
Fe	160 g	37 g	4.2 MT	3.2 MT
TSS	0.06-25 kg	0.4-4.2 kg	1280 MT	970 MT
Trace Elements:				
Al	3.3 g	3.3 g	0.65 MT	0.49 MT
As	0.1 g	0.1 g	0.019 MT	0.014 MT
Ba	<2 g	<2 g	<0.20 MT	0.15 MT
Cd	<0.1 g	<0.1 g	<0.019 MT	<0.014 MT
Mg	120 g	120 g	23.6 MT	17.8 MT
Mn	1.1 g	75 g	0.86 MT	0.65 MT
Mo	2-50 g	1.7 g	2.4 MT	1.8 MT
Pb	19 g	19 g	0.2 MT	0.15 MT
Se	0.5-0.7 g	0.2 g	0.074 MT	0.056 MT
V	5-9 g	5-9 g	1.4 MT	1.0 MT
Zn	1.3 g	1.3 g	0.26 MT	0.19 MT

TABLE 3.7 (Continued)

	Release Per MT of Ore		Release per Annual Model LWR Ore Requirement[c]	
Effluent	Underground Mine	Open-Pit Mine	Option 1	Option 2
Radioactive:				
U	0.00035-0.19 kg	0.005-0.0125 kg	0.6-20.5 MT	0.5-15.8 MT
Ra-226	24-640 μCi	24-640 μCi	2.9-76.8 Ci	2.3-61 Ci
Th-230	12-15 μCi	12-15 μCi	1.6 Ci	1.3 Ci

(a) A. K. Reed, et. al., "Assessment of Environmental Aspects of Uranium Mining and Milling," EPA-600/7-76-036, December 1976.

(b) K. K. Nielson, R. W. Perkins, L. C. Schwendiman, and W. I. Enderlin, "Prediction of the Net Radon Emission From a Model Open Pit Uranium Mine," NUREG/CR-0628, PNL-2889, April 1979.

(c) Option 1--no uranium recycling considered.
Option 2--with uranium recycle credit.

(d) Assumed release rate of 10 m^3/MT ore gal, corresponding to continuous flow of ~1400 gpm from a 770 MT/day model mine.

production rate. The gradual expansion of the affected area during the life of the mine may result in a gradual increase in radon emission as more emanating surfaces are exposed. However, reclamation measures in open-pit mines and the sealing of inactive areas of underground mines will more than offset such increases.

The entries for radon releases and liquid effluent releases in Table 3.7 assume steady-state operation of the model mines. In the decommissioning phase, liquid effluents should cease, but radon releases should continue indefinitely at levels determined by the nature of stabilization and reclamation activities. For this study, underground mines are assumed to be insignificant sources of radon after the mines are closed and ventilation ceases. Nielson et al.[1] estimated the long-term radon emission rate from an unreclaimed, inactive open-pit mine to be 0.168 mCi/yr per metric ton of ore production.

Based on these values, the production of an Option 1 or Option 2 ore requirement would generate a long-term radon source of 18.4 Ci/yr per requirement or 13.9 Ci/yr per requirement, respectively.

3.1.6 Occupational and Public Hazards

Occupational hazards of uranium mining include rockfalls and inhalation or ingestion of radionuclides. These hazards are most acute in underground mines. Radon is of primary concern and is the controlling factor in the design of mine ventilation systems. The inhalation of radon daughters is a known contributor to lung cancer among uranium miners.

Because open-pit mines have sufficient natural ventilation, radon and respirable dust present no significant occupational problems. Likewise, atmospheric dilution of gaseous and particulate effluents from either type of mine reduces the dose rate to the general public. The very low population densities in the uranium-producing regions of the U.S. also reduce the risk to the public. Onsite accidents result in a negligible offsite, public risk.

Comar and Sagan reviewed the literature and presented the range of risk estimates of occupational health effects per 1000 MWe-yr of electric power generation. These estimates are summarized in Table 3.8 and are compared with those in WASH-1224 (and NUREG-0332).

3.1.7 Transportation Requirements

Ore usually is transported from mine to mill in standard, 24-MT capacity dump trucks. Both private and public roads may be used. In most instances, the distance between mine and mill is approximately 5 miles (8 km). However, some small, independent mines may be located over 100 miles (>160 km) from the mill.

The model mines are assumed to be 5 miles (8 km) from the mill. For the case where no uranium is recycled, transport of the underground mine annual ore requirement of 87.4 x 10^3 MT will result in about 3640 trips, totaling 36,400 miles (58,240 km). Transport of the surface mine annual ore requirement of 109.5 x 10^3 MT will require about 4560 trips, totaling 45,600 miles (72,960 km). For the uranium recycle case, the ore requirements will be reduced, so that the underground mine will require 2750 trips, totaling 27,500 miles (44,000 km); and the open-pit mine will require 3450 trips, totaling 34,500 miles (55,200 km).

3.1.8 Decommissioning

Decommissioning material and energy requirements for the reference uranium mine are expected to be minor. Structural materials and equipment contaminated with unacceptable amounts of uranium ore can be placed in excavated portions of the mine and backfilled. Specific material and energy requirements are not presently available. However, based on ratios of construction to decommissioning energy

TABLE 3.8

URANIUM MINING OCCUPATIONAL HAZARDS
(PER ANNUAL MODEL LWR REQUIREMENT)

Hazard	Comar and Sagan[a]	WASH-1224[b] (2/1 PWR/BWR)	NUREG-0332[c] (0.8 GWe-Yr)
Premature Deaths:			
Accident	0.05-0.2	0.09	0.2
Disease	0.002-0.1		0.038
Non-Fatal Injuries:			
Accident	1.8-10	3.5	12
Man-Days Lost from Accidents:		740	

(a) C. L. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy, Vol. 1., 1976.

(b) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, August 1973.

(c) R. L. Gotchy, "Health Effects Attributable to Coal and Nuclear Fuel Cycle Alternatives," Draft, NUREG-0332, 1977.

estimated for other facilities, decommissioning energy requirements per year to support a 1000 MWe Plant can be estimated as:

	Option 1	Option 2
Electricity, MWH	0.93	0.73
Fossil fuels, BTU	6.5×10^7	5×10^7

3.2 URANIUM MILLING

Uranium milling represents the second stage in the uranium fuel cycle, after the mining stage. The main function of the mill is to produce a uranium concentrate. Uranium mills are generally located close to the mines to avoid transporting large amounts of the ore over long distances.

3.2.1 General Description

In the uranium mill, the ore is crushed, ground to powder, and chemically leached, and the uranium is precipitated to produce a concentrate which is generally referred to as "yellow cake".

Leaching is accomplished by either of two processes. The first is called the acid leach process, in which sulfuric acid dissolves the uranium in the ore. The second process is called alkaline leach and usually employs sodium carbonate and sodium bicarbonate solutions for uranium dissolution. The leach liquors are purified and concentrated by ion exchange or by solvent extraction, and uranium is precipitated to produce yellow cake. The uranium product is calcined before shipment. Liquid and solid wastes (tailings) are placed in an impoundment for disposal. The impoundment provides for the evaporation of liquids and the long-term isolation of solids. Table 3.9 shows existing mill types, distribution, and capacity.

3.2.2 Model Description

As shown in Table 3.9, 87 percent of the uranium ore is processed by the acid leach facilities whereas 13 percent is processed by alkaline leach facilities. The model mill facility is assumed to reflect this ratio with a capacity of 1800 MT of ore per day. The average ore grade is assumed to be 0.15 percent. The model mill lifetime is assumed to match the model mine lifetime of 10 years. This composite acid leach-alkaline leach model mill will provide the annual U_3O_8

TABLE 3.9

MILL TYPES AND DISTRIBUTION

Process	Number of Mills	Feed Capacity[a,b,c] Capacity Range (MT/Day)	Total for Process (MT)	Percentage of Total
Acid Leach:				
Solvent Extraction	8	635-6350	24,450	68.8
Ion Exchange	4	360-1630	4,670	13.1
Resin in Pulp Ion Exchange (RIP-IX)	2	360-1360	1,950	5.5
Alkaline Leach	3	360-3080	4,130	11.6
Alkaline Leach RIP-IX	1	360-3080	360	1.0

[a] U.S. Department of Energy, "Statistical Data of the Uranium Industry," GJO-100(78), January 1978.

[b] Robert C. Merrit, The Extractive Metallurgy of Uranium, Colorado School of Mines Research Institute, 1971.

[c] Engineering and Mining Journal, Vol. 179, No. 11, November 1978.

Note: Calculations are based on the following assumptions:

- 87 percent of the ore requirement is processed by the acid leach process, 13 percent by the alkaline leach process.
- Average mill efficiency is assumed to be 91.8 percent.
- Flow rate to the water treatment pond is assumed to be:

  1.5 m^3/MT of ore for the acid leach process

  1.05 m^3/MT of ore for the alkaline leach process.
- Non-conventional milling facilities (in situ leaching, mine water heap leach) are assumed to have negligible impact on the cycle, as compared to conventional facilities.

requirements of about three LWRs in Option 1 (no recycle) and of about four LWRs in Option 2 (uranium recycle).

3.2.3 Materials and Equipment Requirements

Table 3.10 includes averaged amounts of materials consumed to provide the annual LWR fuel requirement. (Also see Table 3.5 for the milling equipment requirements.)

3.2.4 Energy Requirements

Table 3.11 shows rates of energy consumption averaged over the lifetime of the model mill. Energy consumed in facility construction and operation and energy used to produce the process, construction, and equipment materials are included. Average mill energy requirements to provide the annual uranium need for the model LWR power plant operation are also shown.

3.2.5 Effluents

Average release rates from mills using the two main milling processes are shown in Table 3.12. These rates are used to determine the magnitude of releases associated with producing the annual U_3O_8 requirement of the model LWR. Liquid effluents are based on the assumed average flow rates to the tailings pond of 1.5 m^3/MT of ore for the acid leach process and 1.05 m^3/MT of ore for the alkaline leach process and seepage losses of 7 to 10 percent of the tailings liquid. There is no regular surface discharge from the tailings pond.

3.2.6 Occupational and Public Hazards

The estimated occupational hazards of uranium-milling operations are shown in Table 3.13. Table 3.14 lists the major accidents, their estimated probability, and the radiological dose to the population. Table 3.15 lists the radiological effluents from the accidents. The risks from normal operation and accidents are compared in Table 3.16. Also shown is the public risk from normal mining operations.

TABLE 3.10

URANIUM MILLING PROCESS MATERIAL CONSUMPTION

Process Material	Consumption Rate[a] (kg/MT Ore)		Material Consumption Per[a] Annual Model LWR Requirement (10^3 MT)	
	Acid Leach	Alkaline Leach	Option 1	Option 2
Sulfuric Acid	45	---	7.7	5.8
Sodium Chlorate	1.35	---	0.23	0.17
Ammonia	1.05	---	0.18	0.14
Flocculant	0.6	0.01	0.10	0.08
Amine (long chain)	0.015	---	0.0026	0.0019
Alcohol	0.035	---	0.006	0.0045
Kerosene	0.45	---	0.077	0.058
Iron (rods for grinding)	0.25	0.25	0.049	0.037
Sodium Carbonate	---	1.3	0.033	0.025
Sodium Hydroxide	---	12.5	0.32	0.24
Potassium Permanganate	---	3.75	0.096	0.072
Filter Aid	---	0.025	0.00064	0.00048

[a] R. E. Blanco et al., "Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing 'As Low as Practicable' Guides--Milling of Uranium Ores," ORNL/TM-4903, Vol. 1., May 1975.

TABLE 3.11

URANIUM MILLING ENERGY REQUIREMENT
(CONSTRUCTION AND OPERATION)

Source	Per MT of Mill Production	Energy Per Annual Model LWR Requirement[(a,b)] Option 1	Option 2
Construction			
Electricity (MWH)	0.71	1.6×10^2	1.3×10^2
Fossil Fuel (BTU)	3.1×10^7	6.9×10^9	5.4×10^9
Operation			
Process Material Energy:			
Electricity (MWH)	4.13	9.5×10^2	7.4×10^2
Fossil Fuel (BTU)	1.6×10^8	3.7×10^{10}	2.9×10^{10}
Direct Energy:			
Electricity (MWH)	17.3	4.0×10^3	3.1×10^3
Fossil Fuel (BTU)	3.4×10^8	7.7×10^{10}	6.0×10^{10}

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254059, May 1976.

(b) Annual milling requirement of a model power plant is assumed to be 271.1 MT of U_3O_8 for no recycle and 211.8 MT of U_3O_8 for uranium recycle cases.

TABLE 3.12

EFFLUENTS FROM OPERATION OF THE MODEL MILLING FACILITY

Effluents[a,b,c]	Release Rate[d] (Per MT of Ore)		Release Per Annual Model LWR Requirement	
	Acid Leach	Alkaline Leach	Option 1	Option 2
Gases and Suspended Particulates				
Non Radioactive:				
SO_x	0.31 kg	0.42 kg	63.8 MT	48.2 MT
NO_x	0.31 kg	0.42 kg	63.8 MT	48.2 MT
Hydrocarbons	0.25×10^{-3} kg	Negligible	0.043 MT	0.032 MT
CO[e]				
Trace Elements:				
Fly Ash[f]	0.01 kg	0.013 kg	2.05 MT	1.54 MT
Dust[e]				
Radioactive:				
Natural U	36.5×10^{-9} Ci	36.5×10^{-9} Ci	7.19×10^{-3} Ci	5.3×10^{-3} Ci
Th-230	3.8×10^{-9} Ci	2.4×10^{-9} Ci	0.71×10^{-3} Ci	0.54×10^{-3} Ci
Ra-226	2.4×10^{-9} Ci	2.9×10^{-9} Ci	0.48×10^{-3} Ci	0.36×10^{-3} Ci
Rn-222	5.7×10^{-9} Ci	5.86×10^{-3} Ci	1202 Ci	908 Ci
Rn daughters	2.4×10^{-9} Ci	2.4×10^{-3} Ci	0.42×10^{-3} Ci	0.37×10^{-3} Ci

TABLE 3.12 (Continued)

Effluents	Release Rate[(d)] (Per MT of Ore)		Release Per Annual Model LWR Requirement	
	Acid Leach	Alkaline Leach	Option 1	Option 2
Liquids and Suspended Particulates				
Non Radioactive:				
$SO_4^{=}$	2.0-3.3 kg	0.11-0.19 kg	~450 MT	~340 MT
NO_3^{--}	0.012 kg		2 MT	1.5 MT
F^-	4.2×10^{-4} kg	<0.001 kg	~0.1 MT	0.074 MT
Ca^{++}	0.057 kg		9.7 MT	7.4 MT
Cl^-	0.12 kg	0.0089 kg	20.9 MT	15.7 MT
Na^+		0.38 kg	9.7 MT	7.3 MT
NH_3				
Fe	0.024-0.12 kg	---	12.3 MT	9.3 MT
TSS[e]				
Total $CO_3^{=}$		0.6-0.8 kg	8.2 MT	13.7 MT
Trace Elements:				
Al	---	---	---	---
As	0.02-2.0 g	---	~0.17 MT	~0.13 MT
Ba	0.04 g	---	0.007 MT	0.005 MT
Cd	---	---	---	---
Cu	0.14 g	---	0.024 MT	0.018 MT

TABLE 3.12 (Continued)

Effluents	Release Rate[d] (Per MT of Ore)		Release Per Annual Model LWR Requirement	
	Acid Leach	Alkaline Leach	Option 1	Option 2
Mg	7.9-24 g	<0.01 kg	<3 MT	<2 MT
Mn	3.3-7.5 g	---	0.91 MT	0.68 MT
Mo	---	---	---	---
Pb	0.01 g	---	0.002 MT	0.003 MT
Se	---	---	---	---
V	---	---	---	---
Zn	---	---	---	---
Radioactive:				
U	1.6×10^{-6} kg	1.1×10^{-3} kg	0.028 MT	0.02 MT
Ra-226	40×10^{-9} kg	11×10^{-9} kg	7.1×10^{-3} Ci	5.4×10^{-3} Ci
Th-230	9.6×10^{-6} Ci	2.2×10^{-9} Ci	1.6×10^{-3} Ci	1.2×10^{-3} Ci
Solids				
Non Radioactive:				
Ash[e]				

TABLE 3.12 (Continued)

Effluents	Release Rate[d] (Per MT of Ore)		Release Per Annual Model LWR Requirement	
	Acid Leach	Alkaline Leach	Option 1	Option 2
Radioactive:				
U-238 + U-234	34×10^{-6} Ci	34×10^{-6} Ci	6.7 Ci	5.06 Ci
Th-230	400×10^{-6} Ci	422×10^{-6} Ci	79.2 Ci	5.8 Ci
Ra-226	422×10^{-6} Ci	414×10^{-6} Ci	82.8 Ci	62.6 Ci
Rn daughters	422×10^{-6} Ci	414×10^{-6} Ci	82.8 Ci	62.6 Ci

(a) R.E. Blanco et al., "Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle for Use in Establishing 'As Low as Practicable' Guides--Milling of Uranium Ores," ORNL/TM-4903, Vol. 1, May 1976.

(b) U.S. Nuclear Regulatory Commission, "Final Environmental Statement Related to Operation of Lucky McGas Hills Uranium Mill," NUREG-0357, November 1977.

(c) A.K. Reed et al., "Assessment of Environmental Aspects of Uranium Mining and Milling," EPA-600/7-76-036, December 1976.

(d) Assuming seepage losses of seven to ten percent of tailings liquid through pond bottom.

(e) No available data.

(f) No direct generation.

TABLE 3.13

URANIUM MILLING OCCUPATIONAL MORTALITY AND MORBIDITY
(PER 1000 MWe-YEAR)

Hazard	Comar and Sagan[a]	WASH-1224[b] (2/1 PWR/BWR)	NUREG-0332[c] (0.8 GWe-Yr)
Premature Deaths:			
Accident	0.003-0.2	0.003	0.005
Disease	0.013-0.33		0.042
Non-Fatal Injuries:			
Accident	0.6-1.5	0.94	0.6
Man-Days Lost from Accidents			

[a] C.L. Comar and L.A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy, Vol. 1, 1976.

[b] U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, August 1973.

[c] R. L. Gotchy, "Health Effects Attributable to Coal and Nuclear Fuel Cycle Alternatives," Draft, NUREG-0332, 1977.

TABLE 3.14

RADIOLOGICAL RISKS FROM ACCIDENTS IN URANIUM MILLING

Accident[a,b]	Probability (plant-year)$^{-1}$	Pathway	Population Dose Per Annual Model LWR Requirement (man-rem)
Fire in Solvent Extraction Circuit (Class F)	4×10^{-4} to 3×10^{-3}	Possible Inhalation Pathway	8.0×10^{-5} to 6.0×10^{-4} (lung) 5.0×10^{-6} to 3.8×10^{-5} (W.B.)
Release of Tailings Slurry from Tailings Pond (Class A)	4×10^{-2}	Possible Ingestion Pathway	1.5×10^{-2} (bone) 9.5×10^{-4} (W.B.)
Release of Tailings Slurry from Distribution Pipeline (Class A)	1×10^{-2}	Possible Ingestion Pathway	1.6×10^{-4} (bone) 1.0×10^{-5} (W.B.)
Flooding (Class D)	(c)	Ingestion	---
Earthquake (Class D)	(c)	Ingestion/Inhalation	---
Tornado (Class D)	(c)	Inhalation	---

(a) Electric Power Research Institute, "Status Report on the EPRI Fuel Cycle Accident Risk Assessment," EPRI NP-1128, July 1979.

(b) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated With Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(c) Unknown.

TABLE 3.15

RADIOLOGICAL EFFLUENTS FROM POSTULATED ACCIDENTS IN URANIUM MILLING OPERATIONS

Radionuclide	Release From Postulated Accident (Ci/accident)[a]		
	Fire in Solvent Extraction Circuit	Release of Tailings Slurry from Pond	Release of Tailings Slurry from Distribution Pipeline
U 238	3×10^{-3}	1.1×10^{-3}	4.8×10^{-5}
U 235	1.5×10^{-4}	5.3×10^{-5}	2.3×10^{-6}
U 234	3.5×10^{-3}	1.2×10^{-3}	5.2×10^{-5}
Th 234	3.3×10^{-3}	1.1×10^{-3}	4.8×10^{-5}
Th 230	3.3×10^{-3}	6.6×10^{-2}	2.9×10^{-3}
Ra 226	3.3×10^{-5}	1.1×10^{-3}	4.8×10^{-5}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated With Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.16

COMPARISON BETWEEN HEALTH RISKS FROM ACCIDENTS AND FROM NORMAL OPERATIONS IN MINING AND MILLING OPERATIONS

	Risk From Normal Operation[a]		Risk From Accidents[a]	
Fuel Cycle Step	Population Dose Per Annual Model LWR Requirement (man-rem)	Health Risk Per Annual Model LWR Requirement (# of excess cancers)	Population Dose Per Annual Model LWR Requirement (man-rem)	Health Risk Per Annual Model LWR Requirement (# of excess cancers)
Uranium Mining	1.4×10^3 (lung) 2.2×10^3 (bone) 7.2×10^2 (W.B.)	3.3×10^{-1}		0
Uranium Milling	4.0×10^3 (lung) 4.4×10^3 (bone) 1.7×10^3 (W.B.)	8.0×10^{-1}[b]	1.5×10^{-2} (bone) 1.6×10^{-3} (W.B.)	5.6×10^{-7} to 5.9×10^{-7}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated With Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) Covering of tailings pile would reduce this value to 7.3×10^{-2}. See Section 5.5 for a detailed discussion of long term radon releases from tailings piles.

Past operating practices at some mills have resulted in inadequate stabilization of mill tailings. Presently there is an aggressive program to upgrade abandoned sites and modify current operations to ensure adequate long-term public protection from radon releases. The model mill in this report is assumed to have effective stabilization and reclamation-mitigating impacts from tailings storage.

Seepage will cease after the tailings are allowed to dry. Radon and dust emissions will be controlled by a thick clay and overburden cover. While the exact level has yet to be determined, radon emissions can be brought down to near background levels and will not be a significant near-term source of radiation exposure to the public. Long-term effects are discussed in Section 5.5.

3.2.7 Transportation

The yellow cake product is shipped from the mill to the conversion facility in 55-gallon drums that have a capacity of about 0.38 MT U_3O_8, depending on the moisture content. About 40 drums are loaded per truck shipment for a net weight of about 15.2 MT of U_3O_8. Typical shipment distances are 1000 miles. Thus, to provide 271.1 MT for Option 1, 17.8 shipments per year are required, or 35,600 round-trip truck-miles. For Option 2, 13.9 shipments per year are required, or 27,800 round-trip truck miles.

3.2.8 Decommissioning

Decommissioning material and energy requirements for the reference uranium mill are expected to be minor. Structural materials and equipment contaminated with U_3O_8 probably will be removed to a shallow-land burial facility. Mill tailings piles will be stabilized or disposed of as discussed in Section 5.5. Specific material and energy requirements are not presently available. However, based on ratios of construction to decommissioning energy estimated for other facilities, decommissioning energy requirements can be estimated as:

	Option 1	Option 2
Electricity, MWH	0.4	0.33
Fossil fuels, BTU	1.7×10^7	1.4×10^7

3.3 URANIUM CONVERSION

The uranium concentrate (yellow cake) extracted from the ore must be converted to the volatile compound uranium hexafluoride (UF_6) for enrichment by the gaseous diffusion or gas centrifuge processes. The uranium conversion facilities provide the means to produce UF_6 from the yellow cake.

3.3.1 General Description

Two different industrial processes are used for uranium hexafluoride production. The "hydrofluor process" consists of reduction, hydrofluorination and fluorination of the ore concentrates to produce crude uranium hexafluoride, followed by fractional distillation to obtain a pure product. The wet solvent extraction process employs a wet chemical solvent extraction step at the head end of the process to prepare high purity uranium feed before reduction, hydrofluorination, and fluorination steps. Each method is used to produce roughly equal quantities of uranium hexafluoride feed for the enrichment plants. The two commercial plants currently in operation process a combined amount of about 10,000 MT of uranium into uranium hexafluoride per year.

3.3.2 Model Description

The model facility is assumed to have a capacity of 5000 MTU per year, the average of existing plants. It is assumed that the UF_6 is produced in equal amounts by the hydrofluor process and the solvent extraction process. Average annual requirements of the 1000-MWe model LWR are estimated to be 340 MT of naturally enriched UF_6 for Option 1 (no recycle) and 265.8 MT of naturally enriched UF_6 for Option 2 (uranium recycle). The model facility is assumed to have a 30-year life span.

3.3.3 Materials and Equipment Requirements

Estimated construction material requirements of the model conversion facility are shown in Table 3.17, and equipment needs are listed in Table 3.18.

3.3.4 Energy Requirements

Energy requirements of the model conversion facility are shown in Table 3.19. Direct energy consumed in the construction of the facility and in the production of construction materials and facility equipment is averaged over the 30-year expected life of the facility, normalized to the model LWR requirement. Direct energy consumed in facility operation and in the production of process materials also is scaled to the LWR requirement. The LWR model requirement is calculated for both Option 1 and Option 2.

3.3.5 Effluents

Conversion facility effluents associated with production of the model LWR UF_6 requirements for Options 1 and 2 are shown in Table 3.20. Gaseous effluents associated with the facility energy requirements are not included in this table.

3.3.6 Occupational and Public Hazards

Occupational hazards occurrence rates and total occupational hazards associated with the annual model LWR requirements are shown in Table 3.21. An estimate of the facility boundary dosage and 80-km-offsite dosage during normal operation is shown in Table 3.22. A list of postulated major accidents, their estimated probabilities, and the radiological dose to the public from a model conversion facility is given in Table 3.23. Table 3.24 lists the radioactive effluents from the postulated accidents. The risks from normal operation and from accidents are compared in Table 3.25.

TABLE 3.17

CONSTRUCTION MATERIAL REQUIREMENT
(URANIUM CONVERSION)

Material	Model Facility Requirement	Annual Model LWR Requirement	
		Option 1	Option 2
Copper	Unknown	----	----
Structural Steel	64 MT[(a)]	.10 MT	.08 MT
Steel Piping	2830 MT[(b)]	4.4 MT	3.4 MT
Zinc	Unknown	----	----
Concrete	8858 MT[(c)]	13.5 MT	10.5 MT

(a) Based on the ratio of concrete to structural steel in model reactor plant auxiliary building.

(b) Based on twice the amount of process piping removed from a 1500 MT fuel reprocessing facility.

(c) Based on assumption that the model conversion facility is housed in a 240 ft. by 400 ft. by 28 ft. reinforced concrete building, six inches thick with a one ft. thick concrete basepad.

TABLE 3.18

ESTIMATED EQUIPMENT REQUIREMENTS FOR MODEL CONVERSION FACILITY

Material	Model Facility Requirement	Annual Model LWR Requirement	
		Option 1	Option 2
Tanks	463 MT[(a)]	.71 MT	.55 MT
Valves	46 MT[(a)]	.06 MT	.05 MT
Pumps	163 MT[(a)]	.24 MT	.19 MT
Misc.	193 MT[(a)]	.29 MT	.23 MT

[(a)] Based on consideration of the quantities of equipment utilized in a 1500 MT fuel reprocessing facility.

TABLE 3.19

URANIUM CONVERSION ENERGY CONSUMPTION
(CONSTRUCTION AND OPERATION)

	Annual Model LWR Requirement	
	Option 1	Option 2
Construction		
Materials		
Electricity (MWH)	44[a]	34[a]
Fossil Fuel (BTU)	1.7×10^9[a]	1.3×10^9[a]
Direct Energy		
Electricity (MWH)	1.9[a]	1.5[a]
Fossil Fuel (BTU)	$4. \times 10^9$[a]	3.1×10^9[a]
Operation		
Process Materials		
Electricity (MWH)	984[a]	786[a]
Fossil Fuels (BTU)	$.03 \times 10^{12}$[a]	$.02 \times 10^{12}$[a]
Direct Energy		
Electricity (MWH)	2360[a]	1841[a]
Fossil Fuel (BTU)	$.286 \times 10^{12}$[a]	$.22 \times 10^{12}$[a]
TOTAL ELECTRICITY	3390 MWH[a] 2200 MWH[b] 2692 MWH[c] 1861 MWH[d]	2645 MWH[a] 1700 MWH[b] 2100 MWH[c] 1673 MWH[d]
TOTAL FUEL	$.32 \times 10^{12}$ BTU[a] $.026 \times 10^{12}$ BTU[b] $.042 \times 10^{12}$ BTU[c] $.025 \times 10^{12}$ BTU[d]	$.24 \times 10^{12}$ BTU[a] $.02 \times 10^{12}$ BTU[b] $.033 \times 10^{12}$ BTU[c] $.021 \times 10^{12}$ BTU[d]

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, p. 51, May 1976. Material normalized for model facility.

(b) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, p. C-2, April 1974.

(c) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle," EPA-520/9-73-003-B, p. 79, October 1973.

(d) Based on the assumption of 6023 GWe-yr @ .8 capacity factor between 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

TABLE 3.20

CONVERSION FACILITY EFFLUENTS

Effluent	Annual Model LWR Release Requirement	
	Option 1	Option 2
Gases and Suspended Particles		
Non-Radioactive (MT)		
Ammonia	.027[a]	.02[a]
	.1[c]	.09[c]
H_2S	.54[a]	.41[a]
F-	.058[a]	.044[a]
	.14[b]	.11[b]
	.058[c]	.051[c]
Radioactive (Ci)		
U	.00015[b]	.00011[b]
	.0013[c]	.0013[c]
Liquids and Suspended Particles		
Non-Radioactive (MT)		
F-	17.5[b]	13.2[b]
	.19[c]	.16[c]
SO_4	4.5[b]	3.4[b]
	11.9[c]	10.6[c]
NO_3	.1[b]	.076[b]
	.19[c]	.16[c]
Cl-	.2[b]	.15[b]
	3.1[c]	2 9[c]
Na+	3.4[b]	2.6[b]
	10.8[c]	9.6[c]

TABLE 3.20 (Continued)

	Annual Model LWR Release Requirement	
Effluent	Option 1	Option 2
NH_3+	1.6[b]	1.2[b]
	3.8[c]	3.4[c]
Fe	.04[b]	.03[b]
	.05[c]	.044[c]
Radioactive (Ci)		
Ra-226	.0034[b]	.0026[b]
	323μCi[c]	280μCi
Th-230	.0015[b]	.0011[b]
	.0086[c]	.0078[c]
U	.044[b]	.033[b]
	.056[c]	.05[c]
Solids		
Non-Radioactive	40 MT[b]	31.2 MT[b]
Radioactive Solids	$41m^3$[c] (~91MT)	$38m^3$[c] (~83MT)

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle," EPA-520/9-73-003, October 1973.

(b) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH 1248, April 1974.

(c) Based on the assumption of 6023 GWe-yr @ .8 capacity factor between 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

TABLE 3.21

CONVERSION FACILITY OCCUPATIONAL HAZARDS

Hazard	Rate Per MTU	Total Per Annual Model LWR Requirement: Option 1	Option 2
Radiation Dose[e] (person-rem)	[b]	.91[d]	.85[d]
Fatalities	1.98×10^{-6}[a]	0.36×10^{-3}[a]	0.28×10^{-3}[a]
Injuries	2.3×10^{-4}[a]	42.2×10^{-3}[a]	32.9×10^{-3}[a]
Man-days lost[c]	0.03	5.5	4.3

[a] U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy", WASH 1224, December 1974.

[b] Not available directly.

[c] Assumes 6000 man-days lost per fatality and 90 man-days lost per injury.

[d] Based on assumption of 6023 GWe-yr @ .8 capacity factor between 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

[e] Whole body dosage.

TABLE 3.22

HAZARDS TO THE PUBLIC FROM THE MODEL CONVERSION FACILITY

	Population Dose (man-rem/yr)[a]		
	Per MT UF_6	Per Annual Model LWR Requirement	
Critical Organ		Option 1	Option 2
Lung	$22x10^{-6}$ (a)(b)	$4.0x10^{-3}$ (a)(b)	$3.15x10^{-3}$ (a)(b)
	$5.4x10^{-6}$ (a)(c)	$\sim 1x10^{-3}$ (a)(c)	$0.77x10^{-3}$ (a)(c)
	---	.20 (e)	.18 (e)
Bone	$\sim 0.22x10^{-8}$ (b)(a)	$\sim 4x10^{-5}$ (a)(b)	$3.15x10^{-5}$ (a)(c)
Bone	$\sim 5.4x10^{-8}$ (a)(c)	$\sim 1x10^{-5}$ (a)(c)	$0.77x10^{-5}$ (a)(c)
Bone	$2.4x10^{-6}$ (a)(d)	$0.44x10^{-4}$ (a)(d)	$0.34x10^{-4}$ (a)(d)
	---	20.7 (e)	19.1 (e)

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle: Part I--Fuel Supply," EPA-520/9-73-003, October 1973.

(b) At the site boundary.

(c) Eighty km from the facility.

(d) From drinking water at the site boundary.

(e) Total population dose (person-rem) based on assumption of 6023 GWe-yr @ .8 capacity factor between 1975 and 2000. U.S. Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

TABLE 3.23

RADIOLOGICAL RISKS FROM ACCIDENTS IN URANIUM CONVERSION OPERATIONS

Accident[a]	Probability $(\text{plant-yr})^{-1}$	Pathway	Population Dose Per Annual Model LWR Requirement
Uranyl nitrate evaporator explosion (Class E)	$1x10^{-4}$-$1x10^{-3}$	inhalation/ ingestion	$1.7x10^{-3}$ to $1.7x10^{-2}$(lung) $9.5x10^{-6}$ to $9.5x10^{-5}$(W.B.)
Hydrogen explosion in the reduction step (Class E)	$1x10^{-3}$-$5x10^{-2}$	inhalation/ ingestion	$1.7x10^{-2}$ to $8.6x10^{-1}$(lung) $9.5x10^{-5}$ to $4.8x10^{-3}$(W.B.)
Fire in solvent extraction operation (Class F)	$1x10^{-4}$	inhalation	$6.0x10^{-5}$ (Lung) $3.8x10^{-6}$(W.B.)
Release from a hot UF_6 cylinder (Class A)	$3x10^{-2}$	inhalation/ ingestion	$5.7x10^{-2}$(lung) $3.1x10^{-4}$(W.B.)
Valve failure in distillation step (Class A)	$5x10^{-2}$	inhalation/ ingestion	$3.6x10^{-2}$(lung) $1.9x10^{-4}$(W.B.)
Release of raffinate from waste retention pond (Class A)	$2x10^{-2}$	ingestion	$1.8x10^{-3}$(lung) $1.5x10^{-4}$(W.B.)

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated With Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.24

RADIOLOGICAL EFFLUENTS FROM POSTULATED ACCIDENTS IN URANIUM CONVERSION OPERATIONS

Postulated Accident	Radionuclides Released (Ci)[(a)]					
	U-238	U-235	U-234	Th-234	Th-230	Ra-226
Uranyl Nitrate Evaporator Explosion	$3.3x10^{-1}$	$1.5x10^{-2}$	$3.5x10^{-1}$	$3.3x10^{-1}$	---	---
Hydrogen Explosion in Reduction Step	$3.3x10^{-1}$	$1.5x10^{-2}$	$3.5x10^{-1}$	$3.3x10^{-1}$	---	---
Fire in Solvent Extraction Operation	$2.0x10^{-3}$	$9.2x10^{-5}$	$2.1x10^{-3}$	$2.0x10^{-3}$	$2.0x10^{-3}$	$2.0x10^{-5}$
Release From Hot UF_6 Cylinder	$3.6x10^{-2}$	$1.7x10^{-3}$	$3.9x10^{-2}$	$3.6x10^{-2}$	---	---
Valve Failure in Distillation Step	$1.3x10^{-2}$	$6.2x10^{-4}$	$1.4x10^{-2}$	1.3x10-2	---	---
Release of Raffinate From Retention Pond	1.7x10-4	8.0x10-6	1.8x10-4	1.7x10-4	3.0x10-5	3.0x10-3

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.25

COMPARISON BETWEEN RADIOLOGICAL HEALTH RISKS FROM ACCIDENTS AND FROM NORMAL OPERATIONS IN URANIUM CONVERSION

Risk From Normal Operation[a]		Risk From Accidents[a]	
Pop. Dose Per 1000 MWe-yr (man-rem)	Health Risk Per 1000 MWe-yr (# of excess cancers)	Pop. Dose Per 1000 MWe-yr (man-rem)	Health Risk Per 1000 MWe-yr (# of excess cancers)
$8.1x10^{-1}$(lung)	$3.9x10^{-5}$	$9.7x10^{-1}$(lung)	$4.8x10^{-6}$ to
$2.0x10^{-2}$(W.B.)	---	$5.5x10^{-3}$(W.B.)	$4.1x10^{-5}$

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

3.3.7 Transportation Requirements

Although two 10-ton cylinders could be transported per truckload, current practice is to transport natural UF_6 in one 14-ton cylinder per truckload, or 12.5 MT of UF_6 per truckload. Assuming 750 miles between facilities, the 340 MT UF_6 per year for Option 1 would result in about 27 shipments, or 40,800 round-trip truck-miles per year. For Option 2, 265.8 MT UF_6 would result in about 21 shipments, or 31,900 round-trip truck-miles per year. The transportation requirements for the model conversion facility are presented in Table 3.26.

3.3.8 Decommissioning

After the model conversion facility has achieved its design lifetime, it will be decommissioned. Decommissioning can be performed in several ways: (1) the facility can be decommissioned immediately following shutdown; or (2) the facility can be placed in several modes of storage and decommissioned at a later date when some of the radioactivity has decayed. For a facility contaminated solely with uranium, such a delay is not useful in decreasing the in-facility activity levels because of the long uranium half-life. The decommissioning mode chosen for the model facility is, therefore, immediate decommissioning at the end of the design life. Table 3.27 identifies estimated decommissioning energy requirements and transportation requirements.

TABLE 3.26

CONVERSION FACILITY TRANSPORTATION REQUIREMENTS FOR UF_6 NORMALIZED TO ANNUAL MODEL LWR FUEL REQUIREMENT

Shipment[(a,b,c)]	Weight/Shipment ($MT\ UF_6$)	Number of Shipments[(d)]	Total Truck Miles[(e)]
UF_6	12.5	27(21)	41×10^3 (32×10^3)

[(a)] U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH 1224A, Appendix A, 1974.

[(b)] U.S. Atomic Energy Commission, "Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants," WASH 1238, December 1972.

[(c)] U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, April 1974.

[(d)] The numbers in brackets include allowance for U recycle (Option 2).

[(e)] Assumes all shipments made by trucks and two-way trips of ~750 miles.

TABLE 3.27

CONVERSION FACILITY DECOMMISSIONING REQUIREMENTS

Requirement	Per Annual Model LWR Requirement	
	Option 1	Option 2
Direct Energy[a]		
Electricity (MWH)	4.75×10^{-3}	3.75×10^{-3}
Fossil Fuel (BTU)	1.0×10^{7}	0.75×10^{7}
Radioactive Wastes	$11.8 m^3$[b] 9.1 MT[b] .64 Truckload	$9.2 m^3$[b] 7.1 MT[b] .5 Truckload[b]

[a] Based on assumption that decommissioning energ, is equal to .25 percent of the direct construction energy included in Table 3.19.

[b] Assumed equal to the radioactive decommissioning waste generated in the decommissioning of a 1500 MT fuel reprocessing facility.

3.4 URANIUM ENRICHMENT

In the enrichment stage of the uranium cycle, naturally enriched UF_6 (0.71 percent U-235) and, less frequently, recycled UF_6 (~0.8 percent U-235) are processed to increase the U-235 content to the model LWR fuel enrichment level, 3 percent for reload fuel and 2.6 percent for initial core loading. Two types of enrichment facilities are considered: (1) the diffusion type and (2) the centrifuge type. Some of the principal differences between the two types of facilities are:

1. Power requirements for a gaseous diffusion plant are about ten times greater than those for a gas centrifuge enrichment plant.

2. Quantities of waste heat to be dissipated to the environment, therefore, are generally an order of magnitude greater from a gaseous diffusion plant, requiring greater quantities of recirculating makeup water, blowdown, etc.

3. Liquid discharge from the decontamination (uranium recovery) facility at a gaseous diffusion plant is about 50 percent of that at a gas centrifuge plant.

4. Operation of a gas centrifuge plant will require the burial of many more low-level contaminated parts than for a gaseous diffusion plant.

5. Lower manpower requirements for a gaseous diffusion plant yield sanitary-water requirements and laundry and sewage treatment facility loads that are about 40 percent of those for a gas centrifuge plant (and associated rotor fabrication facility).

For these reasons, and because of the present status of the enrichment technology, no attempt is made to provide a composite model similar to the other stages of the uranium cycle. The two types of facilities are treated separately in order to assess the impact of switching from diffusion to centrifuge technologies.

3.4.1 General Description--Gaseous Diffusion Facility

The gaseous diffusion process has been used for the separation of uranium isotopes in this country for more than 30 years. This process takes advantage of the dynamics of molecular diffusion through a membrane barrier. Gaseous uranium hexafluoride flows past a diffusion barrier, and part of the gas diffuses through the barrier to a region of lower pressure. The $^{235}UF_6$ gas molecules are slightly smaller than the $^{238}UF_6$ molecules and on the average have a slightly higher velocity and hence, will come in contact with the barrier more often. Thus, the gas on the low-pressure side of the barrier is slightly enriched in U-235. This gas is then compressed and directed into another diffusion unit, and the process is repeated many times.

3.4.2 Model Description--Gaseous Diffusion

The model gaseous diffusion facility has an assumed capacity of 8750 MTSWU/yr (the model size for the proposed enrichment expansion in 1976). The average annual requirement of the model reactor is estimated to be about 215.8 MTSWU for Option 1 (no recycle) and 208 MTSWU for Option 2 (uranium recycle). In the first case, the facility feed is naturally enriched UF_6; in the second case, natural as well as recycled UF_6 is fed to the process, with the naturally enriched UF_6 requiring 169 MTSWU of the 208 MTSWU total.

3.4.3 Materials and Equipment Requirements--Gaseous Diffusion

Construction materials are itemized in Table 3.28, and major equipment requirements and associated materials content are detailed in Table 3.29. Construction material requirements normalized to the model LWR annual enrichment requirement also are shown in Table 3.28 for Options 1 and 2.

3.4.4 Energy Requirements--Gaseous Diffusion

Table 3.30 shows energy consumption rates associated with construction and operation of the diffusion facility. Energy requirements for

TABLE 3.28

MODEL DIFFUSION FACILITY CONSTRUCTION MATERIALS REQUIREMENTS

		Amount Normalized to Annual LWR Model Requirement[a,b]	
Material	Amount	Option 1	Option 2
Concrete (MT)	550,000	453	437
Fiberglass insulation (MT)	560	0.46	0.44
Reinforcing steel (MT)	9,100	7.5	7.2
Structural steel (MT)	55,000	45	43
Redwood (board-ft)	360,000	300	285

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle," EPA-520/9-73-003, October 1973.

(b) Thirty-year facility lifetime is assumed.

TABLE 3.29

EQUIPMENT REQUIREMENTS AND ASSOCIATED MATERIALS FOR THE MODEL DIFFUSION ENRICHMENT FACILITY

Equipment[a,b]	Number Required[c]	Material (MT)					Production Time (man-hours)
		Steel	Nickel	Aluminum	Copper	Monel	
Gas diffusers	1,180	36,300	1,360	---	---	---	940
Gas compressors	1,180	22,700	900	6,600	---	---	50
Compressor drive motors	1,180	9,100	---	---	3,600	---	250
Switchyards	~4	---	---	---	---	---	---
Transformers	~20	9,100	---	---	1,800	---	2,540
Heat exchangers	1,180	---	---	---	---	---	---
Cooling towers	~20	13,600	---	---	---	270	1,560
Piping[d]	---	22,700	1,200	---	---	---	
Valves	1,500	4,500	450	---	---	---	2,470

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle," EPA-520/9-73-003, October 1973.

(b) Listed items do not have uniform capacity or rating.

(c) Facility lifetime is assumed to be 30 years.

(d) Piping in this item consists of elbows, diffusers, and various lengths of straight pipe.

TABLE 3.30

URANIUM ENRICHMENT ENERGY REQUIREMENTS--DIFFUSION FACILITY (CONSTRUCTION AND OPERATION)

Source	Annual Model LWR Energy Requirement[a,b]		
	Per SWU	Option 1	Option 2
Construction			
Construction Materials:			
Electricity (MWH)	7.4×10^{-3}	1.6×10^{3}	1.5×10^{3}
Fossil Fuel (BTU)	2.6×10^{5}	5.6×10^{10}	5.4×10^{10}
Direct Energy:			
Electricity (MWH)	3.0×10^{-4}	64.7	62.4
Fossil Fuel (BTU)	7.0×10^{4}	1.5×10^{10}	1.4×10^{10}
Operation			
Process Materials:			
Electricity (MWH)	5.8×10^{-3}	1.3×10^{3}	1.2×10^{3}
Fossil Fuel (BTU)	1.4×10^{5}	3.0×10^{10}	2.9×10^{10}
Direct Energy:			
Electricity (MWH)	2.8	6.1×10^{5}	5.8×10^{5}
Gasoline (BTU)	3.6×10^{3}	7.8×10^{8}	7.5×10^{8}
Diesel Fuel (BTU)	3.6×10^{3}	7.8×10^{8}	7.5×10^{8}
Propane (BTU)	3.0×10^{2}	6.5×10^{7}	6.2×10^{7}
Coal (BTU)	3.3×10^{5}	7.1×10^{10}	6.8×10^{10}

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.

(b) Model power plant enrichment requirement is assumed to be 215.8 MT SWU for Option 1 and 208 MT SWU for Option 2.

TABLE 3.31

DIFFUSION FACILITY EFFLUENTS

	Annual Release Rate[a]		
		Normalized to Annual Model LWR Requirement	
Effluent	Model Facility	Option 1	Option 2
Airborne Gases and Suspended Particulates[b]			
Non Radioactive: (MT/yr)			
HF	2.4	0.06	0.06
SO_2:			
Steam Plant:	656	16	16
Diffusion Process	4.6×10^{-3}	$\sim 0.1 \times 10^{-3}$	$\sim 0.1 \times 10^{-3}$
NO_x:			
Steam Plant	525	12.9	12.5
Diffusion Process	1.1	~0.03	~0.03
Particulates:			
Steam Plant	31.5	0.78	0.75
Diffusion Process	0.4	0.01	~0.01
CO	10.5	0.26	0.25
Hydrocarbons	5.3	0.13	~0.13
Cooling Tower Drift (gpm)	25	0.61	0.59

TABLE 3.31 (Continued)

Effluent	Annual Release Rate		
		Normalized to Annual Model LWR Requirement	
	Model Facility	Option 1	Option 2
Radioactive: (Ci/yr)			
U-232	3.3×10^{-5}	---	0.78×10^{-6}
U-233	1.8×10^{-7}	---	4.04×10^{-9}
U-234	3.9×10^{-2}	---	0.93×10^{-3}
U-235	1.5×10^{-3}	3.70×10^{-5}	3.57×10^{-5}
U-236	1.1×10^{-3}	---	2.6×10^{-5}
U-238	6.4×10^{-3}	0.16×10^{-3}	0.15×10^{-3}
Pu-239	4.0×10^{-10}	---	9.5×10^{-12}
Np-237	2.0×10^{-7}	---	4.75×10^{-9}
Tc-99	5.4×10^{-1}	---	13×10^{-2}
Ru-106	7.2×10^{-3}	---	0.17×10^{-3}
Zr-95; Nb-95	1.5×10^{-3}	---	3.57×10^{-5}
Cs-137	1.1×10^{-4}	---	2.71×10^{-6}
Ce-144	1.1×10^{-4}	---	2.71×10^{-6}
Other Fission Products	1.1×10^{-4}	---	2.71×10^{-6}

TABLE 3.31 (Continued)

Effluent	Model Facility	Annual Release Rate: Normalized to Annual Model LWR Requirement: Option 1	Option 2
Liquids and Suspended Particulates			
Non Radioactive: (MT/yr)[(c)]			
Aluminum	0.21	5.0×10^{-3}	4.8×10^{-3}
Aluminum Nitrate	1.44	35.4×10^{-3}	34.1×10^{-3}
Chlorine	1.3	32.6×10^{-3}	31.5×10^{-3}
Chromium	0.24	5.9×10^{-3}	5.7×10^{-3}
Fluorine	0.36	8.9×10^{-3}	8.5×10^{-3}
Nitrate	27.2	0.67	0.65
Nitric Acid	26.7	0.66	0.63
Phosphate	3.6	0.09	~0.09
Tributyl Phosphate	0.05	1.3×10^{-3}	1.2×10^{-3}
Varsol	0.15	3.8×10^{-3}	3.7×10^{-3}
Zinc	2.4	60.0×10^{-3}	58×10^{-3}
Radioactive: (Ci/yr)			
U-232	4.3×10^{-6}	---	$\sim 0.1 \times 10^{-6}$
U-233	2.15×10^{-8}	---	$\sim 0.5 \times 10^{-9}$
U-234	1.44×10^{-3}	---	$\sim 34.2 \times 10^{-6}$

TABLE 3.31 (Continued)

		Annual Release Rate	
		Normalized to Annual Model LWR Requirement	
Effluent	Model Facility	Option 1	Option 2
U-235	5.93×10^{-5}	1.5×10^{-6}	$\sim 1.4 \times 10^{-6}$
U-236	1.32×10^{-4}	---	$\sim 31.4 \times 10^{-6}$
U-238	1.16×10^{-6}	28.6×10^{-9}	$\sim 27.6 \times 10^{-9}$
Pu-239	6.0×10^{-9}	---	$\sim 0.2 \times 10^{-9}$
Np-237	4.0×10^{-6}	---	$\sim 0.1 \times 10^{-6}$
Ru-106	9.3×10^{-2}	---	$\sim 2.2 \times 10^{-3}$
Zr-85; Nb-95	2.0×10^{-2}	---	$\sim 0.48 \times 10^{-3}$
Cs-137	1.5×10^{-3}	---	$\sim 35.7 \times 10^{-6}$
Ce-144	1.5×10^{-3}	---	$\sim 35.7 \times 10^{-6}$
Tc-99	7	---	~0.17

(a) U.S. Energy Research and Development Administration, "Expansion of the U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, April 1976.

(b) Based on a flow rate of 17.1×10^{6} liters/day, 300 days/year.

(c) Includes effluents from operation of coal-fired process steam plant.

material production and equipment fabrication also are included. These data are used to calculate the average annual energy requirement normalized to the model reactor SWU requirements for Options 1 and 2.

3.4.5 Effluents--Gaseous Diffusion

Effluents from the model facility are shown in Table 3.31 and include the effluents from the required process steam plant. These values are normalized to the model reactor requirements and are listed in the last two columns. Liquid effluents are based on an estimated daily facility flow rate of 17.1×10^6 liters. Radioactive effluents are significantly different when Options 1 and 2 are considered because of the presence of fission products in the feed.

3.4.6 Occupational and Public Hazards--Gaseous Diffusion

Data related to occupational hazards are detailed in Table 3.32. Accidents resulting in potential offsite effects are listed in Table 3.33 along with the estimated probability and population radiological dose. Tables 3.34 and 3.35 contain a listing of the radionuclide effluents from the accidents. The risks from normal operation and from accidents are compared in Table 3.36.

The estimated air concentrations of hydrogen fluoride resulting from accidents are shown in Table 3.37. Although these air concentrations will not exist for long periods of time, most fall within the range considered to have a health effect,* 2.5×10^3 to $1.0 \times 10^5 \mu g/m^3$. For comparison purposes, daily 8-hour occupational exposure limits for hydrogen fluoride are 2.5×10^3 $\mu g/m^3$, with tolerable exposures of several minutes duration to 2.5×10^4 $\mu g/m^3$ and lethality at 1.0×10^6 $\mu g/m^3$.

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*National Academy of Sciences, "Biological Effects of Atmospheric Pollutants--Fluorides," 1971.

TABLE 3.32

OCCUPATIONAL HAZARDS OF THE MODEL DIFFUSION FACILITY

Hazard	(Per MTSWU)[a]	Normalized Values for Annual Model LWR Enrichment Requirements[(a)] Option 1	Option 2
Radiological	Not determined	0.48 person-rem[(b)]	0.48 person-rem[(b)]
Non Radiological			
Fatalities	0.3×10^{-6}	2.8×10^{-3}	2.7×10^{-3}
Injuries	1.5×10^{-3}	0.3	~0.3
Man-days lost[(c)]	0.22	44	46

(a) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, December 1974.

(b) Based on assumption that the first new enrichment facility is a gaseous diffusion plant, and subsequent facilities are centrifuge plants. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

(c) Assumes 6000 man-days lost per fatality and 90 man-days lost per injury.

TABLE 3.33

RADIOLOGICAL RISKS FROM ACCIDENTS IN URANIUM ENRICHMENT OPERATIONS

Accident[a]	Probability $(\text{plant-year})^{-1}$	Pathway	Population Dose Per Annual Model LWR Requirements (man-rem)
Catastrophic Fire	4×10^{-4} to 3×10^{-2}	Inhalation	2.9×10^{-3} to 2.2×10^{-1} (lung) 1.6×10^{-5} to 1.2×10^{-3} (w.b.)
Release from a Hot UF_6 Cylinder	4×10^{-1}	Inhalation/ Ingestion	5.1×10^{-1} (lung) 2.4×10^{-3} (w.b.)
Leaks on Failures of Valves or Piping Within Plant	1.8	Inhalation/ Ingestion	2.0×10^{-2} (lung) 1.1×10^{-4} (w.b.)
Criticality	8×10^{-5}	Inhalation/ Ingestion	2.9×10^{-7} (thyroid) 7.6×10^{-9} (w.b.)

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.34

RADIOLOGICAL EFFLUENTS FROM POSTULATED ACCIDENTS IN URANIUM ENRICHMENT OPERATIONS

	Release From Postulated Accident (Ci/Accident)[a]		
Radionuclide	Catastrophic Fire	Release From A Hot UF_6 Cylinder	Leaks or Failures of Valves or Piping
U 238	5.1×10^{-1}	3.5×10^{-2}	7.9×10^{-4}
U 237	3.8×10^{-1}	3.2×10^{-2}	5.8×10^{-4}
U 236	4.7×10^{-2}	5.3×10^{-3}	7.3×10^{-5}
U 235	2.4×10^{-2}	3.8×10^{-3}	3.8×10^{-5}
U 234	6.3×10^{-1}	1.5×10^{-1}	9.7×10^{-4}
Th 234	5.1×10^{-1}	---	7.9×10^{-4}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.35

RADIONUCLIDE RELEASE RESULTING FROM A CRITICALITY INCIDENT AT THE ENRICHMENT PLANT

Nuclide	Activity Released[a] (Ci)	Nuclide	Activity Released[a] (Ci)
Br 80	1.2×10^{-2}	I 136	2.3
Br 80m	5.7×10^{-6}	I 137	3.3×10^{-5}
Br 82	1.9×10^{-6}	Xe 133	1.7×10^{-4}
Br 82m	3.2×10^{-4}	Xe 133m	9.9×10^{-6}
Br 83	3.5×10^{-1}	Xe 135	2.2×10^{-1}
Br 84	3.5	Xe 135m	4.7×10^{-1}
Br 84m	1.5×10^{-1}	Xe 137	9.0×10^{1}
Br 85	7.2	Xe 138	7.0×10^{1}
Br 86	1.5×10^{-1}	Xe 139	1.5×10^{-1}
Br 87	2.1×10^{-1}	Xe 140	2.2×10^{-8}
Kr 83m	3.4×10^{-2}	Th 231	2.0×10^{-9}
Kr 85	3.2×10^{-6}	Th 234	2.2×10^{-10}
Kr 85m	1.3	Pa 234m	1.8×10^{-10}
Kr 87	9.4	U 233	1.7×10^{-16}
Kr 88	6.3	U 234	3.4×10^{-14}
Kr 89	5.2×10^{1}	U 235	4.5×10^{-7}
Kr 90	9.2×10^{-3}	U 236	1.3×10^{-12}
I 128	1.4×10^{-4}	U 237	7.1×10^{-6}
I 130	1.0×10^{-4}	U 238	1.1×10^{-6}
I 131	5.5×10^{-3}	U 239	6.1×10^{-1}
I 132	1.6×10^{-1}	Np 237	4.4×10^{-17}
I 133	1.5×10^{-1}	Np 239	1.5×10^{-3}
I 134	5.2	Np 240	3.5×10^{-12}
I 135	2.3	Pu 239	4.1×10^{-13}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.36

COMPARISON BETWEEN HEALTH RISKS FROM ACCIDENTS AND FROM NORMAL OPERATION AT A URANIUM ENRICHMENT FACILITY

Risk From Normal Operation[a]		Risk From Accidents[a]	
Pop. Dose Per Annual Model LWR Requirement (man-rem)	Health Risk Per Annual Model LWR Requirement (No. of excess cancers)	Pop. Dose Per Annual Model LWR Requirement (man-rem)	Health Risk Per Annual Model LWR Requirement (No. of excess cancers)
1.1 (lung) 1.9×10^{-2} (w.b.)	5.1×10^{-5}	7.5×10^{-1} (lung) 3.7×10^{-3} (w.b.)	2.2×10^{-5} to 3.1×10^{-5}

[a] U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.37

ESTIMATED CONCENTRATIONS IN AIR OF HF GAS RELEASED IN ACCIDENTS

Accident Description[a]	Duration of Release (min)	Amount Released (kg)	In Air (μg/m^3)
Release from feed cylinder (normal or return)	15	1.7x10^3	6.02x10^3 [b]
Release from product cylinder	15	300	1.06x10^3 [b]
Release of tails material	10	3.636	191[b]
Tornado	Unknown	1.7x10^4	4.27x10^4 [c]
Rupture of HF storage tank	Instantaneous portion	397	1.26x10^6
	Delayed portion 2.88x10^4	4.14x10^3	76

(a) U.S. Energy Research and Development Administration, "Expansion of the U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA-1543, April 1976.

(b) Concentration at plant boundary of 1207 m.

(c) Concentration over 1000-acre area at 100-m height.

3.4.7 Transportation Requirements--Gaseous Diffusion

The annual enriched UF_6 requirement of the model LWR is estimated to be 58 MT for either option. A truck typically carries 11 MT of UF_6; therefore, the number of shipments required is expected to be about five, at 1500 miles round trip. This will require a total of 7500 truck-miles.

Table 3.38 shows an estimate of truck and rail requirements during the construction period of the model diffusion facility.

3.4.8 Decommissioning--Gaseous Diffusion

After the model facility has achieved its design lifetime it will be decommissioned. Since contamination is solely uranium, a delay before dismantlement is not useful in decreasing activity levels because of the long uranium half-life. No specific information was found on decommissioning an enrichment facility; however, estimates were made using the following assumptions:

1. The outer 2 inches of concrete are removed for low level burial (concrete assumed to be about 8 inches thick).
2. All fiberglass insulation is removed for burial.
3. All gas diffusers, compressors, compressor drive motors, piping, and valves are removed for burial.

These assumptions result in:

	(Per Annual LWR Model Requirement)	
	Option 1	Option 2
Concrete, MT	113	109
Fiberglass, MT	0.11	[illegible].11
Steel (95300 MT), MT	78	[illegible]
Nickel (3910 MT), MT	3.2	3.1
Aluminum (6600 MT), MT	5.4	5.2
Copper (3600 MT), MT	3.0	2.9

TABLE 3.38

TRANSPORTATION ACTIVITY DURING CONSTRUCTION OF THE MODEL DIFFUSION FACILITY

Transportation Mode[a]	Model Facility Requirement (vehicle miles)	Normalized Annual Model LWR Requirement (vehicle miles)[b]	
		Option 1	Option 2
Trucks			
Initial Construction Period (~5 yrs)	1.35×10^6	1.11×10^3	$\sim 1.07 \times 10^3$
Final Construction Period (~3 yrs)	1.50×10^6	1.23×10^3	$\sim 1.19 \times 10^3$
Total	2.85×10^6	2.34×10^3	$\sim 2.26 \times 10^3$
Rail Cars			
Initial Construction Period (~5 yrs)	2.56×10^6	2.10×10^3	2.00×10^3
Final Construction Period (~3 yrs)	0.30×10^6	0.06×10^3	$\sim 0.06 \times 10^3$
Total	2.86×10^6	2.16×10^3	2.06×10^3

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, April 1976.

(b) Normalization assumed 30-year lifetime of the facility and 8750-MTSWU annual capacity scaled to model LWR requirement of enriched UF_6.

Assuming decontamination energy requirements are about 6 percent of the direct construction energy requirements, the required decontamination energy requirements are:

	Option 1	Option 2
Electricity, MWH	4	3.9
Fossil fuel, BTU	9.5×10^8	8.8×10^8

3.4.9 General Description--Gas Centrifuge Facility

The gas centrifuge enrichment plant consists of a number of centrifuge machines operated in a cascade. These machines are comprised essentially of hollow, vertical cylinders (rotors), which are spun on their axis at a high angular velocity. Gaseous uranium hexafluoride is fed to the centrifuge and is accelerated to approximately the angular velocity of the rotor. Centrifugal force causes steep pressure gradients to be built up in the gas, producing pressure-induced diffusion. This diffusion results in a slightly greater concentration of the lighter uranium isotope (U-235) in the vicinity of the cylinder axis and a slightly greater concentration of the heavier uranium isotope (U-238) near the rotor wall. The centrifuge rotor spins inside an evacuated casing that acts to reduce friction upon the rotating body and provides a protective barrier for surrounding equipment from possible internally generated missiles that result from rotor disintegration. Stationary tubes at the axis of the rotor introduce the feed gas and withdraw enriched and depleted gas.

The conceptual design of a gas centrifuge enrichment facility includes a number of cascades of centrifuge machines operated in parallel in large process buildings. These process buildings will be equipped with feed stations and product and tails withdrawal facilities to maintain the required uranium hexafluoride flow into and out of the cascade system. In addition, a recycle/assembly facility will be located onsite to (1) assemble centrifuge machine subassemblies, (2) repair disabled machines, and (3) provide decontamination and scrap processing. Other support facilities, such as a coal-fired steam plant for process heat, would also be provided.

It should be noted that data on the gaseous diffusion process are based on extensive operating experience that is presently lacking for gas centrifuge facilities.

3.4.10 Model Description--Gas Centrifuge

The model gas centrifuge facility also is assumed to have an enrichment capacity of 8750 MTSWU/yr. In addition to the enrichment portion of the plant, a rotor fabrication plant has been included that provides (1) the manufacturing capacity to produce rotors, (2) facilities to assemble the rotors with commercially produced components, and (3) facilities to balance the completed rotor assembly and transport it to the centrifuge recycle/ assembly plant. The lifetime of the complete enrichment facility is assumed to be 30 years.

This enrichment plant would supply the enrichment needs for about 40 LWR power reactors. The annual need of the model LWR considered in this report is 215.8 MTSWU for Option 1 (no recycle) and 208 MTSWU when credit is taken for Option 2 (uranium recycle). Data detailed in the following sections include plant material and energy requirements, effluents from facility operation, occupational and public health hazards from facility operation, and transportation requirements during plant construction and operation. These data have been presented in terms of both the total impact of the model facility and the impact associated with the annual enrichment requirement of the model LWR. The two options (no recycle and U recycle) also have been introduced to indicate the impacts associated with each option.

3.4.11 Materials and Equipment Requirements--Gas Centrifuge

Estimated quantities of basic construction materials required for an 8750-MTSWU/yr gas centrifuge enrichment plant (including rotor fabrication facilities) are presented in Table 3.39. A breakdown of the major components of the facility and data on their associated material composition are presented in Table 3.40. In addition, materials consumed annually during facility operation have been calculated, as shown in Table 3.41. Information is included that is based on both the quantity required for the model plant and the model LWR annual requirement, as described above.

3.4.12 Energy Requirements--Gas Centrifuge

Energy consumption during construction of a model gas centrifuge and during its operation has been estimated, including petroleum products, fossil fuel, and electrical energy consumption. The annual energy requirement is presented in Table 3.42. Energy consumption during construction, amortized over the lifetime of the plant, appears as part of the annual commitment. Data on energy requirements during centrifuge decommissioning are not available at this time.

3.4.13 Effluents--Gas Centrifuge

Effluents arising from model centrifuge facility operation have been estimated and are presented in Table 3.43. Normal effluents from centrifuge plant operation include nonradioactive and radioactive gases and liquids arising from major process operations. In addition, gaseous effluents from required process steam production have been estimated based on operation of an onsite coal-fired steam plant. These effluents have been estimated for both model centrifuge operation and the annual LWR enrichment requirement for both fuel cycle options.

TABLE 3.39

MATERIALS REQUIRED FOR CONSTRUCTION OF A GAS CENTRIFUGE ENRICHMENT FACILITY (INCLUDING ROTOR FABRICATION PLANT)

Material[a]	Quantity Per Model Centrifuge Plant (tons)[b]	Commitment Per Annual Model LWR Enrichment Requirement (tons)[c]	
		Option 1	Option 2
Concrete	5.0×10^5	410	396
Paving materials	1.1×10^3	0.90	0.87
Transformer oil	280	0.23	0.22
Steel	2.4×10^5	197	190
Aluminum	2.2×10^4	18.0	17.4
Copper	4.3×10^3	3.54	3.41
Zinc	185	0.15	0.14
Miscellaneous	1.0×10^3	0.82	0.79

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, April 1976, pp. 2.3-64, 2.3-103.

(b) Model plant is assumed to supply 8750 MT SWU/yr and to have a lifetime of 30 years.

(c) The yearly requirement of a model LWR is assumed to be 215.8 MTSWU for Option 1 and 208 MTSWU for Option 2.

TABLE 3.40

EQUIPMENT REQUIREMENTS AND ASSOCIATED MATERIALS FOR THE MODEL CENTRIFUGE ENRICHMENT FACILITY

Equipment	Material (MT)[a]					
	Rotor Material	Steel	Aluminum	Iron	Brass	Copper
Centrifuge	61	115,400	7,990	443	151	
Service Module		50,000				
Vacuum System		10,000	2,000			
Steam System		5,000				
Motors		1,000	500			100
Electrical System		1,000				200
RCW System		1,000				
Process Piping and Valves		1,000	5,000			
Air System		500				

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, April 1976.

TABLE 3.41

ESTIMATED ANNUAL MATERIAL CONSUMPTION DURING MODEL GAS CENTRIFUGE OPERATION

Material[a]	Annual Commitment--Model Centrifuge Facility	Commitment Per Annual Model LWR Enrichment Requirement[c]	
		Option 1	Option 2
Steel (MT)	1287	31.7	30.6
Aluminum (MT)	940	23.2	22.3
Iron (MT)	3.34	0.08	0.08
Brass (MT)	16.3	0.40	0.39
Alnico V (MT)	47.7	1.18	1.13
Plastic (MT)	7.6	0.19	0.18
Rotor material (MT)	2200	54.3	52.3
Alumina (MT)	270	6.66	6.42
Diffusion pump oil (liters)	3300	81.4	78.4
Damping oil (liters)	1.7×10^4	419	404
Lubrication oil (liters)	2.6×10^4	641	618
Trichlorotrifluoroethane (liters)	6.8×10^4	1678	1616
Freon-TA (liters)	7.9×10^4	1950	1878
Blanco-Tron-TCM (liters)	3.2×10^4	790	761
Perchloroethylene (liters)	3.2×10^4	790	761

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, pp. 2.3-39, April 1976.

(b) Model plant is assumed to supply 8750 MTSWU/yr.

(c) The yearly requirement of a model LWR is assumed to be 215.8 MTSWU for Option 1 and 208 MTSWU for Option 2.

TABLE 3.42

ESTIMATED ANNUAL ENERGY CONSUMPTION FOR CONSTRUCTION AND OPERATION OF THE MODEL GAS CENTRIFUGE FACILITY

Source[a]	Annual Model Facility Consumption[b]	Commitment Per Annual Model LWR Enrichment Requirement[c]	
		Option 1	Option 2
Construction[d]			
Centrifuge Plant:			
Coal (MT)	8.2×10^3	201	194
Electricity (MWH)	3.0×10^4	747	720
Gasoline and Diesel Fuel (BTU)[e]	1.2×10^{10}	3.0×10^8	2.8×10^8
Rotor Fabrication Plant:			
Coal (MT)[f]	1.9×10^2	4.7	4.5
Electricity (MWH)	2.2×10^3	54.6	52.7
Gasoline and Diesel Fuel (BTU)	1.9×10^9	4.6×10^7	4.4×10^7
Operation:			
Centrifuge Plant:			
Coal (MT)	5.3×10^4	1300	1260
Electricity (MWH)	2.1×10^6	5.2×10^4	5.0×10^4
Gasoline and Diesel Fuel (BTU)	2.5×10^6	6.2×10^8	5.9×10^8
Rotor Fabrication Plant:			
Coal (MT)	1.2×10^4	296	285
Electricity (MWH)	1.4×10^5	3450	3330
Gasoline and Diesel Fuel (BTU)	1.4×10^9	3.4×10^7	3.3×10^7

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, pp. 2.2-6, 2.2-11, April 1976.

(b) Model plant is assumed to provide 8750 MTSWU/yr enrichment capability.

(c) The yearly requirement of a model LWR is assumed to be 215.8 MTSWU for Option 1 and 208 MTSWU for Option 2.

(d) Construction energy requirements have been amortized over the lifetime of the facility (30 years). Construction of the centrifuge plant is assumed to take seven years, while construction of the rotor fabrication plant would require approximately five years.

(e) Assumes 1.4×10^5 BTU/gal of light fuels.

(f) Assumes 2.405×10^7 BTU/ton of coal, or 2.65×10^7 BTU/MT coal.

TABLE 3.43

ESTIMATED EFFLUENTS FROM MODEL GAS CENTRIFUGE OPERATION

Effluent Category[a]	Annual Release for Model Centrifuge Operation[b]	Release Per Annual Model Enrichment Requirement[c]	
		Option 1	Option 2
Airborne Gases and Particulates			
Non Radioactive:[a] (MT/yr)			
HF	0.5	0.012	0.012
NO_x	527	13.0	12.5
SO_2	656	16.2	15.5
Particulates	31.7	0.78	0.75
CO	10.5	0.26	0.25
Hydrocarbons	5.3	0.13	0.13
Ethanol	11.0	0.27	0.26
Radioactive: (Ci/yr)			
U-232	3.3×10^{-5}	0	7.8×10^{-7}
U-233	1.8×10^{-7}	0	4.3×10^{-9}
U-234	3.9×10^{-2}	0	9.2×10^{-4}
U-235	1.5×10^{-3}	0	3.6×10^{-5}
U-236	1.1×10^{-3}	0	2.6×10^{-5}
U-238	6.4×10^{-3}	0	1.5×10^{-4}
Pu-239	4.0×10^{-10}	0	9.5×10^{-12}
Np-237	2.0×10^{-7}	0	4.7×10^{-9}
Tc-99	5.4×10^{-1}	0	0.013
Ru-106	7.2×10^{-3}	0	1.7×10^{-4}
Zr-95	1.5×10^{-3}	0	3.6×10^{-5}
Cs-137	1.1×10^{-4}	0	2.6×10^{-6}
Ce-144	1.1×10^{-4}	0	2.6×10^{-6}
Other Fission Products	1.1×10^{-4}	0	2.6×10^{-6}
Liquids and Suspended Solids			
Non Radioactive: (MT/yr)			
NO_3^-	1.4×10^5	3.5×10^3	3.3×10^3
Al	1.0×10^3	24.7	23.7
Fl^-	9.5×10^2	23.4	22.5

TABLE 3.43 (Continued)

Effluent Category	Annual Release for Model Centrifuge Operation[(b)]	Release Per Annual Model Enrichment Requirement[(c)]	
		Option 1	Option 2
HNO_3	8.8×10^{4}	2.2×10^{3}	2.1×10^{3}
Al	8.4×10^{3}	2.1×10^{2}	2.0×10^{2}
TBP	2.1×10^{2}	5.18	4.97
Varsol	3.2×10^{2}	7.89	7.58
Phosphate	2.9×10^{3}	71.5	68.7
Cr	33.6	0.83	0.80
Zn	336	8.28	7.96
Radioactive: (Ci/yr)			
U-232	7.8×10^{-6}	0	1.8×10^{-7}
U-233	4.1×10^{-8}	0	9.7×10^{-10}
U-234	2.7×10^{-3}	0	6.4×10^{-5}
U-235	1.0×10^{-4}	0	2.4×10^{-6}
U-236	2.6×10^{-4}	0	6.2×10^{-6}
U-238	2.2×10^{-3}	0	5.2×10^{-5}
Pu-239	8.0×10^{-9}	0	1.9×10^{-10}
Np-237	4.0×10^{-6}	0	9.5×10^{-8}
Ru-106	9.3×10^{-2}	0	2.2×10^{-3}
Zr-95	2.0×10^{-2}	0	4.7×10^{-4}
Cs-137	1.5×10^{-3}	0	3.6×10^{-5}
Ce-144	1.5×10^{-3}	0	3.6×10^{-5}
Tc-99	7.0	0	0.17
Other Fission Products	1.5×10^{-3}	0	3.6×10^{-5}

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Statement, ERDA 1543, April 1976.

(b) Model plant is assumed to supply 8750 MTSWU/yr of enrichment capacity.

(c) The yearly requirement of a model LWR is assumed to be 215.7 MTSWU for Option 1 and 208 MTSWU for Option 2.

(d) Includes effluents from operation of coal-fired process steam plant.

3.4.14 Occupational and Public Hazards--Gas Centrifuge

At the present time, only limited information exists concerning possible occupational and public health hazards resulting from gas centrifuge construction and operation. Typically, these hazards are assumed to be similar to those from the gaseous diffusion plant, even though the effluents and construction requirements associated with such a facility are different. Therefore, the hazard data presented in Section 3.4.6 for the gaseous diffusion plant will be used as the basis for this analysis.

3.4.15 Transportation Requirements--Gas Centrifuge

Estimated transportation requirements for the model gas centrifuge plant during construction and operation have been developed and are shown in Table 3.44. Both rail and truck shipments were analyzed, with a combination of short (250-mile) and long (500-mile) hauls included for each transportation mode except for the UF_6 shipment distance of 750 miles. The transportation requirements were not broken down by fuel cycle (Option 1 or 2) because the differences were minimal.

Unlike enrichment by the gaseous diffusion facility, enrichment by the centrifuge facility will generate from failed machines large quantities of waste materials that is contaminated by low levels of uranium. Table 3.45 shows the quantities of waste materials requiring transportation to a disposal facility.

3.4.16 Decommissioning--Gas Centrifuge

After the model enrichment facility has achieved its design lifetime, it will be decommissioned. Since contamination is solely from uranium isotopes (Option 1), a delay before dismantlement is not useful in decreasing the activity levels because of the long uranium half-lives. In case of Option 2, decontamination is judged to be of minor effect because of the small ratio of recycled to natural UF_6 processed. No

TABLE 3.44

ESTIMATED TRANSPORTATION REQUIREMENTS DURING CONSTRUCTION AND OPERATION OF THE MODEL GAS CENTRIFUGE FACILITY

	Requirement Per Model Centrifuge Facility[b]				Annual Model LWR Enrichment Requirement[c,d]			
	Truck Activity		Rail Activity		Truck Activity		Rail Activity	
Activity[a]	(trucks/week)	(vehicle miles/yr)	(cars/week)	(rail miles/yr)	(trucks/week)	(vehicle miles/yr)	(cars/week)	(rail miles/yr)
Construction								
Initial construction period								
250-mile round trip	130	1.7×10^6	(e)	(e)	3.2	4.2×10^4	(e)	(e)
500-mile round trip	130	3.4×10^6	(e)	(e)	3.2	8.4×10^4	(e)	(e)
Final construction period								
250-mile round trip	140	1.8×10^6	75	1×10^6	3.5	4.4×10^4	1.9	2.5×10^4
500-mile round trip	140	3.6×10^6	75	2×10^6	3.5	8.8×10^4	1.9	5.0×10^4
Operation								
Centrifuge replacement components								
250-mile round trip	1	1.3×10^4	30	0.4×10^6	0.03	3.2×10^2	0.8	9.9×10^3
500-mile round trip	1	2.6×10^4	30	0.8×10^6	0.03	6.4×10^2	0.8	2.0×10^4
Shipment of UF^6								
750-mile round trip	78	3.36×10^6	(e)	(e)	2	3.4×10^4	(e)	(e)

(a) U.S. Energy Research and Development Administration, "Expansion of U.S. Uranium Enrichment Capacity," Final Environmental Impact Statement, ERDA 1543, April 1976.

(b) Enrichment capacity of the model plant is assumed to be 8,750 MTSWU/yr.

(c) The yearly requirement of a model LWR is assumed to be 215.8 MTSWU in the case of no uranium recycling (Option 1) and 208 MTSWU for the uranium recycle case (Option 2).

(d) Transportation requirements for no uranium recycling (Option 1) or uranium recycle (Option 2) are almost identical.

(e) No significant rail activity is expected.

TABLE 3.45

PREDICTED WASTE MATERIALS REQUIRING TRANSPORTATION
TO A DISPOSAL FACILITY

Material	Quantity (MT/year)
Steel	1287
Aluminum	940
Iron	3
Brass	16
Alnico V	48
Plastic	8
Rotor material	2200

specific information was found on decommissioning an enrichment facility; however, estimates were made using the following assumptions:

1. The outer 2 inches of typically 8-inch thick concrete walls and floor are removed to low-level burial.

2. All centrifuge, service module, vacuum systems and process piping and valves are removed to low-level burial.

These assumptions result in:

	Option 1	Option 2
Concrete, MT	107	103
Rotor material, MT	0.05	0.05
Steel, MT	144	139
Aluminum, MT	12	11.6
Iron, MT	0.4	0.4
Brass, MT	0.1	0.1

Decontamination energy requirements are assumed to be 1/400 of construction energy requirements; the required decontamination energy requirements are:

	Option 1	Option 2
Electricity, MWH	1.15	1.13
Fossil fuel, BTU	4.8×10^5	4.4×10^5

3.5 FUEL FABRICATION

Enriched UF_6 is transported to the fuel fabrication facilities where it is ultimately converted to UO_2 pellets which are stacked in a group of arrayed fuel rods, referred to as fuel assemblies.

3.5.1 General Description

Uranium hexafluoride, used for the model LWR; is enriched in U-235 to about 3 percent at the enrichment facility. UF_6 is converted to UO_2 primarily by the ammonium diuranate process at the fabrication facility. UO_2 powder is formed into pellets, sintered to achieve the desired density, and ground to final size. Finished pellets are stacked in the fuel rod cladding. A typical PWR assembly includes 289 fuel rods and contains about 460 kg of uranium. A BWR assembly contains 64 fuel rods and about 180 kg of uranium.

3.5.2 Model Description

Three steps are involved in the fuel fabrication process: (1) the conversion of UF_6 to UO_2; (2) the forming of pellets; and (3) the fabrication of fuel assemblies. These three steps may or may not be done at the same facility. Therefore, the model facility is a composite of facilities that perform the entire fabrication process and facilities that perform only part of the process. The analytical model developed in Chapter 6 includes the assumption that additional transportation can be neglected. The model facility used has a capacity of 900 MTU/yr and is assumed to produce 1040 MT of UO_2 in the form of fuel assemblies for LWRs. This facility is capable of providing approximately 23 times the annual requirement of the model LWR. The model facility lifetime is assumed to be 30 years.

3.5.3 Materials and Equipment Requirements

An estimate of fuel fabrication facility materials and major equipment requirements is shown in Tables 3.46 and 3.47. These tables also include normalized requirements based on annual model LWR

TABLE 3.46

CONSTRUCTION MATERIAL REQUIREMENT
(FUEL FABRICATION)

Material[a]	Model Facility Requirement	Annual Model LWR Requirement Option 1 or Option 2
Steel	9600 MT	13.9 MT
Copper	81 MT	.12 MT
Zinc	13.5 MT	.02 MT
Concrete	39700 MT	57.5 MT
Lumber	1065 MT	1.5 MT

(a) Based on an extrapolation from MOX facility construction material quantities included in U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. I, p. 3.2.41, May 1979.

TABLE 3.47

ESTIMATED EQUIPMENT REQUIREMENTS FOR MODEL FUEL FABRICATION FACILITY

Equipment[a]	No.[a]	Shipping Volume[a]	% Dense[b]	Total Mass (lb)
Calciners	3			75,000
Tanks	15	2 m^3	5	25,500
Cranes	2	4.5 m^3	70	107,000
Pumps	6	2 m^3	30	61,000
Blenders	4	2 m^3	50	68,000
Hammermills	2	1 m^3	50	17,000
Hoppers	2	2 m^3	5	3,400
Dissolvers	2	.25 m^3	10	848
Evaporators	2	2 m^3	20	13,600
Furnaces	4	12 m^3	20	162,000
Presses	4	2 m^3	50	68,000
Grinders	2	2 m^3	50	34,000
			Total	585,348 lb 266 MT
			Requirement per model LWR yr	.39 MT

(a)Based on extrapolation from equipment required for a reference MOX fabrication plant (uranium dioxide and pellet/rod formation portions only).

(b)Engineering judgement.

(c)Based on an extrapolation from MOX facility construction energy requirements, U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. I, p. 3.?.41, May 1979.

(d)Based on assumption of 6023 GWeY @ .8 capacity factor between 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

(e)U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle, Part I," EPA-520/9-73-003-B, p. 199, November 1973.

(f)U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, p. E-12, 1974.

requirements. Normalization is based on a projected 30-year lifetime for the fuel fabrication facility and on the fraction of the facility annual output consumed by the model LWR. Normalized process material requirements for the model fuel fabrication facility are shown in Table 3.48.

3.5.4 Energy Consumption

Fuel fabrication energy consumption, normalized to the model reactor facility annual fuel requirement, is presented in Table 3.49. Normalized values of electricity and fossil fuel consumption for the facility construction, materials production, and equipment fabrication and direct energy consumption in the facility operation are shown in the table.

3.5.5 Effluents

Fuel fabrication facility effluents associated with the production of the annual fuel requirements of the model LWR are shown in Table 3.50. Gaseous effluents associated with combustion of fossil fuels in the facility and with supplying the electricity to it are not included in the table, but will be dealt with in the analytical model. Failed equipment and waste generated by the facility are shown in Table 3.51.

3.5.6 Occupational and Public Hazards

Table 3.52 includes the estimated occupational hazards. These hazards are assumed to be identical to those of the conversion facility because no specific data sources were available. Accidents that might cause an offsite risk, their probability, and the population dose are given in Table 3.53. The radiological effluents from these accidents are listed in Tables 3.54 and 3.55. The radiological risks from normal operations and accidents are given in Table 3.56.

TABLE 3.48

PROCESS MATERIAL REQUIREMENTS FOR FUEL FABRICATION FACILITY

	Annual Model LWR Requirement
Zircalloy	29.5 MT

TABLE 3.49

FUEL FABRICATION ENERGY CONSUMPTION (CONSTRUCTION AND OPERATION)

Source	Annual Model LWR Requirement	
Construction[b]		
Material Energy:		
Electricity (MWH)	35.4[a]	
Fossil Fuel (Btu)	1.15×10^{9}[a]	
Direct Energy:		
Electricity (MWH)	1.6[a]	7.0[c]
Fossil Fuel (Btu)	0.35×10^{9}[a]	0.63×10^{9}[c]
Operation		
Direct Energy		
Electricity (MWH)	3850[a]	
Natural Gas (Btu)	8.4×10^{9}[a]	
Process Material Energy		
Electricity (MWH)	7800[a]	
Fossil Fuel (Btu)	9×10^{10}[a]	
TOTAL: Electricity	1718 MWH[d]	1700 MWH[e,f]
Fossil Fuel	4.3×10^{9} Btu[d]	3.7×10^{9} Btu[f]

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.

(b) Facility lifetime is assumed to be 30 years.

(c) Based on an extrapolation from MOX facility construction energy requirements from U.S. Department of Energy, "Technology for Commercial Radiation Waste Management," DOE/ET-0028, Vol. I, p. 3.2.41, May 1979.

(d) Based on assumption of 6023 GWeY @0.8 capacity factor between 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

(e) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle, Part I," EPA-520/9-73-003-B, p. 119, November 1973.

(f) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, p. E-12, April 1974.

TABLE 3.50

FUEL FABRICATION FACILITY EFFLUENTS
NORMAL EFFLUENTS--OPERATIONAL PHASE

Effluent[c]	Release Per Annual Model LWR Requirement
Gases and Suspended Particulates[d]	
Non Radioactive: (MT)	
F^-	0.0064[d]
Radioactive: (Ci)	
U	0.0002[a], 0.00023[d]
Liquids and Suspended Particulates (MT)	
Non Radioactive:	
NH_3	9.5[b], 0.015[d]
NO_3	5.9[b], 1.3[d]
F^-	4.3[b], 0.036[d]
Radioactive: (Ci/yr)	
U	0.022[a], 0.056[d]
Th-234	0.043[a], 0.006[d]
Solids	
Non Radioactive: (MT/yr)	
CaF_2	29.6[b]
Unspecified	31.1[d]
Radioactive: (Ci/yr, buried)	
U	0.25[b] (in CaF_2)

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Cycle, Part II," EPA-520/9-73-003-C, November 1973.

(b) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, April 1974.

(c) Effluent gases associated with generation of the facility electricity needs and combustion of fossil fuels are not included.

(d) Based on the assumption of 6023 GWey capacity @ 0.8 capacity factor between the years 1975 and 2000, U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

TABLE 3.51

FAILED EQUIPMENT AND WASTE GENERATED BY THE FUEL FABRICATION FACILITY

	Annual Volume	Annual Model LWR Requirement
Noncombustable Trash	30.8 MT[a]	1.34 MT
Failed Equipment	123 MT[a]	5.3 MT
Incinerator Ash	30.5 MT[a]	1.33 MT
Concentrated Liquids, Wet Wastes, and Particulate Solids		9.7 m^3[b]

[a] Based on extrapolation of waste disposal requirements, U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 2, May 1979.

[b] Based on an extrapolation from MOX facility requirements, U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. I, p. 3.2.5b, May 1979.

TABLE 3.52

FUEL FABRICATION FACILITY OCCUPATIONAL HAZARDS

	Health Effects[(a)]	
Hazard	Per MTU	Annual Model LWR Fabrication Requirement
Radiological	(b)	10.5 man-rem[(e)]
Non Radiological[(c)]		
Fatalities	1.8×10^{-6}	70.4×10^{-6}
Injuries	2.1×10^{-4}	82.2×10^{-4}
Man-Days Lost[(d)]	0.03	1.15

(a) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1225, December 1974.

(b) Not specified.

(c) Estimated rates are assumed to be the same as those for the conversion facility.

(d) 6000 man-days lost per fatality and 90 days lost per injury.

(e) Based on the assumption of 6023 GWeY capacity @0.8 capacity factor between the years 1975 and 2000. U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, Section F, Appendix A, August 1976.

TABLE 3.53

RADIOLOGICAL RISKS FROM ACCIDENTS IN URANIUM FUEL FABRICATION OPERATIONS

Accidents[a]	Probability $(plant\text{-}yr)^{-1}$	Pathway	Population Dose Per Annual Model LWR Requirement
Hydrogen Explosion in Reduction Furnace	$2x10^{-3}$ to $5x10^{-2}$	inhalation/ ingestion	$1.3x10^{-6}$ to $3.2x10^{-2}$(lung) $6.0x10^{-9}$ to $1.5x10^{-4}$(w.b.)
Major Fire	$2x10^{-4}$	inhalation/ ingestion	$1.3x10^{-4}$ to $1.3x10^{-1}$(lung) $6x10^{-7}$ to $6x10^{-4}$(w.b.)
Fire in a Roughing Filter	$1x10^{-2}$	inhalation/ ingestion	$1.5x10^{-6}$ to $1.5x10^{-3}$(lung) $7.2x10^{-9}$ to $7.2x10^{-6}$(w.b.)
Release from a Hot UF_6 Cylinder	$3x10^{-2}$	inhalation/ ingestion	$1.9x10^{-3}$ to 1.9(lung) $9.2x10^{-6}$ to $9.2x10^{-3}$(w.b.)
Failure of Values or Piping	$4x10^{-3}$	inhalation/ ingestion	$7.2x10^{-5}$ to $7.2x10^{-2}$(lung) $3.5x10^{-7}$ to $3.5x10^{-4}$(w.b.)
Criticality	$8x10^{-4}$	inhalation/ ingestion	$1x10^{-3}$(Thyroid) $3.5x10^{-5}$(w.b.)
Waste Retention Pond Failure	$2x10^{-3}$ to $2x10^{-2}$	ingestion	$4.4x10^{-5}$ to $4.4x10^{-4}$(bone) $2.8x10^{-6}$ to $2.8x10^{-5}$(w.b.)

[a] U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.54

RADIOLOGICAL EFFLUENTS FROM POSTULATED ACCIDENTS IN URANIUM FUEL FABRICATION OPERATIONS

	Radionuclides Released (Ci)[(a)]						
Postulated Accident	U-238	U-237	U-236	U-235	U-234	Th-234	Pa-234
Hydrogen Explosion in Reduction Furnace	3.2×10^{-7} to 3.2×10^{-4}	3.7×10^{-7} to 3.7×10^{-4}	7.1×10^{-8} to 7.1×10^{-5}	5.6×10^{-8} to 5.6×10^{-5}	2.3×10^{-6} to 2.3×10^{-3}		
Major Facility Fire	3.2×10^{-4} to 3.2×10^{-1}	3.7×10^{-4} to 3.7×10^{-1}	7.1×10^{-5} to 7.1×10^{-2}	5.6×10^{-5} to 5.6×10^{-2}	2.3×10^{-3} to 2.3		
Fire in Roughing Filter	8.1×10^{-8} to 8.1×10^{-5}	9.3×10^{-8} to 9.3×10^{-5}	1.8×10^{-8} to 1.8×10^{-5}	5.7×10^{-7} to 5.7×10^{-4}	5.7×10^{-7} to 5.7×10^{-4}		
Release From a Hot UF_6 Cylinder	3.5×10^{-5} to 3.5×10^{-2}	4.0×10^{-5} to 4.0×10^{-2}	7.7×10^{-6} to 7.7×10^{-3}	6.0×10^{-6} to 6.0×10^{-3}	2.4×10^{-4} to 2.4×10^{-2}		
Failure of Valves or Piping	9.7×10^{-6} to 9.7×10^{-3}	1.1×10^{-5} to 1.1×10^{-2}	2.1×10^{-6} to 2.1×10^{-3}	1.7×10^{-6} to 1.7×10^{-3}	6.8×10^{-5} to 6.8×10^{-2}		
Waste Retention Pond Failure	2.4×10^{-2}	2.8×10^{-2}	5.4×10^{-3}	4.2×10^{-3}	1.7×10^{-1}	2.4×10^{-2}	2.4×10^{-2}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.55

RADIONUCLIDE RELEASE RESULTING FROM A CRITICALITY INCIDENT AT THE URANIUM FUEL FABRICATION FACILITY

Nuclide	Activity Released[a] (Ci)	Nuclide	Activity Released[a] (Ci)
Br 80	1.2×10^{-1}	I 136	2.3×10^{1}
Br 80m	5.7×10^{-5}	I 137	3.3×10^{-4}
Br 82	1.9×10^{-5}	Xe 133	1.7×10^{-3}
Br 82m	3.2×10^{-3}	Xe 133m	9.9×10^{-5}
Br 83	3.5	Xe 135	2.2
Br 84	3.5×10^{1}	Xe 135m	4.7
Br 84m	1.5	Xe 137	9.0×10^{2}
Br 85	7.2×10^{1}	Xe 138	7.0×10^{2}
Br 86	1.5	Xe 139	1.5
Br 87	2.1	Xe 140	2.2×10^{-7}
Kr 83m	3.4×10^{-1}	Th 231	2.0×10^{-8} to 2.0×10^{-11}
Kr 85	3.2×10^{-5}	Th 234	2.2×10^{-9} to 2.2×10^{-12}
Kr 85m	1.3×10^{1}	Pa 234m	1.8×10^{-9} to 1.8×10^{-12}
Kr 87	9.4×10^{1}	U 233	1.7×10^{-15} to 1.7×10^{-18}
Kr 88	6.3×10^{1}	U 234	3.4×10^{-13} to 3.4×10^{-16}
Kr 89	5.2×10^{2}	U 235	4.5×10^{-6} to 4.5×10^{-9}
Kr 90	9.2×10^{-2}	U 236	1.3×10^{-11} to 1.3×10^{-14}
I 128	1.4×10^{-3}	U 237	7.1×10^{-5} to 7.1×10^{-8}
I 130	1.0×10^{-3}	U 238	1.1×10^{-5} to 1.1×10^{-8}
I 131	5.5×10^{-2}	U 239	6.1 to 6.1×10^{-3}
I 132	1.6	Np 237	4.4×10^{-16} to 4.4×10^{-19}
I 133	1.5	Np 239	1.5×10^{-2} to 1.5×10^{-5}
I 134	5.2×10^{1}	Np 240	3.5×10^{-11} to 3.5×10^{-14}
I 135	2.3×10^{1}	Pu 239	4.1×10^{-12} to 4.1×10^{-15}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risks Associated with Accidents in the LWR Supporting Fuel Cycle," EPA 600/5-78-013, June 1978.

TABLE 3.56

COMPARISON BETWEEN RADIOLOGICAL HEALTH RISKS FROM ACCIDENTS AND NORMAL OPERATIONS IN URANIUM FUEL FABRICATION OPERATIONS

Risk From Normal Operation[a]		Risk From Accidents[a]	
Pop. Dose Per Annual Model LWR Requirements (man-rem)	Health Risk Per Annual Model LWR Requirements (# of excess cancers)	Pop. Dose Per Annual Model LWR Requirements (man-rem)	Health Risk Per Annual Model LWR Requirements (# of excess cancers)
1.3(lung) 6.2×10^{-3}(W.B.)	5.4×10^{-5}	2.1(lung) 1×10^{-3}(thyroid) 4.4×10^{-5} to 4.4×10^{-4}(bone) 1×10^{-2}(W.B.)	1.6×10^{-7} to 8.9×10^{-5}

[a] U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

3.5.7 Transportation Requirements

Fresh fuel usually is shipped by truck, with each shipment containing 12 PWR fuel assemblies or 32 BWR fuel assemblies. (Appendix I.4 discusses the generic package assumed for the composite model.) The model LWR is based on an annual requirement of 47 PWR fuel assemblies and 81 BWR fuel assemblies; therefore, the number of shipments per year is about 4 per PWR and 2-1/2 per BWR. Assuming 1000 miles between facilities, about 13,000 round-trip truck-miles are required. Low-level waste shipments are discussed in Section 3.9.

3.5.8 Decommissioning

After the model fuel fabrication facility has achieved its design lifetime, it is assumed to be decommissioned. Decommissioning can be performed in several ways: (1) the facility can be decommissioned immediately following shutdown or (2) the facility can be placed in several modes of storage and decommissioned at a later date when some of the radioactivity has decayed. For a facility solely contaminated with uranium, such a delay is not useful in decreasing the in-facility activity levels because of the long uranium half-life. The decommissioning mode chosen for the model facility is, therefore, immediate decommissioning at the end of the design life. Table 3.57 identifies estimated decommissioning energy requirements and transportation requirements. The occupational hazards associated with the decommissioning operations of the model fuel fabrication facility are presented in Table 3.58.

TABLE 3.57

DECOMMISSIONING REQUIREMENTS FOR A REFERENCE FUEL FABRICATION FACILITY

	Total Requirement	Annual Model LWR Requirement
Materials:		
Steel	675 MT[a]	.98 MT
Equipment	150 MT[a]	.28 MT
Energy:		
Electricity	10 MWH[a]	01 MWH
Waste Disposal Requirement	700 MT[b]	1.0 MT

[a] Based on extrapolation of waste disposal requirements, U.S. Nuclear Regulatory Commission, "Technology, Safety, and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant," NUREG/CR-0129, Vol. 1, February 1979.

[b] Based on extrapolation from MOX facility decommissioning requirements, U.S. Department of Energy, "Management of Commercially Generated Radioactive Waste," DOE/EIS-0046-D, Vol. 2, p. 0-10, April 1979.

TABLE 3.58

OCCUPATIONAL HAZARDS FOR DECOMMISSIONING A REFERENCE FUEL FABRICATION FACILITY

	Total	Annual Model LWR Fuel Requirement
Transportation Accidents		
Injuries	1.0[a]	1.4×10^{-3}
Fatalities	.066[a]	9.5×10^{-5}
Decommissioning Operation Accidents		
Injuries	2.0[a]	2.9×10^{-3}
Fatalities	.014[a]	2.0×10^{-5}
Radiological Exposure	76 man-rem[b]	.11 man-rem

[a] Based on extrapolation from MOX facility decommissioning requirements, U.S. Nuclear Regulatory Commission, "Technology, Safety, and Costs of Decommissioning a Reference Small Mixed Oxide Fuel Fabrication Plant," NUREG/CR-0129, Vol. I, pp. 11-28, February 1979.

[b] Assuming exposure for the large UO_2 facility is equal to worker exposure during decommissioning of a small MOX fabrication facility.

3.6 NUCLEAR POWER PLANT (LWR)

The fuel cycle stages that have been described provide uranium fuel for electrical power production at the nuclear power plant. The LWR utilizes energy released during the U-235 fission process to heat the coolant. This heated coolant is used to produce steam for electrical production by steam turbine generators.

3.6.1 General Description

Present-day nuclear power generators in the U.S. primarily include two types of light-water cooled reactors: (1) the pressurized water reactor (PWR) and (2) the boiling water reactor (BWR). In the PWR, the coolant is maintained at a high pressure (~2250 psi) to inhibit boiling. Steam for turbine electrical generation is produced by allowing the heated primary coolant to transfer heat to a secondary coolant within the confines of a steam generator. The secondary coolant is kept at a lower pressure, such that boiling can occur in the steam generator, producing steam for subsequent turbine operation. The BWR operates on a direct cycle where the process steam is generated directly in the reactor vessel, utilizing low-pressure coolant. The steam generated in the reactor vessel is separated from excess moisture and passes directly to the steam turbines.

In either reactor type, the steam typically enters a three-stage turbine consisting of both high- and low-pressure stages. Turbines drive electric generators, producing electricity for delivery to the utility grid for distribution.

3.6.2 Model Description

At the present time, PWRs comprise about two-thirds of the light-water generating capacity committed through 1982. This trend is assumed to continue through the year 2000. Therefore, for the purposes of this study, the model LWR facility is assumed to be a composite model representing a 2:1 ratio of PWRs to BWRs. This PWR to BWR ratio has been employed to determine the requirements for LWR construction materials, amount of energy consumed, quantities of effluents released, and occupational and public health effects, as described in the following sections.

In addition to these LWR model requirements, other model parameters utilized were: (1) power level of 1000 MWe, (2) capacity factor of 75 percent, (3) plant lifetime of 30 years, and (4) utilization of either nonrecycled fuel (Option 1) or a mixture of nonrecycled and recycled uranium fuel (Option 2). The resulting LWR model reactor produces 750 GWe-yr annually.

3.6.3 Materials and Equipment Requirements

Quantities of basic construction materials required for a 1000-MWe power plant have been estimated and are presented in Table 3.59.

3.6.4 Energy Requirements

Energy consumption during model LWR construction, operation, and decommissioning has been estimated, including consumption of petroleum products and direct use of electrical power. The requirements during construction and operation are listed in Table 3.60. Energy consumption during construction has been averaged over the assumed lifetime of the plant and appears as an annual commitment. The estimated energy requirement during decommissioning of the model facility is presented in Table 3.61, based on either complete dismantlement of the station or preparation of the facility for safe storage, with no consideration given to energy consumed in deferred dismantlement. The energy expenditure would be spread over approximately 4 years for the complete dismantlement procedure or 16 months during preparation for safe storage.

TABLE 3.59

ESTIMATED QUANTITIES OF BASIC CONSTRUCTION MATERIALS IN THE MODEL LWR

	Estimated Quantity (MT)		
Material	PWR	BWR	Model LWR[e]
Aluminum	18-45[a,f]	45-54[d,c]	40
Asbestos	90-138[b,a]	45-90[d,b]	100
Cadmium	<1[a,f]	<1[d]	<1
Chromium	150-415[f,a]	110-150[c,d]	230
Concrete	1.7×10^5	1.9×10^5[c]	1.8×10^5
Copper	726-2000[a,f]	907-2000[c,d]	1390
Lead	7.5-47[f,a]	7.5[d]	20
Magnesium	783	520[b]	695
Manganese	400-467[f,a]	209-400[c,d]	390
Molybdenum	2.5-164[f,a]	2.5-128[d,a]	80
Nickel	100-484[f,a]	49-100[c,d]	220
Silver	<1[f,a]	1[d]	<1
Steel	$(1-5.4 \times 10^4$[f,g]	1.0×10^4[d]	1.9×10^4
Tin	0.05-2[f,a]	0.05[d]	0.7
Zinc	2-100[a,f]	100[d]	70

(a) R. H. Bryan and I. T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MWe PWR Power Plant," ORNL-TM-4515, June 1974.

(b) Federal Energy Administration, "Project Independence Blueprint Task Force Report/Nuclear Energy," Final Task Force Report, 1974.

(c) J. P. Albers, et al., "Demand and Supply of Non-Fuel Minerals and Materials for the United States Energy Industry, 1975-90," USGS Professional Paper 1006-A, 1976.

(d) U.S. Nuclear Regulatory Commission, "Phipps Bend Nuclear Plant Units 1 and 2, Proposed by the Tennessee Valley Authority," Final Environmental Statement, NUREG-0168, February 1977.

(e) Quantities based on a 2:1 ratio of PWR to BWR requirements. For a range of values, the average was utilized. Values were rounded and represent a 30-year lifetime of the plant.

(f) U.S. Nuclear Regulatory Commission, "Yellow Creek Nuclear Plant Units 1 and 2, Proposed by the Tennessee Valley Authority," Final Environmental Statement, November 1977.

(g) U. S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 1, May 1979.

TABLE 3.60

ANNUAL ENERGY REQUIREMENT FOR THE MODEL NUCLEAR POWER PLANT
(CONSTRUCTION AND OPERATION)

	Annual Requirement[a]					
	PWR (1000-MWe)		BWR (1000-MWe)		Model[c]	
Activity	10^6 BTU	MWH	10^6 BTU	MWH	10^6 BTU	MWH
Construction[b]						
Construction Materials	257,467	6,543	258,567	6,383	257,833	6,490
Direct Energy	61,933	288	58,467	272	60,778	283
Operation						
Auxiliary Diesel Fuel	12,607	---	12,607	---	12,607	---
Process Materials	272,635	8,557	272,635	8,551	272,635	8,551
Total Annual Energy Requirements	604,642	15,382	602,276	15,206	603,853	15,324

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.
(b) Construction energy requirements have been amortized over an assumed 30-year plant lifetime.
(c) Model consists of 2/3 PWR and 1/3 PWR reactor characteristics.

TABLE 3.61

ESTIMATED ENERGY CONSUMPTION DURING FACILITY DECOMMISSIONING

Decommissioning Sequence	Petroleum Products[a] ($\times 10^6$ BTU)	Electrical Power (MWH)
Immediate Dismantlement	1.4×10^6	2.33×10^5[b]
Safe Storage and Subsequent Dismantlement	1.4×10^6	2.3×10^5[c]

[a] Estimates based on construction requirements for model LWR. Assumed decommissioning by immediate dismantlement would require 75 percent of the construction requirement, and preparation for safe storage would require one percent of that amount, Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.

[b] U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," NUREG/CR-0130, Vol.1, pp 10-11, 10-19, June 1978.

[c] Based on the assumption that safe storage plus subsequent dismantlement will require essentially the same amount of energy as immediate dismantlement.

3.6.5 Effluents

Radioactive and nonradioactive effluents for a model LWR operating on the uranium fuel cycle are presented in Table 3.62. Also, an estimated breakdown of the nonradiological and radiological effluents from model LWR operation and decommissioning are presented in Tables 3.62, 3.63, and 3.64. Normal operational LWR effluents are composed of (1) gaseous releases from oil or diesel support systems and radioactive off-gas treatment systems; (2) liquid effluents from application of chemical treatment systems and liquid radwaste operations; and (3) radioactive solid wastes from application of solid radwaste operations and nonradioactive domestic waste operations. Effluents from cooling towers are negligible in comparison to other liquid discharges and will not be considered here.

Only nonradiological effluents are generated during construction. These effluents are composed primarily of liquid effluents from construction facilities and preoperational chemical cleaning operations; (1) solid effluents from clearing and demolition/construction wastes, (2) domestic wastes, and potentially hazardous wastes, and (3) gaseous effluents composed of dust and smoke from equipment operations and burning. These effluents are controlled by various regulations and/or permits and are considered to be minimal in comparison with effluents from operation and decommissioning. Noise can also be considered as primarily a construction effluent and originates from blasting and operation of heavy construction equipment. Noise effluents are also considered minimal.*

Effluents arising from decommissioning activities consist primarily of radioactive particulate releases during demolition and large volumes

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*U.S. Nuclear Regulatory Commission, "Final Environmental Statement for the Phipps Bend Nuclear Plant. Units 1 and 2," NUREG-0168, February 1977, "Final Environmental Statement for the Hartsville Nuclear Plants," NUREG-75/039, June 1975.

TABLE 3.62

LWR NORMAL EFFLUENTS--OPERATIONAL PHASE

	Release Per Annual Model LWR Requirement[a]		
Effluent Category	BWR	PWR	Model LWR
Airborne Gases and Particulates			
Non Radioactive: (MT/yr)[b]			
SO_x			150
NO_x			180
Hydrocarbons			4
CO			4
Particulates			13
Radioactive: (Ci/yr)[c]			
H-3	40	1031	703
Kr-85	272	441	384
Xe-133	3000	1.1×10^4	8531
Other Noble Gases	3563	497	1500
I-131	0.28	0.023	0.11
I-133	1.0	0.022	0.36
Particulates	0.23	0.056	0.11
C-14	8.9	7.5	8.0
Liquids and Suspended Solids			
Non Radioactive: (MT/yr)[d]			
$SO_4^=$	35	82	66
CL^-	40	28	32
Na^+	38	51	47
Radioactive: (Ci/yr)[c]			
Sr-90	9.4×10^{-6}	7.5×10^{-5}	5.3×10^{-5}
Cs-134	0.012	0.023	0.020

TABLE 3.62 (Continued)

Effluent Category	Release Per Annual Model LWR Requirement		
	BWR	PWR	Model LWR
CS-137	0.023	0.031	0.028
I-131	0.21	0.049	0.113
H-3	40	225	163
Other Fission Products	0.0028	0.084	0.057
Corrosion and Activation Products	0.021	0.014	0.016
Solids			
Non Radioactive: (m^3/yr)	260	260	260
Radioactive: (m^3/yr)[e]	430	360	385

[a]Unless otherwise noted, data were obtained from U.S. Nuclear Regulatory Commission, "Final Generic Environmental Impact Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," (GESMO), NUREG-0002, Vols. 3 and 4, August 1976. Data were modified to represent model reactor parameters. Only model LWR data given.

[b]Primarily effluents from oil or diesel support systems.

[c]Data for uranium fueled reactor.

[d]U.S. Nuclear Regulatory Commission, "Phipps Bend Nuclear Plant, Units 1 and 2, Proposed by the Tennessee Valley Authority," Final Environmental Statement, NUREG-0168, February 1977, and "Watts Bar Nuclear Plant, Units 1 and 2, Proposed by the Tennessee Valley Authority," Final Environmental Statement, NUREG-0352, June 1978.

[e]Low-level waste arising from radwaste treatment system. U.S. Energy Research and Development Administraton, "Alternatives for Managing Wastes from Reactors and Post-Fission Operations in the LWR Fuel Cycle," ERDA-76-43, Vol. 1, pp. 2.22-2.25, May 1976.

TABLE 3.63

ANTICIPATED AIRBORNE RADIOACTIVE RELEASES DURING ROUTINE PWR DECOMMISSIONING OPERATIONS

	Estimated Atmospheric Radioactive Release (μCi)[a,b]	
Operation	Immediate Dismantlement	Preparation for Safe Storage
Segmenting of Nonactivated Stainless Steel	75.4	---
Segmenting of Activated Reactor Vessel and Internals	0.7	---
Waste Handling of Bioshield Concrete	1.75	---
Surface Cleaning Operations	5.3	1.0
Final Chemical Decontamination	0.8	0.04
In Situ Chemical Decontamination	0.7	---
Removal of Bioshield	5×10^{-3}	---
Removal of Concrete	1×10^{-5}	---
Fixing Residual Contamination	---	15

(a) U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," NUREG/CR-0130, Vol. 2, Appendix J, p. J-5, June 1978.

(b) Total releases for the entire activity. For the immediate dismantlement procedure these activities are spread over approximately four years. Identification of individual radionuclides is highly dependent upon activity. Exposure calculations based on these releases have taken into account the detailed radionuclide breakdowns.

TABLE 3.64

SUMMARY OF MATERIAL VOLUMES FOR DISPOSAL FROM REFERENCE PWR DECOMMISSIONING

Material Category[a]	Disposal Volume (m^3)	Number of Shipments	Shipment Type
Activated:		216	Truck
Metal	484		
Concrete	707		
Contaminated:		1,147	Truck
Metal and Miscellaneous	5,465		
Concrete	10,613		
Radioactive Wastes	618	180	Truck
TOTAL	17,887	1,543	

[a] U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," NUREG/CR-0130, Vol. 2, Appendix G, p. G-26, June 1978.

of activated or contaminated materials requiring disposal. These releases have been estimated from data on the decommissioning of a reference PWR.

3.6.6 Occupational and Public Hazards

Occupational and public health hazards associated with construction, operation, and decommissioning have been estimated based on industry data. Estimated occupational lost-time injuries and fatalities from LWR construction are presented in Table 3.65. Table 3.66 presents similar estimates for decommissioning operations for a PWR, and these are assumed to be applicable to a BWR also. Operation of the model LWR is estimated to produce occupational and public hazards (specifically, injuries, disabilities, or premature death) of a magnitude identified in Table 3.67. Estimates of radiation exposure to workers and to the general public during normal operation are listed in Tables 3.68, and 3.69. Occupational exposure during LWR operation was determined from actual reactor data whereas population exposure during operation was based on a dose modeling effort. The calculated radiation exposures from decommissioning activities are based on assumed operations performed on a model PWR. The calculations are based on release mechanism estimates and modeling efforts because industrial experience with the decommissioning of major facilities is almost nonexistent.

Postulated accidents that might occur during operation of the reference LWR and their radiological consequences must also be considered. These accidents have been divided into nine classes, ranging in severity from trivial to very serious. In general, accidents in the high potential consequence end of the spectrum have a low likelihood of occurrence, and those with low potential consequence have a higher likelihood.

The first eight classes of accidents considered all result in exposures to an assumed individual at the site boundary that are less

TABLE 3.65

ESTIMATED OCCUPATIONAL LOST-TIME INJURIES AND FATALITIES FROM MODEL LWR CONSTRUCTION

	Heavy[a] Construction	Light[a] Construction	Operational[a] Support	Total
Frequency of Accidents/ 10^6 man-hours				
Fatalities	4.2×10^{-2}	3.0×10^{-2}	2.3×10^{-2}	
Lost-time injuries	10.0	5.4	2.1	
Model LWR Construction				
Fatalities:[b]				
Number	8.0×10^{-2}	1.6×10^{-1}	2.8×10^{-2}	2.7×10^{-1}
Man-days lost	480	960	168	1608
Lost-Time Injuries:[b]				
Number	19	29	3	51
Man-days lost	950	1450	150	2250
man-hours[c]	1.9×10^6	5.3×10^6	1.2×10^6	8.4×10^6

(a) U.S. Atomic Energy Commission, "Operational Accidents and Radiation Exposures Experienced within the U.S.A.E.C. 1943-1970," WASH-1192, 1971.

(b) Assumes 50 man-days lost per injury and 6000 man-days per fatality.

(c) Estimated construction requirement based on manpower estimates for the Washington Public Power Supply System's Units 3 and 5. Assumed 8-hour shift/man, 250 workdays/yr. Community Development Services, Inc., "An Analysis of the Socioeconomic Impacts of WNP-3 and WNP-5," Washington Public Power Supply System, Seattle, Washington, October 1975.

TABLE 3.66

ESTIMATED OCCUPATIONAL LOST-TIME INJURIES AND FATALITIES FROM DECOMMISSIONING OPERATIONS FOR A REFERENCE PWR

	Heavy[a] Construction	Light[a] Construction	Operational[a] Support	Total
Frequency of Accidents/ 10^6 Man-hours				
Fatalities	4.2×10^{-2}	3.0×10^{-2}	2.3×10^{-2}	9.5×10^{-2}
Lost-time injuries	10.0	5.4	2.1	17.5
Immediate or Deferred Dismantlement				
Fatalities	6.7×10^{-3}	1.0×10^{-2}	6.4×10^{-3}	2.3×10^{-2}
Lost-time injuries[b]	1.6	1.8	0.59	4.0
Man-hours	1.6×10^5	3.4×10^5	2.8×10^5	7.8×10^5
Preparation for Safe Storage				
Fatalities	---	3.6×10^{-3}	2.3×10^{-3}	5.9×10^{-3}
Lost-time injuries	---	6.5×10^{-1}	2.1×10^{-1}	8.6×10^{-1}
Man-hours	---	1.2×10^5	1.0×10^5	2.2×10^5

(a) U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station, NUREG/CR-0130, Vol. 1, pp. 11-23, June 1978.

(b) As defined by the American National Standards Institute, Methods of Recording and Measuring Work Injury Experience, ANSI 216.1, 1967.

TABLE 3.67

OCCUPATIONAL AND PUBLIC HAZARDS FROM ANNUAL OPERATION OF THE MODEL LWR

	Occupational Injuries/ Personal Disability[a]	Premature Death[a-f]
Occupational:[g]		
Accident	1.2-1.3[c,d,e,f]	0.010-0.013
Disease	0.05-0.17[d]	0.024-0.057
General Public:		
Disease	0.0005-0.02[d]	0.008-0.17

[a] Includes normal operations and postulated accidents.

[b] Equivalent to 6000 man-days lost.

[c] C. C. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy, Vol. 1, pp. 581-599, 1976.

[d] U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, August 1973.

[e] U.S. Nuclear Regulatory Commission, "Health Effects Attributable to Coal and Nuclear Fuel Cycle Alternatives," NUREG-0332, September 1977.

[f] H. Inhaber, "Risk of Energy Production," Canadian Atomic Energy Control Board, AECB 1119, March 1978.

TABLE 3.68

AVERAGE ANNUAL OCCUPATIONAL RADIATION EXPOSURE RATES AT U.S. LWRs

Year	Number of Reactors	Yearly Average[a] man-rem/GWe-yr
1969	7	1100
1970	9	1700
1971	11	1200
1972	17	1200
1973	23	1800
1974	32	1300
1975	44	1100
1976	53	1200
Average Exposure		1325

[a] L. A. Johnson, "Occupational Radiation Exposure at Light-Water Cooled Power Reactors 1976," NUREG-0323, March 1978.

TABLE 3.69

CALCULATED ANNUAL POPULATION DOSE FROM OPERATION OF THE MODEL LWR

Source	Dose (person-rem/yr)[a]							
	Total Body	GI Tract	Bone	Liver	Kidney	Thyroid	Lung	Skin
BWR								
Tritium	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Radiocarbon	81.0	81.0	40.5	81.0	81.0	81.0	81.0	81.0
Radioiodine	0.12	0.12	0.034	0.034	0.034	43.0	0.047	0.034
Krypton-85	0.076	0.076	0.076	0.076	0.076	0.076	0.164	0.076
Other Noble Gases	1.26	1.26	1.26	1.26	1.26	1.26	1.33	3.06
Other Gaseous Releases	10.3	11.2	21.9	10.7	9.94	9.56	9.84	9.56
Liquid Releases	1.44	1.04	0.66	1.87	1.27	41.9	1.05	---
Total	94.64	95.14	64.87	95.38	94.02	177.2	93.87	94.17
PWR								
Tritium	11.34	11.34	11.34	11.34	11.34	11.34	11.34	11.34
Radiocarbon	72.0	72.0	36.0	72.0	72.0	72.0	72.0	72.0
Radioiodine	9.36×10^{-3}	7.35×10^{-3}	2.25×10^{-3}	2.25×10^{-3}	2.25×10^{-3}	3.50	3.02×10^{-3}	2.25×10^{-3}
Krypton-85	0.123	0.123	0.123	0.123	0.123	0.123	0.266	10.4

TABLE 3.69 (Continued)

Source	Dose (person-rem/yr)							
	Total Body	GI Tract	Bone	Liver	Kidney	Thyroid	Lung	Skin
Other Noble Gases	3.64	3.64	3.64	3.64	3.64	3.64	3.76	8.67
Other Gaseous Releases	4.51	4.46	6.86	5.09	4.39	4.05	4.21	4.05
Liquid Releases	4.83	4.39	0.676	5.32	4.35	8.48	4.42	---
Total	96.45	95.96	58.64	97.52	95.84	103.13	96.00	106.5
Model LWR								
Total	95.85	95.69	60.72	96.81	95.23	127.82	95.29	102.39

[a] U.S. Nuclear Regulatory Commission, adapted from "Final Generic Environmental Impact Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," (GESMO), NUREG-0002, Vol. 3, p. IV C-122-126, August 1976. Data modified to represent model reactor parameters. Population doses were estimated using "average" population densities higher than actual population densities.

than those resulting from a 1-year exposure to the maximum permissible concentration given by 10CFR Part 20. Accidents in Class 9 involve sequences of postulated failures more severe than those postulated for the design basis for protective systems and engineering safety features.

Analyses of Class 9 accidents formerly were excluded from environmental impact reports because of their estimated low occurrence rates. Recently, a number of studies included Class 9 accidents in their analyses.* The Reactor Safety Study, WASH-1400 (RSS), identified nine release categories for PWR accidents and five categories for BWR. The first seven PWR categories and the first four BWR categories include core melt. These are assumed to be typical of Class 9 accidents. Using the fractional quantities of the various nuclides estimated to be released in each category, their relative contribution to the whole-body dose, and the probability of occurrence per reactor year for each category, the radiological impact is about 800 person-rems. Alternatively, under the assumption that the probability of core melt per year is less than 9×10^{-5},* and the radiological consequences are $2 \times 10^{6} - 10^{7}$ person-rems, the annual radiological impact is estimated to be 180 - 900 person-rems. These estimates are based on a uniform population density of 400 people per square mile around the model LWR. The associated mortality rate is estimated to be less than 0.12 per year for the model plant. However,

*U.S. Nuclear Regulatory Commission, "An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants," (Reactor Safety Study) Main Report WASH-1400, October 1975.

U.S. Nuclear Regulatory Commission, "Revised Draft Environmental Statement by the Office of Nuclear Reactor Regulation, Related to the Proposed Manufacture of Floating Nuclear Power Plants and Offshore Power Systems," NUREG-0127, Revision 1, May 1978.

Federal Ministry of Research and Technology, "The German Risk Study," August 1979.

in view of the Lewis Committee** critique of WASH-1400 methodology and because of the approximate nature of these calculations, these estimates and others of similar nature will only be used to compare the health impact of the two cycles under investigation.

A description of the eight classes of accidents for a reference PWR and BWR are given in Table 3.70. A summary of the radiological consequences of these postulated accidents for a specific BWR and PWR plant are presented in Table 3.71. The data for the BWR are taken from the Federal Environmental Impact Statement for the Phipps Bend Nuclear Plant and from the Federal Environmental Impact Statement for the Watts Bar Nuclear Plant, which is a PWR.

3.6.7 Transportation Requirements

The estimated transportation requirements during operation and decommissioning of the model LWR are presented in Table 3.72. These requirements include shipments of spent fuel from the reactor annually during plant operation and disposal of waste volumes from reactor decommissioning. Low-level waste shipments during reactor operation are discussed in Section 3.9. These round-trip requirements total 3×10^6 truck miles and 5×10^4 rail miles over the assumed 34 years of operation and decommissioning activities.

3.6.8 Decommissioning

The model LWR facility is assumed to be decommissioned after it has achieved its design lifetime. Decommissioning can be performed in several ways: (1) the facility can be decontaminated and decommissioned immediately following shutdown or (2) the facility can be placed in either a protective storage mode or a layaway mode and

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**H.S. Lewis et al., "Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission," NUREG/CR-0400, September 1978.

TABLE 3.70

CLASSIFICATION OF POSTULATED ACCIDENTS AND OCCURRENCES

Class	NRC Description	Examples[(a)] PWR	BWR
1.	Trivial incidents	Evaluated under routine releases.	Evaluated under routine releases.
2.	Small releases outside containment	Evaluated under routine releases.	Evaluated under routine releases.
3.	Radioactive waste system failure.	Leakage from waste gas tank, radwaste secondary tank leakage, release of waste gas tank contents, and release of radwaste secondary tank contents.	Equipment leakage or malfunction, release of waste gas storage tank contents, release of liquid waste storage tank contents.
4.	Fission products to primary system (BWR)	Not applicable.	Fuel cladding defects, off-design transients that induce fuel failures above those expected.
5.	Fission products to primary and secondary systems (PWR)	Off-design transients that induce fuel failure above those expected with steam generator tube leak and steam generator tube rupture.	Not applicable.
6.	Refueling accident	Fuel assembly drop and heavy object drop onto fuel in core.	Fuel bundle drop, heavy object drop onto fuel in core.
7.	Spent fuel handling accident	Fuel assembly drop in fuel storage pool, heavy object drop onto fuel rack, and fuel cask drop.	Fuel assembly drop in fuel storage pool, heavy object drop onto fuel rack, fuel cask drop.
8.	Accident initiation events considered in design basis evaluation	Reactor coolant system pipe breaks, rod ejection accident, and steam line breaks outside containment.	Small and large coolant pipe break, instrument line break, control rod drop accident, small and large steamline break.
9.	Hypothetical sequence of failures more severe than Class 8.	Not evaluated.	Not evaluated.

(a) U.S. Nuclear Regulatory Commission, "Final Environmental Statement, Phipps Bend Nuclear Plant, Units 1 and 2, Proposed by the Tennessee Valley Authority," NUREG-0168, February 1977. "Draft Environmental Statement, Watts Bar Nuclear Plant, Units 1 and 2, Proposed by the Tennessee Valley Authority," NUREG-0352, June 1978.

TABLE 3.71

SUMMARY OF RADIOLOGICAL CONSEQUENCES OF POSTULATED ACCIDENTS

Class	Event[a]	Estimated Fraction of 10 CFR Part 20 limit at site boundary[b]		Estimated Dose to Population in 50-mile radius, (man-rem)	
		PWR	BWR	PWR	BWR
1.0	Trivial incidents	(c)	(c)	(c)	(c)
2.0	Small releases outside containment	(c)	(c)	(c)	(c)
3.0	Radwaste system failures				
3.1	Equipment leakage or malfunction	0.006	0.078	0.52	7.2
3.2	Release of waste gas storage tank contents	0.024	0.31	0.06	29.0
3.3	Release of liquid waste storage contents	0.002	<0.001	0.215	<0.1
4.0	Fission products to primary system (BWR)				
4.1	Fuel cladding defects	N.A.	(c)	N.A.	(c)
4.2	Off-design transients that induce fuel failures above those expected	N.A.	0.003	N.A.	0.7
5.0	Fission products to primary and secondary systems (PWR)		N.A.		N.A.
5.1	Fuel cladding defects and steam generator leaks	(c)		(c)	

TABLE 3.71 (Continued)

Class	Event	Estimated Fraction of 10 CFR Part 20 limit at site boundary(b)		Estimated Dose to Population in 50-mile radius, (man-rem)	
		PWR	BWR	PWR	BWR
5.2	Off-design transients that induce fuel failure above those expected and steam generator leak				
5.3	Steam generator tube rupture	0.028		2.38	
6.0	Refueling accidents				
6.1	Fuel bundle drop	0.004	0.002	0.32	0.2
6.2	Heavy object drop onto fuel in core	0.065	0.014	5.25	1.3
7.0	Spent fuel handling accident				
7.1	Fuel assembly drop in fuel storage pool	0.001	0.003	0.08	0.3
7.2	Heavy object drop onto fuel rack	0.061	0.006	0.34	0.5
7.3	Fuel cask drop	0.061	0.12	5.15	11.0
8.0	Accident initiation events considered in design basis evaluation in the Safety Analysis Report				
8.1	Loss-of-coolant accidents				
	Small break	0.002	<.001	0.32	<0.1
	Large break	0.057	0.035	27.39	26.0

TABLE 3.71 (Continued)

Class	Event[(a)]	Estimated Fraction of 10 CFR Part 20 limit at site boundary[(b)] PWR	BWR	Estimated Dose to Population in 50-mile radius, (man-rem) PWR	BWR
8.1[(a)]	Break in instrument line from primary system that penetrates the containment	N.A.	<.001	N.A.	<0.1
8.2[(a)]	Rod ejection accident (PWR)	---	N.A.	---	N.A.
8.2[(b)]	Rod drop accident (BWR)	N.A.	0.005	N.A.	1.1
8.3[(a)]	Steamline breaks (PWRS outside containment)				
	Small break	0.0001	N.A.	0.012	N.A.
	Large break	0.0003	N.A.	0.024	N.A.
8.3[(b)]	Steamline break (BWR)	N.A.		N.A.	
	Small break		0.003		0.3
	Large break		0.014		1.3
9.0[(d)]					

[(a)]Doses calculated are based on airborne transport of radioactive materials resulting in both a direct and an inhalation dose. Evaluation of the accident doses assumes that the environmental monitoring program and appropriate additional monitoring would detect the presence of radioactivity in the environment, allowing remedial action to limit exposure from other potential pathways.

[(b)]Represents the calculated fraction of a whole body dose of 500 mrem, or the equivalent dose to an organ.

[(c)]These radionuclide releases are considered in developing the gaseous and liquid source terms presented in Section 3 and are included in the doses in Section 5 of the Final Environmental Impact Statement for any PWR or BWR plant.

[(d)]See discussion in Section 3.6.6.

TABLE 3.72

ESTIMATED TRANSPORTATION REQUIREMENTS FOR MODEL LWR OPERATION AND DECOMMISSIONING

Activity[(a,b)]	Material Shipped	Transport Mode	Number of Shipments	Average Shipping Distance (miles)	Total Miles Traveled
Operation[(c)]	Spent Fuel	Truck	44	2,000	8.75×10^4
	Spent Fuel	Rail	4	2,000	8×10^3
Decommissioning[(d)]	Activated Metal and Concrete	Truck	195	2,000	3.9×10^5
		Rail	21	2,000	4.2×10^4
	Contaminated Metal and Concrete	Truck	1,147	2,000	2.3×10^6
	Radioactive Waste	Truck	180	2,000	3.6×10^5

(a) Composite information from U.S. Atomic Energy Commission Reports WASH-1224A, 1974; WASH-1238, 1972; and WASH-1248, 1974.

(b) U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Pressurized Water Reactor Power Station," NUREG/CR-0130, Vol. 2, App. G, p. G-26, June 1978.

(c) This is an annual requirement for spent fuel transport. Low-level waste shipments are covered in Section 3.9.

(d) Decommissioning activities are expected to take up to four years.

decommissioned at a later date when some of the radioactivity in the facility has decayed. The protective storage mode requires that the facility be modified to the extent that most support services can be secured and access can be restricted through the use of sealed barriers. Operational support during this mode is minimized. In layaway, the facility is essentially maintained in a dormant condition, which requires more operational support. The choice between the two probably will be a totally economic one.

For a facility like the reference LWR, use of delayed decommissioning has some advantages because short-lived fission and activation products in the facility will decay before decommissioning takes place.

Information concerning material volumes, energy comsumption, and occupational and public hazards during LWR decommissioning activities has been presented in previous sections of 3.6. Specifically, Table 3.61 lists the estimated energy consumption during LWR decommissioning. A summary of the material volumes for disposal of decommissioning waste for a reference PWR is presented in Table 3.64. Occupational lost-time injuries and fatalities from decommissioning activities are given in Table 3.66.

3.7 FUEL REPROCESSING

The fuel discharged from the model LWR includes substantial amounts of uranium as well as fission products and transuranic elements. Uranium recovery from the spent fuel reduces the annual ore and yellow cake requirements, but requires handling and processing of relatively large amounts of radioactive isotopes. This stage of the uranium cycle is treated only in Option 2 where uranium recycle is considered.

3.7.1 General Description

Spent fuel assemblies arrive by rail or truck at the reprocessing facility in heavily shielded casks. Fuel assemblies are unloaded and stored in the spent fuel storage pool. These assemblies are later transferred to the separation area, where each one is sheared into segments a few inches long to expose the fuel to a dissolver liquor (nitric acid). After about 8 hours in the dissolver, the hulls, which contain 0.1 to 1 percent of the heavy metal content of the spent fuel assembly, are washed and transfered to solid waste storage. Fission products are extracted from the dissolved fuel by countercurrent contact with an organic solvent. The decontaminated uranium and plutonium stream is then partitioned by further solvent extraction into one stream containing only uranium and one stream containing a mixture of plutonium and uranium. The uranium stream is purified, and the uranium is temporarily stored as uranium nitrate. Uranium nitrate is subsequently converted to UF_6 in the UF_6 manufacturing facility where it is stored in cylinders for subsequent shipment to the enrichment facility. The plutonium stream is converted to plutonium oxide and stored onsite indefinitely. Alternatively, the oxide could be disposed of in a deep geological repository.

3.7.2 Model Description

The model facility is assumed to have a reprocessing capacity of 1500 MTU/yr of spent fuel and an operating life of 30 years, the values proposed for recent plants. The facility uses nitric acid leach and the Purex extraction process. Recovery efficiency is assumed to be 99.5 percent for uranium and plutonium. The annual reprocessing requirement for the model LWR is then calculated to be 38.8 MTU. (Assuming ~36 MTU in the spent fuel at the end of each operating year, plus ~110 MTU discharged from the last core.)

3.7.3 Materials and Equipment Requirements

The materials and major equipment requirements for the model facility are presented in Tables 3.73 and 3.74. Normalized values of the materials requirements are based on the model facility capacity and on 38.8 MTU in the spent fuel to be processed annually for the model LWR.

3.7.4 Energy Requirements

Energy consumption of the model reprocessing facility, normalized to the recycled fuel requirements of the model reactor, is detailed in Table 3.75. Normalization is based on an average annual reactor requirement of 38.8 MTU and a model reprocessing facility annual capacity of 1500 MTU. Construction energy consumption has been amortized over the lifetime of the facility.

3.7.5 Effluents

Table 3.76 shows reprocessing facility effluents normalized to LWR annual reprocessing requirements (38.8 MTU). Effluents associated with the facility energy requirements are not included in the table.

3.7.6 Occupational and Public Hazards

Estimated hazards and hazard rates for the reprocessing facility workers are shown in Table 3.77. A projected average annual dose to the public within 3 km from the facility perimeter during normal operation is detailed in Table 3.78. A variety of major accidents, their estimated probabilities, and the radiological dose to the public from operation of the model reprocessing facility are presented in Table 3.79. Tables 3.80 through 3.89 list the radioactive effluents

TABLE 3.73

REPROCESSING FACILITY CONSTRUCTION MATERIAL REQUIREMENTS

Material	Model Facility Requirement[b]	Annual Model LWR Requirement[c]
Reinforcing steel (MT)	1,810[a]	0.56[a]
	25,700[d]	22.0[d]
Structural steel (MT)	9,070[a]	7.82[a]
Concrete (MT)	88,800[a]	76.56[a]
	288,900[d]	249[d]
Fiberglass insulation (MT)	91[a]	0.08[a]
Redwood (board-ft)	60,000[a]	51.73[a]
	4,700 m^3[d]	4 m^3[d]
Copper (MT)	145[d]	0.13[d]
Zinc (MT)	9[d]	0.007[d]
Aluminum (MT)	220[d]	0.9[d]

(a) U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle, Part II--Nuclear Power Reactors," EPA-520/9-73-003-C, November 1973.

(b) Model facility capacity is 1500 MTU/yr.

(c) Annual reprocessing requirement per model LWR is 38.8 MT.

(d) U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management,"DOE/ET-0028, p. 3.2.31, May 1979.

TABLE 3.74

EQUIPMENT REQUIREMENT FOR THE REPROCESSING FACILITY

Item	No. of Units Required[(a,b)]
135-Ton crane	1
Five-Ton crane	2
Three-Ton crane	2
Al canister	5
Tanks	~100
Conveyors	~50
Pumps	~25
Heat exchangers	~20
Cooking tower	1
Centrifuge	2
Motors	~50
Shafts	~50
Seals	~100
Containers	~200
Piping (meters)	1000

[(a)]Model facility capacity is 1500 MTU/yr.

[(b)]U.S. Environmental Protection Agency, "Environmental Analysis of the Uranium Fuel Cycle, Part II--Nuclear Power Reactors," EPA-520/9-73-003-C, November 1973.

TABLE 3.75

ENERGY REQUIREMENT FOR REPROCESSING FACILITY
(CONSTRUCTION AND OPERATION)

Source	Annual Model LWR Reprocessing Requirement[b]	
Construction		
Construction Materials Energy:		
Electricity (MWH)	195[a]	
Fossil Fuel (Btu)	7.28×10^9[a]	
Direct Energy:		
Electricity (MWH)	8.6[a]	0.64[f]
Fossil Fuel (Btu)	1.85×10^9[a]	2×10^3 gal[f]
Operation		
Process Materials Energy:		
Electricity (MWH)	128[a]	
Fossil Fuel (Btu)	3.37×10^9[a]	
Direct Energy:		
Electricity (MWH)	382[a], 4000[f], 450[d], 4500[e]	
Fossil Fuel (Btu)	2.39×10^8[a], 2.94×10^{10}[c], 2.5×10^5 gal.	

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1976.

(b) Reprocessing requirement for a model LWR is assumed to be 38.8 MTU/yr.

(c) U.S. Nuclear Regulatory Commission, "Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," NUREG-0116, October 1976.

(d) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, April 1974.

(e) U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, p. E-24, August 1976.

(f) U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, p. 3.2.31, May 1979.

TABLE 3.76

REPROCESSING FACILITY EFFLUENTS NORMALIZED TO MODEL LWR ANNUAL REPROCESSING REQUIREMENTS

Effluent	Release Per Model LWR Requirement[a] (b)	(c)	(d)
Gases and Particulates			
Non Radioactive: (MT/yr)			
NO_x	5.5	18.6	16.9
F^-	0.11	0.06	0.05
Radioactive: (Ci/Yr)			
H-3	16.7×10^3	20×10^3	18.1×10^3
C-14[b]		26.4	24
Kr-85	350×10^3	442×10^3	400×10^3
I-129	2.4×10^{-3}	0.037	0.03
I-131	2.4×10^{-2}	0.15	0.83
Fission Products	1.0×10^3	0.19	0.18
Transuranics	.004	0.26	0.23
Liquids			
Non Radioactive (MT/Yr)			
Na^+	5.3	0.02	0.02
Cl^-	0.2	0.1	0.09
SO_4	0.4	0.02	0.02
NO_3^-	0.2	0	0
Radioactive: (Ci/Yr)			
H-3	2.5×10^3		
Ru-106	0.15×10^3		
Cs-137	0.08×10^3		
Sr-90	4.3		
Solids	(buried) 0.52		

(a) Effluents associated with the facility energy needed are not included.

(b) U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, April 1974.

(c) U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, p. E-24, August 1976.

(d) U.S. Nuclear Regulatory Commission, "Environmental Survey of the Processing and Waste Management Portions of the LWR Fuel Cycle," A Task Force Report NUREG-0116, Supplement 1 to WASH-1248, October 1976.

TABLE 3.77

MODEL REPROCESSING FACILITY OCCUPATIONAL HAZARDS

Hazard	Health Effects[a] Per MTU	Health Effects[a] Per Annual Model LWR Reprocessing Requirement
Radiological	0.63[b]	24 man-rem[d]
Non Radiological[b]		
Fatalities	1.8×10^{-6}	7.0×10^{-5}
Injuries	2.1×10^{-4}	8.2×10^{-3}
Man-Days Lost[c]	0.019	1.15

(a) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1225, December 1974.

(b) Estimated rates are assumed to be the same as those for the conversion facility.

(c) 6000 man-days lost per fatality and 20 days lost per injury.

(d) U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, p. E-24, August 1976.

TABLE 3.78

PROJECTED AVERAGE ANNUAL POPULATION DOSAGE FROM NORMAL OPERATION OF THE FUEL REPROCESSING FACILITY

		Average Annual Dose[(a)] (mrem/yr at 3 km)	
Source	Critical Organ	Model Facility[(b)]	Normalized to Model LWR Reprocessing Requirement[(c)]
Kr-85	Whole Body	0.38	9.8×10^{-3}
	Lung	0.75	19×10^{-3}
	Skin	13	0.34
	Gonads	0.50	13×10^{-3}
H-3	Whole Body	3.2	0.08
	Gonads	3.2	0.08
I-129	Thyroid--Infant	1.4	36×10^{-3}
	Thyroid--Adult	0.4	10×10^{-3}
I-131	Thyroid--Infant	13	0.34
	Thyroid--Adult	0.8	21×10^{-3}
Actinides	Lung	1	26×10^{-3}
Total:		365 person-rem (U.S. pop.)[(d)] 237 person-rem (foreign pop.)	

(a) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, December 1974.

(b) Model facility has assumed capacity of 1500 MTU/yr.

(c) Reprocessing requirements for a model LWR are assumed to be 38.8 MTU/yr.

(d) U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, Vol. IV, p. E-24, August 1976.

TABLE 3.79

RADIOLOGICAL RISKS FROM ACCIDENTS IN FUEL REPROCESSING

Accident	Accident[a] Likelihood $(\text{plant-yr})^{-1}$	Population Dose Per Annual[a] Model LWR Requirement (man-rem)
A.1 Explosion in High Aqueous Waste Concentrator		
a. Normal HEPA Filtration	$\sim 10^{-5}$	$5.3\text{x}10^{-2}$(G.I.)
		$1.0\text{x}10^{-4}$(W.B.)
b. HEPA Filter Failure	$\sim 10^{-8}$	$7.7\text{x}10^{-5}$(G.I.)
		$2.2\text{x}10^{-6}$(W.B.)
A.2 Explosion in Low Aqueous Waste Concentrator		
a. Normal HEPA Filtration	$\sim 10^{-4}$	$3.5\text{x}10^{-2}$(G.I.)
		$6.5\text{x}10^{-5}$(W.B.)
b. HEPA Filter Failure	$\sim 10^{-7}$	$3.7\text{x}10^{-5}$(G.I.)
		$1.1\text{x}10^{-7}$(W.B.)
A.3 Explosion in High Aqueous Feed Tank		
a. Normal HEPA Filtration	$\sim 10^{-5}$	$2.0\text{x}10^{-1}$(G.I.)
		$3.7\text{x}10^{-4}$(W.B.)

TABLE 3.79 (Continued)

Accident	Accident[a] Likelihood $(\text{plant-yr.})^{-1}$	Population Dose Per Annual[a] Model LWR Requirement (man-rem)
b. HEPA Filter Failure	$\sim 10^{-7}$	$2.0\text{x}10^{-3}$(G.I.) $3.8\text{x}10^{-6}$(W.B.)
A.4 Explosion in Waste Calciner		
a. Normal HEPA Filtration	$\sim 10^{-6}$	$5.3\text{x}10^{-2}$(G.I.) $1.0\text{x}10^{-4}$(W.B.)
b. HEPA Filter Failure	$\sim 10^{-9}$	$5.6\text{x}10^{-5}$(G.I.) $3.0\text{x}10^{-7}$(W.B.)
A.5 Explosion in Iodine Adsorber	$2\text{x}10^{-4}$	$8.8\text{x}10^{-3}$(Thyroid) $2.2\text{x}10^{-5}$(W.B.)
B.1 Solvent Fire in Codecontamination Cycle		
a. Normal HEPA Filtration	10^{-4} to 10^{-6}	$3.3\text{x}10^{-2}$ to $3.3\text{x}10^{-4}$(G.I.) $5.3\text{x}10^{-5}$ to $5.3\text{x}10^{-7}$(W.B.)
b. HEPA Filter Failure	10^{-7} to 10^{-9}	$3.5\text{x}10^{-5}$ to $3.5\text{x}10^{-7}$(G.I.) $1.3\text{x}10^{-7}$ to $1.3\text{x}10^{-9}$(W.B.)

TABLE 3.79 (Continued)

Accident	Accident[a] Likelihood $(plant\text{-}yr.)^{-1}$	Population Dose Per Annual[a] Model LWR Requirement (man-rem)
B.2 Solvent Fire in Plutonium Extraction Cycle		
a. Normal HEPA Filtration	10^{-4} to 10^{-6}	3.5×10^{-8} to 3.5×10^{-10}(Bone) 7.2×10^{-10} to 7.2×10^{-12}(W.B.)
b. HEPA Filter Failure	10^{-9} to 10^{-10}	6.0×10^{-7} to 6.0×10^{-9}(Bone) 1.2×10^{-8} to 1.2×10^{-10}(W.B.)
B.3 Ion-Exchange Resin Fire		
a. Normal HEPA Filtration	10^{-1} to 10^{-4}	4.4×10^{-1} to 4.4×10^{-4}(G.I.) 8.4×10^{-4} to 8.4×10^{-7}(W.B.)
b. HEPA Filter Failure	10^{-6} to 10^{-9}	1.9×10^{-3} to 1.9×10^{-6}(Bone) 4.1×10^{-5} to 4.2×10^{-8}(W.B.)
C.1 Fuel Assembly Rupture and Release in Fuel Receiving and Storage		
a. Normal HEPA Filtration	10^{-1} to 10^{-2}	1.6×10^{-2} to 1.6×10^{-3}(G.I.) 3.0×10^{-5} to 3.0×10^{-6}(W.B.)
b. HEPA Filter Failure	10^{-4} to 10^{-5}	1.6 to 1.6×10^{-1}(G.I.) 3.0×10^{-3} to 3.0×10^{-4}(W.B.)

TABLE 3.79 (Continued)

Accident	Accident Likelihood[a] $(\text{plant-yr.})^{-1}$	Population Dose Per Annual[a] Model LWR Requirement (man-rem)
C.2 Dissolver Seal Failure		
a. Normal HEPA Filtration	$\sim 10^{-5}$	3.7×10^{-8}(lung) 5.3×10^{-9}(W.B.)
b. HEPA Filter Failure	$\sim 10^{-8}$	3.7×10^{-6}(lung) 5.3×10^{-7}(W.B.)
C.3 Release from a Hot UF_6 Cylinder	$\sim 5\times10^{-2}$	3.7×10^{-1}(lung) 1.7×10^{-3}(W.B.)
D.1 Criticality		
a. Normal HEPA Filtration	8×10^{-3} to 3×10^{-5}	5.6×10^{-6} to 2.1×10^{-8}(W.B.)
b. HEPA Filter Failure	8×10^{-6} to 3×10^{-8}	4.7×10^{-8} to 1.7×10^{-10}(Lung) 6.5×10^{-9} to 2.6×10^{-11}(W.B.)

[a] U.S. Atomic Energy Commission, "Environmental Survey of the Uranium Fuel Cycle," WASH-1248, April 1974.

TABLE 3.80

RADIONUCLIDE RELEASE RESULTING FROM AN HAW CONCENTRATOR EXPLOSION AT THE REPROCESSING FACILITY

Nuclide	Activity in Fuel[a] (Ci/MTHM)	Activity Released[a,b] (Ci)
Sr-89	9.0×10^{4}	3.1×10^{-4}
Sr-90	8.4×10^{4}	2.9×10^{-4}
Y-90	8.4×10^{4}	2.9×10^{-4}
Y-91	1.9×10^{4}	6.6×10^{-4}
Zr-95	3.5×10^{5}	1.2×10^{-3}
Nb-95	6.5×10^{5}	2.3×10^{-3}
Ru-103	1.2×10^{5}	1.3×10^{2}
Ru-106	6.1×10^{5}	6.4×10^{2}
I-129	3.6×10^{-2}	3.1×10^{-3}
I-131	1.6	1.4×10^{-1}
Cs-134	2.4×10^{5}	8.3×10^{-4}
Cs-137	1.2×10^{5}	4.2×10^{-4}
Ce-141	7.9×10^{4}	2.7×10^{-4}
Ce-144	8.8×10^{5}	3.1×10^{-3}
Pm-147	$14. \times 10^{5}$	4.8×10^{-4}
Pu-238	4.3×10^{3}	1.5×10^{-5}
Pu-239	3.2×10^{2}	1.1×10^{-6}
Pu-240	6.3×10^{2}	2.2×10^{-6}
Pu-241	1.7×10^{5}	5.9×10^{-4}
Pu-242	3.6	1.3×10^{-8}
Am-241	2.5×10^{2}	8.7×10^{-7}
Am-242	4.0	1.4×10^{-8}
Cm-242	4.4×10^{4}	1.5×10^{-4}
Cm-243	3.4×10^{1}	1.2×10^{-8}
Cm-244	5.7×10^{3}	2.0×10^{-6}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risks Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 10^5. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of filter failure, however, the ruthenium activity released is assumed to be the following: Ru 103 = 1.7×10^2 Ci; Ru 106 = 8.5x102 Ci.

TABLE 3.81

RADIONUCLIDE RELEASE RESULTING FROM A LAW CONCENTRATOR EXPLOSION AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	5.0×10^{-7}
Sr-90	4.7×10^{-7}
Y-90	4.7×10^{-7}
Y-91	1.1×10^{-6}
Zr-95	2.0×10^{-5}
Nb-95	3.6×10^{-5}
Ru-103	8.4
Ru-106	4.3×10^{1}
I-129	4.0×10^{-3}
I-131	1.8×10^{-1}
Cs-134	1.3×10^{-6}
Cs-137	6.7×10^{-7}
Ce-141	4.4×10^{-7}
Ce-144	4.8×10^{-6}
Pm-147	7.8×10^{-7}
Pu-238	1.1×10^{-8}
Pu-239	8.1×10^{-10}
Pu-240	8.1×10^{-10}
Pu-241	4.3×10^{-7}
Pu-242	9.1×10^{-12}
Am-241	1.4×10^{-9}
Am-242	2.2×10^{-11}
Cm-242	2.5×10^{-7}
Cm-243	1.9×10^{-10}
Cm-244	3.2×10^{-8}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 10^5. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of simultaneous filter failure, the ruthenium activity released is assumed to be the following: Ru 103 = 9.1 Ci; Ru 106 = 4.6×10^1 Ci.

TABLE 3.82

RADIONUCLIDE RELEASE RESULTING FROM A HAF TANK EXPLOSION AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	2.1×10^{-3}
Sr-90	2.0×10^{-3}
Y-90	2.0×10^{-3}
Y-91	4.5×10^{-3}
Zr-95	8.2×10^{-3}
Nb-95	1.5×10^{-2}
Ru-103	4.8×10^{2}
Ru-106	2.4×10^{3}
I-129	7.2×10^{-2}
I-131	3.2
Cs-134	5.7×10^{-3}
Cs-137	2.8×10^{-3}
Ce-141	1.9×10^{-3}
Ce-144	2.1×10^{-2}
Pm-147	3.3×10^{-3}
Pu-238	1.0×10^{-4}
Pu-239	7.6×10^{-6}
Pu-240	1.5×10^{-5}
Pu-241	4.0×10^{-3}
Pu-242	8.5×10^{-8}
Am-241	5.9×10^{-3}
Am-242	9.5×10^{-8}
Cm-242	1.0×10^{-3}
Cm-243	8.0×10^{-7}
Cm-244	1.4×10^{-4}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the single HEPA filter. In the event of failure of the filter, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 10^3. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of filter failure, however, the ruthenium activity released is unchanged.

TABLE 3.83

RADIONUCLIDE RELEASE RESULTING FROM AN EXPLOSION IN THE WASTE CALCINER AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	3.1×10^{-4}
Sr-90	2.9×10^{-4}
Y-90	2.9×10^{-4}
Y-91	6.6×10^{-4}
Zr-95	1.2×10^{-3}
Nb-95	2.3×10^{-3}
Ru-103	1.3 x 10[illegible]
Ru-106	6.4×10^{3}
I-129	3.1×10^{-3}
I-131	1.4×10^{-1}
Cs-134	8.3×10^{-4}
Cs-137	4.2×10^{-4}
Ce-141	2.7×10^{-4}
Ce-144	3.1×10^{-3}
Pm-147	4.8×10^{-4}
Pu-238	1.5×10^{-5}
Pu-239	1.1×10^{-6}
Pu-240	2.2×10^{-6}
Pu-241	5.9×10^{-4}
Pu-242	1.3×10^{-8}
Am-241	8.7×10^{-7}
Am-242	1.4×10^{-8}
Cm-242	1.5×10^{-4}
Cm-243	1.2×10^{-8}
Cm-244	2.0×10^{-6}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 10^5. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of simultaneous filter failure, the ruthenium activity released is assumed to be the following: Ru 103 = 1.4×10^3 Ci; Ru 106 = 6.6×10^3 Ci.

TABLE 3.84

RADIONUCLIDE RELEASE RESULTING FROM A FIRE IN THE CODECONTAMINATION CYCLE AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	1.5×10^{-7}
Sr-90	7.1×10^{-7}
Y-90	7.1×10^{-7}
Y-91	3.7×10^{-7}
Zr-95	4.2×10^{-6}
Nb-95	7.7×10^{-6}
Ru-103	1.6
Ru-106	3.8×10^{1}
I-129	1.2×10^{-4}
I-131	1.7×10^{-4}
Cs-134	1.6×10^{-6}
Cs-137	9.8×10^{-7}
Ce-141	8.7×10^{-8}
Ce-144	4.9×10^{-6}
Pm-147	1.1×10^{-6}
Pu-238	3.7×10^{-7}
Pu-239	2.7×10^{-8}
Pu-240	5.4×10^{-8}
Pu-241	1.4×10^{-5}
Pu-242	3.1×10^{-10}
Am-241	2.1×10^{-9}
Am-242	3.4×10^{-11}
Cm-242	1.6×10^{-7}
Cm-243	2.9×10^{-10}
Cm-244	4.8×10^{-8}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/6-78-013, June 1978.

(b) The values tabulated are for normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 10^5. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of simultaneous filter failure, the ruthenium activity released is assumed to be the following: Ru 103 = 1.8 Ci; Ru 106 = 4.2×10^1 Ci.

TABLE 3.85

RADIONUCLIDE RELEASE RESULTING FROM A FIRE IN THE PLUTONIUM EXTRACTION CYCLE AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Pu-238	8.8×10^{-7}
Pu-239	6.5×10^{-8}
Pu-240	1.3×10^{-7}
Pu-241	3.5×10^{-5}
Pu-242	7.3×10^{-10}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the three series HEPA filters. In the event of simultaneous failure of the filters, the values in this column are increased by a factor of 1.6×10^{6}.

TABLE 3.86

RADIONUCLIDE RELEASE RESULTING FROM AN ION-EXCHANGE RESIN FIRE AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	1.2×10^{-9}
Sr-90	1.2×10^{-9}
Zr-95	3.5×10^{-6}
Nb-95	6.8×10^{-6}
Ru-103	9.3×10^{-2}
Ru-106	5.4×10^{-1}
I-129	2.8×10^{-8}
I-131	1.2×10^{-6}
Cs-134	2.7×10^{-9}
Cs-137	1.9×10^{-9}
Ba-137m	1.7×10^{-9}
Ce-144	8.4×10^{-9}
Np-238	9.1×10^{-6}
Pu-238	3.3×10^{-6}
Pu-239	2.4×10^{-7}
Pu-240	4.4×10^{-7}
Pu-241	1.2×10^{-4}
Cm-242	6.0×10^{-10}
Cm-244	7.1×10^{-11}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the three series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine and ruthenium, are increased by a factor of 1.6×10^6. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged. Ruthenium is part vapor and part particulate. In the event of simultaneous filter failure, the ruthenium activity released is assumed to be the following: Ru 103 = 9.3×10^{-1} Ci; Ru 106 = 5.4 Ci.

TABLE 3.87

RADIONUCLIDE RELEASE RESULTING FROM A FUEL ASSEMBLY RUPTURE AND RELEASE IN FUEL RECEIVING AND STORAGE AREA AT THE REPROCESSING FACILITY

Nuclide	Activity Release (Ci)[a,b]
Ru-103	3.8×10^{-3}
Ru-106	1.9×10^{-2}
I-129	1.6×10^{-11}
I-131	7.2×10^{-10}
Cs-134	1.1×10^{-7}
Cs-137	5.4×10^{-8}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associatd with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values given assume normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column are increased by a factor of 10^5.

TABLE 3.88

RADIONUCLIDE RELEASE RESULTING FROM A DISSOLVER SEAL FAILURE AT THE REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a,b]
Sr-89	6.52×10^{-6}
Sr-90	4.67×10^{-5}
Y-90	4.67×10^{-5}
Y-91	1.64×10^{-5}
Ar-95	4.57×10^{-5}
Nb-95	9.71×10^{-5}
Ru-103	4.16×10^{-6}
Ru-106	6.88×10^{-4}
Ag-110	3.93×10^{-7}
Sb-125	2.03×10^{-5}
Te-127	3.54×10^{-6}
Te-129	4.20×10^{-8}
I-129	3.92×10^{-6}
I-131	3.10×10^{-12}
Cs-134	2.11×10^{-5}
Cs-137	1.24×10^{-4}
Ce-141	7.46×10^{-7}
Ce-144	5.18×10^{-4}
Pm-147	2.71×10^{-4}
Eu-154	1.44×10^{-6}
Eu-155	3.78×10^{-5}
U-234	1.66×10^{-10}
U-235	2.64×10^{-12}
U-236	8.24×10^{-12}
U-238	2.87×10^{-10}
Pu-238	1.89×10^{-5}
Pu-239	3.85×10^{-6}
Pu-240	5.24×10^{-6}
Pu-241	5.71×10^{-4}
Am-241	2.95×10^{-6}
Am-243	5.41×10^{-8}
Cm-242	1.73×10^{-5}
Cm-244	1.44×10^{-6}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values calculated are for normal operation of the two series HEPA filters. In the event of simultaneous failure of the filters, the values in this column, with the exception of iodine, are increased by a factor of 10^5. Since iodine is assumed to be a vapor, the activity released is assumed to be unchanged.

TABLE 3.89

RADIONUCLIDE RELEASE RESULTING FROM A CRITICALITY INCIDENT AT THE FUEL REPROCESSING FACILITY

Nuclide	Activity Released (Ci)[a]	Nuclide	Activity Released (Ci)[a]
Br-80	2.4×10^{-5}	I-136	4.6×10^{-3}
Br-80m	1.1×10^{-8}	I-137	6.6×10^{-8}
Br-82	3.8×10^{-9}	Xe-133	1.7×10^{-3}
Br-82m	6.4×10^{-7}	Xe-133m	9.9×10^{-5}
Br-83	7.0×10^{-4}	Xe-135	2.2
Br-84	7.0×10^{-3}	Xe-135m	4.7
Br-84m	3.0×10^{-4}	Xe-137	9.0×10^{2}
Br-85	1.4×10^{-2}	Xe-138	7.0×10^{2}
Br-86	3.0×10^{-4}	Xe-139	1.5
Br-87	4.2×10^{-4}	Xe-140	2.2×10^{-7}
Kr-83m	3.4×10^{-1}	Th-231[b]	2.0×10^{-13}
Kr-85	3.2×10^{-5}	Th-234[b]	2.2×10^{-14}
Kr-85m	1.3×10^{1}	Pa-234m[b]	1.8×10^{-14}
Kr-87	9.4×10^{1}	U-233[b]	1.7×10^{-14}
Kr-88	6.3×10^{1}	U-234[b]	3.4×10^{-18}
Kr-89	5.2×10^{2}	U-235[b]	4.5×10^{-11}
Kr-90	9.2×10^{-2}	U-236[b]	1.3×10^{-16}
I-128	2.8×10^{-7}	U-237[b]	7.1×10^{-10}
I-130	2.0×10^{-7}	U-238[b]	7.1×10^{-10}
I-131	1.1×10^{-5}	U-239[b]	6.1×10^{-5}
I-132	3.2×10^{-4}	Np-237[b]	4.4×10^{-21}
I-133	3.0×10^{-4}	Np-239[b]	1.5×10^{-7}
I-134	1.0×10^{-2}	Np-240[b]	3.5×10^{-16}
I-135	4.6×10^{-3}	Pu-239[b]	4.1×10^{-17}

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) The values tabulated are for normal operation of the two HEPA filters. In the event of simultaneous failure of the filters, these values are increased by a factor of 10^5.

from the postulated accidents. The risks from normal operation and accidents are compared in Table 3.90.

3.7.7 Transportation Requirements

Transportation from the reprocessing facility includes (1) HLW, cladding hulls, and TRU-contaminated LLW by rail to a geologic repository; (2) LLW by truck to a shallow-land burial; and (3) UF_6 by rail to the enrichment facility. As discussed in Appendix I.4, a cask of HLW would contain the waste from processing 113 MTHM; therefore, about 3 shipments per year of HLW are needed. Similarly, 9.2 shipments per year of cladding hulls are needed. About one truck shipment of TRU-contaminated LLW per year is required. These shipments are tabulated in Section 3.8.7. The 56 MT of UF_6 would require about 4.2 truck shipments. Assuming 1000 miles between facilities, about 24,400 round-trip rail-miles and 10,400 round-trip truck-miles are required for the model reactor. Truck shipment of LLW is included in Section 3.9.

3.7.8 Decommissioning

The model reprocessing facility is assumed to be decommissioned after it has reached its design lifetime. Decommissioning can be performed in several ways: (1) the facility can be decontaminated and decommissioned immediately following shutdown or (2) the facility can be placed in either a protective storage mode or a layaway mode and decommissioned at a later date when some of the radioactivity in the facility has decayed. The protective storage mode requires the facility to be modified to the extent that most support services can be secured and access can be restricted through the use of sealed barriers. Operational support during this mode is minimized. In layaway, the facility is essentially maintained in a dormant condition, which requires more operational support. The choice between the two probably will be a totally economic one.

TABLE 3.90

COMPARISON BETWEEN RADIOLOGICAL HEALTH RISKS FROM ACCIDENTS AND NORMAL OPERATION IN FUEL REPROCESSING OPERATIONS

Risk from Normal Operation[a]		Risk from Accidents[a]	
Population Dose per Annual Model LWR Requirement (man-rem)	Health Risk per Annual Model LWR Requirement (# of excess cancers)	Population Dose per Annual Model LWR Requirement (man-rem)	Health Risk per Annual Model LWR Requirement (# of excess cancers)
1500 (thyroid)	3.6×10^{-1} [b]	2.4 (G.I.)	4.7×10^{-5} to 1.7×10^{-4}
790 (W.B.)		8.8×10^{-3} (thyroid)	
		6.3×10^{-3} (W.B.)	
		1.9×10^{-3} (bone)	
		3.7×10^{-1} (lung)	

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

(b) Control of C 14 emissions to one percent of normal release, coupled with proposed EPA radiation protection control on Kr 85, I 129, and plutonium would reduce this value to 1.3×10^{-2}.

For a facility such as the reference fuel reprocessing plant, use of delayed decommissioning has some advantages because short-lived fission products in the facility will decay before decommissioning takes place.

All three potential decommissioning modes have been considered in this study. Tables 3.91 through 3.94 provide information on decommissioning material, energy, and effluent loads. The public and occupational health impacts and quantities of radioactive waste from decommissioning operations at the model reprocessing facility are presented in Tables 3.95 and 3.96.

TABLE 3.91

MATERIAL AND ENERGY REQUIREMENTS RELATED TO DECOMMISSIONING A FUEL REPROCESSING FACILITY

	Safe Storage, 30 Years Delayed Dismantlement Total Requirement[(a)]
Materials	
Steel	1,600 MT
Paper, Wood, Plastics	130 MT
Equipment	500 MT
Energy	
Fossil Fuel	No estimate available
Electricity	25 MWH

(a) U.S. Department of Energy, "Technology for Commercial Radioactive Waste," DOE/ET-0028, Vol. 4, p. 8.5.12, May 1979.

TABLE 3.92

FAILED EQUIPMENT AND FACILITY WASTE

	Per Annual Model LWR Requirement[a]
Failed Equipment	4.3 MT (2.7 Ci)
Non-combustable Waste	4.7 MT (6600 Ci)
Concentrated Decontamination Solution	.4 m^3 (activity content unknown)
Packaged Incinerated Waste (ILW+LLW)	1.0 MT (activity content unknown)

[a] U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 2, May 1979.

TABLE 3.93

ACTIVITY RELEASE TO ATMOSPHERE DURING INTERMEDIATE DISMANTLEMENT

Activity Released	2×10^{-3} Ci[a]

[a] U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant," NUREG-0278, October 1977.

TABLE 3.94

ESTIMATED ACCIDENTAL RELEASES OF RADIONUCLIDES DURING DECOMMISSIONING

Accident	Ci to Atmosphere	1st Year Dose[a] Maximum Individual[b] (mrem) Bone	1st Year Dose[a] Maximum Individual[b] (mrem) Lung	50-Year Dose Commitment[a] Maximum Individual[b] (mrem) Bone	50-Year Dose Commitment[a] Maximum Individual[b] (mrem) Lung	Estimated Frequency[e]
Main Process Building						
Segmentation by Plasma Torch of Equipment not Chemically Decontaminated	1.7E-6[c]	7.5E-6	2.4E-5	5.1E-4	3.2E-5	Medium
Filter Failure During Chemical Decontamination	4.0E-4[c]	1.8E-3	5.6E-3	1.2E-1	7.6E-3	Medium
Liquid Waste Storage Area						
Loss of Contamination Control System-Plasma Torch	1.9E-3[d]	1.3E-1	4.4E-1	5.1E+0	5.1E-1	High
Segmentation by Plasma Torch of Equipment not Chemically Decontaminated	1.9E-2[d]	1.3E+0	4.4E+0	5.1E+1	5.1E+0	Medium
Tornado	2.8E-2[d]	1.9E+0	6.5E+0	7.5E+1	7.5E+0	Low
Filter Failure During Chemical Decontamination	6.0E-2[d]	4.1E+0	1.4E+1	1.6E+2	1.6E+1	Medium
Severe Earthquake	3.3E+0[d]	2.3E+2	7.7E+2	8.8E+3	8.8E+2	Low
Waste Solidification Plant (WSP)						
Filter Failure During Chemical Decontamination	5.0E-6[c]	1.5E-5	4.8E-5	6.0E-4	5.5E-5	Medium
Loss of Contamination Control System-Plasma Torch	1.3E-5[c]	3.9E-5	1.2E-4	1.6E-3	1.4E-4	High
Loss of Filtration During Vacuuming	7.5E-5[c]	2.3E-4	7.2E-4	9.0E-3	8.3E-4	Medium

(a) U.S. Nuclear Regulatory Commission, "Technology, Safety and Costs of Decommissioning a Nuclear Fuel Reprocessing Plant," NUREG-0278, October 1977.

(b) Maximum exposed individual is located one kilometer from the facility.

(c) Release from 100 m stack.

(d) Release at ground level.

(e) High: greater than 1E-2 per year; medium: 1E-2 to 1E-5 per year; low: less than 1E-5 per year.

TABLE 3.95

PUBLIC AND OCCUPATIONAL SAFETY IMPACT OF REFERENCE FUEL REPROCESSING FACILITY DECOMMISSIONING

Type of Safety Concern	Source of Safety Concern	Units	Immediate Dismantlement	Protective Storage with Deferred Dismantlement After[c]			Layaway with Deferred Dismantlement After[c]		
				10 Years	30 Years	100 Years	10 Years	30 Years	100 Years
Public Safety[a]									
Radiation Exposure	Decommissioning Operations	man-rem	10.2	8.2	5.1	2.0	8.2	5.1	2.0
	Transportation	man-rem	8.5	7.1	5.0	2.1	7.1	5.0	2.1
	Interim Care	man-rem	---	neg[b]	neg[b]	neg[b]	neg[b]	neg[b]	neg[b]
Occupational Safety									
Serious Lost-time Injuries	Decommissioning Operations	no./mode	1.7	1.9	1.9	1.9	1.75	1.75	1.75
	Transportation	no./mode	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Fatalities	Decommissioning Operations	no./mode	0.0091	0.010	0.010	0.010	0.0096	0.0096	0.0096
	Transportation	no./mode	0.012	0.012	0.012	0.012	0.012	0.012	0.012
	Interim Care	no./mode	---	0.00084	0.0024	0.0081	0.0038	0.012	0.038
Radiation Exposure	Decommissioning Operations	man-rem	512	426	296	124	423	290	113
	Transportation	man-rem	20.2	16.7	11.6	4.7	16.7	11.6	4.7
	Interim Care	man-rem	---	1.8	4.4	8.6	12.8	31.4	61.4

(a) Radiation doses from postulated accidents are not included. They are given in Section 8 of this report.

(b) neg = negligible. Radiation doses to the public from normal interim care activities were not analyzed in detail, but are expected to be significantly smaller than those from decommissioning operations.

(c) U.S. Nuclear Regulatory Commission, "Technology, Safety, and Costs of Decommissioning a Nuclear Fuel Reprocessing Plant," NUREG-0278, October 1977.

TABLE 3.96

RADIOACTIVE WASTES FROM DECOMMISSIONING

Disposition of Waste[a,b]	Volume	Weight	Curies
Deep Geologic Disposal	4600m^3	3700MT	2.5×10^7
Shallow Land Burial	3100m^3	2300MT	4×10^3

[a] Shipment distances are assumed to be 2400 KM for the transport of TRU waste to a Federal Repository and 800 KM for the transport of non-TRU waste to a commercial burial ground.

[b] U.S. Nuclear Regulatory Commission, "Technology, Safety, and Costs of Decommissioning a Reference Nuclear Fuel Reprocessing Plant," NUREG-0278, Vol. 1, October 1977.

3.8 DEEP GEOLOGIC WASTE DISPOSAL

The final step in the nuclear fuel cycle is concerned with the utlimate disposal of nuclear waste generated throughout the rest of the cycle. Although several methods are proposed for interim storage of intermediate- and high-level wastes, including spent fuel pools at reactors; away-from-reactor (AFR) spent fuel storage; and retrievable surface storage facilities (RSSF), ultimate disposal is expected to occur in deep geologic formations. The current practice of shallow-land burial of low-level wastes, occurring from all fuel cycle steps, may or may not continue the future and is covered in the next section. Disposal of such wastes also can be accomplished in a deep geologic repository.

In spite of the numerous interim disposal options available for intermediate- and high-level wastes, disposal of these types of wastes is assumed to be exclusively by burial in deep geologic formations such as the model waste repository considered here.

3.8.1 General Description

Current deep geologic waste repository designs are based on room and pillar mining in various rock formations at depths of 1000 to 3000 ft. The typical components of such a repository include (1) high-, intermediate-, and low-level waste-handling facilities; (2) mine operations and mined material handling facilities; (3) mine supply and exhaust ventilation systems; (4) men, materials, and waste shafts; and (5) radwaste treatment facilities. In such a concept, corridors and rooms are excavated in the rock at the desired storage level, and waste is placed in these rooms by either stacking (shielded intermediate- or low-level waste drums) or burial in the room floors (intermediate- and high-level waste). Filled rooms ultimately would be backfilled with the excavated material and sealed. Waste for burial would arrive at the repository via truck or railcar and would be unloaded, inspected, overpacked if necessary, and transferred down the mine shafts to the storage level for transport to a particular room for storage.

3.8.2 Model Description

The model repository utilizes conventional deep geologic disposal, and four types of rock formations are considered: salt, shale, granite, and basalt. Two repository types have been considered in this analysis: one for spent fuel disposal and one for disposal of high-level reprocessing waste. The spent fuel repository handles unreprocessed, spent reactor fuel either directly from the LWR spent fuel cooling pool or from an AFR spent fuel storage facility (AFR spent fuel storage is excluded from this study because none of these facilities are currently operating). The reprocessing waste repository would handle solidified high-level reprocessing wastes and intermediate-level wastes from reprocessing plants (including spent fuel cladding).

The lifetime and capacity of each reference repository design are presented in Table 3.97. These values have been utilized to normalize the data presented in the following sections.

3.8.3 Materials and Equipment Requirements

The estimated annual materials requirements for construction and operation of the model geologic repository are indicated in Table 3.98, both in terms of the annual commitment per metric ton heavy metal (MTHM) stored and the annual commitment per 1000-MWe model LWR support. The construction requirements are amortized over the lifetime of the repository, and values are given for the expected operational life for the four rock types considered.

3.8.4 Energy Requirements

Energy consumption during repository construction and operation has been estimated and is presented in Table 3.99. Again, the construc-

TABLE 3.97

REFERENCE REPOSITORY CHARACTERISTICS

Repository Type[a]	Operation Life (years)	Rock Media	Capacity (MTHM)[b] Option 2a[c]	Capacity (MTHM) Option 2b[d]
Spent Fuel	15	Salt	51,100	51,100
	24	Granite	121,600	121,600
	17	Shale	64,500	64,500
	24	Basalt	121,600	121,600
Reprocessing Waste	14	Salt	39,500	76,500
	19	Granite	69,000	69,000
	12	Shale	30,500	30,500
	12	Basalt	56,000	56,000

(a) U.S. Department of Energy, "Management of Commercially Generated Radioactive Waste," Draft Environmental Impact Statement, DOE/EIS-0046-D, Vol. 1, April 1979.

(b) MTHM of HLW stored. Based on 38 MTHM of spent fuel and 7.6 MTHM of reprocessed waste per GWe-yr.

(c) Option 2a: Assumes uranium-recycle only, plutonium in HLW.

(d) Option 2b: Assumes uranium-recycle only, plutonium stored as PuO_2.

TABLE 3.98

ANNUAL MATERIAL REQUIREMENTS FOR CONSTRUCTION AND OPERATION OF A GENERIC GEOLOGIC REPOSITORY

	Annual Commitment Per MTHM Stored[(a)]		Commitment Per Annual LWR Requirement[(b)]	
Resource	Spent Fuel Repository	Reprocessing Waste Repository	Spent Fuel Repository	Reprocessing Waste Repository
Steel (MT)				
Construction Steel	0.014-0.022	0.025-0.052	0.51	0.22
Canister/Fuel Overpacks	$(3.9\text{-}5.5) \times 10^{-5}$	$(5.7\text{-}10) \times 10^{-5}$	1.3×10^{-3}	4.5×10^{-4}
Retrievability Sleeves	$(6.0\text{-}17.1) \times 10^{-3}$	0.023-0.082	0.33	0.30
Concrete (MT)	0.22-0.36	0.43-0.99	8.3	4.1
Copper (MT)	$(1.9\text{-}3.0) \times 10^{-4}$	$(3.5\text{-}7.2) \times 10^{-4}$	7.0×10^{-3}	3.1×10^{-3}
Zinc (MT)	$(4.8\text{-}7.3) \times 10^{-5}$	$(8.4\text{-}18) \times 10^{-5}$	1.7×10^{-3}	7.5×10^{-4}
Aluminum (MT)	$(3.8\text{-}5.8) \times 10^{-5}$	$(6.6\text{-}14) \times 10^{-5}$	1.4×10^{-3}	5.9×10^{-4}
Lumber (m^3)	$(2.0\text{-}3.0) \times 10^{-3}$	$(3.7\text{-}7.7) \times 10^{-3}$	0.07	0.03

(a) Based on environmental analyses included in U.S. Department of Energy, "Environmental Aspects of Commercial Radioactive Waste Management," Document DOE/ET-0029, May 1979. The range of individual resources included is based on analysis of four geologic rock formations: salt, shale, granite, and basalt.

(b) Based on 38 MTHM of spent fuel and 7.6 MTHM of reprocessed waste per GWe-yr. Numbers reflect the median of the commitment range.

TABLE 3.99

ESTIMATED ANNUAL ENERGY COMSUMPTION DURING REPOSITORY CONSTRUCTION AND OPERATION

Energy Resource[a]	Annual Commitment/MTHM Stored		Commitment Per Annual Model LWR Requirement[b]	
	Spent Fuel Repository	Reprocessing Waste Repository	Spent Fuel Repository	Reprocessing Waste Repository
Petroleum Products				
Propane (Btu)	69-105	112-258	3306	1406
Gasoline (10^6 Btu)	0.43-0.59	0.71-1.6	19.4	8.7
Diesel Fuel (10^6 Btu)	4.8-9.2	7.7-20	266	205
Fossil Fuel (MT)				
Coal	0.62-1.19	1.0-2.73	34.4	14.2
Electricity (kWh)	$(1.1-1.6) \times 10^3$	$(1.8-3.8) \times 10^3$	51.3×10^3	21.3×10^3

(a) Based on environmental analyses included in U.S. Department of Energy, "Environmental Aspects in Commercial Radioactive Waste Management," Document DOE/ET-0029, May 1979. Values given have been modified to yield quantities consumed per year of repository operation per MTHM of fuel stored. The range of values included is based on analysis of four geologic rock formations: salt, shale, granite, and basalt.

(b) Based on 38 MTHM spent fuel and 7.6 MTHM reprocessed waste per GWe-yr. Numbers reflect the median of the commitment range.

tion commitment has been amortized over the lifetime of the facility. Three energy resources have been considered: petroleum products, fossil fuels, and electrical energy.

3.8.5 Effluents

Effluents arising from model repository construction and operation have been estimated for both repository concepts and for all four rock types. These estimates, based on the annual release per MTHM stored, are presented in Table 3.100. Construction effluents, primarily from diesel fuel combustion, have been included and have been amortized over the facility lifetime. Radioactive releases are considered to be negligible under normal operating conditions, with the major effluents during the entire operation arising from handling and storage of excavated material.

3.8.6 Occupational and Public Hazards

Occupational and public health hazards associated with construction and operation of the model repository have been developed. Estimated occupational lost-time injuries and fatalities from repository construction are presented in Table 3.101. Estimates of radiation exposure to workers and to the general public during normal repository operation are shown in Table 3.102. The values given here are for the maximum expected exposure resulting from operation of the facility and are based on the worst-case repository setting.

Numerous studies have assessed the probabilities and consequences of a variety of accidents at a deep geologic waste repository. The most common accidents* studied to date include: (1) the minor failure of a spent fuel canister and (2) a waste package (spent fuel or other waste

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*These accidents are by no means the entirety of those covered in the literature; however, they represent those that are the most serious and the most frequently studied.

TABLE 3.100

ESTIMATED EFFLUENTS DURING CONSTRUCTION AND OPERATION OF THE REFERENCE REPOSITORY

Effluent Category[a]	Annual Release Per MTHM Stored: Spent Fuel Repository	Annual Release Per MTHM Stored: Reprocessing Waste Repository	Release Per Annual Model LWR Requirement: Spent Fuel Repository	Release Per Annual Model LWR Requirement: Reprocessing Waste Repository
Airborne Gases and Particulates				
Non Radioactive: (MT/MTHM-yr)				
SO_x	$(5.1\text{-}10) \times 10^{-3}$	$(3.9\text{-}21) \times 10^{-3}$	6.5×10^{-1}	9.4×10^{-2}
NO_x	0.01-0.017	0.015-0.038	1.2	0.2
Hydrocarbons	$(7.9\text{-}14) \times 10^{-3}$	$(1.4\text{-}3.0) \times 10^{-3}$	4.2×10^{-1}	1.7×10^{1}
CO	0.008-0.012	0.016-0.030	0.38	0.17
Particulates[b]	$(3.1\text{-}5.6) \times 10^{-4}$	$(5.6\text{-}13) \times 10^{-4}$	1.6×10^{-2}	70.7×10^{-4}
Dust[c]	0.02-0.27	0.03-0.38	5.5	1.5
Radioactive: (Ci/MTHM-yr)[d]				
Rn-222	$\sim 10^{-6}$	$\sim 10^{-6}$	$\sim 3.8 \times 10^{-5}$	$\sim 7.6 \times 10^{-6}$
Rn-220	$\sim 10^{-6}$	$\sim 10^{-6}$	$\sim 3.8 \times 10^{-5}$	$\sim 7.6 \times 10^{-6}$
Other	$\sim 10^{-6}$	$\sim 10^{-9}$	$\sim 3.8 \times 10^{-5}$	$\sim 7.6 \times 10^{-9}$
Liquids Plus Suspended Solids[e]				
Solids				
Non Radioactive: (MT/MTHM-yr)	13-16	21-35	551	231
Radioactive:	(f)	(f)	(f)	(f)

(a) Unless otherwise noted, data are based on environmental analyses included in U.S. Department of Energy, "Environmental Aspects of Commercial Radioactive Waste Management," Document DOE/ET-0029, May 1979.

(b) Particulates from petroleum and fossil fuel combustion.

(c) Dust emissions from surface handling of excavated material.

(d) Estimates based on analyses presented in Union Carbide Corporation, "Contribution to Draft Generic Environmental Impact Statement on Commercial Waste Management: Radioactive Waste Isolation in Geologic Formations," UCC/OWI, Y/OWI/TM-44, April 1978.

(e) Estimated to be negligible.

(f) Radioactive solids will be disposed of onsite.

TABLE 3.101

ESTIMATED OCCUPATIONAL LOST-TIME INJURIES AND FATALITIES FROM REFERENCE REPOSITORY CONSTRUCTION

	Surface Facility Construction[a]	Underground Mining Operations[a]	Total
Frequency of Accidents/ 10^6 man-hours[b]			
Fatalities	0.17	0.53	0.92
Lost-Time Injuries	13.6	25.0	38.6
Spent Fuel Repository[c]			
Fatalities	1	6-15	7-16
Lost-Time Injuries	59-89	300-700	359-789
Man-Hours	$(4.0\text{-}6.5) \times 10^6$	$(1.2\text{-}2.8) \times 10^7$	
Reprocessing Waste Repository[c]			
Fatalities	1	6-11	7-12
Lost-Time Injuries	45-71	300-500	345-571
Man-Hours	$(3.3\text{-}5.2) \times 10^6$	$(1.2\text{-}2.0) \times 10^7$	

(a) Based on environmental analyses included in U.S. Department of Energy, "Environmental Aspects of Commercial Radioactive Waste Management," Document DOE/ET-0029, May 1979.

(b) Injury and fatality rate based on information in National Safety Council, Accident Facts, Chicago, 1974.

(c) Range of values represents construction in four rock types: salt, granite, shale, and basalt.

TABLE 3.102

ESTIMATED MAXIMUM OCCUPATIONAL AND PUBLIC RADIOLOGICAL EXPOSURE FROM NORMAL REFERENCE REPOSITORY OPERATION

Exposed Population	Dose Commitment[(a)] (man-rem/MTHM)
Work Force[(b)]	0.022
Regional Population[(c)]	8.2×10^{-4}

[(a)] Based on environmental analyses included in U.S. Department of Energy, "Environmental Aspects of Commercial Radioactive Waste Management," Document DOE/ET-0029, May 1979.

[(b)] Maximum exposure occurs from a reprocessing waste repository in granite.

[(c)] Dose due primarily to radon releases from excavation. Maximum exposure occurs from a spent fuel repository in granite.

type) dropped down the mine shaft. Other low probability/high consequence events have been addressed. These most often include the case of repository breach by a direct meteorite strike and faulting of the repository and subsequent groundwater transport of radionuclides.

The postulated minor failure of a spent fuel cask is discussed in DOE/ET-0028, "Technology for Commercial Radioactive Waste Management". This type of accident is estimated to occur about once per year and is caused by rough handling during transportation and unloading, or by the presence of a canister defect. The result is the formation of a pin hole leak in the canister that contains one failed fuel rod in a PWR fuel assembly. Gaseous activity from the one failed rod is assumed to be released from the canister over a 2-day time period. The nuclides and associated activities released are identified as:

Radionuclide	Quantity (Ci)
^{85}Kr	3
^{14}C	4×10^{-5}
^{129}I	5×10^{-6}
^{3}H	5×10^{-3}

The second class of postulated accidents, assuming that a waste package is dropped down the mine shaft, is by far the more serious. The waste package may consist of any of the following: (1) spent fuel (i.e., four spent PWR fuel assemblies) containing a total equivalent of 2 MTHM; (2) four high-level waste (HLW) canisters, each containing three MTHM equivalent; (3) one canister of fuel residue wastes that includes short lengths of the fuel cladding with some residual fuel, massive end fittings, fuel support grids, and assorted springs, spacer elements, and fuel bundle support rods; (4) one canister containing three drums of intermediate-level waste (ILW); or (5) 12 drums of low-level waste (LLW).

In the first accident scenario, four canisters, each containing a spent PWR fuel assembly, are dropped down the mine shaft. This accident is postulated to occur with a frequency of 1×10^{-5}/year.* The canisters breach upon contact and release the nuclides given in Table 3.103 over a 1-year period. The spent fuel assemblies are assumed to have been stored for 10 years after being removed from the reactor.

The second accident scenario involves the dropping of four high-level waste (HLW) canisters down the mine shaft. This event is postulated to occur with a frequency of 7×10^{-7}/year.** The canisters are breached on contact and release the nuclides given in Table 3.104 to the mine atmosphere (<10μm particle size). This accident is the most serious from the standpoint of variety and magnitude of nuclide release.

The third scenario considers dropping a fuel residue waste canister down the mine shaft. This accident is postulated to occur with a frequency of 2×10^{-6}/year.** One canister is dropped and is breached upon contact, releasing the nuclides given in Table 3.105 to the mine atmosphere (<10μm particle size). The fuel residue waste is assumed to have decayed for 10 years before shipment to the waste repository.

The fourth scenario considers dropping an intermediate-level waste canister containing three 55-gal. drums and is postulated to occur with a frequency of 2×10^{-5}/year.** The drums are breached on contact and release the given nuclides to the mine atmosphere, as given in Table 3.106 (<10μm particle size). The ILW is assumed to have decayed 10 years before shipment to the waste repository.

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*U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 4, p. 7.4.31, May 1979.

**U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 1, p. 7.5.33, May 1979.

TABLE 3.103

FISSION PRODUCTS, ACTINIDES AND ACTIVATION PRODUCTS RELEASED FROM A POSTULATED SPENT FUEL ASSEMBLY CANISTER DROP DOWN MINE SHAFT

Radionuclide	Release[(a)] (Ci/MTHM)
Activation Products	
C-14	4.0×10^{-2}
Fe-55	8.0×10^{-3}
Co-60	4.0×10^{-2}
Ni-59	3.0×10^{-5}
Ni-63	4.0×10^{-3}
Zr-93	9.0×10^{-5}
Fission Products (From Once-Through Cycle and Uranium-Only Recycle)	
H-3	8.5
Kr-85	4000
Sr-90	5.2×10^{2}
Y-90	5.2×10^{2}
Zr-93	1.7×10^{-2}
Tc-99	1.3×10^{-1}
Ru-106	3.4
Rh-106	3.4
Cd-113m	7.0×10^{-2}
Sb-125	5.3
Te-125m	2.2
I-129	6×10^{-3}
Cs-134	5.7×10^{1}
Cs-137	7.5×10^{2}
Ba-137m	7.5×10^{2}
Ce-144	8.2×10^{-1}
Pr-144	8.2×10^{-1}
Pm-147	6.4×10^{1}

TABLE 3.103 (Continued)

Radionuclide	Release[a] (Ci/MTHM)
Actinides (From Once-Through Cycle Only)	
Th-228	1.3×10^{-4}
Th-231	1.6×10^{-4}
Th-234	3.2×10^{-3}
Pa-233	3.1×10^{-3}
Pa-234m	3.2×10^{-3}
U-232	1.4×10^{-4}
U-234	7.4×10^{-4}
U-235	1.6×10^{-4}
U-236	2.2×10^{-3}
U-237	1.7×10^{-2}
U-238	3.2×10^{-3}
Np-237	3.1×10^{-3}
Np-239	1.4×10^{-1}
Pu-238	2.0×10^{1}
Pu-239	2.9
Pu-240	4.5
Pu-241	6.9×10^{2}
Pu-242	1.6×10^{-2}
Am-241	1.6×10^{1}
Cm-244	9.0

(a) U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.104

FISSION PRODUCTS, ACTINIDES, AND ACTIVATION PRODUCTS RELEASED FROM POSTULATED HIGH-LEVEL WASTE CANISTER DROP DOWN MINE SHAFT

Radionuclide	Release Ci/MTHM)[a,b]		
	Cycle IIa[c]	Cycle IIb[d]	Cycle III[e]
Fission Products			
H-3	1.5	1.5	1.6
Kr-85	3.0×10^{1}	3.0×10^{1}	2.8×10^{1}
Sr-90	3.1×10^{2}	3.1×10^{2}	2.9×10^{2}
Y-90	3.1×10^{2}	3.1×10^{2}	9.2×10^{2}
Zr-93	1×10^{-2}	1×10^{-2}	9.6×10^{-3}
Tc-99	7.8×10^{-2}	7.8×10^{-2}	7.8×10^{-2}
Ru-106	2.0	2.0	2.3
Rh-106	2.0	2.0	2.3
Cd-113	4.0×10^{-2}	4.0×10^{-2}	3.9×10^{-2}
Sb-125	3.2	3.2	3.5
Te-125	1.3	1.3	1.4
Cs-134	3.4×10^{1}	3.4×10^{1}	3.4×10^{1}
Cs-137	4.5×10^{2}	4.5×10^{2}	4.5×10^{2}
Ba-137m	4.2×10^{2}	4.2×10^{2}	4.3×10^{2}
Ce-144	4.9×10^{-1}	4.9×10^{-1}	4.8×10^{-1}
Pr-144	4.9×10^{-1}	4.9×10^{-1}	4.8×10^{-1}
Pm-147	3.8×10^{1}	3.8×10^{1}	3.8×10^{1}
Sm-151	6.6	6.6	6.6
Eu-154	2.2×10^{1}	2.2×10^{1}	2.5×10^{1}
Eu-155	7.2×10^{-1}	7.2×10^{-1}	7.8×10^{-1}
Actinides			
Th-228	6.8×10^{-5}	1.2×10^{-6}	1.4×10^{-6}
Pu-233	2.8×10^{-3}	2.8×10^{-3}	2.4×10^{-3}
U-232	7.3×10^{-5}	6.5×10^{-7}	6.5×10^{-7}
U-234	5.1×10^{-4}	6.3×10^{-6}	2.2×10^{-5}

TABLE 3.104 (Continued)

Radionuclide	Release Ci/MTHM)[a,b]		
	Cycle IIa[c]	Cycle IIb[d]	Cycle III[e]
U-237	9.8×10^{-3}	4.9×10^{-5}	8.2×10^{-5}
Np-237	2.8×10^{-3}	2.8×10^{-3}	---
Np-239	8.1×10^{-2}	8.1×10^{-2}	2.8×10^{-1}
Pu-238	1.8×10^{1}	1.9×10^{-1}	4.4×10^{-1}
Pu-239	1.8	8.7×10^{-3}	1.0×10^{-2}
Pu-240	2.7	1.9×10^{-2}	5.8×10^{-2}
Pu-241	3.9×10^{2}	1.9	3.3
Am-241	1.0×10^{1}	2.2	4.3
Cm-244	4.9	4.9	2.9×10^{1}

(a)Four HLW drums were assumed to be dropped with an equivalent of three MTHM per drum.

(b)It was assumed that HLW had decayed for ten years before shipment to repository.

(c)Cycle IIa: uranium-recycle only, plutonium in HLW.

(d)Cycle IIb: uranium-recycle only; plutonium stored.

(e)Cycle III: uranium and plutonium recycle.

TABLE 3.105

ACTIVATION PRODUCTS RELEASED FROM A POSTULATED FUEL RESIDUE WASTE CANISTER DROP DOWN MINE SHAFT

Radionuclide	Release (Ci/MTHM)[a]
C-14	6×10^{-5}
Fe-55	8×10^{-3}
Co-60	4×10^{-2}
Ni-59	3×10^{-5}
Ni-63	4×10^{-3}
Zr-93	9×10^{-5}

[a] U.S. Environmental Protection Agency, "Scoping Assessment of the Environmental Health Risk Associated with Accidents in the LWR Supporting Fuel Cycle," EPA-600/5-78-013, June 1978.

TABLE 3.106

FISSION PRODUCTS, ACTINIDES, AND ACTIVATION PRODUCTS RELEASED FROM A POSTULATED INTERMEDIATE-LEVEL WASTE CANISTER DROP DOWN MINE SHAFT

Radionuclide	Release (Ci/container-MTHM)[a]
Fission Product	
H-3	1.0×10^{-2}
I-129	4.7×10^{-6}
Zr-93	3.4×10^{-5}
Ru-106	7.6×10^{-3}
Rh-106	7.6×10^{-3}
Actinides	
U-234	2.8×10^{-5}
U-235	9.6×10^{-7}
U-236	1.6×10^{-5}
U-237	1.7×10^{-4}
U-238	1.9×10^{-5}
Pu-238	4.7×10^{-1}
Pu-239	3.2×10^{-2}
Pu-240	6.6×10^{-2}
Pu-241	1.1×10^{1}
Activation Products	
C-14	6.7×10^{-6}
Fe-55	4.0×10^{-3}
Co-60	1.0×10^{-2}
Ni-59	3.0×10^{-5}
Ni-63	4.4×10^{-4}
Zr-93	1.8×10^{-5}

[a] Assuming that a canister contains three ILW drums.

The last scenario considered is the dropping of 12 low-level waste (LLW) drums (55-gal) and is estimated to occur with a frequency of 3×10^{-6}/year.* The drums are breached on contact and release the nuclides given in Table 3.107 to the mine atmosphere (<10μm particle size). The LLW is also assumed to have decayed for 10 years before shipment to the waste repository.

Numerous low probability/high consequence events at a deep geologic waste repository have received extensive coverage. Specifically, Claiborne and Gera** assessed the relative probabilities and consequences of a variety of accident scenarios in a deep geologic repository in bedded salt at a New Mexico site. They identified the direct impact of a large meteorite into the waste repository as the event with the most serious potential consequences. However, the likelihood of such an event is estimated to be 1.6×10^{-13}/year; hence, such an event was dismissed as being insignificant. The same study also identified faulting in the repository, followed by progressive displacement of the waste and direct contact with circulating groundwater, as a more likely means of failure. The probability of this event is estimated as much less than 4×10^{-11}/year. Based on their overall analysis of failure events and potential consequences, Claiborne and Gera conclude that disposal of high-level waste at the bedded salt site will result in negligible risks to future individuals or populations.

Another study by Logan et al.*** addressed various accident scenarios, probabilities, and consequences at a reference waste repository in

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*U.S. Department of Energy, "Technology for Commercial Radioactive Waste Management," DOE/ET-0028, Vol. 1, p. 7.5.33, May 1979.

**H.C. Claiborne and F. Gera, "Potential Containment Failure Mechanisms and Their Consequences at a Radioactive Waste Repository in Bedded Salt in New Mexico," ORNL-TM-4639, October 1974.

***S.E. Logan et al., "Development and Application of a Risk Assessment Method for Radioactive Waste Management," EPA-520/6-78-005, July 1978.

TABLE 3.107

FISSION PRODUCTS, ACTINIDES AND ACTIVATION PRODUCTS
RELEASED FROM A LOW-LEVEL WASTE CANISTER
DROP DOWN MINE SHAFT

Radionuclide	Release (Ci/container-MTHM)[a]
H-3	5.0×10^{-9}
I-129	6.7×10^{-7}
Zr-93	1.2×10^{-8}
Ru-106	1.0×10^{-5}
Rh-106	1.0×10^{-5}
Actinides	
Pu-238	6.3×10^{-2}
Pu-239	4.3×10^{-3}
Pu-240	8.9×10^{-3}
Pu-241	1.4
Activation Products	
C-14	9.4×10^{-11}
Fe-55	5.7×10^{-8}
Co-60	1.4×10^{-7}
Ni-59	4.2×10^{-10}
Ni-63	6.2×10^{-9}
Zr-93	1.3×10^{-11}

[a] Assuming 12 LLW drums are dropped.

bedded salt at a New Mexico location. Their conclusions indicate that before 700,000 years from the time of waste burial, the major contributor to expected risk was a volcanic explosion at the site. After 700,000 years, leaching of the waste by groundwater begins to dominate the risk. They estimated that faulting sufficient to fracture the bedded salt formation and interconnect upper and lower aquifers was the most likely means for this failure to occur. The probability that this event would occur was estimated to be 1.4×10^{-7}/year.

A series of these low-probability/high-consequence accidents are also discussed in DOE/ET-0028, Vol. 4. The case of repository breach because of impact of a large meteorite is postulated to occur with a frequency of 2×10^{-13}/year. The consequence of this accident results in the release of 1 percent of the total repository inventory on impact, with one-half going to local fallout and one-half going to stratospheric dispersion.

The case of faulting followed by contact with circulating groundwater was also considered in this study. The estimated frequency of a fault intersecting the repository was assumed to be 4.10^{-11}/year. The probability that a high-pressure aquifer which will connect the waste with some surface access exists is estimated to be 5×10^{-3}. Therefore, the overall expected probability of occurrence for this accident is 2×10^{-13}/year. Once faulting and groundwater contact occur, the inventory of spent fuel, HLW, ILW, and LLW in the repository becomes available for leaching and transport to the surface.

Several other low-probability/high-consequence class accidents are discussed in this reference and in additional literature. Some of the postulated accidents more frequently addressed are: (1) tornado strike to mine surface storage area; (2) breach of repository because of nuclear warfare; (3) repository breach by drilling; (4) volcanism;

(5) erosion by glaciation; and (6) sabotage. These types of accidents will not be discussed here.

3.8.7 Transportation Requirements

Transportation requirements throughout this section have been based on the material leaving the facility. Thus, spent fuel or reprocessing wastes have been discussed in previous sections. However, the analytical model includes the option of spent fuel retrieval and subsequent processing in the model reprocessing facility. In this case, transportation requirements will be defined as in Section 3.7.7. Transportation requirements for a reference repository with reprocessing are given in Table 3.108.

3.8.8 Decommissioning

Decommissioning material and energy requirements for the reference deep geologic waste repository are expected to be minor. Contaminated structural materials and equipment can be placed in the mine excavation rooms during the backfilling operation. Presently, no substantive information concerning decommissioning of a deep geologic repository has been found; hence, the effects of such activities have not been included in this analysis.

TABLE 3.108

TRANSPORTATION REQUIREMENTS FOR A REFERENCE REPOSITORY WITH REPROCESSING

Waste Type	Number of Shipments Per RRY[(a)]
HLW	3[(b)]
Cladding Waste	9.2[(b)]
TRU-LLW	1[(c)]

(a) From Section 3.7.7

(b) rail

(c) truck

3.9 SHALLOW-LAND BURIAL OF WASTES

To date, essentially all low-level radioactive waste from both military and commercial use of nuclear materials has been disposed of by shallow-land burial. This waste generally has consisted of by-product material (including fission products), special nuclear materials (including transuranics, i.e., TRU), and source materials. Currently, only non-transuranic (<10 nCi/gm alpha activity), low-level waste is being accepted for burial with no capacity for retrieval.

Among the typical commercial sources of this low-level waste (LLW) are (1) university and industrial research centers, (2) medical diagnostic and treatment units, (3) nuclear power plant operations, and (4) other related fuel cycle activities. However, commercial LWR power plant operations and associated fuel cycle activities combined produce by far the largest volume of LLW. Therefore, for the purposes of this study, these will be the only source terms of LLW considered.

3.9.1 General Description

Six commercial, low-level waste burial grounds currently exist. They are located at West Valley, NY; Barnwell, SC; Morehead, KY (Maxey Flats); Sheffield, IL; Beatty, NV; and Richland, WA Only three of these facilities -- Barnwell, Beatty, and Richland -- are currently open. Similar wastes from military activities are being disposed of at five sites operated by the Department of Energy (DOE). The existing burial grounds are located in different geographic areas and, consequently, have varying hydrogeological characteristics. The four eastern commerical sites generally are classified as humid sites whereas the two western sites are considered dry sites. Although operational and engineering practices are essentially similar at all sites, individual site characteristics (i.e., ar   l rainfall, soil type, etc.) require that these practices be care   controlled, and strict monitoring programs are necessary to minimize the potential for release of radionuclides from the buried waste to the environment.

Earthen trenches are used at all sites as the primary burial facility. The trench design is similar at all facilities, with physical dimensions ranging from 60 to 120 m long, 8 to 20 m wide, and 5 to 8 m deep. Techniques to cover and seal the waste in the trenches vary with local climate, soil, and ground water conditions. Usually 1 to 3 meters of soil or excavation fill is mounded and graded over the top of the waste to facilitate runoff of surface water from precipitation. The engineering practices at this phase of burial are crucial because the single most important factor affecting the containment capability of the burial ground is the degree to which ground and surface water can contact the waste and, by leaching, cause subsequent migration of radionuclides.

The waste usually is shipped and buried in 55-gallon (210 ℓ) steel drums, in plywood, or in fiberboard boxes. Waste packaging methods currently in use are not intended to provide containment of the waste following burial because the soil is considered to be the primary container.

3.9.2 Model Facility Description

The model low-level waste burial site is assumed to be located in the humid, eastern United States because it has been estimated that about 90 percent of commercial low-level wastes will be generated in the central and eastern United States (based on currently planned nuclear power production). As of the year 1977, 80 percent of all commercial LLW had been disposed of in eastern sites.

The site will accept only low-level, non-TRU waste, that is packaged in 55-gallon steel drums. The majority of LLW is presently transported and buried in this manner, and the Department of Transportation (DOT) has published a proposed rule permitting only Class A containers (drums) to be used for transporting LLW in the future. However, licensing gives no credit for the waste package as a barrier, and any differences between package types as a barrier to actual releases following burial are not expected to be significant. Therefore, steel drums were assumed to be the reference transportation and burial containers for the purpose of calculating materials requirements.

A standard burial trench is assumed to be 100 m long by 12 m wide by 6 m deep, with capabilities for trench water monitoring and removal and treatment of water leachate. The capacity of the model commercial burial site over a 20-year lifetime will be 1.2×10^6 m^3, which represents an average of the capacities of the six existing commercial LLW disposal facilities. The capacities of the existing commercial sites range from 2×10^5 m^3 to 3×10^6 m^3.

3.9.3 Materials and Equipment Requirements

Although no specific information was found, the estimated annual materials requirements for construction and operation of the model LLW burial site are assumed to be negligible when compared to similar overall requirements for other facilities in the LWR fuel cycle. Resource materials for the construction of the site normally would be minimal amounts of steel, concrete, alumninum, and lumber. The equipment requirements during lifetime operation of the site would probably consist of ten to 20 front-end loaders, several heavy roller/compactors, and monitoring and testing equipment for trench surveillance.

3.9.4 Energy Requirements

Energy consumption during construction and operation of the model LLW burial site also has been estimated to be negligible over the life of the site when compared to other fuel cycle steps. Negligible amounts of petroleum products (gasoline, diesel fuel, oil) will be used in burial and grading operations, and small amounts of electricity will be used in a warehouse facility for administrative and record-keeping purposes. The amount of energy required for shipment of LLW per reference reactor year is given as the energy equivalent of 16 MT of coal. A reference reactor year (RRY) is a 1000 MWe reactor, assumed to be operating at 80 percent of its maximum capacity for 1 year.

3.9.5 Effluents

Effluents arising from model LLW burial site construction and operation will include nonradioactive and radioactive species. Nonradioactive effluents during construction and operation will result primarily from combustion of diesel fuel; however, no measures of quantities emitted were found. Effluents originating from combustion of diesel fuel during the transportation of LLW to burial sites have been estimated in Table 3.109.

The release and transport of radionuclides away from the disposal site may occur by several mechanisms:

(1) Contamination of the site surface from lateral migration through the soil zone from trench to land surface may result in radionuclide dispersal.

(2) Surface contamination caused by spills during burial and trench pumping operations may lead to subsequent transport of the contaminants by surface water.

(3) Atmospheric dispersion via the evaporator plume produced by volume reduction or solidification of low-level liquid waste may result in significant amounts of radionuclide dispersal to offsite locations.

(4) Subsurface migration of leach contaminants along joints and bedding planes in the underlying strata may lead to ground water contamination.

TABLE 3.109

SUMMARY OF ENVIRONMENTAL IMPACTS OF TRANSPORTATION OF RADIOACTIVE WASTES PER RRY (U RECYCLE)

Effluents	Amount (MT)[a]
Chemical	
Gases (including entrainment)	
SO_x	0.045
NO_x	0.62
Hydrocarbons	0.062
CO	0.38
Particulates	0.022
Other Gases	
Liquids	None
Solids	None
Radiological (Ci)	None
Thermal (10^9Btu)	0.014

(a) U.S. Nuclear Regulatory Commission, "Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," NUREG-0116, Supplement 1 to WASH-1248, October 1976.

Both on- and offsite surface and ground water release of 3H and other radionuclides have been observed at the West Valley, NY, and Maxey Flats, KY, sites, among others. Tritium is the predominant radionuclide identified in stack effluents from evaporation of wastes at the Maxey Flats burial grounds where discharge rates of ^3H ranged up to 1.9×10^3 μCi/sec. NUREG-0456 presents both calculated and measured release rates of several radionuclides from the evaporator plume at Maxey Flats (see Table 3.110) and annual release rates of certain radionuclides from continuous waste-handling operations at that burial site (see Table 3.111). Although operational practices at the Maxey Flats site may not be considered ideal because of the radionuclide releases experienced at the site, these practices and release rates are assumed to apply to the model burial facility. This is a conservative assumption because the actual performance of the model LLW burial facility, including the possible release of radionuclides over the long term, is uncertain at this time.

3.9.6 Occupational and Public Hazards

Occupational and public health hazards associated with the construction and operation of the model LLW burial facility may be divided into nonradiological and radiological consequences. Nonradiological hazards to workers during construction of the burial site would be related to the building of warehouses, office and administrative buildings, etc. There also would be occupational hazards to workers operating heavy equipment during the excavation of burial trenches over the life of the facility. No specific data were found on LLW occupational construction risks. Trade-specific data would be reasonable, but was not considered here because the impact is small compared with other facilities in the fuel cycle. No potential risks to the public are anticipated during construction of the model burial facility.

Occupational workers may be expected to receive routine doses of radiation during normal operations at the burial site, primarily from

TABLE 3.110

RELEASE RATES FROM EVAPORATOR PLUME

Nuclide	Calculated Release[a,b] Rate (pCi/sec/RRY)	Measured Release[a,b] Rate (pCi/sec/RRY)
H-3	4.5×10^{6}	4.1×10^{6}
Co-60	1.1×10^{1}	8.5
Sr-90	4.2×10^{-1}	9.0×10^{-2}
Cs-137	6.4×10^{1}	3.3×10^{2}
Pu-239	1.5×10^{-3}	2.0×10^{-3}

[a] U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?" NUREG-0456, June 1978.

[b] Calculated and measured release rates are from the Maxey Flats LLW Burial Facility.

TABLE 3.111

CONTINUOUS OPERATIONAL RELEASE RATES PER RRY

Nuclide	Annual Release Rate[a,b] (pCi/sec/RRY)
H-3	1.4
Co-60	0.48
Sr-90	6.3×10^{-4}
Cs-137	0.35
I-129	1.4×10^{-6}
Pu-239	4.1×10^{-3}

(a) U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste--What Waste Goes Where?" NUREG-0456, June 1978.

(b) Continuous operational releases came from normal waste handling procedures at the Maxey Flats site and do not include release rates from evaporator plume.

handling and burial activities. Data from NUREG-0216 give a range of exposures experienced in the operation of burial ground facilities. Doses ranged from 2 to 17.6 man-rem in the year 1974 and were as high as 36.2 man-rem for one facility in the year 1976 (see Table 3.112).

Occupational workers involved in the transportation of LLW to burial sites and members of the public also may receive radiation doses from normal waste shipments. Data from WASH-1238 indicate that the annual cumulative doses to truck drivers might be about one person-rem; to garagemen or service men, about 0.002 person-rem; to onlookers, about 0.6 person-rem if shipments are by truck and 0.1 person-rem if by rail; and to the general public along the shipping route, 0.4 person-rem if by truck and 0.1 person-rem if by rail. These doses are based on an average shipping distance of 500 miles, about 25 Ci/shipment, and 46 truckloads/year. NUREG-0116 gives radiological impacts from LLW shipments for two fuel cycle options; (1) U-recycle only (Option 2) and (2) the once-through, (Option 1) throwaway cycle. For uranium recycling only, 14.4 shipments/year and 23 Ci/shipment by truck are assumed, for an average shipping distance of 500 miles. For the throwaway cycle, 13.1 shipments/year containing 23 Ci/shipment for an average shipping distance of 500 miles were assumed. Transport workers may receive from 0.56 - 0.61 person-rem; onlookers, 0.13 - 0.14 person-rem; and residents, 0.12 - 0.13 person-rem (see Table 3.113).

Two atmospheric pathways that would affect offsite doses to members of the public during normal operation are considered significant. One is low-level, continuous release to the atmosphere from normal waste-handling operations of radioactive material which is carried offsite by dispersion (see Table 3.114). The second source of airborne release is from the evaporator plume, resulting from volume reduction or solidification of low-level liquid wastes. Tables 3.115 and 3.116 are based on Maxey Flats evaporator plume data. Finally,

TABLE 3.112

ANALYSIS OF BURIAL GROUND OPERATIONAL EXPOSURE EXPERIENCE

Site[a]	Year	Average Annual Individual Whole Body Exposure (rems)	Integrated Population Dose (person-rem)	Volume (ft^3)	Activity (Curies)	Man-Rem (ft^3)	Man-Rem (Curies)
Washington	1974	0.5	2.0	50,000	12,000	4.0×10^{-5}	1.6×10^{-4}
	1975	0.6	2.4	53,000	113,000	4.5×10^{-5}	2.1×10^{-5}
	1976	1.5	7.5	101,000	104,000	7.4×10^{-5}	7.2×10^{-5}
Nevada	1973	1.4	7	137,000	3,745	5.1×10^{-5}	1.9×10^{-3}
	1974	1.9	10	145,000	24,000	6.9×10^{-5}	4.2×10^{-4}
	1975	1.9	11	175,000	18,000	6.3×10^{-5}	6.1×10^{-4}
South Carolina	1976	0.88	36.2	1,420,000	90,200	2.5×10^{-5}	4.0×10^{-4}
Illinois	1969-1972	0.68	25.7	548,000	21,500	4.7×10^{-5}	1.2×10^{-3}
	1973	0.78	12.5	304,000	2,830	4.1×10^{-5}	4.4×10^{-3}
	1974	0.88	17.6	437,000	3,200	4.0×10^{-5}	5.5×10^{-3}
Total			132	3,370,000	392,000		

[a] Public comments and Task Force Responses regarding: U.S. Nuclear Regulatory Commission, "The Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," NUREG-0216, Supplement 2 to WASH-1248, Appendix H, March 1977.

TABLE 3.113

RADIOLOGICAL IMPACTS FROM WASTE SHIPMENTS

(NORMAL OPERATION)

Type of Shipment	Fuel Cycle Option[a]			
	U-Recycle Only		Throwaway (no recycle)	
	Exposure (Person-rem)[b]	Number of People Exposed	Exposure (Person-rem)[b]	Number of People Exposed
Low-Level				
Transport Workers	0.61	75	0.56	70
General Public - onlookers	0.41	70	0.13	65
- residents	0.13	$2.2x10^6$	0.12	$2.0x10^6$

(a) U.S. Nuclear Regulatory Commission, "Environmental Survey of the Reprocessing and Waste Management Portions of the LWR Fuel Cycle," NUREG-0116, Supplement 1 to WASH-1248, October 1976.

(b) Approximate number of shipments is 14.4 for U-Recycle, and 13.1 for Throwaway cycle, with an activity of 23 Ci/shipment. Maximum exposure rate from waste drums is assumed to be 10 mrem/hr at six feet.

TABLE 3.114

CONTINUOUS OPERATIONAL RELEASE RATES/RRY OF WASTE

Nuclide[a]	Annual Release Rate (pCi/sec/RRY)[b]	Concentration At Site Boundary (pCi/ℓ/RRY)	Inhalation Dose to Maximum Individual (mrem/yr/RRY)[c]	Critical Organ
H-3	1.4	2.6×10^{-8}	3.3×10^{-8}	Whole Body
Co-60	0.48	8.9×10^{-9}	5.3×10^{-5}	Lung
Sr-90	6.3×10^{-4}	1.3×10^{-11}	1.3×10^{-7}	Bone
I-129	1.4×10^{-6}	2.6×10^{-14}	1.2×10^{-9}	Thyroid
Cs-137	0.35	6.5×10^{-9}	4.0×10^{-10}	Liver
Pu-239	4.1×10^{-3}	7.4×10^{-11}	1.8×10^{-3}	Bone

(a) U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?" NUREG-0456, June 1978.

(b) Radionuclide releases result from normal waste handling practices and do not include radionuclide release from evaporator plume.

(c) Maximum individual dose is 500m downwind, with the average windspeed being 5.1 m/sec, and the release is from ground level.

TABLE 3.115

DOSE RATES FROM EVAPORATOR PLUME RELEASES

Nuclide[a]	Concentration at Boundary (pCi/ℓ/RRY)	Critical Organ	Dose (mrem/yr/RRY)[b]
H-3	4.3×10^{-2}	Whole Body	5.5×10^{-2} WB
Co-60	1.1×10^{-7}	Lung	6.3×10^{-4} L
Sr-90	4.1×10^{-4}	Bone	4.0×10^{-4} B
Cs-137	6.3×10^{-7}	Liver	5.5×10^{-4} LI

[a] U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?" NUREG-0456, June 1978.

[b] Exposure occurs at site boundary (500 m) from a continuous release from ten-m-high evaporator stack.

TABLE 3.116

ESTIMATED ANNUAL DOSE TO LIMITING RECEPTOR FROM EVAPORATOR STACK DISCHARGE

Radionuclide[a]	Solubility	Critical Organ	DCF[b] (rem/μCi)	χ_i (μCi/m³)	Annual Dose[c,d] (mrem)
H-3	sol.	Total body	1.71×10^{-4}	1.8×10^{-3}	2.6
Co-60	sol.	GI tract	2.13×10^{-2}	8.0×10^{-10}	1.4×10^{-4}
	insol.	Lung	7.44×10^{-1}		5.0×10^{-3}
Sr-90	sol.	Bone	1.11×10^{-1}	7.6×10^{-10}	7.1×10^{-2}
Cs-137	sol.	Total body	4.52×10^{-2}	1.0×10^{-7}	3.8×10^{-2}

(a) U.S. Environmental Protection Agency, "Radiological Measurements at the Maxey Flats Radioactive Waste Burial Site--1974 to 1975," EPA-520/5-76-020, January, 1977.

(b) DCF (Dose Conversion Factor) taken from ICRP Publications 2, 6, 10, and 10A.

(c) Annual dose to the limiting receptor, who is assumed to be an occupant of a residence 800m NNE of the ten-m-tall stack, is calculated by assuming a standard breathing rate of 23m³/day and an annual average radionuclide concentration χ_i μCi/m³ of the evaporator effluent.

$$\text{Dose, mrem/yr} = 23\frac{\text{m}^3}{\text{day}} \times 365\frac{\text{days}}{\text{yr}} \times \frac{10^3\text{mrem}}{\text{rem}} \times \text{DCF} \times \chi_i \frac{\mu\text{Ci}}{\text{m}^3}$$

$$= 8.4 \times 10^6 \times \chi_i \times \text{DCF}$$

(d) Not normalized to RRY.

offsite population doses from migrating ground water and surface water releases that have been contaminated by radionuclides leached from burial trenches have been calculated (see Tables 3.117 and 3.118).

Members of the general public may be exposed to radiation from one of several pathways because of radionuclides transported away from the burial trenches after decommissioning. Several mechanisms of radionuclide transport that would result in onsite doses to the public after institutional control of the site is relinquished have been identified. They are: (1) direct inhalation of contaminated dust by a reclaimer, (2) direct gamma exposure; and (3) use of water from a well at the site boundary. Direct gamma exposure after 100 years is significant only for ^{137}Cs and would amount to 10 mrem/yr/RRY of waste. Dose rates from direct inhalation of contaminated dust by a reclaimer and use of water from a well at the site boundary are presented in Table 3.119.

The preceeding tables were based on an eastern site and may be referred to as short-term effects that would occur during or shortly after operations at the site. Long-term effects include the migration-type sources and sources that might arise if the land were disturbed by a reclaimer. A summary of the short- and long-term effects discussed above is given in Table 3.120 for both eastern and western sites. These data are from a different reference, and the dose rates are smaller.

3.9.7 Transportation Requirements

Estimates for the transportation requirements of the model LLW burial site have been calculated. The average number of truck shipments of packaged, non-TRU LLW per RRY is 6? for Option 1 and 65 for Option 2. The distribution between fuel cycle facilities is given in Table 3.121. Using 750 miles as an average distance between facilities, 94,500 round-trip truck-miles are required in Option 1, and 97,500 round-trip truck-miles are required in Option 2. It is assumed that

TABLE 3.117

DOSE RATES FROM GROUNDWATER TRANSPORT

Nuclide[a]	Leach Constant (yr^{-1})	Peak Release Rate Into Surface Water (Ci/yr/RRY)	Time of Peak (yr)	Dose to Maximum Individual (mrem/yr/RRY)[b]
H-3	10^{-1}	1.9×10^{0}	85	2.2×10^{-1}
Tc-99	10^{-4}	2.0×10^{-6}	95	1.3×10^{-6}
I-129	10^{-1}	2.1×10^{-4}	85	1.7×10^{-1}
Ni-59	10^{-4}	6.1×10^{-7}	2.5×10^{5}	6.5×10^{-7}
Pu-239	10^{-5}	6.2×10^{-15}	8.0×10^{5}	5.2×10^{-13}

(a) U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?" NUREG-0456, June 1978.

(b) The calculations are based on a maximally exposed individual, consuming 100 percent of his drinking water requirements from the river without the benefit of filtration, sedimentation, or other treatment which would reduce the concentrations of contamination, and provide an upper estimate of the doses received from groundwater transport to surface waters.

TABLE 3.118

DOSE RATES FROM SURFACE WATER TRANSPORT

Nuclide[a]	Normalized Trench Water Concentration (pCi/ℓ/RRY) Measured	Normalized Trench Water Concentration (pCi/ℓ/RRY) Calculated	Activity Entering Creek[b] (Ci/yr/RRY)	Maximum Individual Ingestion Dose[c] (mrem/yr/RRY)
H-3	7.4×10^{5}	4.0×10^{6}	4.6×10^{-3}	5.3×10^{-5} WB[e]
Co-60	2.4×10^{4}	3.0×10^{3}	1.5×10^{-4}	6.6×10^{-4} GI-LIT
Sr-90	3.7×10^{1}	1.4×10^{2}	2.3×10^{-2}	1.9×10^{-4} B
Tc-99	(d)	3.4×10^{-3}	2.1×10^{-11}	1.4×10^{-11} GI-LIT
I-129	(d)	7.2×10^{-1}	4.4×10^{-9}	3.5×10^{-6} T
Cs-137	1.8×10^{3}	1.8×10^{4}	1.1×10^{-5}	1.3×10^{-4} L
Pu-239	2.1×10^{1}	4.2 x 10[illegible]	1.3×10^{-9}	1.1×10^{-7} B

(a) U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?," NUREG-0456, June, 1978.

(b) Based on calculated trench water concentrations.

(c) Maximum individual ingestion dose assumes all one's drinking water is taken from the creek.

(d) No data available.

(e) B = Bone
L = Liver
GI-LIT = Gastrointestinal and Lower Intestinal Tracts
T = Thyroid
WB = Whole Body

TABLE 3.119

MAXIMUM INDIVIDUAL DOSE RATES/RRY OF WASTE FROM INHALATION OF CONTAMINATED DUST BY A RECLAIMER AND INGESTION OF WELL WATER AT SITE BOUNDARY

Nuclide	Maximum Individual Dose Rate[(a)] (mrem/yr/RRY) Inhalation[(b)]	Well Water[(c)]
H-3	0	2.3
Fe-55	0	0
Co-60	0	0
Sr-90	5.7×10^{-4}	0.013
Tc-99	2.8×10^{-9}	2.7×10^{-6}
I-129	6.1×10^{-6}	3.6×10^{-4}
Cs-137	1.6×10^{-3}	0
Pu-239	9.6	1.1×10^{-3}

(a) U.S. Nuclear Regulatory Commission, "A Classification System for Radioactive Waste Disposal--What Waste Goes Where?" NUREG-0456, June 1978.

(b) The inhalation of contaminated dust by a reclaimer event is first considered to occur 150 years after institutional control has ceased.

(c) The well water reclamation event is site specific. Values listed are for a potential well drilled at boundary of Maxey Flats LLW Burial Site.

TABLE 3.120

SUMMARY OF RADIOLOGICAL IMPACTS FOR A SHALLOW LAND BURIAL FACILITY

	Eastern Site	Western Site
	(mrem/yr/RRY)	
Long-Term Effects[a]		
Reclaimer Inhalation[b]	0.060	0.060
Food Pathway	0.620	0.620
Reclaimer Direct Gamma Exposure[b]	0.340	0.340
Short-Term Effects[a]		
Onsite Well Water Consumption	0.080	0.040
Accidental Airborne Releases	0.200	C.200
Transportation Exposures[c]	0.010	0.030

[a] Ford, Bacon & Davis Utah, Inc., "Evaluation of Alternative Methods for the Disposal of Low-Level Radioactive Wastes," NUREG/CR-0680, July 1979. Data divided by 1,000 to obtain values per RRY.

[b] Assumed to occur only once, and lasting for ten hours.

[c] Assuming the total dose is borne by 1000 persons.

TABLE 3.121

LOW-LEVEL WASTE TRANSPORTATION REQUIREMENTS

	Number of Shipments Per RRY[a]	
	Option 1	Option 2
Conversion	4	3
Fabrication	6	6
Reactor	52	52
Reprocessing	0	3[b]
Total	62	64

[a] R.G. Lebo et al., "Nuclear Carrier Business Volume Projections: 1980-2000," ORNL/Sub-1381/1, May 1980

[b] Does not include TRU-contaminated LLW sent to geologic repository

the mode of transportation of LLW to a shallow-land burial facility is to be exclusively by truck.

3.9.8 Decommissioning

The occupational dose is not anticipated to be any different in the decommissioning of a LLW burial facility than during normal operation. Post-decommissioning dosage to the general public may result from any one of the pathways of radionuclide release discussed in Section 3.9.6 (e.g., direct inhalation of contaminated dust by a reclaimer). Pathways of radionuclide release such as evaporator plume, continuous release from normal operation, etc. obviously will no longer be significant after decommissioning.

Long-term caretaker requirements will be necessary to insure the integrity of the burial facility and to guard against the release of radionuclides before their decay. Also, unrestricted use of the burial facility land by future generations must be guarded against.

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4.0 THE COAL ENERGY PRODUCTION CYCLE

The coal cycle is comprised of the following stages:

1. Mining.
2. Processing.
3. Storage.
4. Power production.
5. Waste disposal.

The first two fuel cycle stages provide cleaned, processed coal for combustion in the fourth stage, a power plant that produces electricity by converting the chemical energy of coal into thermal energy by combustion. A third stage, storage of coal at the power production facility, is considered as a separate stage in order to identify effluents specific to that stage. The waste disposal stage includes treatment and disposal of heat, liquid wastes, and solid wastes produced during the power production stage. Major facilities included in each stage of the coal cycle are summarized in Table 4.1.

Because of the differences in methods of mining, coal characteristics, and modes of transportation between the eastern and western parts of the United States, the coal cycle is analyzed from a regional point of view in this study. Both underground and strip coal mines are common in the East; most western coal is obtained from strip mines. Most eastern coal is transported by barges and/or trains whereas most western coal is transported by unit trains.

Table 4.2 shows the amounts of coal required annually to operate a 1000 MWe power plant, the reference facility for this study. These figures are based on typical heat values for eastern and western coal and the other assumptions listed as footnotes in the table.

TABLE 4.1

COAL CYCLE FACILITIES

Coal Cycle Stage	Typical Facilities/Activities
Mining	Surface/underground mines
	Refuse disposal
	Waste water treatment
	Primary size reduction
Processing	Crushing/grinding
	Cleaning
	Drying
	Waste water treatment
	Solid waste disposal
Coal storage	Unloading facilities
	Conveying
	Storage piles (active and reserve)
	Surge bin
	Pulverizer
Power production	Pulverized coal boiler
	Steam turbine/generator
	Electrostatic precipitator (ESP)
	Flue gas desulfurization (FDG)
Water treatment/waste disposal	Natural draft wet cooling tower
	Waste water treatment
	Sludge/solid waste disposal pond

TABLE 4.2

ESTIMATED ANNUAL COAL REQUIREMENT FOR A MODEL COAL-FIRED PLANT

		Annual Coal Requirement (10^6 MT)[h]	
Stage	Coal Type	Model Plant	Unit Energy Production[a]
Power Plant[b]	Eastern	2.23	3.43
	Western	2.68	4.13
Coal Transportation and Storage[c]	Eastern	2.24	3.44
	Western	2.69	4.14
Coal Processing	Eastern[d]	2.41	3.71
	Western[e]	2.79	4.29
Mining	Eastern underground[f]	1.20	1.84
	Eastern strip[f]	1.21	1.87
	Western strip[g]	2.79	4.29

(a) Unit Energy = 1000 MW yr.

(b) Thirty-four percent plant efficiency and 65 percent capacity factor.

(c) Transportation, loading, unloading, and storage losses are assumed to be 0.4 percent.

(d) Seven percent loss in coal processing (1/3 of the coal is cleaned).

(e) 3.5 percent loss in coal processing (1/3 of the coal is cleaned).

(f) Assuming 49.6 percent and 50.4 percent strip.

(g) Assuming all western coal is strip mined.

(h) Assuming 11,640 BTU/lb for eastern coal and 9,670 BTU/lb for western coal (Table 4.3).

4.1 COAL MINING

4.1.1 General Description

In mining, coal is extracted from a bed or seam overlaid by soil or a rock formation. Choice of an extraction technique depends on (1) overburden thickness, (2) coal deposit characteristics, (3) geotechnical considerations, and (4) hydrologic properties, all of which may vary considerably from site to site or even within a given site. The strong dependence of environmental effects, occupational hazards, and energy costs on variable mine conditions makes hazard assessment difficult. The following analysis uses average conditions in the definition of a mining model. Local conditions at individual mines vary from those of the model and result in different health, safety, and energy use impacts.

4.1.2 Model Description

The present study consid[illegible] from idealized western and eastern coal-producing regions of the United States. Data on 1977 coal production for use by electric utilities in these regions are given in Table 4.3. On the basis of these data, model facilities are defined for a western strip mine, an eastern strip mine, and an eastern underground mine. The two eastern mines are combined in a composite model (49.6 percent underground and 50.4 percent open-pit) eastern mine. Western underground and lignite strip mines are not considered because of their minor contribution to production.

The model western strip mine is based on the coal seam and overburden thicknesses typical of the Powder River Basin of Wyoming. Annual production from the mine is 4.10×10^6 MT, which is 1.5 times the coal requirement of a 1000 MWe power plant. The model eastern strip mine is based on the coal seam and overburden thicknesses of the Illinois coal basin, which has an annual production rate of 3.55×10^6 MT. The model eastern underground mine has an annual production rate of

TABLE 4.3

U.S. COAL PRODUCTION FOR ELECTRIC UTILITY PLANTS IN 1977

Type of Coal Mine[(a)]	Annual Production (10^6 tons)	Heat Value (BTU/lb)	Percent of Total[(b)]	
			East	West
Eastern Underground	172.7	11,640[(c)]	49.6	
Eastern Strip	175.5	11,640[(c)]	50.4	
Western Underground	13.9	9,670[(d)]		10
Western Strip	102.1	9,670[(d)]		72.9
Western Strip Lignite	24.0	6,590[(e)]		17.1

(a) Federal Energy Regulatory Commission, "Annual Summary of Cost and Quality of Electric Utility Plant Fuels," DOE/FERC - 0015, UC-13, 1977.

(b) Breakdown is based on 1976 Coal Production data. "Energy Data Reports," DOE/EIA/0128, November 1978.

(c) Weighted average for 348 x 10^6 tons mined in the East.

(d) Weighted average for 116 x 10^6 tons mined in the West.

(e) Weighted average for 24 x 10^6 tons mined in the West.

9.64×10^5 MT. The power plant fed by these model mines is assumed to use 1.20×10^6 MT of strip mined coal and 1.21×10^6 MT of coal mined underground annually. Therefore, the surface mine supplies about three annual requirements whereas the underground mine supplies 0.8 annual requirements. Materials, effluents, energy use, and other data for each model mine are normalized on the model power plant requirement basis.

4.1.3 Material and Equipment Requirements

The material requirements for coal mines, including the model mines, are listed in Table 4.4. The equipment requirements for the model mines are listed in Tables 4.5, 4.6, and 4.7. The reported requirement estimates may be too high because no allowance is made for equipment salvage and reuse. The material requirements are reported on the basis of coal production rate and may not correlate exactly with actual material demands. However, the scope of the present analysis precludes a more detailed correlation.

4.1.4 Energy Requirements

The energy requirements for coal mines are listed in Table 4.8. Electrical consumption results from the use of electric stripping shovels in surface operations, the exclusive use of electric-powered equipment in underground activities, and operation of support facilities such as mine shops and coal-loading stations. Petroleum consumption is attributable to excavation and haulage equipment used in surface mining.

4.1.5 Effluents

Coal mining results in effluent releases onto the surface areas around the mining sites; into streams, rivers, lakes, and local ground water supplies; and into the air. In general, effluent releases from mining operations are dramatically affected by local conditions, especially in the West with its arid climate and persistent high winds. A

TABLE 4.4

ESTIMATED BASIC MATERIAL REQUIREMENT FOR COAL MINING

	Annual Requirement MT/10⁶ MT Coal Mined[b]		Annual Model Requirement (MT)	
Material[a]	Surface Mine	Underground	East	West
Aluminum	0.07	0.08	0.18	0.2
Antimony	0.08	0.03	0.14	0.23
Asbestos	0.01	0.004	0.02	0.03
Boron	0.004	0.0005	0.006	0.01
Cadmium	0.008	0.001	0.011	0.023
Chromium	0.20	0.99	1.43	0.57
Cobalt	0.003	0.001	0.005	0.009
Concrete	14.06	23.43	45.12	39.22
Copper	2.59	1.68	5.15	7.22
Iron	107.63	96.46	246	300.3
Lead	0.046	0.176	0.267	0.173
Manganese	0.834	0.826	2.0	2.33
Molybdenum	0.078	0.035	0.136	0.218
Nickel	0.312	0.239	0.664	0.87
Niobium	0.003	0.001	0.005	0.008
Silver	0.001	0.0005	0.002	0.003
Tin	0.0005	0.005	0.0065	0.002
Vanadium	0.003	0.001	0.005	0.008
Zinc	0.007	0.021	0.034	0.021
Explosives	~50	~2	~62	~140

[a] U.S. Geological Survey, "Demand and Supply of Non-fuel Minerals and Materials for the United States Energy Industry, 1975-90--A Preliminary Report," Professional Paper 1006 - A, B, 1976.

[b] Estimated mine lifetime is 20 years.

TABLE 4.5

WESTERN OPEN-PIT MINE EQUIPMENT REQUIREMENT

Item[a,b]	Depreciation Life (yr)	Number of Original Equipment	Number of Replacements	Total Number
Dragline (45 cu. yd.)	20	1	0	1
Bulldozer (with dragline)	10	1	1	2
Drill (overburden)	10	1	1	2
Wheel tractor scraper (with overburden drill)	5	1	3	4
Cable handler and reel	20	1	0	1
Coal drill	10	1	1	2
Shovel (coal)	20	1	0	1
Front-end loader (with coal shovel)	5	1	3	4
Truck (coal hauler)	7	7	13	20
Road grader	10	1	1	2
Wheel tractor scraper (reclamation and roads)	5	4	12	16
Bulldozer (reclamation and roads)	10	4	4	8
Water truck	10	1	1	2
Lubrication truck	10	1	1	2
Mechanic truck	5	1	3	4
Welding truck	5	1	3	4
Electrician truck	5	1	3	4
Supply truck	5	1	3	4
Explosive truck	5	1	3	4
Pickup truck	3	3	17	20
Forklift	5	1	3	4
Crane truck	10	1	1	2
Pump	10	3	3	6
Substation (1000 KVA)	20	2	0	2
Cable (ft)	5	16,000	48,000	64,000
Service buildings (ft^2)	20	36,000	0	36,000
Drill bits	---	---	---	15,000

(a) U.S. Bureau of Mines, "Basic Estimated Capital Investment and Operating Costs for Coal Strip Mines," Information Circular 8661, 1974.

(b) Estimated mine lifetime is 20 years.
Estimated mine annual capacity is 4.6×10^6 tons.
Estimated annual model plant requirement is 2.79×10^6 MT.

TABLE 4.6

EASTERN (ILLINOIS) OPEN-PIT MINE EQUIPMENT REQUIREMENT

Item[a,b]	Depreciation Life (yr)	Initial Requirements	Number of Replacements	Total Number
Stripping shovel	20	1	0	1
Drill (overburden)	10	2	2	4
Wheel tractor scraper (on overburden with drills)	5	1	3	4
Bulldozer (with strip shovel)	10	1	1	2
Cable handler and reel	20	1	0	1
Coal shovel	20	1	0	1
Front-end loader (with coal shovel)	5	1	3	4
Truck (coal haulers)	7	6	10	16
Road grader	10	1	1	2
Wheel tractor scraper (reclamation and roads)	5	3	9	12
Bulldozer (reclamation and roads)	10	3	3	6
Water truck	10	1	1	2
Lubrication service truck	10	1	1	2
Mechanic truck	5	1	3	4
Welding truck	5	1	3	4
Electrician truck	5	1	3	4
Supply truck	5	1	3	4
Explosive truck	5	1	3	4
Pickup truck	3	3	17	20
Forklift	5	1	3	4
Crane truck	10	1	1	2
Pump	10	2	2	4
Electrical equipment (10,000 KVA substation)	20	2	0	2
Cable (ft)	5	14,000	0	70,000
Service buildings (ft^2)	20	36,000	0	36,000
Drill bits	---	---	---	30,000

(a) U.S. Bureau of Mines, "Basic Estimated Capital Investment and Operating Costs for Coal Strip Mines," Information Circular 8661, 1974.

(b) Estimated mine lifetime is 20 years.
Estimated mine annual capacity is 3.9×10^6 tons.
Estimated annual model plant requirement is 1.21×10^6 MT (open-pit) and 1.2×10^6 (underground).

TABLE 4.7

EASTERN UNDERGROUND MINE EQUIPMENT REQUIREMENT

Item[a,b]	Depreciation Life (yr)	Initial Quantity	Number of Replacements	Total Number
Continuous miner	10	6	6	12
Loading machine	10	6	6	12
Shuttle car	10	12	12	24
Roof bolter	10	8	8	16
Ratio feeder	10	6	6	12
Auxiliary fan	10	7	7	14
Mantrip Jeep	10	6	6	12
Mechanic Jeep	10	3	3	6
Personnel Jeep	10	4	4	8
Trickle rock duster	10	8	8	16
Trickle duty rock duster	10	7	7	14
Supply motor	10	3	3	6
Supply car	10	25	25	50
36-inch rope-type belt conveyor (ft)	10	25,740	25,740	51,480
Mainline belt power center (300 KVA)	20	5	0	5
Section belt power center (150 KVA)	20	5	0	5
Section power center (1,000 KVA)	20	6	0	6
Section rectifier (200 kW)	20	6	0	6
Section switch house	20	6	0	6
Sectionalizing switch cable	20	7	0	7
High voltage (HV) cable [300 million circular mill aluminum (MCM AL)] (ft)	20	12,000	0	12,000 ft
PLM coupler	10	15	15	30
Section cable and coupler	10	---	---	---
Rectifier for track haulage	20	1	0	1
Trolley wire (ft)	5	24,740	74,220	$\sim 10^5$
Track (60-lb) (ft)	20	24,740	0	24,740
Fresh water lines (ft)	20	24,740	0	24,740
Pumps and lines	10	5	5	10
Scoop tractor	5	7	21	28
Battery charger	10	7	7	14
All service mask	5	12	36	48

TABLE 4.7 (Continued)

Item[a,b]	Depreciation Life (yr)	Initial Quantity	Number of Replacements	Total Number
Breathing apparatus	5	12	36	48
Self rescuer	5	250	750	1,000
Stretcher set	5	8	24	32
Safety light	5	100	300	400
Methanometer	5	100	300	400
Fire chemical car	5	4	12	16
Lamp (including accessories)	5	250	750	1,000
Dust sampler	5	20	60	80
Concrete portal	20	5	0	5
Bulk rock dust facility	10	1	1	2
Substation and distribution	20	1	0	1
Ventilation fan (dual)	20	1	0	1
Service buildings (ft^2)	20	36,000	0	36,000
Front-end loader	10	1	1	2
Forklift	10	1	1	2
Bulldozer	10	1	1	2
Utility truck	5	1	3	4
Pickup truck	5	1	3	4
Roof bolts	---	---	---	10,000
Mine drainage treatment plant	10	1	1	2

(a) U.S. Bureau of Mines, "Basic Estimated Capital Investment and Operating Costs for Underground Bituminous Coal Mines," Information Circular 8689, 1975.

(b) Estimated mine lifetime is ten years.
Estimated mine annual capacity is 1.06×10^6 tons.
Estimated annual model plant requirements is 1.21×10^6 MT (open-pit) and 1.2×10^6 MT (underground).

TABLE 4.8

COAL MINING ENERGY REQUIREMENTS

Source[a,b]	Consumption per MT			Annual Model Plant Requirement[c]	
	Western Open-Pit	Eastern Open-Pit	Eastern Underground	West	East
Electricity (KWH)	2.8	5	13	7.8×10^6	22×10^6
Petroleum Products[d]	42×10^3	38×10^3	---	120×10^9	46×10^6

(a) U.S. Bureau of Mines, "Basic Estimated Capital Investment and Operating Costs for Underground Bituminus Coal Mines," Information Circular 8689, 1975.

(b) A.K. Burton, "Capital and Operating Parameters for Off Highway Trucks," Mining Engineering, January 1978.

(c) Estimated coal requirements per model plant are:

2.79×10^6 MT western strip, or
1.2×10^6 MT eastern underground, plus
1.21×10^6 MT eastern open-pit.

(d) 140,000 gal. is assumed.

partial listing of estimated effluent release rates for the coal mining stage is shown in Table 4.9.

The impact of coal mining on surface areas depends on the type of mining operation. Surface mining, for example, results in alteration of current land use, changes in topography, loss of vegetation, and alteration of soils; the major surface effect from underground mining is subsidence. Because these effects have only a secondary impact on public health, they are not quantified in this analysis.

Releases from mining operations into local water supplies vary according to the type of mining operation. The major pollutants to aquatic systems are (1) mine drainage, (2) sediment runoff, (3) the mixing of fresh water with contaminated waters, (4) loss of fresh water supplies, and (5) the addition of trace metals to water systems. Mine drainage is the most common and potentially the most serious pollutant and, thus, is the only one quantified in this study. The movement of trace metals released to water systems, either from mine drainage or leaching from coal seams, is difficult to trace because the chemical forms of these substances are unknown. The final disposition and potential health effects from these trace metals are unknown.

Ambient fugitive dust levels are increased during both surface and underground mining activities. However, the nature and extent of the emission source depend on the location and size of the mine, specific mining activity, and existing abatement practices. Offsite releases may be less than the emission rates shown in Table 4.9 because much of the dust settles within the mine boundary. However, smaller particles tend to settle more slowly than large particles and can be carried further from the mine. No specific information is available on the percentage of small dust particles that escapes the mine area.

TABLE 4.9

EFFLUENTS FROM COAL MINING

	Release Rate, ppm				
Effluent	Eastern Surface	Eastern Underground		Western Surface	
Mine Drainage[c]					
TDS	4060[a]	4749[a]	4000[b]	2867[a]	2700[b]
TSS	549[a]	228[a]	20[b]	96[a]	20[b]
Total iron	52.0[a]	352[a]	3.0[b]	0.78[a]	0.50[b]
Dissolved iron	50.1[a]	268[a]	0.3[b]	0.15[a]	0.10[b]
Mn	45.1[a]	7.3[a]	2.0[b]	0.61[a]	0.10[b]
Al	71.2[a]	43.4[a]	1.0[b]	0.20[a]	0.10[b]
Zn	1.7[a]	1.5[a]	0.05[b]	0.14[a]	0.03[b]
Ni	0.71[a]	0.72[a]	---	0.02[a]	---
Hardness	1944[a]	1218[a]	---	1290[a]	650[b]
Sulfate	1842[a]	2370[a]	3000[b]	1297[a]	1400[b]
Ammonia	6.5[a]	12.0[a]	3.0[b]	4.19[a]	3.0[b]
Alkalinity	5[a]	59[a]	---	313[a]	---
Cl^-			100[b]		15[b]
F^-			1.0[b]		1.0[b]
Ca			200[b]		100[b]
Mg			50[b]		125[b]
K			10[b]		25[b]
Cu			0.01[b]		0.02[b]
Fugitive dust[a,d]					

(a) R.V. Watkins, "Activities, Effects and Impacts of the Coal Fuel Cycle," TEKNEKRON, Inc., Draft Report, Contract No. NRC-03-78-076, June 1979.

(b) U.S. Nuclear Regulatory Commission, "The Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977.

(c) The pH of eastern surface, eastern underground, and western surface effluents is 3.6, 4.0, and 7.0, respectively.

(d) Fugitive dust is given in units of kg/10^6 ton of mined coal as 0.44×10^6 for both eastern and western surface mines. Data were not found for eastern underground mines.

4.1.6 Occupational and Public Hazards

Safety hazards associated with coal mining are dependent on mine type, local geotechnical conditions, and mine design or operating practices. Major sources of occupational hazards in underground mines include rockfalls, fires, explosions, and equipment-related hazards. Respiration of dust may lead to pneumoconiosis (black lung disease) and subsequent disability. Surface mine hazards are mainly in the operation and maintenance of equipment and in the handling of explosives. The difference between underground and surface mining hazards is shown by the fatality rates: $0.082/10^6$ MT for surface mines and $0.49/10^6$ MT for underground mines. A high correlation exists be.ween inexperience and the fatality rate; therefore, any surge in employment is likely to be accompanied by a rise in fatalities. Although lack of mining experience can be alleviated by adequate training programs, future versions of the model described in Chapter 6.0 should consider the possible effect of workforce expansion on fatality and injury rates. Tables 4.10, 4.11, and 4.12 show estimates of occupational hazards data, public risks, and manpower requirements for the coal mining industry.

Comar and Sagan (see Footnote (a) Table 4.10) and the authors of WASH-1224 examined the literature to determine death and injury risks because of mining operations in order to support a model plant operating at 75 percent capacity. The results of the two studies are compared in Table 4.10. While the actual mining conditions do not conform to the conditions of the present model, the reported ranges identify the magnitude of health effects expected from the impact of the model mines.

Coal mining presents very little risk to the general public although some fugitive dust emissions (less than 10 microns in size) are respirable and may represent a health risk to those living downwind from a mine site. Combustion of slag coal in waste piles may produce harmful gases. Subsidence of underground mines may affect the

TABLE 4.10

COAL MINING OCCUPATIONAL HAZARD DATA

Hazard[a]	Comar and Sagan[b]	WASH-1224[c]
Premature Deaths		
Accident	0.45 - 0.99	0.96
Disease	0 - 3.5	
Non-fatal Injuries		
Accident	22 - 49	39.8
Disease	0.6 - 48	
Man-days Lost from Accidents		8186

(a) Hazards associated with the mining requirement for operation of the model coal-fired power plant.

(b) C.L. Comar and L.A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy, 1, 1976.

(c) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, August 1973.

TABLE 4.11

RISKS TO THE PUBLIC FROM MINING AND PREPARATION OF COAL

Hazard[a]	NUREG-0332[b]	Comar and Sagan[c]
Premature Deaths		
Coal Mining	0	
Coal Preparation	10	1 - 10

[a] Risk associated with the mining and preparation requirements for operation of the model coal-fired power plant.

[b] R.L. Gotchy, "Health Effects Attributable to Coal and Nuclear Fuel Cycle Alternatives," NUREG-0332, September 1977.

[c] C.L. Comar and L.A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy, 1, 1976.

TABLE 4.12

MANPOWER REQUIREMENTS FOR MINING COAL

Mine Type[a]	Estimated Productivity[b]		Annual Mining Man-days per Model Power Plant Requirements	
	MT/man-day	man-day/10^6MT	Eastern Plant	Western Plant
Open-Pit	35	28,600	34,600	79,700
Underground	11	91,000	109,000	---

(a) Federal Energy Administration, "Project Independence Blueprint Final Task Force Report: Coal," November 1974.

(b) Estimates represent an average value for new and experienced employees.

integrity of surface structures, but this is primarily a potential economic effect. Failure of berms enclosing water treatment ponds presents flooding risks. Although loss of life has occurred from such failures, there is uncertainty about the level of risk these occurrences impose on the public.

4.1.7 Transportation Requirements

Transportation requirements of model surface mines are assumed to be met by 120-ton (109-MT) trucks. Coal is hauled over private roads to processing or loading facilities within 3 miles (4.8 km) of the mines. For the western annual coal requirement of 2.79×10^6 MT to supply a model generating plant, about 25,600 trips, covering a total of 154,000 miles (246,000 km), are required. The eastern surface mine annual production of 1.2×10^6 MT requires 11,000 trips, totaling 66,000 miles (106,000 km).

Coal preparation facilities are assumed to be incorporated in the surface facilities of the eastern underground mine. Coal is delivered by mine conveyor or shuttle cars directly to the preparation plant.

4.1.8 Decommissioning

No information was found on the decommissioning of a coal mine. Structural materials and equipment that are not to be used at another site can be placed in the excavated portions of the mine and backfilled.

4.2 COAL PROCESSING

Coal processing is the second stage in the coal fuel cycle and basically consists of two processes: crushing and cleaning. Crushing produces coal of a size suitable for power plant use and for cleaning. Cleaning provides a product that is more environmentally acceptable, has more desirable combustion characteristics, and is more economical. In addition, meeting requirements for decreased SO_2 emissions from coal-fired plants by cleaning may be preferable to relying on flue gas desulfurization.

4.2.1 General Description

Coal processing plants are typically located adjacent to large mines or are centrally located for processing the production of several smaller mines. Such plants range in size from a few hundred tons to 20,000 tons per day in capacity. In 1972, 49 percent of the total U.S. coal production underwent some form of cleaning in addition to crushing; in 1973, 67 percent of all bituminous coal and lignite was cleaned.

The coal is first crushed and screened to a predetermined size. If the coal is cleaned, mechanical washing methods utilizing density differences between the coal and its impurities (slate, rock, sulfur-bearing pyrites) are used to separate the waste materials from the coal. Such methods include the use of centrifugal force and gravitational settling. The coal fines transported by water in these washing techniques are recovered by the use of settling ponds or a closed circuit separation system that includes a thickener and vacuum filtration.

Drying may be required for utilization of low-sulfur western coal (which has a relatively high moisture content) as a substitute for eastern bituminous coal in boilers designed for eastern coal. This step avoids derating of the boiler, incomplete combustion, and carbon carryover to areas not covered by soot blowers.

Coal cleaning may be practiced for a variety of reasons. First, removal of noncombustible materials from the coal reduces transportation costs. In addition, cleaning at the mine site before shipping generally results in less severe waste disposal problems than at the point of use. Cleaning also reduces the quantity of particulates in flue gases at the power plant, increases the heating value of the coal fed to the boiler, and reduces the sulfur content of the coal. Finally, cleaning promotes the uniformity of the chemical and physical properties of coal. Typical results of coal washing beneficiation are presented in Table 4.13.

4.2.2 Model Description

Processing plants are provided at each model mine and are capable of handling the total annual mine output. The model facilities in each region are assumed to provide coal crushing operations for the entire mine output and cleaning activities for 33 percent (the current cleaning rate in this country) of that output. During coal processing, a 7 percent product loss is assumed for eastern coal, and a 3.5 percent loss is assumed for western coal. The useful life span of the plant is assumed to be 30 years.

The annual coal processing requirement to support the model coal-fired plant, taking processing losses into account, is 2.41×10^6 MT for eastern coal and 2.79×10^6 MT for western coal. Material requirements, effluents, energy consumption, and other data are provided based on these coal requirements.

4.2.3 Materials and Equipment Requirements

Basic equipment requirements for the model processing facilities are listed in Table 4.14. The major material requirements are steel and

TABLE 4.13

AVERAGE ASH, TOTAL AND PYRITIC SULFUR CONTENT, AND WASHABILITY DATA FOR COALS FROM THE APPALACHIAN AND EASTERN INTERIOR REGIONS

Region[a]	Raw Coal Ash, %	Raw Coal Pyritic S, %	Raw Coal Total S, %	HV[e] BTU/lb	Sulfur Reduction Obtained in Washability Tests for 3/8-in Top Size Coal: 90% Yield[b] Pyritic S Reduction, %	90% Yield[b] Total S Reduction, %	60% Yield[b] Pyritic S Reduction, %	60% Yield[b] Total S Reduction, %	HV[e] BTU/lb
Northern Appalachian (Pa., northern W. Va., Ohio, Md.)	14.7	2.03	3.07	(d)	56	33	76	46	(d)
Southern Appalachian[c] (southern W. Va., Va., Tenn.)	11.2	0.79	0.93	12,000	(d)	(d)	(d)	(d)	13,200
Eastern Interior (Ill., Ind., western Ky.)	14.1	2.29	3.92	11,000	47	23	70	39	12,100

(a) Research and Education Association, "Sulfur Reduction Potential of U.S. Coals," Modern Energy Technology 2, pp. 1413-1422, 1975.

(b) Clean coal yield expressed as a percentage of raw coal fed to coal washing process.

(c) Alabama coals are not included in these data.

(d) No data.

(e) TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-078-076, June 1979.

TABLE 4.14

EQUIPMENT REQUIREMENTS FOR COAL PROCESSING PLANT

Equipment Item	Materials
Crusher	Steel
Screen	Steel
Slurry Sump	Steel, Concrete
Cyclone	Steel
Classifying Sump	Steel, Concrete
Vibrating Screens	Steel
Refuse Conveyor	Steel, Concrete
Secondary Sump	Steel, Concrete
Secondary Cyclone	Steel
Dewatering Screen	Steel
Centrifuge	Steel
Product Conveyor	Steel, Concrete
Solids and Clarification Cyclones	Steel

concrete; however, no information is available that specifies the required material quantities.

4.2.4 Energy Requirements

Estimates of the annual energy requirement for construction and operation of the model processing facility are not available.

4.2.5 Effluents

Effluents arising from coal processing plant operations are presented in Table 4.15. Airborne effluents result primarily from fugitive dust releases from crushing operations and from combustion products from energy supplied to the plant. Liquid effluents are based on the utilization of settling ponds for coal/waste separation. Utilization of closed circuit water systems for this washing procedure would significantly reduce these effluents; however, no data were found for such a system. The liquid effluents identified apply to surface water contamination only. Because no data were found to quantify these effluents, they do not apply to subsurface or ground water contamination from refuse piles or to the leachate from settling ponds.

4.2.6 Occupational and Public Hazards

Estimates of the occupational and public hazards associated with operation of the coal processing facilities are presented in Table 4.16.

4.2.7 Transportation Requirements

Based on the present transportation modes utilized by industry, the annual transportation requirements for operation of the model coal-fired power plant are presented in Table 4.17. Coal transportation is the subject of more detailed discussion in Appendix I.

TABLE 4.15

ESTIMATED EFFLUENTS FROM COAL PROCESSING

Effluents[a]	Release Rate, $MT/10^6$ MT of Processed Coal (MT)	Annual Release per Model Coal-Fired Power Plant Annual Requirement[b]	
		Eastern (MT/yr)	Western (MT/yr)
Airborne Gases and Particulates			
Particulates	30	22.1	26.5
SO_2	0.17	0.13	0.15
NO_x	20	14.7	17.7
Hydrocarbons	7.9	5.81	7.0
CO	5.6	4.13	4.95
Liquids plus Suspended Solids			
Total dissolved solids	1.1×10^3	825	957
Total suspended solids	19.8	14.6	17.5
Al_+	1.42	1.05	1.26
NH_3	1.68	1.24	1.50
Total ferrous metals			
Dissolved Fe	0.24	0.18	0.21
Suspended Fe	2.19	1.61	1.94
Mn	1.19	0.88	1.05
Ni	0.09	0.07	0.08
SO_4	620	462	561
Zn	0.17	0.13	0.15
Solids	9.0×10^5	6.6×10^5	7.9×10^5

(a) U.S. Department of Energy, Environmental Data for Energy Technology Policy Analysis 1: Summary, NCP/EV-6119/1, January 1979.

(b) Plant annual requirement is assumed to be 2.23×10^6 MT for eastern coal and 2.68×10^6 MT for western coal. Assumes 33 percent of coal supply is cleaned.

TABLE 4.16

ESTIMATED OCCUPATIONAL AND PUBLIC HEALTH HAZARDS ASSOCIATED WITH OPERATION OF COAL PROCESSING FACILITIES

	Annual Risk per Model Coal-Fired Power Plant Processed Coal Requirement		
	Injuries and Personal Disability	Premature Death	Man-days lost Accidents
Occupational Exposure	0.058-3[a,b,c]	0.02-0.05[a,b,c]	144-305[a,c]
Public Exposure	---	1-10[b]	---

[a] NESS Environmental Data Book, "Characterizations and Data in the Area of Coal," Vol. IV, Review Draft, August 1978.

[b] C.L. Comar and L.A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy 1, 1976.

[c] U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternative Sources of Electrical Energy," WASH-1224, August 1973.

TABLE 4.17

ESTIMATED COAL TRANSPORTATION REQUIREMENTS FROM THE PROCESSING PLANT TO THE MODEL COAL-FIRED PLANT

	Annual Requirements for Operation of the Model Coal-Fired Plant[a,b]			
	Number of Shipments[c]		Mileage[d] (mi)	
Transport Mode	Eastern	Western	Eastern	Western
Railroad	172	206	1.0×10^5	1.2×10^5
Barge	123	147	1.2×10^5	1.5×10^5

(a) U.S. Nuclear Regulatory Commission, "The Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977.

(b) Estimated coal transportation need for model plant is based on 2.23×10^6 MT of eastern coal and 2.68×10^6 MT of western coal.

(c) Based on 70 percent railroad use and 30 percent barge utilization.

(d) Based on 600-mile average round trip for rail, 1000 miles for barge.

Coal can be transported from the processing plant to the model coal-fired electric generating station by a variety of means, including rail, barge, truck, and slurry pipeline. Although all these options are being employed in widely varying degrees across the United States, transportation by truck and slurry pipeline is minor and has been neglected.

Railroads presently move 60 to 70 percent of the nation's annual coal production. Unit trains (normally consisting of several diesel electric locomotives, 70 to 100 open-top hopper cars with a capacity of 100 to 105 tons each, and one caboose) are used by the industry as the most expeditious modes for transporting coal by rail. The capacity of a unit train is about 10^4 tons, and the trains are estimated to travel an average distance of 300 miles from the processing plant to the power plant.

Inland waterways currently are utilized to transport 25 to 30 percent of the annual coal production. Barging operations generally are performed with ten to 20 barges of about 1000-ton capacity, each pushed by a 1000-hp towboat. They are assumed to travel an average distance of 500 miles from the mine to generating stations. Newer, larger barges and superships (up to 67,500-ton capacities) are anticipated to make water transport of coal even more attractive in the future.

4.2.8 Decommissioning

No information was found on decommissioning a coal processing facility. The processing plant is assumed to be adjacent to or near a coal mine. Therefore, structural material and equipment that are not to be used in another facility can be placed in the mine excavation and backfilled.

4.3 STORAGE

4.3.1 General Description

Coal storage at a power plant includes facilities which:

1. Handle coal as it arrives via rail, truck, or barge.
2. Store coal in active or reserve coal piles.
3. Convey stored coal from storage piles to the crusher house.
4. Pulverize coal and mix it with preheated air before combustion.

4.3.2 Model Facility Description

Upon arrival at the plant, the coal is removed from the transport vehicle at an unloading facility. These facilities are required to handle the shipments summarized in Table 4.17. The coal is then moved to either of two stockpiles: the live storage pile or the reserve pile. The live pile is used to maintain a steady coal supply to the burners between scheduled shipments with the minimum practical pile surplus. The permanent reserve typically holds a 100-day supply in a compacted pile to guard against interruptions in delivery. The pile arrangement allows for easy mechanical movement from permanent to live storage using crawler tractors with push blades.

The coal is conveyed from the live storage pile to a crusher house supplied with equipment for pulverizing and drying the coal and a 1500-ton capacity surge bin that provides continuous feed to the burner feed system. A ventilation system equipped with dust collection capability is provided to prevent coal dust releases, either inside the building or to the atmosphere. In addition to preventing particulate emissions, this system is also designed to minimize the potential for coal dust explosions. The pulverized coal is mixed with preheated air before combustion.

4.3.3 Materials and Equipment Requirements

The major material and equipment requirements for coal storage facilities are summarized in Table 4.18. Amounts of various materials required for the storage facility are included in the requirements for the overall power plant (Section 4.4.3). Chemicals for dust suppression and temperature control instrumentation for the reserve coal storage pile are provided as part of the model facility but have a negligible impact on the overall plant requirements and are not included in Table 4.18.

4.3.4 Energy Requirements

The principal energy requirements for the coal storage facility include diesel fuel for tractors and electricity for operating conveyors, fans, motors, the pulverizing facility, and the unloading facility. The electricity is supplied by reducing the net power plant output. Heated air for driers is supplied by hot flue gases. All these energy requirements are included as part of the overall power plant requirements (Section 4.4.4)

4.3.5 Effluents

Airborne emissions (including dust and gases from coal pile oxidation), water runoff, and noise are the major effluents from the operation of a typical coal storage facility. Water runoff contains coal particles and various minerals and trace elements that can lead to acidic discharges to local surface water and ground water supplies, particularly during heavy rains or flooding. These effluents are summarized in Table 4.19. The incremental quantity of airborne effluents resulting from spontaneous combustion in the coal storage piles or coal dust explosions in the pulverizer area is not included because data which quantify the potential for such incidents were not found.

TABLE 4.18

EQUIPMENT AND MATERIAL REQUIREMENTS FOR A TYPICAL COAL STORAGE FACILITY

Component	Number Required[a]	Materials
Railroad unloading facility	1	Steel, Concrete
Barge unloading facility	1	Steel, Concrete
Crawler tractors	2	Steel
Conveyor	1	Steel
Pulverizer	1	Steel
Drier	1	Steel
Surge bin	1	Steel
Ventilation fans	Several	Steel
Cyclone dust collector	1	Steel

(a) Federal Energy Administration, "Project Independence Blueprint Final Task Force Report: Availabilities, Requirements and Constraints on Materials, Equipment, and Construction," November 1974.

TABLE 4.19

ESTIMATED EFFLUENT RELEASES FROM COAL STORAGE FACILITIES

Type or Source	Effluent	Quantity or Concentration[a]
Airborne	Dust	14.3 MT/yr (Eastern plant)
		17.2 MT/yr (Western plant)
Water runoff[b]	TSS	1,551 ppm
	TDS	754 ppm
	$SO_4^=$	401 ppm
	Fe	39 ppm
	Mn	0.69 ppm
	Si	10.1 ppm
	CN	<0.001 ppm
	BOD_5	<3.8 ppm
	COD	1,436 ppm
	NO_3^-	0.31 ppm
	PO_4	
	Sb	4.6 ppm
	As	15.7 ppm
	Be	
	Cd	0.002 ppm
	Cr	0.004 ppm
	Cu	0.08 ppm
	Pb	0.06 ppm
	Ni	3.1 ppm
	Se	19.9 ppm
	Ag	
	Zn	0.8 ppm
	Hg	<0.001 ppm
	Tl	

TABLE 4.19 (Continued)

Type or Source	Effluent	Quantity or Concentration
Water runoff (continued)	Cl^-	0.27 ppm
	Total organic carbon	280 ppm
	pH	6.78 ppm
Unloading facilities	Noise	<50 db

[a] TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-78-076, June 1979.

[b] Average values. Actual amounts vary depending on type and amount of coal required at a specific facility and local rainfall conditions.

4.3.6 Occupational and Public Hazards

Occupational hazards associated with construction and operation of coal storage facilities are included in Section 4.4.6 for the overall power plant. Increased hazards to onsite personnel resulting from fires in coal storage piles or coal dust explosions in pulverizer facilities are not included because the potential for such incidents cannot be quantified. Hazards to the public from such accidents result from the incremental quantity of airborne effluents that are discussed in Section 4.3.5. Hazards to the public are significant only in cases of water-borne effluent releases that might occur as the result of such natural phenomena as flooding. The potential for such accidental releases has not been estimated.

4.3.7 Transportation

Transportation of coal to the storage facility at the power plant site is considered in Section 4.2.7. No additional offsite transportation requirements have been identified.

4.3.8 Decommissioning

No information was found on the decommissioning of coal storage facilities. Decommissioning would involve removing most of the coal to a power plant to utilize the energy content and covering residue with soil or deep filling of the site before reclamation. The effort is expected to be minimal compared with to the other operations in the coal cycle.

4.4 POWER PRODUCTION

4.1.1 General Description

The model power plant consists of facilities which:

1. Maintain controlled, efficient coal combustion.
2. Produce stream for use in turbine electric generators.
3. Regulate and distribute power to an offsite grid.
4. Control flue gas releases (particulates and SO_2).

In conventional electric power generating plants, the heat transfer system leads to production of superheated steam (usually at super-critical pressures) to drive the main turbines and generators. Modern coal-fired plants produce steam at 3500 psig, superheated to 1000°F with 1000°F reheat, and require 8500 to 10,000 BTU to produce a kilowatt-hour of electricity (corresponding to a conversion efficiency of 34 to 40 percent).

Coal combustion results in the production of sulfur oxides, nitrogen oxides, and particulate matter in the form of fly ash and bottom ash. Other potential effluents such as trace elements and radionuclides are produced in smaller quantities. Federal, state, and local air quality emissions standards require the control of such releases and have dictated the use of emission control technologies. A variety of such controls exists; however, discussions of the suitability of a particular control technology for a specific power plant location and configuration are considered beyond the scope of this document. The assumed control technology for the model power plant facility is specified in the discussion below.

4.4.2 Model Description

The model coal-fired electric generating plant consists of a dry bottom pulverized coal-fired boiler and a single-unit steam turbine and generator rated at 1000 MWe output. The overall plant has a thermal efficiency of 35 percent, a capacity factor of 65 percent, and a lifetime of 30 years. Coal requirements and characteristics assumed for the model facility are summarized in Table 4.20.

Emission control facilities include electrostatic precipitators (ESP) for particulates and lime/limestone scrubbers for flue gas desulfurization (FGD). For a boiler in which 80 percent of the ash in the feed coal is released as fly ash with a mass-weighted median size of 10-20 μ, particulate collection efficiency is assumed to be at least 99 percent. The FGD system is a wet, throwaway process with 85 percent sulfur reduction efficiency. A FGD system is required for the model eastern plant burning medium-to-high sulfur coal and also is included for the model western plant to conform to more stringent state and local air quality standards.

Control of NO_x emissions is achieved through combustion condition modifications such as low excess air firing and modern burner design.

The model plant utilizes a natural draft wet cooling tower for waste heat disposal and onsite treatment and disposal of liquid and solid wastes. These are discussed in Section 4.5.

4.4.3 Material and Equipment Requirements

The major material requirements for a typical 800 MWe coal-fired power plant are presented in Table 4.21. These requirements include the materials to manufacture the major equipment items presented in Table 4.22. Because these requirements are plant specific, they have not been scaled to the model plant. The material requirements also include the requirements for coal storage and waste disposal facilities.

TABLE 4.20

COAL REQUIREMENTS FOR THE MODEL FACILITY

Coal Type[a]	Quantity, 10^6 MT	HV, BTU/lb	Sulfur, Percentage	Ash, Percentage
Eastern	2.23	12,500	2.3	7.7
Western	2.68	9,670	0.8	6.3

[a] From Section 6, Table 6.5.

TABLE 4.21

MAJOR MATERIAL REQUIREMENTS FOR A MODEL COAL-FIRED POWER PLANT

Material	Quantity (tons)[a,b]
Aluminum	225
Copper	400-430[c]
Concrete (cu. yds.)	37,000[d]-53,500
Steel	29,000
Steel pipe & tube	5,650
Stainless steel	540
Steel forgings	350
Manganese	99.0
Molybdenum	37.3
Chrome	108
Nickel	9
Cobalt	trace
Silicon	trace
Tungsten	trace
Vanadium	3.4

(a) Includes material to manufacture major equipment items.

(b) Federal Energy Administration, "Project Independence Blue Print Final Task Force Report: Facilities," November 1974.

(c) J.P. Albers et al., "Demand for Non-fuel Minerals and Materials by U.S. Energy Industry 1975-1990," Geological Survey, U.S. Department of the Interior, 1976.

(d) Tennessee Valley Authority, "The Bull Run Steam Plant," Technical Report 38, 1967.

TABLE 4.22

MAJOR EQUIPMENT REQUIREMENTS FOR A MODEL COAL-FIRED POWER PLANT

Item[a]	Number Required	Capacity
Compressors	3	2,250 hp
	3	175 hp
	2	60 hp
Pressure Vessels	5	150-500,000 gal
	5	10-20,000 gal
Tanks	15	10-10,000 gal
	25	100-1,000 gal
Pumps	82	0-25 hp
	15	25-100 hp
	30	100-1,000 hp
	2	4,500 hp
Fabricated steel plate		1,075 tons
Power boilers	1	80,000 lb/hr
	1	5.46×10^6 lb/hr
Transformers	9	480 MVA
	2	75 MVA
	18	45 MVA
	14	30-40 MVA
	5	≤15 MVA
Turbines	1	800 MW
	2	22,170 hp
Valves and pipe fittings	500	up to 84 inches
Condensers	(b)	(b)

(a) Federal Energy Administration, "Project Independence Blue Print Final Task Force Report: Facilities," November 1974.

(b) No data found.

4.4.4 Energy Requirements

The principal energy requirements for the model coal-fired electric generating plant are listed in Table 4.23. These include requirements for the coal storage and waste disposal facilities.

4.4.5 Effluents

Release rates of airborne gases and particulates from operation of typical coal-fired steam plants are tabulated in Table 4.24. Effluents have been estimated for combustion of low-sulfur western coal and the higher sulfur western coal, both with and without particulate and sulfur control for both eastern and western plants.

Releases of trace elements (summarized in Table 4.25) are dependant on their concentration in the feed coal and can vary considerably among coal types. These elements are released during the combustion phase of the coal fuel cycle as particulates and volatile elements in the flue gas. The elements of major concern include arsenic, beryllium, cadmium, chromium, fluorine, mercury, nickel, and lead; most of these are volatilized during combustion and either condense on the fly ash particles or remain almost completely in the gas phase and escape up the stack.

Radionuclide effluents are summarized in Table 4.26. They are released in the noncombustible mineral matter of the bottom ash and fly ash, except for the gases and volatilized minerals that are released on combustion and incorporated directly into the flue gases. The more volatile trace elements (primarily lead and polonium) become concentrated on the smaller fly ash particles, resulting in the depletion of certain elements in bottom ash and their consequent enrichment in fly ash. These smaller particles are less efficiently collected and, thus, preferentially escape from the plant.

TABLE 4.23

ESTIMATED ANNUAL ENERGY REQUIREMENTS FOR MODEL COAL-FIRED POWER PLANT

	Energy Requirement			
	Thermal[c]	Electric[c]		
Activity	10^9 BTU	10^9 BTU	10^3 MW-hr	Percentage of Plant Output
Plant Construction				
Materials energy	4214	1519	468	
Direct energy consumption	1013	53	16	
Plant Operation (total)	2540	264	77	
Coal transport (in-plant)	(e)	(e)	(e)	(e)
Pulverizing	(e)	(e)	(e)	(e)
Burner blowers	(e)	(e)	(e)	(e)
Precipitators	(e)	(e)	(e)	0.2[b]-0.3[a]
Flue gas desulfurization	(e)	(e)	(e)	3-7[a,b,d]
Cooling tower	(e)	(e)	(e)	2[b]
Water treatment	(e)	(e)	(e)	<0.01[b]

(a) Argonne National Laboratory, "Environmental Control Implications of Generating Electric Power from Coal," ANL/ECT-1, Vol. II, December 1976.

(b) TEKNEKRON, Inc., "Activity, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-78-076, June 1979.

(c) Normalized to 747 MWe system. Oak Ridge Associated Universities, "Energy Requirements for Fluidized-Bed Coal Combustion in 800-1,000 MW Steam Electric Power Plants," ORAU/IEA(M) 77-4, February 1977.

(d) R.N. Budwani, "Fossil-Fired Power Plants: What It Takes to Get Them Built," Power Engineering, May 1978.

(e) Data not found.

TABLE 4.24

ESTIMATED EFFLUENTS FROM POWER PRODUCTION

Effluent	Release Rate, gm/MW-hr Western Uncontrolled	Western Controlled	Eastern Uncontrolled	Eastern Controlled
SO_2	5630,[a] 4010-4540,[a] 7048,[f] 5380[a]	1055[f]	33,500,[c] 4918-16,650,[d] 12,334[f]	3600,[c] 492-1665,[d] 1850[f]
NO_x	3280,[a] 3337,[f] 6279[a]	2001,[f] 6652[a]	3500,[c] 2781[f]	3480,[c] 1668[f]
CO	4.0,[a] 7.7[a]	7.7[a]	NA	4.0[c]
HC	1.2,[a] 2.3[a]	2.3[a]	NA	1.0[c]
Aldehydes	1.0,[a] 1.8[a]	1.9[a]	NA	1.0
Particulates	470,[a] 900[a]	68-113,[d] 94[f]	480[c]	500,[c] 42-72,[a] 72[f]

[a] Market Oriented Program Planning Study, National Energy Plan-II, "Coal Combustion, Table 5-3," Basis: 65 percent capacity factor, 98.5 percent efficient venture scrubber.

[b] Hittman Associates, "Environmental Impacts, Efficiency and Cost Energy Supply and End Use," HIT-S93, November 1974.

[c] U.S. Department of Energy and U.S. Environmental Protection Agency, Energy/Environment Fact Book, DOE & EPA - 600/9-77-041, December 1977.

[d] U.S. Nuclear Regulatory Commission, "Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977. Basis: 90 percent FGD, 100 percent capacity factor, 99.5 percen[illegible] [illegible]fficiency.

[e] "Annual Environmental Analysis Report," 4, Simulation Data Base, Mitrele Div./Mitre [illegible]

[f] TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft R[illegible]port, Cont[illegible] No. NRC-02-78-076. Basis: 70 percent capacity factor, 99.5 percent ESP efficiency, unclean[illegible] co[illegible] [illegible] percent FGD.

NA = Data not found.

TABLE 4.25

TRACE ELEMENT EMISSIONS FROM POWER PRODUCTION

Effluent	Release Rate, gm/MW-hr			
	Western Uncontrolled[a]	Western Controlled	Eastern Uncontrolled	Eastern Controlled
As	0.029	0.006-0.011,[d] 0.006[f]	NA	0.060,[f] 0.029-0.083[d]
Ba	NA	0.079-0.38,[d] 0.63[f]	NA	0.26,[f] 0.098-0.14[d]
Cd	0.026	0.004-0.005,[d] <0.001[f]	NA	<0.001,[f] 0.026,[d] 0.005[a]
Cr	0.057	0.024-0.036,[d] 0.012[f]	NA	0.027,[f] 0.060-0.10[d] 0.21[a]
Co	NA	0.012,[d] 0.002[f]	NA	0.010,[f] 0.028-0.035[d]
Pb	0.046	0.008-0.045,[d] 0.006[f]	NA	0.011,[f] 0.041-0.38,[d] 0.35[a]

TABLE 4.25 (Continued)

Effluent	Release Rate, gm/MW-hr			
	Western Uncontrolled[a]	Western Controlled	Eastern Uncontrolled	Eastern Controlled
Mn	NA	0.017-0.027,[d] 0.011[f]	NA	0.005,[f] 0.034-0.13[d]
Hg	0.095	0.014-0.015[d]	NA	0.002-0.005,[f] 0.049[d]
Se		0.038-0.091,[a] 0.002[f]	NA	0.006,[f] 0.091-0.15[d]
V		0.031-0.053,[d] 0.014[f]	NA	0.042,[f] 0.083-0.11[d]
Zn	1.36	0.057-0.24,[d] 0.013[f]	NA	0.049,[f] 0.076-0.083[d]
Ni	0.077		NA	0.057-0.11,[f] 0.064[a]
Sb		0.002[f]	NA	0.005[f]

TABLE 4.25 (Continued)

Effluent	Release Rate, gm/MW-hr			
	Western Uncontrolled[a]	Western Controlled	Eastern Uncontrolled	Eastern Controlled
Ga		0.005[f]	NA	0.013[f]
Mo		<0.001[f]	NA	0.002[f]
Br		<0.001[f]	NA	0.001[f]
Sn			NA	0.002[f]
Cu			NA	0.033-0.046[f]

(a) Market Oriented Program Planning Study, National Energy Plan-II, "Coal Combustion, Table 5-3," Basis: 65 percent capacity factor, 98.5 percent efficient venture scrubber.

(b) Hittman Associates, "Environmental Impacts. Efficiency and Cost Energy Supply and End Use," HIT-S93, November 1974.

(c) U.S. Department of Energy and U.S. Environmental Protection Agency, Energy/Environment Fact Book, DOE & EPA - 600/9-77-041, December 1977.

(d) U.S. Nuclear Regulatory Commission, "Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977. Basis: 90 percent FGD, 100 percent capacity factor, 99.5 percent ESP efficiency.

(e) "Annual Environmental Analysis Report," 4, Simulation Data Base, Mitrele Div./Mitre Corp. MTR-7626.

(f) TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-78-076. Basis: 70 percent capacity factor, 99.5 percent ESP efficiency, uncleaned coal, 85 percent FGD.

NA = Data not found.

TABLE 4.26

RADIONUCLIDE EFFLUENTS FROM POWER PRODUCTION

Effluent	Release Rates, mCi/yr[(a)]			
	Western Uncontrolled	Western Controlled	Eastern Uncontrolled	Eastern Controlled
U-238	234-529	32-72	82	(a)
Ra-226	283-369	20-35	58	9-19
Pb-210	172-345	36-107	385	30-89
Po-210	463	36-107	385	30-89
Th-232	209-308	17-20	44	7-13
Ra-228	191	16-25	159	12
K-40	751	42-44	492	106
Rn-222[(b)]	800-2600	800-2600	800-2600	800-2600

(a) H.L. Beck et al., "Perturbations on the Natural Radiation Environment Due to the Utilization of Coal as an Energy Source," Environmental Measurements Laboratory, U.S. Department of Energy.

(b) Based on all the Rn content of the feed coal released as part of the flue gas.

In addition to the effluents listed in Tables 4.24, 4.25, and 4.26, releases to the environment can occur from the coal storage piles, ash settling ponds, and nonregenerable desulfurization processes. A listing of the effluents associated with these sources, along with representative material concentrations, is presented in Section 4.5.5.

4.4.6 Occupational and Public Hazards

Occupational and public health hazards associated with construction and operation of a model coal-fired plant are based on estimated manpower requirements and are presented in Table 4.27. Construction manpower estimates include engineering, crafts, and project management during construction. These estimates have risen significantly in recent years because of increased size and complexity, added requirements for environmental considerations, declining labor productivity, and increases in the ratio of supervision to craft manpower. Variables that can impact the design and construction manpower requirements include (1) site specific design of environmental facilities for flue gas and water discharge, (2) control of thermal pollution, (3) design considerations associated with specific fuel and ash systems, (4) local labor conditions, (5) work rules including safety requirements, (6) weather conditions during construction, and (7) extent of shop fabrication. Occupational lost-time injuries and fatalities have been calculated for both facility construction and operation. Risks to the public (primarily related to effluent release) have been estimated only for plant operation. Hazards from accidents and from accidental releases of pollutants that have potential impacts on public health are not included.

4.4.7 Transportation Requirements

No significant offsite transportation requirements during facility operation have been identified.

TABLE 4.27

OCCUPATIONAL AND PUBLIC HEALTH HAZARDS FROM THE CONSTRUCTION AND OPERATION OF A MODEL COAL-FIRED PLANT

	Construction					Operation					
		Accident Frequency/ 10^6 man hours[a]		Lost-Time Injuries			Fatalities				
	Man-hours required[b]	Lost-time injuries	Fatalities	No.	Man-days lost	Man-hours required	No.	Man-days lost[d]	Lost-time injuries and disabilities	Fatalities	Man-days lost
Occupational Hazards	84×10^6[b] 4.8×10^6[e] 8.8×10^6[f] 3.6- 8.5×10^6[h]	13.6	0.17	114	5720	0.24×10^6[e] 0.23- 1.4×10^6[h]	1.4	5200	0.9-5.5[a,b,c] 0.88[g]	$(8.5-59)\times10^{-3}$[a,b,c] 20×10^{-3}[g]	150-845[b,c] 320[g]
Public	---	---	---	---	---	---	---	---	650[b]	0.065-100[b,c]	4550[b]

(a) C. L. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy 1, 1976.

(b) H. Inhaber, "Risk of Energy Production," AECB1119/Rev. 2, November 1978.

(c) U.S. Atomic Energy Commission, "Comparative Risk-Cost-Benefit Study of Alternate Sources of Electrical Energy," WASH-1224, August 1973.

(d) Assumes 50 man-days lost per injury and 3700 man-days lost per fatality.

(e) Federal Energy Administration, "Project Independence Blue Print Final Task Force Report: Facilities," November 1974.

(f) Power Engineering, May 1978, Basis: 7-10 man hours/ke-hr.

(g) NESS Environmental Data Book, "Characterizations and Data in the Area of Coal," Vol. IV, Review Draft, August 1978.

(h) TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-78-076.

4.4.8 Decommissioning

No information was found on the decommissioning of a coal-fired power plant. The material volumes given in Table 4.18 would be removed, and the occupational accident frequency rate of Table 4.27 would be applicable.

4.5 WASTE DISPOSAL

4.5.1 General Description

Onsite waste disposal facilities include systems which:

1. Transfer waste heat to the atmosphere via wet cooling towers.
2. Treat and dispose of solid and liquid wastes produced during plant operation.

4.5.2 Model Facility

Waste heat contained in turbine exhaust is transferred to the atmosphere by means of cooling towers. The most prevalent type currently in use in electric utilities is the natural draft wet cooling tower in which turbine exhaust is introduced at the bottom of the tower and flows upward through numerous layers of fill material. The heat extracted by the cooling air is exhausted to the atmosphere, and the condensed water is returned to the boiler. Natural draft cooling towers rely on the temperature and density difference between heated exhaust air and incoming ambient air to induce flow through the tower.

Liquid wastes that must be treated and ultimately discharged include sanitary water, ash transport water, cooling tower and boiler blowdown, various metal- and plant-cleaning wastes, and several low volume waste streams (e.g., scrubber waste water, waste streams from water treatment systems, condenser tube leaks, in-plant drainage systems, etc.). Storm water runoff from coal storage areas and solid waste disposal ponds must also be treated in the waste water treatment facility.

Major sources of solid wastes include bottom ash from the boiler (approximately 20 percent of the coal ash leaves the boiler as bottom ash) and fly ash, which is collected by the precipitator (>99 percent collection efficiency assumed). These solid wastes are usually mixed with the sludge from the FGD unit (about 50 percent solids) and stored in a solid waste disposal landfill. These landfill facilities are assumed to have control methods to prevent surface and subsurface water pollution, primarily through the leaching of toxic chemicals from ash. These methods include prevention or diversion of surface and subsurface water flows, proper drainage, and development of vegetative cover. Scrubber wastes present more difficult problems because it is physically impossible to dewater the sludge to the extent required to support weight (e.g., in a landfill). Although current practice favors disposal of unstabilized sludge, chemical fixation and combination of the sludge with fly ash to produce material suitable for landfill is the assumed disposal method for this study. This accounts for the uncertainty as to whether FGD sludge is considered a "hazardous waste" and, thus, requires the more controlled method of disposal. The amounts of solid wastes that must be stored for a model power plant are summarized in Table 4.28.

4.5.3 Materials and Equipment Requirements

The major material and equipment requirements for waste treatment and disposal facilities at a model coal-fired plant are included in Tables 4.21 and 4.22.

4.5.4 Energy Requirements

Energy requirements for operation of the waste treatment facilities primarily consist of electricity to run fans and pumps. This requirement is included in the overall plan energy requirements shown in Table 4.23.

4.5.5 Effluents

Waste heat is released to the environment from several sources (see Table 4.29). Other effluents from waste heat disposal include cooling

TABLE 4.28

SOLID WASTES FROM MODEL COAL-FIRED POWER PLANTS

Source	Quantity, gm/MW-hr
Bottom Ash	8,000-10,420,[a] 15270-16,430[c]
Recovered Fly Ash	31,450-41,240,[a] 60,150-64,690[c]
Recovered Fly Ash plus Bottom Ash	22,000-46,470,[c] 13,470[d]
Precipitator Sludge[g]	55,730,[a] 106,600-114,600,[c] 12,860-17,770,[f] 73,630-77, 780[e]

(a) Hittman Associates, "Environmental Impacts, Efficiency and Cost Energy Supply and End Use," HIT-593, November 1974.

(b) U.S. Department of Energy and U.S. Environmental Protection Agency, Energy/Environment Fact Book, 600/9-77-041, December 1977.

(c) NESS Environmental Data Book, "Characterizations and Data in the Area of Coal," Vol. IV, Review Draft, August 1978.

(d) Oak Ridge Associated Universities, "Energy Requirements for Fluidized-Bed Coal Combustion in 800-1,000 MW Steam Electric Power Plants," ORAU/IEA (M) 77-4, February 1977.

(e) Argonne National Laboratory, "Environmental Implications of Generating Electric Power from Coal," ANL/ECT-1, Vol. II, December 1976.

(f) U.S. Nuclear Regulatory Commission, "The Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977.

(g) Dry weights based on 50 percent moisture.

TABLE 4.29

SOURCES OF WASTE HEAT IN A COAL-FIRED POWER PLANT

Source	Quantity, MW/MW Output
Condenser losses	1.6-1.8,[c] 1.2[d]
Stack losses	0.22-0.30,[c] 0.32[d]
Cooling tower losses	0.0056[b]
Internal plant losses	0.12-0.21,[c] 0.17[d]
Total	2.7,[d] 25.2[a]

[a]Oak Ridge Associated Universities, "Energy Requirements for Fluidized-Bed Coal Combustion in 800-1,000 MW Steam Electric Power Plants," ORAU/IEA (M) 77-4, February 1977.

[b]Federal Energy Administration, "Project Independence Blueprint Final Task Force Report: Facilities," November 1974.

[c]NESS Environmental Data Book, "Characterizations and Data in the Area of Coal," Vol. IV, Review Draft, August 1978.

[d]U.S. Nuclear Regulatory Commission, "The Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977.

tower drift that may contain dissolved and suspended solids. The drift produces a plume that may create a ground fog under unfavorable meteorological conditions, thereby reducing visibility in the vicinity of the tower. The composition of these effluents is included with other liquid effluents.

Potential effluents from the various plant waste water streams include suspended and dissolved solids, metal ions, variations in pH levels, oil and grease, and other organic compounds. The type and quantity of effluents discharged from different waste water streams vary widely depending on such factors as mode of operation, make-up water quality, pretreatment requirements, in-plant treatment requirements, water chemistry control programs, extent of water re-use, and site-specific plant pollution control programs. Estimates of concentrations of various constituents in these waste water streams are summarized in Table 4.30. It should be noted that the quantity and type of water pollutants discharged from coal-fired power plants are not as easily identified or quantified as are air pollutants. Quantification is further complicated by the fact that utilities seldom monitor the composition of in-plant wastewater streams; therefore, the literature contains little data on this subject.

Effluents are released to the atmosphere and groundwater from solid waste disposal operations. Atmospheric releases consist primarily of fugitive dust resulting from hauling and land-filling operations; these releases have the same chemical composition as the bottom ash and fly ash. Groundwater releases are mainly leachates from the wet sludge and can include concentrations of various trace elements. These are difficult to quantify, however, because surrounding soils tend to absorb these contaminants before they reach surrounding aquifers in significant amounts.

Table 4.31 summarizes the trace element effluents from solid waste disposal operations. These effluents are generally released in the

TABLE 4.30

EFFLUENTS FROM WASTE WATER STREAMS FROM A TYPICAL COAL-FIRED POWER PLANT

	Concentration of Constituent, ppm					
Effluent	Coal Pile Drainage	Ash Pond Effluent	Scrubber Filtrate Effluent	Cooling Tower Drift	Cooling Tower Blowdown	Boiler Blowdown
TSS	864[d]	1000[d]		18-20[e]	18-20[e]	<1.0-10.0[c], 23[d]
TDS	2500-16000[a]	40-720[a]	5650[a], 3200-15000[c], 15000[g]	156-175[e]	264[f], 156-175[e]	50-700[c]
BOD_5						
COD			60-390[c]			
Organics					~80[c]	
pH[b]	8.2-12.5[d]	7.0[f]	3.0-10.7,[c] 8.3[g]		6.0-7.0[c], 8.7[f]	8.5-11.0[c]
<u>Trace Elements</u>						
A	66-440[a]	1.4-6.1[a]	--[a]			
As	0.01-0.60[a], 0.04[d]	0.009-0.08[a], <1-6.0[c]	<0.004[a], 0.14[g], <0.004-0.3[c]			
Be	--	--	<0.001[a], <0.002-0.14[c]			
B	--, 3.6[d]	--	9[a], 8.0-46.0[c]			
Ca	31-490[a]	32-280[a], 0-0.4[c]	1450[a], 520-3000[c]		51.2[f]	
Cd	--	--	0.025[a], 0.004-0.11[c], 0.003[g]			
Cr	--, 0.27[d]	0.008-0.05[a], 2.2-3.6[b]	0.008[a], 0.01-0.5[c], 0.09[g]		10-200[c]	
Cu	0.43-1.4[a]	<0.01-0.22[a], 0-7.2[c]	<0.003[a], 0.01[g], <0.002-0.2[c]			<0.05-2.0[c]
Cl	--	--	1850[a], 2300[g], 420-4800[c]		0.3-1.0[c], 75[f]	<0.01-10.0[c]
Fe	240-1800[a]	0.1-16[a]	--, 0.02-8.1[c]			
F^-	--	--	1.3[a], 0.07-10[c], 6.2[g]			
Hg	--, 0.003[d]	0.02-0.05[c]	<0.00006[a], 0.05[g], 0.0004-0.07[c]			
K	--	--	22[a], 5.4-32[c]		17.6[f]	
Mg	1.2-480[a]	<0.1-14[a], 30-1200[c]	220[a], 3.0-2750[c]		27.6[f]	
Mn	8.9-45[a]	<0.01-0.39[a], 2.6-4.8[c]	--, 0.09-2.5[c]			

TABLE 4.30 (Continued)

Effluent	Coal Pile Drainage	Ash Pond Effluent	Scrubber Filtrate Effluent	Cooling Tower Drift	Cooling Tower Blowdown	Boiler Blowdown
	Concentration of Constituent, ppm					
Na	--	--, 30-300[c]	130[a], 14.0-2400[c]		83.6[f]	30-400[c]
Ni	0.74-4.5[a]	--, 2.6-6.0[c]	--, 0.05-1.5[c]			
Pb	--	<0.01-0.23[a],	0.010[a], 0.01-0.4[c], 0.25[g]			
Se	0.001-0.03[a], 0.10[d]	0.012-0.025[a], 0.1-1.8[c]	0.022[a], <0.001-2.2[c] 0.08[g]			
$SO_4^=$	1800-9500[a], 6880[d]	58-230[a], 510[d]	1100[a] 720-10,000[c] 10000[g]		16.4[f]	100-400[c]
Zn	2.3-16[a]	<0.01-0.59[a]	0.002[a], 0.01-0.35[c] 0.2[g]		8-35[c]	
PO_4			0.03-0.41[c]		15-60[c], 2.0[f]	10-150[c]
Phenols						
NH_3					2-20[c], 1.2[f]	

(a) P.P. Leo and J. Rossoff, "Control of Waste and Water Pollution from Coal-Fired Power Plants," Second R&D Report, The Aerospace Corporation, EPA-600/7-78-224, pp. 143 and 140, November 1978.

(b) Values given for pH are unitless.

(c) TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract No. NRC-03-78-076.

(d) ANL/ECT-1, Vol. II.

(e) NESS Environmental Data Book, "Characterizations and Data in the Area of Coal," Vol. IV, Review Draft, August 1978.

(f) D.L. Drummonds, "Power Plant Water and Waste Management," Power Engineering, July 1978.

(g) U.S. Department, "An Asessment of the Solid Waste Impact of the National Energy Plan," BNL-50708, February 1978.

TABLE 4.31

TRACE ELEMENT EFFLUENTS FROM SOLID WASTE DISPOSAL

Element	Concentration,[a] ppm
As	0.01-33.0
Ba	2.00-500.0
B	41.80-211.0
Cd	0.40-25.0
Cr	1.60-17.0
Cu	10.00-104.0
Pb	1.00-290.0
Hg	0.01-6.0
Ni	13.00-75.2
Se	2.10-60.0
V	50.00-100.0
Zn	139.00-2,050.0

(a) U.S. Department of Energy and U.S. Environmental Protection Agency, Energy/Environment Fact Book, DOE/EPA-600/9-77-041, December 1977.

form of surface water runoff and leachate intrusion into ground water. However, the chemical form of these elements is generally unknown and is an important determinant in the transport mechanisms and toxic effects.

Radionuclide effluents from power plant solid wastes are summarized in Table 4.32. The major source of these wastes is the bottom ash from the combustion process that is sluiced to a holding pond or is stored in a landfill. However, the potential for redistribution of the radionuclides present in these wastes by leaching or other mechanisms is not known.

4.5.6 Occupational and Public Hazards

Occupational hazards resulting from construction and operation of onsite waste disposal facilities are included with the values for the overall power plant in Section 4.4.6. Hazards to the public are related primarily to effluent release and are significant only in cases of accidental releases such as breaching of a disposal pond or water overflow from a pond during heavy rain or flooding. The potential and consequences for such accidents have not been estimated.

4.5.7 Transportation Requirements

No significant offsite transportation requirements have been identified for operation of onsite waste disposal facilities.

4.5.8 Decommissioning

No information was found on the decommissioning of an onsite waste disposal facility. Decommissioning would involve covering landfills and ponds with a layer of soil and establishing a ground cover. Potential problems associated with the reclamation of landfill sites were discussed in Section 4.5.2.

IMAGE EVALUATION
TEST TARGET (MT-3)

6″

MICROCOPY RESOLUTION TEST CHART

IMAGE EVALUATION
TEST TARGET (MT-3)

6″

MICROCOPY RESOLUTION TEST CHART

TABLE 4.32

RADIONUCLIDE EFFLUENTS FROM WASTE DISPOSAL[a]

Element	Effluent,[a] mCi/plant-yr	
	Western Coal	Eastern Coal
U-238	101-189	124
Ra-226	128-169	110
Pb-210	54-94	(b)
Po-210	(b)	(b)
Th-232	101-148	96
Ra-228	101-142	(c)
K-40	418-459	866

(a) H.L. Beck et al., "Perturbations of the Natural Radiation Environment Due to the Utilization of Coal as an Energy Source," Environmental Measurements Laboratory, U.S. Department of Energy.

(b) Released as part of flue gas.

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5.0 OTHER CONSIDERATIONS

5.1 CLIMATIC CHANGES

Effluents from the two EPCs under study are not only capable of affecting local air quality but can also contribute to regional or global climatic changes. In general, climatic changes are induced by long-term, substantial releases of certain effluents. Climatic changes will have a health impact. The contribution of a single coal or nuclear power plant to such effects is negligibly small. However, such contributions must be taken into account when considering the long range national or international impact of power production. Assessment of the nature and the magnitude of the climate-health impact is impractical at the present time and must await resolution of controversies in the scientific community.

5.1.1 The Greenhouse Effect

Carbon dioxide is the major effluent from coal combustion; however, it is not referred to as a pollutant. Atmospheric measurements have indicated a steady increase in CO_2 concentration.[1,2,3,4,5] Carbon dioxide buildup in the atmosphere affects the climate through the "greenhouse" effect," the increase in atmospheric temperature when CO_2 molecules trap the heat radiated from the surface of the earth. Molecules of CO_2 tend to have minor effects on short wavelength incoming radiation, while absorbing the longer wavelength radiation (infrared waves 5- to 50μ) from the earth's surface.

It has been postulated that a doubling of the CO_2 concentration in the atmosphere could raise the temperature in the middle latitudes by about 3°C and near the poles by 9 - 12°C.[2] It also has been estimated that the emission of 1.2×10^{12} MT of CO_2[1] is associated with an average increase in earth temperature of 1°C. Such postulated increases may result in changes in rainfall patterns and possible gradual melting of the polar ice.

The rate of increase of CO_2 in the atmosphere depends on a complex balance between its emission and uptake mechanisms (sources and sinks). The two major sources identified for CO_2 emission are the burning of fossil fuel and forest fires. Natural CO_2 uptake mechanisms in the terrestrial biosphere are wood and soil humus; in the oceans, dissolved inorganic carbon; and in shallow water sediments, organic residue.[6] Storage in sea water is the dominant mechanism. It was claimed recently that the major source of CO_2 in the atmosphere is forest cutting and burning.[7,8,9,10,11] Broecher and co-workers tried to explain why the increase in CO_2 atmospheric concentration is only half as much as expected if all releases in the last decade from fossil fuel burning had remained in the air. They concluded that the ocean uptake and regrowth of forests cut in the past may have compensated for the excess CO_2.

The contribution of the model coal-fired plant to the greenhouse effect is uncertain, and the quantitative relationship of the greenhouse effect to human health impact is less certain. For these reasons, the health impact of CO_2 will be ignored in this study.

5.1.2 Other Climatic Effects

Two other effluents may have the potential to induce a climatic change. First, heat and moisture releases from the coal-fired plants and LWRs have the potential to change local climate.[11,12] The energy flux from cities can be as much as four times that from solar heating (global average). One of the climatic changes produced by cities is an increase in precipitation from 5 to 10 percent,[13] but other climatic changes are harder to assess. In addition to increased heat convective activity, cities also add a variety of particulates and aerosols to the atmosphere, and climatic changes may be due to the heat, the aerosols/particulates alone, or some combination of both. While the heat releases from a point source such as a power plant are not truly analogous to the very large area source from a city, the increase in convective activity in and around cities from large power stations has the potential to augment natural convective processes. The result may be an increase in thunderstorm violence or, under some conditions, a dimunition of this violence because of early triggering of the storm.

If the thermal energy of a large power-generating facility is spread uniformly at a heat flux density no greater than that of New York City (i.e., three to four times the average solar heat flux at the ground), it is not likely to augment the natural convective activity any more than the contribution of a very large city. Since the concentrated heat addition of a power-generating facility could result in greater convective activity, this effect should be considered in setting criteria for siting power parks. On the other hand, a larger heat emission value could be used for the non-power-park model plants of this study. For example, the Hartsville and Phipps Bend nuclear power reactor sites occupy sites of 1.58 and 2.0 km^2 per 1000 MWe whereas a value of less than 1 km^2/MWe would be required to approach the energy flux of New York City.[14] Therefore, it is concluded that heat dissipation effects can be neglected for this study.

Large water vapor additions occur, except in the case of dry cooling systems, and the result may be increased fogging and icing. However, in the case of once-through cooling, the effect is reduced and spread out, and because of the large plume rise distance for natural draft towers, the problem is virtually eliminated. Another effect of the large water vapor addition is an increase in atmospheric convective activity. The natural accumulation of water vapor in the atmosphere during periods of strong convection is 10^6 gm/sec/km^2.[13] The evaporative cooling rate for a 1000 MWe power plant typically results in a moisture release of about 5.6×10^5 gm/sec or 2.2×10^6 gm/sec per four-plant site. On a 16 km^2 site typical of the model facility, the moisture rate would be about 15 percent of that from natural causes (depending on local conditions). Therefore, the cooling system of a 16-square-kilometer site containing four model LWR units would have little atmospheric effect compared with natural atmospheric dynamics.[14]

The other potential effect is related to the release of Kr-85 in the uranium EPC. It was postulated that substantial releases of Kr-85 can induce changes in the electrical characteristics of the atmosphere that will affect the heat exhange between the atmospheric layers through thunderstorms. No data have been found to quantify this effect.

5.2 ACID RAIN

Acid rain is recognized as one of the most serious ecological problems of burning fossil fuel.[1,4,15,16] Sulfur and nitrogen oxide pollutants interact with the oxygen and moisture in the atmosphere to produce sulfuric and nitric acids. These acids are then scavenged from the atmosphere by precipitation.

Because of the presence of carbon dioxide in the atmosphere, the natural pH value for precipitation is 5.6.[15] Currently, precipitation in the eastern United States has a mean annual pH value between 4 and 4.5 whereas some storms have a pH value as low as 3.0.[15]

Acid rain tends to leach nutrients from the soil and change its chemistry. This change affects plant life and vegetation growth. Higher acidity has been observed in the lake waters of northern Europe and the eastern United States and Canada.[17,18] Aquatic life is adversely affected by the increased acidity. This effect ranges from inhibition of algae growth to large fish kills following acid snow melts.[15] In addition, increased acidity in the lake waters increases the solubility of metals and mobilizes heavy metals in the bottom sediments.[4,19] The human food chain and, subsequently, human health is affected by acid rain. The magnitude of this effect still requires a complete scientific evaluation.

Quantification of the contribution of the model coal-fired plant to the increase in rain or snow acidity is complicated by too many unknowns in the atmospheric transport and deposition mechanisms to be considered in this study.

5.3 EFFECTS OF SABOTAGE AND DIVERSION

Sabotage can affect both EPCs under investigation, but it is generally of major concern only in case of the nuclear EPC. Diversion of nuclear material is applicable to the nuclear EPC and is discussed below in general terms, with greater emphasis on Options 1 and 2 (once-through fuel and uranium recycle options) analyzed in this report. However, it is important to note that Option 3 (Pu recycle and mixed oxide LWR fuel option), which is not considered in this report, represents a greater diversion concern than the other two options. The subject of nuclear proliferation is still controversial. Although proliferation has a potential world-wide health impact, this subject is beyond the scope of this study.

The objective of sabotage would be to expose the public or workers to radiation or to threaten such action. Sabotage could be carried out by (1) outsiders (non-EPC facility workers or employees), (2) collusion between outsiders and insiders, or (3) by a group of insiders. Motivation for such an act would vary with the saboteur or group of saboteurs and could be political, psychological, or for monetary gain. Sabotage would have to be carefully planned, requiring detailed knowledge about the target facility layout and design features and might require procurement of sabotage aids (firearms, ancillary devices, etc.). A sabotage group might enhance its effectiveness with a large attack force, but such a force would increase the likelihood of the group's exposure. The most important potential sabotage targets are the model LWR, followed by the reprocessing facility, and, to a lesser degree, the model repository becuase of its remote location from populated centers. The potential consequences of sabotage in the fuel fabrication facility increase with processing of mixed oxide fuels (Option 3).

Diversion is the theft of SSNM*, SNM**, or radioactive waste for the purpose of constructing a dispersal weapon that would expose the public to radiation or to the ingestion of potentially carcinogenic isotopes. Weapons-quality fissionable materials may be used to manufacture homemade bombs.[1] The explosion of such devices (in case the divertors have the know-how and adequate fabrication capabilities) may result in an impact that varies from limited to considerable property destruction and fatalities (depending on the size of the explosion and the affect-area population density). Moreover, dispersal of plutonium or radioactive waste in the air, water supplies, or land areas will also induce varying degrees of health effects.

Table 5.1 shows conservative estimates of amounts of fissionable materials and the critical time required to convert these materials to nuclear explosive components.[20]

It is also important to note that transportation links in the nuclear EPC are highly vulnerable to acts of sabotage and diversion and have been identified as the weakest links in the cycle.[21,22]

To combat acts of sabotage and diversion, strict safeguard measures are taken. The layout and design of modern facilities include many features that enhance access and surveillance controls, including security forces, TV and intrusion monitors, SNM detectors, etc. An elaborate material accounting scheme is also used to detect materials unaccounted for (MUF). Transportation of SSNM or quantities of SNM

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*SSNM: "Strategic Special Nuclear Material" contains more than 20 percent by weight of U-235, U-233, or Pu.

**SNM: "Special Nuclear Material" contains less than 20 percent by weight of U-235, U-233, or Pu or is material of any enrichment of U-235, U-233, or Pu containing a high level of radioactive fission products.

TABLE 5.1

THRESHOLD AMOUNTS AND CRITICAL TIMES

Material Composition	Threshold[a] Amount	Material Form	Critical Time[b]	
			Activity Less Than 10^5 Cu/kg	Activity More Than 10^5 Ci/kg
Plutonium	8 kg	Metal	2 days	---
		Pure compounds	2 weeks	---
		Other compounds	6 weeks	2 months
Low enriched uranium less than 10% enrichment	75 kg U-235	All	12 months	15 months

[a] Threshold Amounts: the approximate amount of nuclear material required to produce a nuclear explosive.

[b] Critical Time: The approximate time required to convert nuclear material from safeguarded forms to nuclear explosives components.

above the threshold amounts is escorted by a security force with proper communications capabilities. Present inclinations are to locate reprocessing and fuel fabrication facilities in close proximity to plants to minimize or eliminate plutonium transportation risks (Option 3)

Even under the assumption that these security measures can all be breached, there are many other features that either discourage the saboteurs or divertors or make their target unworthy of the effort. Among these features is the high activity in spent fuel or high-level waste and the massive shipment casks, the low enrichment levels in the fuel materials, and the contamination of Pu-239 with other Pu isotopes making it an unattractive weapon material. Moreover, a serious release accident has to coincide with a very special weather pattern to have a major health impact.

An accurate estimation of the consequence of sabotage and diversion acts is difficult because of the uncertainties involved. Taylor[23] suggested that a homemade bomb yield would be equivalent to 100 tons of TNT, and one or two of these explosions may occur within the next 50 years. Using these numbers and assuming 400 operating reactors within the next 50 years, one can conclude that the number of fatalities per reactor year ranges between 3.4×10^{-3} and ten, where the lower and upper bounds are calculated for average, national, and high-density urban areas, respectively.

The consequences of sabotage or diversion may be large, but highly uncertain. Relating these consequences to one power plant year operation will unavoidably involve some degree of arbitrariness and speculation.

5.4 FUEL RESOURCES DEPLETION AND EXPLORATION

Planning for a new power plant includes assuring its fuel supply during its projected lifetime. It is always desirable to use the highest quality coal or the highest grade uranium ore to supply power plant fuel requirements. Unfortunately the high-grade ore deposits are rapidly being depleted, which will eventually lead to the use of high sulfur coal or low-grade uranium ore. Thus, exploration for new resources is essential for both of the EPCs.

Exploration programs start with the selection of a number of potential mining sites. This is followed by a reconnaissance survey and sampling missions, possibly by a seismic survey of these areas, and finally by construction of temporary roads and by drilling boreholes to assess the potential of candidate sites.

Reconnaissance activities may include the use of planes or land-based vehicles. Road construction, excavation, and hole drilling involve the use of heavy machinery and explosives. These activities thus represent some risk to the personnel involved. Moreover, the use of heavy machinery and transporation vehicles enhances erosion and increases sedimentation load of local streams.[4] The boreholes drilled may penetrate several aquifers and can result in leakage between them. Consequently, exploration has ecological and health impacts. These impacts are judged negligible to the overall results of this investigation.

5.5 LONG-TERM EFFECTS

At least two results of producing electricity from coal and uranium fuels may produce effects many years afterwards: (1) emanation of radon from uranium ore milling waste piles and from coal waste piles, and (2) possible future breach of fossil and nuclear waste repositories. Although the nuclear aspects of these two results have received more attention, the coal aspects deserve attention also. The nuclear effects are controversial and have been the subject of recent attention. The uranium mill tailings situation is discussed first, followed by the other long-term effects in Section 5.5.2.

5.5.1 Uranium Mill Tailings

Tailings from the uranium milling process are released as a slurry which is discharged into the tailings pond. After mill operations cease, the pond is left to dry up leaving behind dry residues which are piled in the vicinity of the mill. Tailings contain radioactive isotopes, mainly uranium and uranium decay products. These decay products include Th-230 which decays to Ra-226 with a half-life of 8×10^4 years. Ra-226 decays in Rn-222 which is a short-lived noble gas with a halflife of 3.72 days. Rn-222 progeny include the alpha emitting isotopes Po-218, Bi-214 and Po-214.

The health hazards associated with mill tailings includes inhalation of wind blown dust, inhalation of radon progeny, exposure to gamma radiation from radon and its progeny, and ingestion of surface water containing radionuclides leached from the pile or food exposed to contaminated water.[24]

Uranium milling facilities are usually located in sparsely population areas. Liquid waste treatment programs, as well as the discharge of liquid wastes to streams that are not used for irrigation or public water supplies, assure a very low level of exposure of the neighboring population. Exposure to gamma radiation is insignificant except for locations directly over the unstabilized tailing piles or when tailings are used for land fill and other construction long term Rn-222 transport as the principal factor that may make a significant contribution to population dosages.

One method of controlling the release of radon is called stabilization. Mill tailings can be stabilized by grading the tailings area to facilitate drainage and covering the tailings with rubble and dirt. Thick earth covers of 8 to 20 feet are estimated to reduce radon emanation by 80 to 95 percent and also to protect the pile against wind and surface water erosion.[25] Covering a 15-feet-deep dry pile with 2 feet of earth reduces the radon release by about 25 percent, while 20 feet of earth cover can result in an attenuation factor of 10.[25] Thin earth covers, especially those supporting vegetation, minimize the release of wind-blown dust but have a negligible effect on radon release.

Asphalt can be used as a radon diffusion barrier. An asphalt layer of one-fourth of an inch topped with two feet of earth is equivalent to 16 feet of earth containing 4 percent moisture. A 5/16-inch layer of asphalt is equivalent to 20 feet of earth.[25] The earth cover is provided mainly to protect the asphalt from weathering, especially from freezing and thawing which can induce cracks. The earth cover is topped by coarse rock or vegetation to reduce erosion.

Pile stabilization or asphalt sealing can thus minimize radon emanation from the tailings. Unfortunately cracks will eventually develop in the asphalt layer. Although these cracks may be detected and patched, from a long term view point (considering the Th-230 halflife), it is evident that pile stabilization or sealing with asphalt is only an interim rather than a permanent solution of the problem of controlling radon release.

More permanent solutions can be achieved by disposal of the tailings in underground uranium mines as part of the mine decommissioning procedure. Open-pit mines can be partially backfilled with mine waste from subsequent mine operations until the pit bottom is well above the water table and then tailings can be used as fill and covered with a thick layer of earth topped by vegetation or coarse rock.

Another solution can be achieved by chemical extraction of Th-230 and Ra-226 as a part of the milling process. Thorium and Radium can be disposed in a high level waste repository or irradiated in a reactor for transmutation.[26] Implementation of these procedures would add significantly to the cost of recovering uranium.

Estimation of the long term effects of radon emanation from tailings piles has stirred a lot of controversy in the scientific community. Health effects estimates have produced widely varying values. A study of EPA[27] used a model mill facility with a capacity identical to the one in Sction 3.2. The model was assumed to produce 18 x 10^6 MT of tailings over a 30-year period; the tailings occupied an area of 10^6 square meters; and the radon release rate was assumed to be 550 Ci/year during plant operations and 16 x 10^3 Ci/year from the dry tailings in the post operations period. A simplified dispersion model was used to estimate 121 cases of lung cancer in the U.S. (200 in the northern hemisphere) from the first 100-year dose commitment from 30 years of operation. Since the annual mill production of U_3O_8 can supply 5.4 GWe-yr, the estimated 100-year dose commitment per LWR year can result in about 0.8 lung cancers in the U.S. (1.23 in the northern hemisphere).[27] Use of a different dispersion model resulted in reducing these estimated to 0.2 lung cancers in the U.S. (0.37 in the northern hemisphere) for a 100-year dose commitment per LWR year under the assumption of no population growth.[28] Pohl[29] raised the issue that the long halflife of Th-230 will result in health effects from the release of Rn-222 for thousands of years. Extending the 100-year results indefinitely, the integrated effect of mill tailings from 1 year of LWR operation is estimated to be about 160 lung cancers in the U.S. (about 300 for the northern hemisphere). Assuming that the U.S. population will grow to 3×10^8 in the early decades following the year 2000, the number of lung cancers will increase from 160 to about 240 cases per LWR year.[29]

Results of Pohl's study[29] have been labeled as conservative.[30] On the other hand, Cohen[30] calculated smaller values using an original approach. The rate of radon release from the mill tailings reported[27] to be about 500 picocuries/m^2 sec. The average rate of natural radon release from land surfaces in the U.S. is about 1 picocurie/m^2 sec and an average value of 1200 lung cancer cases is estimated in the U.S. from this source. If it is assumed that radon from the tailings associated with one LWR year operation is uniformly dispersed in the U.S., the estimated potential health effect is about 2.5×10^{-4} case of lung cancer per year (4.1×10^{-4} in the northern hemisphere). It should be pointed out that uniform dispersal is a conservative assumption if we take into consideration the relatively short halflives of Rn-222 and its more important progeny and the long transport distance from mill sites to population centers. This assumption does not allow for dry deposition or washout of the radioactive isotopes. Using these results and assuming population growth to 3×10^8, the overall time integrated number of lung cancers will be about 30 in the U.S.

In conclusion, Rn-222 releases from inactive uranium-mill tailings have the potential of affecting future generations. In view of the uncertainties that we are facing, adequate disposal of mill tailings should be considered, especially those near population centers. The U.S. Congress has recently appropriated funds for this purpose. The value of 0.8 case of lung cancer in Table 3.16 sums up the effects of radon from mill tailings resulting from 1 year of operation of the model reactor. The summing period ranges from 100 years to about 3000 years. During this period we expect that adequate disposal of the tailing will be achieved.

5.5.2 Other Long-Term Effects

Coal contains small quantities of U-238, U-235, Th-232 and their decay products. The uranium content in U.S. coal varies from 0.2 to more than 25 ppm, with an average content of about 1 ppm.[32] Because coal waste piles will emit radon, they present a problem similar to that of the uranium mill tailings. However, unlike mill tailings, coal waste piles are generally close to population centers.

Another controversial issue is the possibility of future breach of the containment of a high-level waste geologic repository. Long-lived isotopes can be released to the biosphere after violent natural phenomena, human intrusion, or slow underground water transport. The consensus of previous studies in the U.S. and Europe[33,34,35] is that migration of nuclear waste in underground water is of greater concern than the possibility of sudden disruptive event. In underground aquatic transport water enters the repository, dissolves the waste form, and the waste-bearing ground water migrates to the biosphere. The potential for waste release is influenced by waste management practices, repository site and geology, repository design and waste form, the waste package, and other engineered release barriers selected. For reasonable site location and repository design no plausible mechanisms can cause release earlier than a thousand years after waste disposal.

By that time, fission products that dominate early risk will have decayed to insignificant levels (i.e., about that of natural uranium ore). Although risk assessment studies are uniformly optimistic in their evaluation of long-term safety, these is no broad consensus that safety has been either demonstrated or proven.

Solid waste from a coal-fired power plant contains many toxic elements. Although the nuclear waste repository contains materials that may be more hazardous, the solid waste from the coal plant are not disposed of an carefully as nuclear wastes. Since coal-plant solid waste are disposed of much closer to population centers, the possibility of future breach of a coal-plant solid waste disposal area by natural phenomena or human intrusion should be considered in future studies.

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6.0 THE ANALYTICAL MODEL

In this section, an analytical model is derived to examine the health risks of electricity generation from uranium and coal fuels. Analytical expressions are derived to estimate the magnitude of the primary and secondary requirement (R) variables and their associated effluent source terms. The effluents-dispersion model, exposure, and exposure-health impact models are detailed, and the basic assumptions underlying their structure are discussed.

Generally, requirement variables are derived in a linear fashion using scaling factors. These factors specify the portion of the variable (output tonnage, electricity consumption, etc.) used in supplying the annual power plant requirements for fuel material. This assumption seems reasonable because the model facilities are composite and were selected to represent an average of the currently operating facilities.

A typical number of primary and secondary requirement variables calculated for each stage in the two EPCs under investigation are presented in Figure 6.1. Table 6.1 lists the three basic activities and their associated primary and secondary requirement variables.

The requirement variables use four indices (i, j, k and l) for identification purposes. The first index (i) identifies the EPC and the life cycle phase; the second index (j) identifies the stage in the EPC; the third (k) and fourth (l) are used to identify the nature of the primary and secondary requirements.

Table 6.2 presents a user's key to the identification of the four indices. As an example, R(3, 2, 9, 5) represents the amount of electric energy (l = 5) required for equipment fabrication, (k = 9) for the uranium milling facility, and (i = 3, j = 2) in the construction phase.

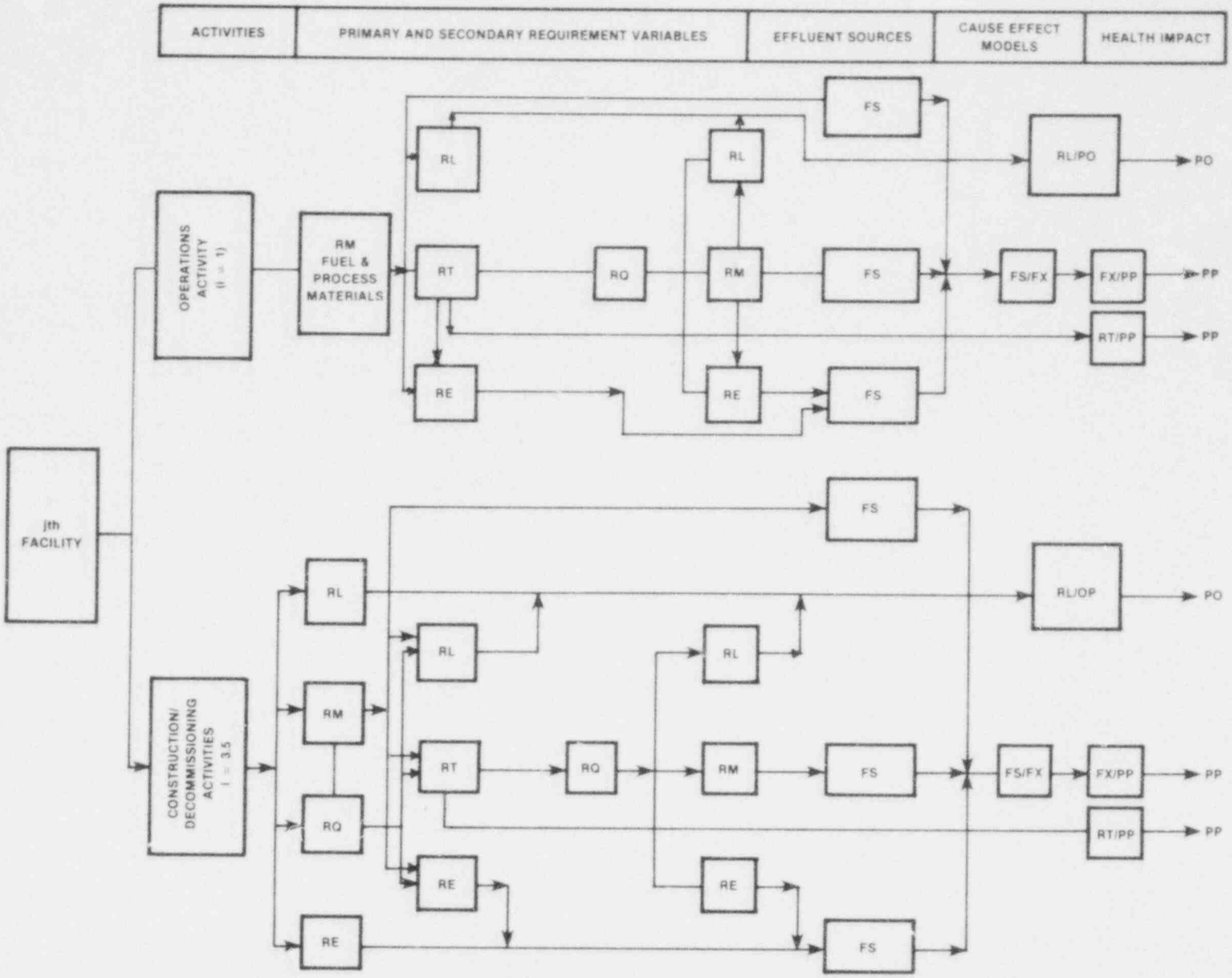


FIGURE 6.1. METHODOLOGY TREE

TABLE 6.1

ACTIVITIES AND RELATED PRIMARY AND SECONDARY REQUIREMENT VARIABLES

Activity	Primary Requirement Variable		Secondary Requirement Variable	
	Description	Identifier	Description	Identifier
A-1 Operations:				
	Fuel Material Requirement	R(1,j,2,0)	Direct Energy Requirement	R(1,j,2,5)
			Manpower Requirement	R(1,j,2,6)
			Transportation Requirement	R(1,j,2,7)
			Process Material Requirement	R(1,j,2,8)
A-2.1 Construction:				
	Material Requirement	R(3,j,8,0)	Material Production Energy Requirement	R(3,j,8,5)
			Material Production Manpower Requirement	R(3,j,8,6)
			Material Production Transportation Requirement	R(3,j,8,7)
	Direct Manpower Requirements	R(3,j,6,0)		
	Direct Energy Requirements	R(3,j,5,0)		
	Major Component and Equipment Requirement	R(3,j,9,0)	Major Component and Equipment Fabrication Energy Requirement	R(3,j,9,5)
			Major Component and Equipment Fabrication Manpower Requirement	R(3,j,9,6)
			Major Component and Equipment Fabrication Transportation Requirement	R(3,j,9,7)
			Major Component and Equipment Fabrication Material Requirement	R(3,j,9,8)
A-2.2 Decommissioning:				
	Energy Requirement	R(5,j,5,0)		
	Manpower Requirement	R(5,j,6,0)		
	Waste Transportation Requirement	R(5,j,7,0)		

TABLE 6.2

KEY FOR VARIABLE IDENTIFICATION

j (Stage)		k (Primary Requirement)		l (Secondary Requirement)	
Uranium	Coal	Uranium	Coal	Uranium	Coal
				0 For Primary Variable	0 For Primary Variable
1 Mining	1 Mining (east)	1 Input	1 Input	1 Gross Weight	1 U. G. Coal
2 Milling	2 Processing (east)	2 Stage Output	2 Stage Output	2 Weight With Cask	2 Open-Pit
3 Conversion	3 Storage (east)	3 Non-Electrical Energy	3 Non-Electrical Energy	3 Non-Electrical Energy	3 Non-Electrical Energy
4 Enrichment	4 Power Plants (east)	4 Waste	4 Waste	4 Waste	4 Waste
5 Fuel Fabrication	5 Mining (west)	5 Electrical Energy	5 Electrical Energy	5 Electrical Energy	5 Electrical Energy
6 LWR	6 Processing (west)	6 Manpower	6 Manpower	6 Manpower	6 Manpower
7 Reprocessing	7 Storage (west)	7 Transportation	7 Transportation	7 Transportation	7 Transportation
8 Waste Disposal	8 Power Plant (west)	8 Materials	8 Materials	8 Materials	8 Materials
	9 Waste Disposal	9 Equipment	9 Equipment	9 Equipment	9 Equipment

i = 1, 3, 5: Uranium EPC is the Operations, Construction, and Decommissioning Phases, respectively.
i = 2, 4, 6: Coal EPC is the Operations, Construction, and Decommissioning Phases, respectively.

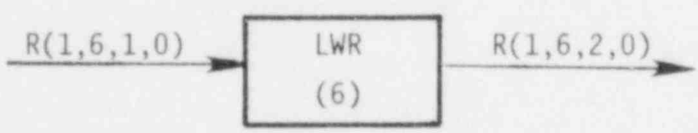
6.1 FUEL MATERIAL REQUIREMENT VARIABLES

In this subsection, the analytical expressions for the fuel materials in the uranium and coal EPCs are derived. The fuel material requirement variables are the most important in the model because they measure the operations activities and, hence, because of their long-range nature, have the highest potential impact on health.

6.1.1 Fuel Material Requirement in the Uranium EPC R(i,j,k,l) (k = 1, 2; l = 0, 1)

A schematic diagram of fuel material flow in the case of the uranium EPC is shown in Figure 6.2. This diagram includes Option 1 where no recycling is considered and Option 2 where uranium recycling is accounted for. The following is a stage by stage derivation of the fuel material requirement variables. Amounts of uranium are represented for each stage input and output. In addition, the corresponding overall weights that account for the chemical form and structural materials associated with these inputs and outputs also are expressed.

LWR (Stage 6)



During a projected life span of 30 years, the model LWR will be provided with an initial full core load, followed by 29 annual partial core reloads. The average annual uranium requirement for Stage 6 can thus be expressed as

$$R(1,6,1,0) = [RU60 + 29\ RU6A]/30 \qquad (6.1)$$

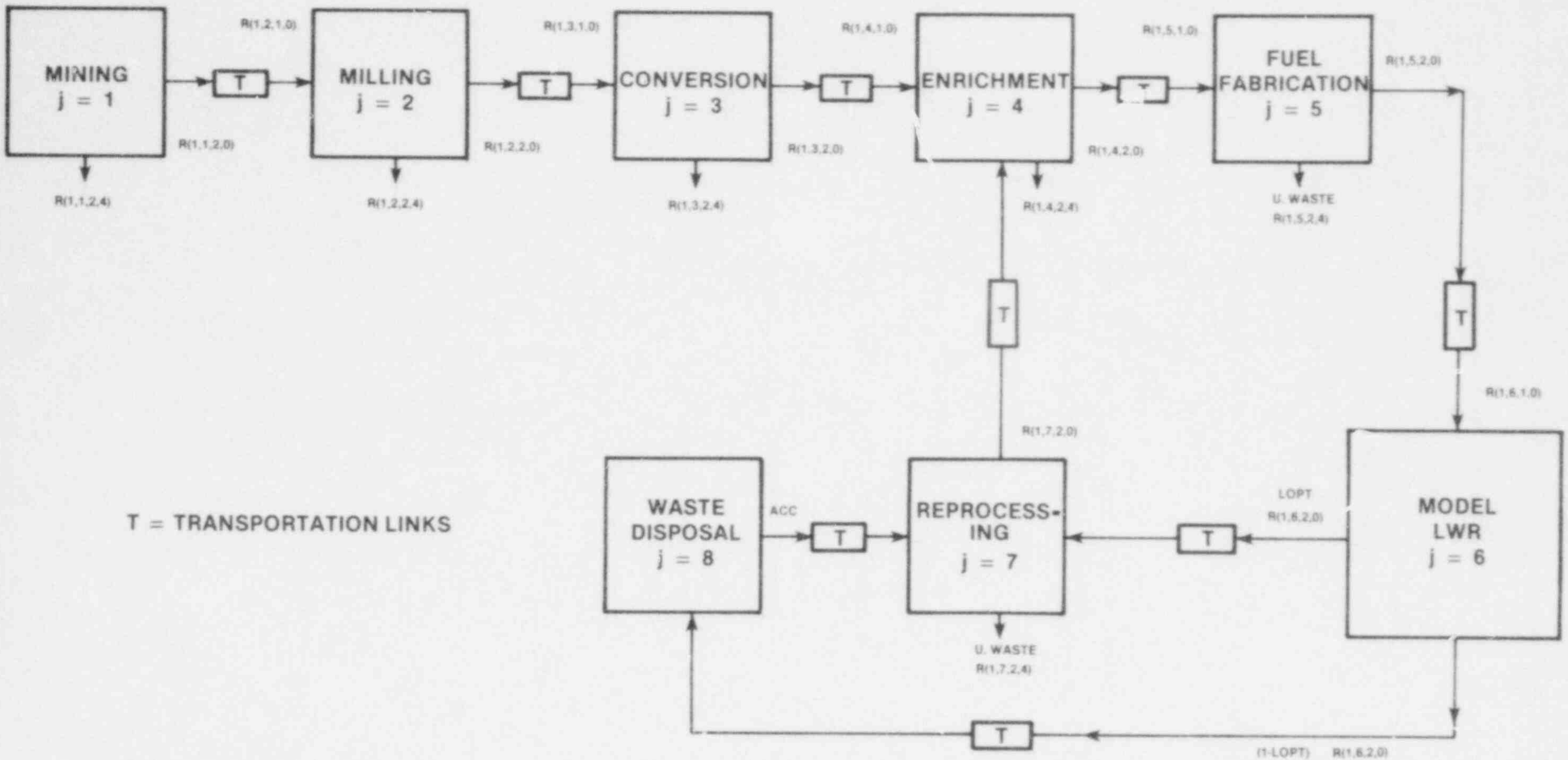


FIGURE 6.2. URANIUM FUEL MATERIAL REQUIREMENT FLOW DIAGRAM

where R(1,6,1,0) is the averaged annual fuel requirement in MTU (representing the input to Stage 6); RU60 is the initial core uranium requirement in MTU; and RU6A is the annual core uranium requirement in MTU.

The uranium supplied for the initial core is assumed to be enriched in the U-235 isotope to a value given by ENR(0) whereas ENR(5) is the enrichment of the annual reload.

The discharged uranium fuel corresponding to R(1,6,1,0) is given in MTUs by

$$R(1,6,2,0) \cong R(1,6,1,0) \qquad (6.2)$$

This equation indicates that the amount of uranium in the spent fuel is almost the same as the input. However, the spent fuel enrichment is significantly different as denoted by ENR(6).

Equations (6.1) and (6.2) express the amounts of uranium in the input and output to Stage 6. In order to account for the chemical composition of the ceramic fuel (UO_2) and the structural materials in the fuel assemblies, the overall weight corresponding to the input and output variables is given in MTs by

$$R(1,6,1,1) = R(1,6,1,0) \times \frac{270}{238} \times \text{WASSY} \qquad (6.3)$$

similarly

$$R(1,6,2,1) = R(1,6,2,0) \times \frac{270}{238} \times \text{WASSY} \qquad (6.4)$$

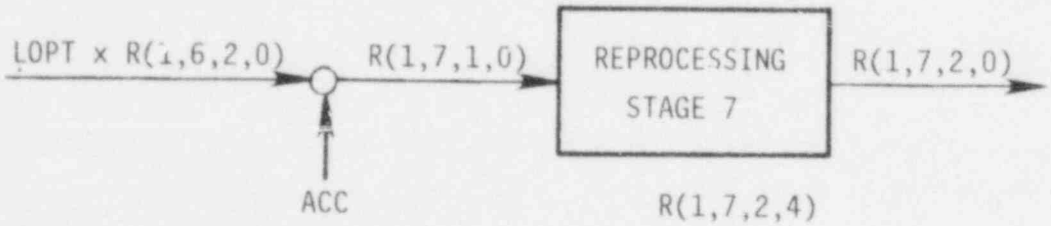
where $\frac{270}{238}$ is a correction factor (MT of UO_2 per MTU), and

WASSY is the ratio of assembly weight to the weight of UO_2 per assembly.

Reprocessing (Stage 7)

Spent fuel reprocessing is considered in Option 2 only. However, in order to build flexibility into the model, the mathematical treatment of this stage uses binary variables that take the value of zero in case of Option 1 and take a nonzero value in case of Option 2. These nonzero values define the extent of reprocessing policy selected by the analyst. In general, the reprocessing stage is assumed to handle the spent fuel output from Stage 6 (LWR) as well as some spent fuel from the retrievable spent fuel portion of the repository (Stage 8) as shown in Figure 6.2. The input to the reprocessing stage is given by

$$R(1,7,1,0) = LOPT \times R(1,6,2,0) + ACC \quad (6.5)$$



where R(1,6,2,0) is Stage 6 discharge in MTUs.

$$
LOPT \begin{cases} 0 \text{ in case of Option 1} \\ 1 \text{ in case of Option 2} \end{cases}
$$

$$
ACC \begin{cases} 0 \text{ in case of Option 1} \\ C \text{ MTU if additional accumulated spent fuel is processed} \\ \text{(Option 2 only)} \end{cases}
$$

The Stage 7 output in MTUs is given by

$$R(1,7,2,0) = R(1,7,1,0) \times EFF(1,7) \qquad (6.6)$$

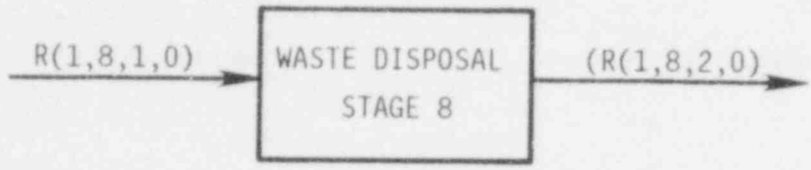
where R(1,7,2,0) is the stage output related to R(1,7,1,0) in MTUs with the same enrichment ENR(6). EFF(1,7) is the reprocessing facility efficiency because the model reprocessing facility is assumed to have produced UF_6 for shipment to the enrichment plant (Stage 4). The amount of uranium hexafluoride in MTs corresponding to R(1,7,2,0) can be written as

$$R(1,7,2,1) = R(1,7,2,0) \times \frac{352}{238} \qquad (6.7)$$

The amount of uranium lost during reprocessing is described in MTUs by

$$R(1,7,2,4) = R(1,7,1,0)[1 - EFF(1,7)]. \qquad (6.8)$$

Waste Disposal (Stage 8)



Following the discussion in the last subsection, the amount of uranium input to Stage 8 is given in MTUs by

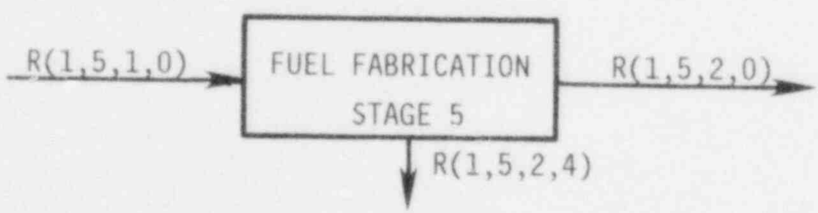
$$R(1,8,1,0) = (1 - LOPT) \times R(1,6,2,0). \quad (6.9)$$

The amount of uranium in MTUs retrieved from Stage 8 is

$$R(1,8,2,0) = ACC. \quad (6.10)$$

The right-hand terms in Equations (6.9) and (6.10) carry the same meaning as before.

Fuel Fabrication (Stage 5)



Under the assumption that transportation losses between Stages 5 and 6 are insignificant, the output of Stage 5, given in MTUs, is equivalent to the input of Stage 6 or

$$R(1,5,2,0) = R(1,6,1,0). \qquad (6.11)$$

The fuel fabrication facility is assumed to receive enriched UF_6 from Stage 4 and to convert the UF_6 to finished UO_2 pellets stacked in fuel assemblies. In order to supply R(1,5,2,0) MTU in the form of pellets, the amount of uranium in MTUs fed to the Stage can be expressed as

$$\begin{aligned} R(1,5,1,0) &= R(1,5,2,0)/EFF(1,5) \\ &= R(1,6,1,0)/EFF(1,5) \end{aligned} \qquad (6.12)$$

where EFF(1,5) is the Stage 5 efficiency.

The amount of UF_6 in MTUs corresponding to R(1,5,1,0) is given by

$$R(1,5,1,1) = R(1,5,1,0) \times \frac{352}{238}. \qquad (6.13)$$

The amount of uranium waste R(1,5,2,4) is given by the difference between the input R(1,5,1,0) and the output R(1,5,2,0).

Enrichment (Stage 4)

The enrichment facility uranium output requirement variable R(1,4,2,0) consists of two components: the first is enrichment ENR(5) for the reactor annual feed; the second is a normalized amount of the initial core loading with enrichment ENR(0). The inputs to the enrichment facility are naturally enriched UF_6 (enrichment ENR(4)) and recycled UF_6 (enrichment ENR(6)) shipped from the reprocessing stage.

Assuming negligible losses in transporting UF_6 from Stage 4 to Stage 5, the enrichment stage output, given in MTUs, is equivalent to Stage 5 input

$$R(1,4,2,0) = R(1,5,1,0). \qquad (6.14)$$

Equivalently, in units of MT UF_6

$$R(1,4,2,1) = R(1,5,1,1)$$

where

$$R(1,4,2,1) = R(1,4,2,0) \times \frac{352}{238}$$

Figure 6.3 shows the method used for calculating the amount of natural uranium feed R(1,4,1,0), giving the required output R(4,1,2,0) and taking credit for recycling Stage 7 (reprocessing) output. The naturally enriched uranium requirement in MTUs is given by

$$R(1,4,1,0) = \frac{1}{[ENR(4)-ENRT]} \left[(BETA \times ENR(5) + (1.0 - BETA)\right. \\ (ENR(0) - ENRT) \times R(1,4,2,0) \\ \left. - (ENR(6) - ENRT)\ R(1,7,2,0)\right] \qquad (6.15)$$

or equivalently in MT UF_6

$$R(1,4,1,1) = R(1,4,1,0) \times \frac{352}{238}$$

where, ENRT is the tailings enrichment and

$$BETA = \frac{29\ RU6A}{RU60 + 29RU6A}$$

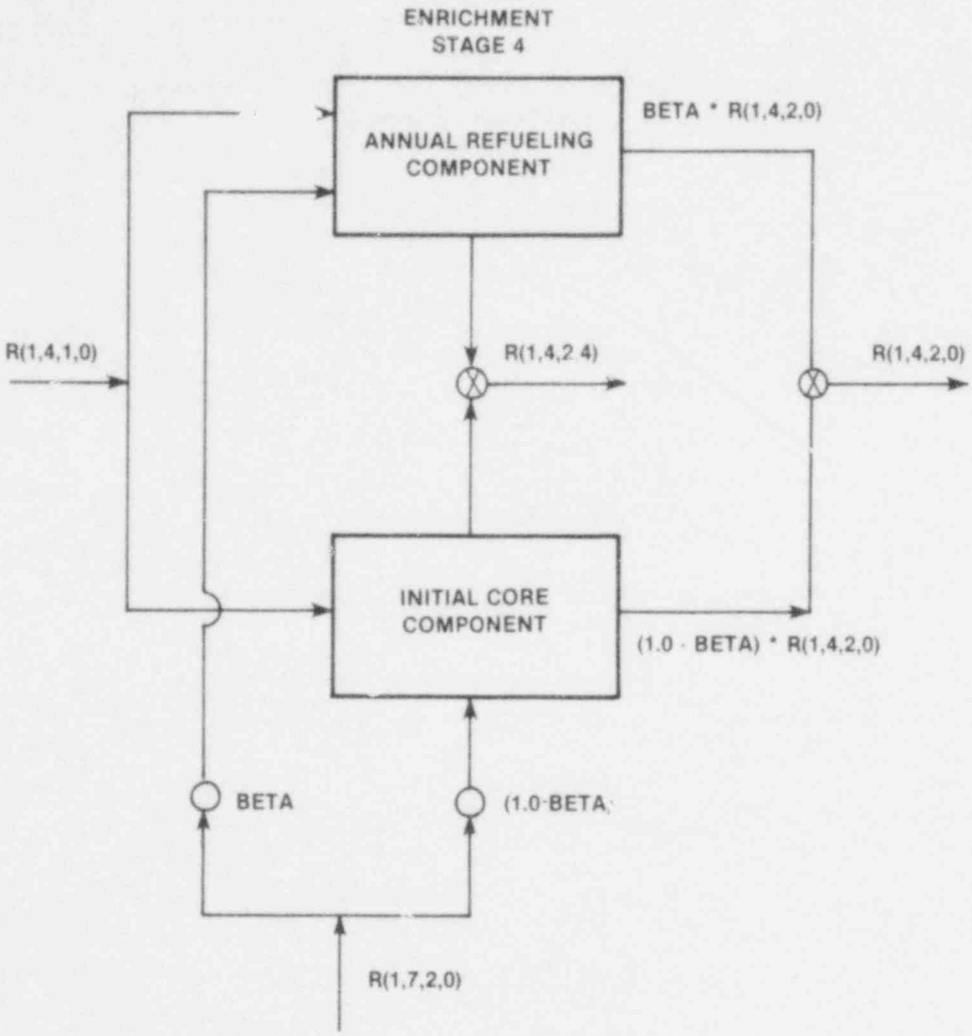


FIGURE 6.3. ENRICHMENT STAGE INPUT AND OUTPUT VARIABLES

RU6A and RU6O are defined in Section 6.1.1 LWR (Stage 6). The quantities ENR(6), ENR(5), ENR(0) are defined above.

The amount of tailings is given in MT UF_6 as

$$R(1,4,2,1) = [R(1,4,1,0) + R(1,7,2,0) - R(1,4,2,0)] \times \frac{352}{238} \tag{6.16}$$

The separative work (SWU) required to generate R(1,4,2,0) is

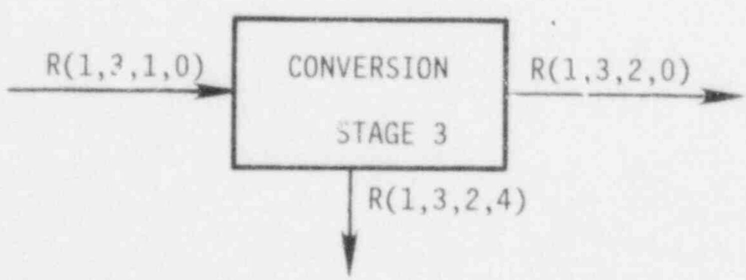
$$\begin{aligned} SWU\ (MT) = \frac{1}{R(1,4,1,0)} & [R(1,4,2,0)(BETA \times ENR(5) + (1.0 - BETA) \\ & ENR(0))\ V(5) - R(1,7,2,0) \times V(4) \\ & - R(1,4,1,0) \times V(4) + (R(1,4,1,0) + R(1,7,2,0) \\ & - R(1,4,2,0))\ V(T)] \end{aligned} \tag{6.17}$$

where all the terms carry the same meaning as before, and where

$$V(i) = (2 \times ENR(i) - 1) \times \ln [ENR(i)/(1 - ENR(i)] \tag{6.18}$$

$$i = 0,4,5,6$$

Conversion (Stage 3)



Assuming negligible UF_6 transportation losses between Stages 3 and 4, the output requirement variable in MTUs for Stage 3 is

$$R(1,3,2,0) = R(1,4,1,0). \qquad (6.19)$$

The amount of uranium input in MTUs required to produce R(1,3,2,0) is given by

$$R(1,3,1,0) = R(1,3,2,0)/EFF(1,3) \qquad (6.20)$$

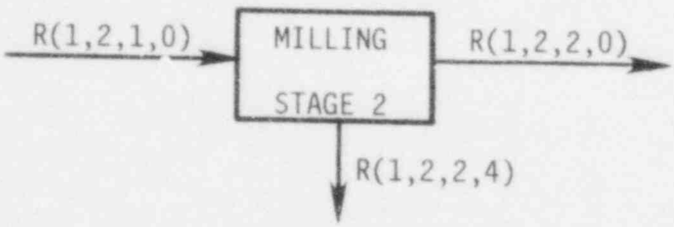
where EFF(1,3) is the conversion facility efficiency.

The amount of U_3O_8 in MTUs corresponding to R(1,3,1,0) is written as

$$R(1,3,1,1) = R(1,3,1,0) \times \frac{842}{3 \times 352} \qquad (6.21)$$

Conversion facility uranium losses R(1,3,2,4) are the difference between the input R(1,3,1,0) and the output R(1,3,2,0).

Milling (Stage 2)



Assuming negligible U_3O_8 losses by transportation, the milling facility output in MTUs is related to Stage 3 input by

$$R(1,2,2,0) = R(1,3,1,0). \qquad (6.22)$$

Facility input is given in MTUs as

$$R(1,2,1,0) = R(1,2,2,0)/EFF(1,2). \qquad (6.23)$$

This amount is equivalent in MTUs of ore to

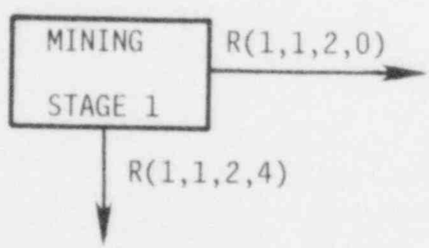
$$R(1,2,1,1) = R(1,2,1,0) \times \frac{842}{3 \times 238} /GRADE \qquad (6.24)$$

where EFF(1,2) is the milling facility efficiency, and GRADE is the ore grade.

The amount of uranium in MTUs in the mill tailings is given by

$$R(1,2,2,4) = R(1,2,1,0) - R(1,2,2,0). \qquad (6.25)$$

Mining (Stage 1)



The amount of uranium in MTUs to be mined to supply the milling facility with its uranium requirement R(1,2,1,0) is expressed as

$$R(1,1,2,0) = R(1,2,1,0)/ (1 - TLOSS(1,2)) \quad (6.26)$$

where TLOSS(1,2) is the mine to mill transportation loss factor.

The amount of ore in MTUs mined is related in a similar manner to R(1,2,1,1) by

$$.(1,2,1,1)/(1 - TLOSS(1,2)). \quad (6.27)$$

The mined overburden is a very low-grade uranium ore, and the amount of uranium in the overburden is given in MTUs by

$$R(1,1,2,4) = R(1,1,2,1) \times FMINE(1) \times FMINE(2) \quad (6.28)$$

where FMINE(1) is the amount of overburden removed per MT of ore mined, and FMINE(2) is the amount of uranium per MT of overburden.

6.1.2 Fuel Material Requirements in the Coal EPC R(2,i,k,l) (k = 1, 2; l = 0, 1)

Schematic diagrams for eastern and western coal flow in the case of the coal EPC are shown in Figures 6.4 and 6.5. The eastern coal diagram is distinguished by two modes of mining: underground and open-pit. Only open-pit mining is considered for western coal. In general, basic differences between eastern and western facilities will

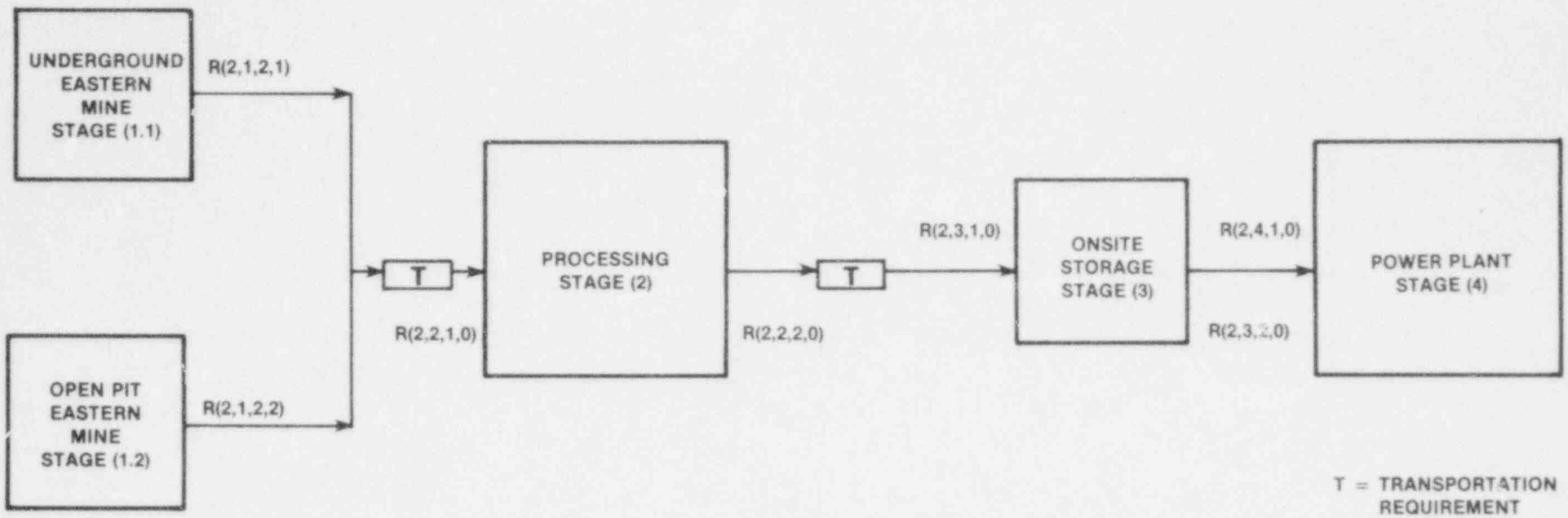


FIGURE 6.4. EASTERN COAL REQUIREMENT FLOW DIAGRAM

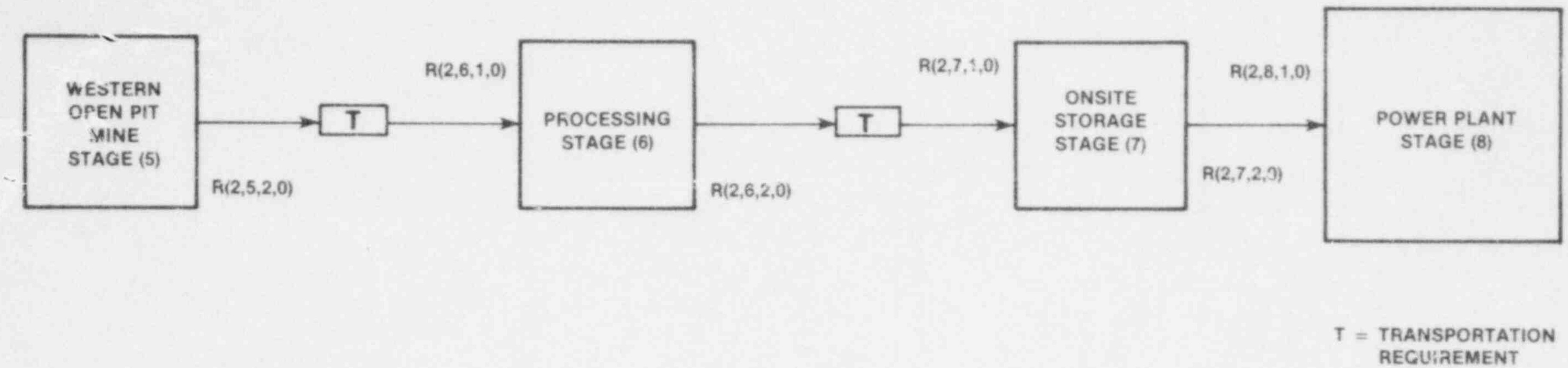
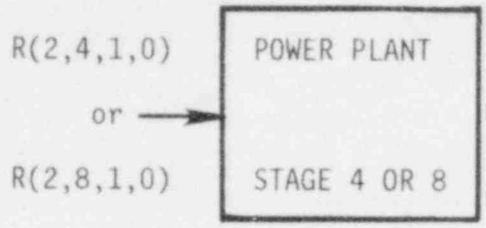


FIGURE 6.5. WESTERN COAL REQUIREMENT FLOW DIAGRAM

be stressed in the model. Waste treatment is not shown in the figures because analysis in this section is devoted to fuel materials only.

Power Plant (Stages 4 and 8)



The amount of coal feed in MT to the boilers in the power plant is calculated by the following equation for an eastern plant

$$R(2,4,1,0) = \frac{\text{Amount of Net Electric Energy Generated Annually}}{\text{Plant Efficiency} \times \text{Energy Released per Unit Weight}}$$

$$= \frac{10^6 \text{ KW} \times (24 \times 365) \times 3412.8 \text{ (BTU/KWhr)} \times \text{Capacity Factor}}{EFF(2,4) \times HAV(4) \times 2205 \text{ (lb/MT)}}$$

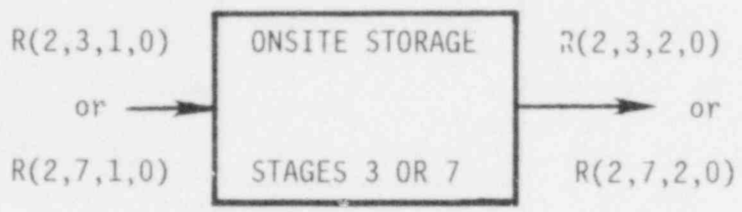
$$R(2,4,1.0) = 13.56 \times 10^9 \times \frac{CAP}{EFF(2,4) \times HAV(4)} \tag{6.29}$$

Similarly, for the western plant

$$R(2,8,1,0) = 13.56 \times 10^6 \times \frac{CAP}{EFF(2,8) \times HAV(8)} \tag{6.30}$$

where CAP is a typical power plant capacity factor and EFF(2,4) and EFF(2,8) are eastern and western power plant efficiencies. HAV(4) and HAV(8) represent an average heat value for eastern and western coal, respectively, in units of BTU/lb. R(2,4,1,0) and R(2,8,1,0) are the amounts of coal in MT burned annually in the eastern and western plants, respectively.

Coal Storage (Stages 3 and 7)



Under the assumption that handling losses are negligible, the output of the storage stage in MTs is equivalent to the power production stage coal input thus

$$R(2,3,2,0) = R(2,4,1,0) \qquad (6.31)$$

$$R(2,7,2,0) = R(2,8,1,0). \qquad (6.32)$$

The amount of eastern coal delivered to the storage area is

$$R(2,3,1,0) = R(2,3,2,0)/EFF(2,3), \qquad (6.33)$$

and the amount of western coal is

$$R(2,7.1,0) = R(2,7,2,0)/EFF(2,7) \qquad (6.34)$$

where EFF(2,3) and EFF(2,7) are the storage efficiencies in the East and West, respectively.

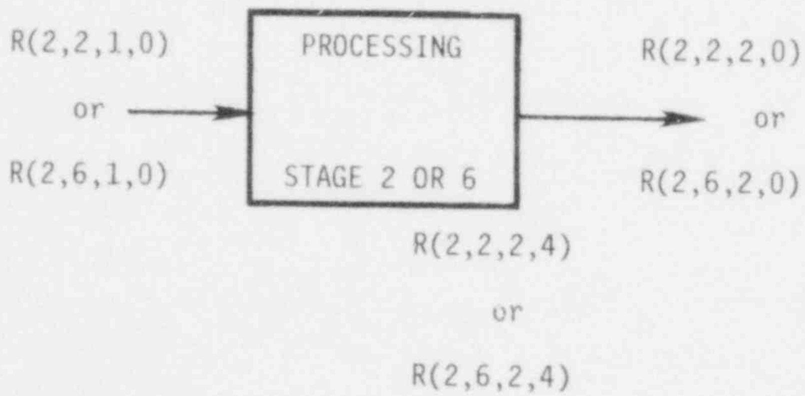
The amount of coal waste in MTs in the East is

$$R(2,3,2,4) = R(2,3,1,0) - R(2,3,2,0). \quad (6.35)$$

The amount of coal waste in MTs in the West is

$$R(2,7,2,4) = R(2,7,1,0) - R(2,7,2,0). \quad (6.36)$$

Coal Processing (Stages 2 and 6)



Processed coal is transported over relatively long distances from the processing facility to the power plant site. Coal dust transportation losses are not negligible and are assumed to be proportional to the processed coal hauling distance. The relationship between the storage stage coal input in MTs and the output in MTs of the processing stage can be written as

$$R(2,2,2,0) = R(2,3,1,0)/(1 - TLOSS(2,3) \times D(2,3)) \qquad (6.37)$$

$$R(2,6,2,0) = R(2,7,1,0)/(1 - TLOSS(6,7) \times D(6,7)) \qquad (6.38)$$

where TLOSS(2,3) and TLOSS(6,7) are the transportation losses per MT/Mile. D(i,j) is the distance between the i^{th} and j^{th} facility in miles.

Stage input in MT of coal is

$$R(2,2,1,0) = R(2,2,2,0)/EFF(2,2) \qquad (6.39)$$

$$R(2,6,1,0) = R(2,6,2,0)/EFF(2,6) \qquad (6.40)$$

where EFF(2,2) and EFF(2,6) are the processing efficiencies.

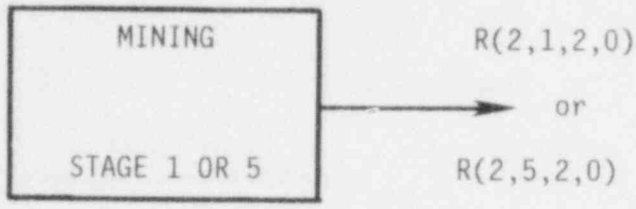
Amounts of coal in MTs lost are given as

$$R(2,2,2,4) = R(2,2,1,0) - R(2,2,2,0). \qquad (6.41)$$

Similarly,

$$R(2,6,2,4) = R(2,6,1,0) - R(2,6,2,0). \qquad (6.42)$$

Coal Mining (Stages 1 and 5)



The amount of coal mined should be sufficient to deliver the input requirement to the processing stage and to compensate for handling losses; thus, the eastern mines are required to deliver

$$R(2,1,2,0) = R(2,2,1,0)/(1-TLOSS(1)). \qquad (6.43)$$

Similarly, for western mines

$$R(2,5,2,0) = R(2,5,1,0)/(1-TLOSS(5)) \qquad (6.44)$$

where TLOSS(1) and TLOSS(2) represent an average fraction of the coal lost in handling at the mine site and transportation to the processing facility site for eastern and western coal, respectively. Because eastern coal is partially mined underground and partially surface mined, the underground mined coal MT requirement is

$$R(2,1,2,1) = R(2,1,2,0) \times GAMMA(1), \qquad (6.45)$$

and the open-pit mined coal MT requirement is

$$R(2,1,2,2) = R(2,1,2,0)\ (1 - GAMMA(1)) \qquad (6.46)$$

where GAMMA(1) is the fraction of eastern coal mined in underground mines.

In the case of western coal, it is assumed that GAMMA(5) = 0; thus, all the western coal is considered to be open-pit mined.

6.2 ENERGY REQUIREMENT VARIABLES

Energy is consumed during operations, construction, and decommissioning activities. It is supplied either as electric energy or by the combustion of natural gas, coal, or petroleum products. The combustion of fossil fuels is used to generate electricity or to supply steam and process heat. The methodology tree (Figure 6.1) shows the energy requirement variable (RE) appearing in various locations in the tree and at different levels. The operations activities requiring energy are fuel material production and transportation. In the case of construction activities, energy is required for actual construction, for construction materials production, and for major equipment and component materials and fabrication and for all of their associated transportation requirements.

It is important to note that the two EPCs interact through the electric energy requirement component of RE. Electricity supplied to any particular facility can be generated by a coal-fired plant or by a nuclear plant or by some combination of both. The public and occupational health impacts associated with the facility electric energy requirement have to be charged properly to the two cycles. This is achieved by using an interactive procedure that starts with the initial estimate and the health impact for the whole cycle in the absence of electrical energy requirements, properly scaled to reflect the facility consumption. The cycle interaction is discussed further in Section 6.10.

In this section, general expressions for the electrical and nonelectrical energy requirements are derived. Preliminary values for the different parameters in these equations are listed and are based on the data accumulated in Sections 3 and 4 and supplemented by other references. Expressions for transportation-related energy consumption are included in the transportation Section (Section 6.5).

6.2.1 Energy Requirement in the Nuclear EPC

Electrical and nonelectrical energy requirements are detailed in this subsection. A general formulation for the energy requirement is derived for all the uranium EPC stages: in the operations, construction, and decommissioning phases. Typical expressions or values of the different parameters in the model are listed in Table 6.3.

Energy Requirement in the Operations Phase (i = 1)

The electrical energy requirement (l or k = 5) variable for the j^{th} stage can be expressed as

$$R(1,j,2,5) = EE\phi(1,j,2,5) \times R(1,j,2,0) \qquad (6.47)$$

where R(1,j,2,0) is the fuel material requirement variable for the j^{th} stage in MTU. EEϕ is the rate of electrical energy consumption in operations and production of process materials in MWhr/MTU of the j^{th} facility output. Thus, the rate of electrical energy consumption is the sum of two components

$$EE\phi(1,j,2,5) = EED(1,j,2,5) + EEP(1,j,2,5)$$

with EED and EEP representing the direct energy and process material related electric energy consumption rate.

Similarly, the nonelectric energy (l = 3) is expressed as

$$R(1,j,2,3) = EN\phi(1,j,2,3) \times R(1,j,2,0) \qquad (6.48)$$

TABLE 6.3

ENERGY CONSUMPTION RATES IN THE NUCLEAR EPC

j (Stage)	i (Phase)	Variable	Expression or Value[a]	Units
1. Mining	1	EEϕ(1,1,2,5)	$17.78 \frac{0.208}{GRADE} \times EFF(2) \times (1 - TLOSS(2))$	MWH/MTU Mined
		ENϕ(1,1,2,3)	23.4×10^6 EEϕ(1,1,2,5)	BTU/MTU Mined
	3	EEC(3,1,2,5)	.09 EEϕ(1,1,2,5)	MWH/MTU Mined
		ENC(3,1,2,3)	6.36×10^6 EEϕ(1,1,2,5)	BTU/MTU Mined
	5	EEG(5,1,2,5)	4×10^{-3}	MWH/MTU Mined
		ENG(5,1,2,3)	2.8×10^5	BTU/MTU Mined
2. Milling	1	EEϕ(1,2,2,5)	21.38	MWH/MTU
		ENϕ(1,2,2,3)	495×10^6	BTU/MTU
	3	EEC(3,2,2,5)	.71	MWH/MTU
		ENC(3,2,2,3)	31×10^6	BTU/MTU
	5	EEG(5,2,2,5)	1.7×10^{-3}	MWH/MTU
		ENG(5,2,2,3)	7.4×10^4	
3. Conversion	1	EEϕ(1,3,2,5)	14.5	MWH/MTU
		ENϕ(1,3,2,3)	13.4×10^8	BTU/MTU
	3	EEC(3,3,2,5)	0.16	MWH/MTU
		ENC(3,3,2,3)	7.4×10^6	BTU/MTU

TABLE 6.3 (Continued)

j (Stage)	i (Phase)	Variable	Expression or Value[a]	Units
	5	EEG(5,3,2,5)	2.0×10^{-5}	MWH/MTU
		ENG(5,3,2,3)	0.44×10^{5}	BTU/MT
4-1. Enrichment Diffusion	1	EEφ(1,4,2,5)	2.82×10^{3}	MWH/MTSWU
		ENφ(1,4,2,3)	4.77×10^{8}	BTU/MTSWU
	3	EEC(3,4,2,5)	7.7	MWH/MTSWU
		ENC(3,4,2,3)	3.3×10^{8}	BTU/MTSWU
	5	EEG(5,4,2,5)	0.44	MWH/MTSWU
		ENG(5,4,2,3)	4.4×10^{6}	BTU/MTSWU
4-2. Enrichment Centrifuge	1	EEφ(1,42,2,5)	2.56×10^{2}	MWH/MTSWU
		ENφ(1,42,2,3)	1.97×10^{8}	BTU/MTSWU
	3	EEC(3,42,2,5)	3.7	MWH/MTSWU
		ENC(3,42,2,3)	2.7×10^{7}	BTU/MTSWU
	5	EEG(5,42,2,5)	0.9×10^{-2}	MWH/MTSWU
		ENG(5,42,2,3)	6.8×10^{4}	BTU/MTSWU
5. Fuel Fabrication	1	EEφ(1,5,2,5)	300	MWH/MTU
		ENφ(1,5,2,3)	25.27×10^{8}	BTU/MTU
	3	EEC(3,5,2,5)	.93	MWH/MTU
		ENC(3,5,2,3)	38.6×10^{6}	BTU/MTU
	5	EEG(5,5,2,5)	2.3×10^{-4}	MWH/MTU
		ENG(5,5,2,3)	---	

TABLE 6.3 (Continued)

j (Stage)	i (Phase)	Variable	Expression or Value[a]	Units
6. LWR[b]	1	EEφ(1,6,2,5)	220.4	MWH/MTU
		ENφ(1,6,2,3)	73.5×10^8	BTU/MTU
	3	EEC(3,6,2,5)	174.5	MWH/MTU
		ENC(3,6,2,3)	82.11×10^8	BTU/MTU
	5	EEG(5,6,2,5)	130 - 197[c]	MWH/MTU
		ENG(5,6,2,3)	12.0×10^8[c]	BTU/MTU
7. Reprocessing	1	EEφ(1,7,2,5)	14.2	MWH/MTU
		ENφ(1,7,2,3)	1.0×10^8	BTU/MTU
	3	EEC(3,7,2,5)	5.69	MWH/MTU
		ENC(3,7,2,3)	2.55×10^8	BTU/MTU
	5	EEG(5,7,2,5)	.02	MWH/MTU
		ENG(5,7,2,3)	---	BTU/MTU
8. High Level Waste[b]	1	EEφ(1,8,2,5)	1.0 - 4.0	MWH/MTHM
		ENφ(1,8,2,5)	1.38×10^8	BTU/MTHM
	3	EEC(1,8,2,5)	.273	MWH/MTHM
		ENC(1,8,2,3)	19.6×10^6	BTU/MTHM
	5	EEG(1,8,2,5)	---	
		ENG(1,8,2,3)	---	

(a) Oak Ridge Associated Universities, "Net Energy from Nuclear Power," PB-254-059, May 1979.

(b) Based on Option 1, ten canisters include 38.8 MT of fuel or equivalent waste.

(c) Assuming dismantlement, ten percent of these values are assumed for decontamination.

with

$$EN\phi(1,j,2,3) = END(1,j,2,3) + ENP(1,j,2,3)$$

where $EN\phi$ is the rate of fossil fuel energy consumption in BTU per MTU, and END and ENP are the direct energy and process material energy components of $EN\phi$.

Energy Requirement in the Construction Phase (i = 3)

In this derivation, construction energy (electrical and nonelectrical) has three components. The first is the direct energy consumed in construction (k = 5,3; l = 0); the second is the energy consumed in the production of construction materials and materials in the major components (k = 8, l = 5,3); and the third is related to the j^{th} facility equipment major components fabrication (k = 9, l = 5,3). Because of the format of the currently available data and for simplicity, these three components are integrated as a single variable for electrical and nonelectrical energy. Thus, for the case of electrical energy, the overall requirement in the construction phase is

$$R(3,j,2,5) = R(3,j,5,0) + R(3,j,8,5) + R(3,j,9,5).$$

Similarly, for nonelectrical energy

$$R(3,j,2,3) = R(3,j,3,0) + R(3,j,8,3) + R(3,j,9,3).$$

These energy requirement variables in MWhrs and BTUs are then expressed in terms of the fuel material requirement variable as

$$R(3,j,2,5) = EEC(3,j,2,5) \times R(1,j,2,0) \quad (6.49)$$

$$R(3,j,2,3) = ENC(3,j,2,3) \times R(1,j,2,0) \quad (6.50)$$

where EEC and ENC are the rates of consumption of electrical and nonelectrical energy normalized to per MTU of the fuel material output from the j^{th} model facility.

Energy Requirement in the Decommissioning Phase (i = 5)

Energy used in the decommissioning phase can be expressed in MWhrs and BTUs in a fashion similar to Equations (6.49) and (6.50)

$$R(5,j,2,5) = EEG(5,j,2,5) + R(1,j,2,0) \quad (6.51)$$

$$R(5,j,2,3) = ENG(5,j,2,3) + R(1,j,2,0) \quad (6.52)$$

where EEG and ENG are the rates of electric and nonelectric energy consumption in MWhr/MTU and BTU/MTU, respectively.

6.2.2 Energy Requirement in the Coal EPC

The general formulation of the energy requirement variables in this section is identical to that of Section 6.2.1. Typical values for the different energy consumption rates are listed in Table 6.4. Unfortunately, the available data are not as complete as that in Table 6.3.

TABLE 6.4

ENERGY CONSUMPTION RATES IN THE COAL EPC

j (Stage)	i (Phase)	Variable: Description	Variable: Identifier	Expression Or Value	Units
1[a] Eastern Mines	2 Operation and Construction	Electrical energy consumption rate for underground eastern mines	EEφU(2,1,2,5)	13.0	KWH/MT
		Electric energy consumption rate for open-pit mines	EEφφ(2,1,2,5)	5.0	KWH/MT
		Nonelectrical energy consumption rate for U.G. mines	ENφU(2,1,2,3)	0.0	BTU/MT
		Nonelectric energy consumption rate for open-pit mines	ENφφ(2,1,2,3)	38.0×10^3	BTU/MT
5[a] Western Mines	2 Operation and Construction	Electrical energy consumption rate for U.G. mines	EEφU(2,5,2,5)	0.0	KWH/MT
		Electrical energy consumption rate for open-pit mines	EEφφ(2,5,2,5)	2.8	KWH/MT
		Nonelectrical energy consumption rate for U.G. mines	ENφU(2,5,2,3)	0.0	BTU/MT
		Nonelectrical energy consumption rate for open-pit mines	ENφU(2,5,2,3)	42.0×10^3	BTU/MT

TABLE 6.4 (Continued)

j (Stage)	i (Phase)	Variable: Description	Variable: Identifier	Expression Or Value	Units
1 Eastern Mines	6 Decommissioning	Electric energy consumption rate (U.G.)	EEGU(6,1,2,5)	---	
		Electric energy consumption rate (O.P.)	EEGφ(6,1,2,5)	---	
		Nonelectric energy consumption rate (U.G.)	ENGU(6,1,2,3)	---	
		Nonelectric energy consumption rate (O.P.)	ENGφ(6,1,2,3)	---	
5 Western Mines	6[b]		EEGU(6,5,2,5)	---	
			EEGφ(6,5,2,5)	---	
			ENGU(6,5,2,3)	---	
			ENGφ(6,5,2,3)	---	
2 Eastern Processing	2[b]		EEφ(2,2,2,5)		
			ENφ(2,2,2,3)	28.1×10^{3}	BTU/MT
6 Western Processing			EEφ(2,6,2,5)		
			ENφ(2,6,2,3)		

TABLE 6.4 (Continued)

j (Stage)	i (Phase)	Variable: Description	Variable: Identifier	Expression Or Value	Units
2	4[b] Construction		EEC(4,2,2,5)		
			ENC(4,2,2,3)		
6			EEC(4,6,2,5)		
			ENC(4,6,2,3)		
2	6[b] Decommissioning		EEC(6,2,2,5)		
			ENC(6,2,2,3)		
6			EEC(6,6,2,5)		
			ENC(6,6,2,3)		
3 Eastern Storage	2[b] Operation		EEφ(2,3,2,5)		
			ENφ(2,3,2,3)		
7 Western Storage			EEφ(2,7,2,5)		
			ENφ(2,7,2,3)		
	4[b]				
	6[b]				

TABLE 6.4 (Continued)

j (Stage)	i (Phase)	Variable Description	 Identifier	Expression Or Value	Units
4 Eastern[c] Power Plant	2[b]		EEφ(2,4,2,5)	0.2[d]	MWH/MT
			ENφ(2,4,2,3)	1.14×10^6	BTU/MT
8 Western[b] Power Plant			EEφ(2,8,2,5)	0.2	MWH/MT
			ENφ(2,8,2,3)	0.95×10^6	BTU/MT
4	4[b]		EEC(4,4,2,5)	0.22	MWH/MT
			ENC(4,4,2,3)	2.3×10^6	BTU/MT
8			EEC(4,8,2,5)	0.18	MWH/MT
			ENC(4,8,2,3)	1.95×10^6	BTU/MT
4	6[b]		EEG(6,4,2,5)	---	
			ENG(6,4,2,3)	---	
8			EEG(6,8,2,5)	---	
			ENG(6,8,2,3)	---	

(a) Mine construction is part of the operation phase.

(b) Variable description is deleted to avoid repetition.

(c) Waste disposal is included in the power plant operations.

(d) Based on approximately eight percent consumption of the plant output.

It is important to note the significant difference in the energy rates when comparing the eastern and western coal EPCs.

Energy Requirement in the Operations Phase (i = 2)

The electric and nonelectric energy requirement variables in MWhrs and BTUs for the j^{th} stage can be expressed as

$$R(2,j,2,5) = EE\phi(2,j,2,5) \times R(2,j,2,0) \qquad (6.53)$$

$$R(2,j,2,3) = EN\phi(2,j,2,3) \times R(2,j,2,0) \qquad (6.54)$$

where EEϕ and ENϕ are the electric and nonelectric energy average consumption rates in MWhr/MT coal and BTU/MT, coal respectively, and R(2,j,2,0) is the coal requirement from the j^{th} model facility output in MT.

In the special case of coal mining, the coal is partially produced from underground mines and partially from open-pit mines. Energy consumption rates for these methods of mining are quite different. The average consumption rates are given by

$$EE\phi(2,j,2,5) = EE\phi U(2,j,2,5) \times GAMMA(j) + EE\phi\phi(2,j,2,5)\ (1 - GAMMA(j)). \qquad (6.55)$$

Similarly,

$$EN\phi(2,j,2,5) = EN\phi U(2,j,2,5) \times GAMMA(j) + EN\phi\phi(2,j,2,5) \times (1 - GAMMA(j)) \qquad (6.56)$$

where the j = 1,5 for the eastern and western mines, respectively, and EEφU and EEφφ are the electric energy requirement rates for the underground mines and open-pit mines, respectively. ENφU and ENφφ are the nonelectric energy requirement rates for the underground mines and open-pit mines, respectively, and GAMMA(j) is the fraction of coal mined in underground mines (See Section 6.1.2).

Energy Requirement in the Construction Phase (i = 4)

The energy requirement variables in MWhrs and BTUs can be written as

$$R(4,j,2,5) = EEC(4,j,2,5) \times R(2,j,2,0) \qquad (6.57)$$

$$R(4,j,2,3) = ENC(4,j,2,3) \times R(2,j,2,0) \qquad (6.58)$$

where EEC and ENC are the energy consumption rates in MWhr/MT coal and BTU/MT Coal, respectively.

Energy Requirement in the Decommissioning Phase (i = 6)

Energy used in the decommissioning phase is expressed as

$$R(6,j,2,5) = EEG(6,j,2,5) \times R(2,j,2,0) \qquad (6.59)$$

$$R(6,j,2,3) = ENG(6,j,2,5) \times R(2,j,2,0) \qquad (6.60)$$

where EEG and ENG are the decommissioning energy consumption rates.

6.3 MANPOWER REQUIREMENTS AND OCCUPATIONAL HAZARDS

Manpower requirements during the operations, construction, and decommissioning phases of the various stages in the nuclear and coal EPCs are formulated in this section. Manpower requirements are used to calculate injuries, sicknesses, and mortalities resulting from occupational exposure and industrial occupational hazards. Injuries, sicknesses, and mortalities are then converted to a number of person-days lost using typical average hospitalization data (or days-off data) associated with the corresponding type of health effect. In one case of occupational deaths, the number of person-days lost is assumed to be 6000. Manpower occupational hazards associated with transportation are treated separately in Section 6.5.

Manpower Requirements and Occupational Hazards for the Nuclear EPC (Operation, Construction, and Decommissioning) (i = 1, 3, and 5)

The manpower requirements in person-years for the j^{th} facility are calculated by the expression

$$R(i,j,2,6) = R(1,j,2,0) \times RL(i,j) \qquad (6.61)$$

where R(i,j,2,6) is the manpower requirements in person-years for the j^{th} facility during the i^{th} phase of its lifetime. R(1,j,2,0) is the fuel material requirement variable for the j^{th} facility, and RL(i,j) is the manpower requirement rate in person-years per MTU of the j^{th} model facility output and during the i^{th} phase (operations i = 1, i = 3 construction, i = 5 decommissioning).

The occupational health effects associated with equation 6.61 are given in person-days lost by

$$PO(i,j,m) = R(i,j,2,6) \times HE(i,j,m) \times DL(i,j,m) \tag{6.62}$$

where PO(i,j,m) is the number of person-days lost by the m^{th} type health effect associated with the manpower requirement R(i,j,2,6) for the j^{th} facility and during the i^{th} phase (m = 1 for injuries, m = 2 sickness, and m = 3 mortality). HE(i,j,m) is the rate of occurrence of the m^{th} type health effect in the j^{th} facility and during the i^{th} phase per person-year of productive labor. DL(i,j,m) is the number of person-days lost associated with the m^{th} type health effect in the j^{th} facility and during the i^{th} phase of operation.

In case of radiation-induced sicknesses and mortalities, the parameter HE(i,j,m) is treated as a composite parameter with induced sickness or mortality per person-year given as

$$HE(i,j,m) = DOSR(i,j) \times ER(i,j,m) \tag{6.63}$$

where DOSR(i,j) is the exposure rate in mrem/person-year in the j^{th} facility, and during the i^{th} phase, ER(i,j,m) is the rate of induction of the m^{th} health effect per person-rem.

From Equation (6.62), the overall person-days lost for the j^{th} facility can be expressed as

$$PO(j) = \sum_i \sum_m PO(i,j,m). \tag{6.64}$$

Parts of different parameters in Equations 6.61, 6.62, and 6.63 are partially listed in Chapter 4 of this report.

6.3.2 Manpower Requirements and Occupational Hazards for the Coal EPC (Operation, Construction and Decommissioning) (i = 2, 4 and 6)

In this cycle, occupational radiation exposure is insignificant. Equations identical to Equations (6.61), (6.62), and (6.63) are used to calculate manpower requirements and associated health impact. Some of the parameters in these equations are listed in Chapter 4 of this report.

6.4 EFFLUENT SOURCE TERMS

Pollutants are emitted during construction, operation, and decommissioning of the various facilities of the coal and nuclear EPCs. Pollutants are also emitted during construction and process materials preparation and during major component and equipment fabrication. In addition, pollutants are associated with transportation and energy production to supply the various energy requirements of the facilities. This section is devoted to direct emissions associated with construction, operations, and decommissioning of the facilities in the two EPCs under investigation. Emissions associated with transportation activities, material preparation activities, and equipment fabrication activities are treated in Sections 6.5, 6.6, and 6.7.

6.4.1 Direct Effluents Source Terms for the Nuclear EPC (i = 1, 3 and 5)

Direct effluents have two main categories. The first category is associated with normal activities and is called controlled effluents. The second category is associated with the occurrence of abnormal events or equipment failures that result in significant releases. Normal releases are more significant (as far as the magnitude of health effect is concerned) than accidental (or uncontrolled) releases because of the remote likelihood of the occurrence of large-magnitude accidental releases.[1-3] However, it is recognized that a realistic treatment of accidental releases might disprove this claim. For this reason, detailed treatments are included. The effluent source terms are expressed in the general form

$$FS(i,j,2,n) = R(2,j,2,0) \times f(i,j,n) \qquad (6.65)$$

where FS(i,j,2,n) is the amount of n^{th} effluents emitted in MT or curies from the j^{th} facility and during the i^{th} phase. R(2,j,2,0) is the fuel material requirement variable (MTU) from the j^{th} facility, and f(i,j,n) is the emission rate (or factor) for the n^{th} effluent from the j^{th} facility during the j^{th} phase in units of MT/MTU or Ci/MTU.

The emission rate f(i,j,n) is the sum of two basic components. The first, fn(i,j,n), is associated with the normal (day-to-day) emissions of the n^{th} pollutant. The second, fa(i,j,n), is the contribution of accidental releases to the overall emission rate. Based on the discussions in Chapter 2 of this report, fa(i,j,n) can be expressed as

$$fa(i,j,n) = \sum_{u} Cu(i,j,u,n)\ p(u) \tag{6.66}$$

where Cu is the consequential source term for the n^{th} effluent associated with the occurrence of the v^{th} accident per IMTU of the annual output of the j^{th} facility; p(0) is the estimated probability of occurrence of the v^{th} accident per year.

Chapter 3 of this report includes the data base for the calculation of these parameters.

Direct Effluent Source Terms for the Coal EPC (i = 2, 4 and 6)

An effluent source term, a general expression like that of equation F.1, can be used to estimate the source terms in the case of the coal EPC. However, in some cases, the determination of the emission rate f(i,j,n) is not straightforward, as in the case of the power plant operations (i = 2 and j = 4 or 8). In this case, the emission rates are sensitive to the coal composition, the types of pollution controls, and the mathematical availability of any installed controls. Typical background information[3,4] about coal used in the eastern and western coal EPCs is shown in Table 6.5.

In general, the emission rate f(i,j,n) for the case of eastern and western coal power plants burning eastern and western coal, respectively, is given in units of MT/MT of coal by

$$f(i,j,n) = a \times P(j,n) \{((1 - CEF(n)) \bar{A}(j,n) + A(j,n)\} \qquad (6.67)$$

where a is the emission coefficient; P(j,n) is the average percentage of the n^{th} pollutant precursor in the coal fed to the j^{th} type (eastern or western) plant; and CEF(n) is the control efficiency for the n^{th} type pollutant. A(j,n) and $\bar{A}(j,n)$ are the availability and unavailability of the n^{th} pollutant control in the j^{th} facility.

The emission rate as presented in Equation 6.66 has two components, a controlled component and an uncontrolled component that accounts for failures of the pollution control devices. Table 6.6 lists typical values for the parameters in Equation 6.67.

Both the eastern and western power plants are assumed to use dry bottom pulverized coal-fired boilers. Electrostatic precipitators are used in both stations. Electrostatic precipitators control particulate emission. Their control efficiencies vary with particle size. It is recognized that emitted particles with sizes smaller than two microns have significant impact on human health[5] whereas larger size particles are of minor significance. Therefore, Table 6.6 quotes particulate collection efficiency for particulates ≤ 2 microns and shows the percentage of particles in this size range for typical uncontrolled particulate emission. More than 30 trace elements were identified in the power plant emissions. Volatile trace elements tend

TABLE 6.5

COAL CHARACTERISTICS

Coal Type	Heat Value, BTU/lb	Sulfur Percent	Ash Percent	Remarks
Eastern bituminus	12,000	2.6	9.9	Assuming 49 percent of eastern coal is cleaned
Cleaned eastern bituminus	13,200	2.1	5.6	
Average	12,500	2.3	7.7	
Western	9,670	0.8	6.3	About 10 percent of western coal is cleaned.

TABLE 6.6

PARAMETERS FOR EFFLUENTS EMISSION RATES CALCULATION

Effluent	n	j (Stage)	a	CEF(n)	A(j,n)	Remarks
SO_x	1	4	19×10^{-3}	0.8 - 0.9	0.75 - 0.95	Flue gas desulfurization is used only in the eastern plants burning high sulfur coal.
NO_x	2	4,8	9×10^{-3}	0	0	Control is achieved by combustion modification.
Particulates	3	4,8	0.34×10^{-3}	0.85	0.75 - 0.95	$a = 0.85 \times 10^{-3}$ for all particulates; 4 percent of these particulates are assumed to be $\leq$ 2 microns.
CO	4	4,8				
Hydrocarbons	5	4,8	0.15×10^{-3}	0	0	Gaseous hydrocarbons are not controlled; solid hydrocarbons are treated with the particulate emissions.

to condense on the emitted particulates. Moreover, smaller particulates offer larger surface-to-volume ratio and tend to be more enriched in the volatile trace elements by a factor ranging from 3 to 18.[5]

Data about trace elements concentration are highly uncertain and vary over a wide range. Crude estimates of their emission factors will be used in future upgrades of the analytical model.

Radioactivity is also released with coal-fired plant emissions.[6] Estimates of the activity released in the presence (and in case of failure) of electrostatic precipitator control will also be provided in the upgraded model.

6.5 TRANSPORTATION REQUIREMENTS

In this section, the transportation requirements for the two EPCs are analyzed based on Reference 24. Secondary requirement variables directly related to transportation also are modeled in separate subsections. These secondary requirements are transportation energy (fuel) requirements, manpower requirements, equipment requirements, and transportation effluents source terms. Some impact variables also are discussed and correlated with the transportation requirements.

6.5.1 Transportation Requirements for the Nuclear EPC

For simplicity, generally, it is assumed here that individual transportation links involve either the truck mode or the rail mode. An exception is the shipment of spent fuel which is assumed to be 50% by truck and 50% by rail. Thus, the materials transported by rail are 50% of the spent fuel, the high-level waste, and the cladding waste. An additional simplification is that inter-plant shipments are neglected, e.g., between enrichment plants, and shipment of UO_2 powder by some fuel fabricators to a separate fuel assembly facility.

Operations Transportation Requirements (i = 1)

During the operations phase, it is necessary to transport fuel materials, process materials, and process waste. Fuel materials transportation dominates the other two and is considered only in this section. The following is a brief qualitative overview of transportation requirements.

- Shipment of the Uranium Ore from the Mine to the Mill.

  Uranium ore is transported by truck for an average distance of 5 miles from the model mine to the model mill. The average shipment is assumed to be 24 MT of ore.

- Shipment of Yellow Cake to the Conversion Facility.

  Yellow cake concentrate is packaged in 210 liter drums holding an average of 0.38 MT of yellow cake. Drums are shipped by truck for an average distance of 1000 miles to the model conversion facility. An average truck shipment contains about 40 drums or the equivalent of 15.2 MT of yellow cake. The tare weight of the drums is 23 kg.

- Shipment of Uranium Hexafluoride (UF_6) to the Enrichment Facility.

  Natural UF_6 is assumed to be shipped by truck 750 miles to an enrichment facility in a 14-ton cylinder containing 12.5 MT of UF_6. The cylinder tare weight is 2400 kg.

- Shipment of Enriched UF_6 to the Fuel Fabrication Facility.

  Enriched UF_6 is assumed to be shipped 750 miles in 2.5 ton cylinders containing 2.28 MT of UF_6. The tare weight is 1425 kg and includes a protective overpack. Five cylinders are shipped per truck load.

- Shipment of Fresh Fuel Assemblies to the Reactor Site.

  Each shipment consists of six packages, each containing two PWR or four BWR assemblies, are assumed to be shipped 1000 miles by truck to the reactor. The tare weight of the package is assumed to be 3.6 MT.

- Shipment of Spent Fuel to the Repository.

  In this study, 50 percent of the spent fuel shipment is assumed to be by truck, and 50 percent is by rail. The truck cask is assumed to carry one PWR or two BWR assemblies containing 0.59 MT UO_2. The composite rail cask can carry 8.5 PWR or 30 BWR fuel assemblies containing 5.0 MT UO_2. An average of 1000-miles shipping distance is assumed between the reactor site and the reprocessing plant or between the reactor site and the deep geologic waste repository.

- Shipment of Recyclec UF_6.

  One 14-ton cylinder is assumed to be used for shipping recycled UF_6 1000 miles to the enrichment facility. Each truck tailer can carry one cylinder the 1000-mile distance.

- Waste Shipment to the Repository.

  High-level waste is shipped 1000 miles by rail to a geologic repository. The reusable cask tare weight is 75 MT, and each shipment will result in a disposable materials requirement of 2560 kg of glass and 2550 kg of stainless steel.

  Cladding waste is also shipped by rail to a geologic repository. The reusable cask tare weight is 25 MT, and 3 are shipped per railcar. The three casks would transport 63 ft^3 of hulls and would result in a disposal materials requirement of 540 kg of sand and 230 kg of stainless steel.

- Low-Level Waste Shipment.

  Low-level waste from fuel fabrication, reactor, and reprocessing facilities is assumed to be shipped 750 miles by truck to a shallow land burial facility. Reprocessing facilities also generate LLW that is TRU-contam ated and must be shipped 1000 miles to a deep geological repository. The shipment sizes and disposable material requirements are discussed in Section I.4.5.

Based on the above discussion, transportation requirements for the j^{th} facility fuel material output R(1,j,2,1) to the m^{th} facility (m = j + 1 in most cases) can be described in truck-miles by the general expression

$$R(1,j,2,7) = \frac{R(1,j,2,1) \times 2DU(j,m)}{CANC(j) \times CANN(j)} \qquad (6.68)$$

where R(1,j,2,1) is the j^{th} facility output requirement variable in MT of fuel material. CANC(j) is the canister capacity in MT of fuel material. CANN(j) is the number of canisters per truck trailer or railcar. (Note that the product of CANC(j) and CANN(j) is taken as the truck capacity in MT of ore in the case j = 1.) DU(j,m) is the one-way hauling distance (miles) between the j^{th} and m^{th} facilities.

Truck fuel consumption R(1,j,7,3) is based on given rates of diesel fuel usage per ton-mile (or, equivalently, MT-KM). Because a truck is assumed to be loaded on a one-way trip and to be carrying empty canisters on the return trip, the transportation fuel requirement in BTUs is given by

$$R(1,j,7,3) = \left\{ \frac{2\{TRW(j) + CANN(j) \times CANW(j)\}}{CANC(j) \times CANN(j)} + 1 \right\} R(1,j,2,1) \times DU(j,m) \times TRFR \qquad (6.69)$$

where CANW(j) is the empty canister weight in MT; TRW(j) is the truck weight in MT; and TRFR is the fuel consumption rate in BTU/MT Mile. A similar expression can be used for rail.

The first term in Equation 6.69 represents the two-way trip contribution of the truck and empty canisters whereas the second term is the weight of fuel material.

Typical numerical values for the different parameters of Equations 6.68 and 6.69 are tabulated in Table 6.7.

Construction Transportation Requirements (i = 3)

Construction materials are transported to the j^{th} facility site from the material productions or material acquisition locations. The normalized number of truck-miles used to transport the k^{th} material to the j^{th} facility is given by

$$R(3,j,k,7) = \frac{R(3,j,k,0)}{TRCAP(k)} \times 2D(k,j,) \qquad (6.70)$$

where k identifies the material type (e.g., 80 for cement, 81 for steel, etc.), and D(k,j,) is the distance given in miles between the k^{th} material initial location to the j^{th} facility. TRCAP(k) is the amount of the k^{th} material per truck (MT). The overall truck-miles associated with construction are determined by summing over given values of k.

Decommissioning Transportation Requirements (i = 5)

Transportation requirements depend on the type of decommissioning used. If complete dismantlement is desired, the transportation requirement can be given by an expression similar to Equation 6.70.

TABLE 6.7

TRANSPORTATION PARAMETERS FOR THE NUCLEAR EPC

From Stage j	To Stage m	DU(j,m) Miles	Canister Information			
			CANC	CANN	CANW	Remarks[a]
1 Mine	2 Mill	5	24 MT	1	0	Uranium ore transportation; No cans; CANC represents truck capacity
2 Mill	3 Conversion facility	1000	0.38 MT	40	23 Kg	Yellow cake transportation
3 Conversion facility	4 Enriched fuel	750	12.5 MT UF_6	1	2400 Kg	Naturally enriched UF_6
4 Enriched fuel	5 Fuel fabrication	750	2.28 MT UF_6	5	1425 Kg	Enriched UF_6
5 Fuel fabrication	6 LWR	1000	1.18 MT UO_2	6	3.6 MT	Fresh fuel assemblies
6 LWR	7 Reprocessing	1000	0.59 MT UO_2 5.0 MT UO_2	1 1	20 MT 65 MT	Spent fuel assemblies-truck Spent fuel assemblies-rail
7 Reprocessing	4 Enrichment	1000	12.5 MT UF_6	1	2400 Kg	Recycled UF_6

TABLE 6.7 (Continued)

From Stage j	To Stage m	DU(j,m) Miles	Canister Information			
			CANC	CANN	CANW	Remarks[a]
7 Repro-cessing	8 Waste disposal	1000	12.6 MTHM	1	100 MT	High level waste-rail
		1000	1340 Kg	1	65 MT	Cladding Waste-rail
6 Reactor	8 Waste disposal	1000	0.59 MT UO_2	1	60 MT	Spent fuel assemblies-truck
			5.0 MT UO_2	1	65 MT	Spent fuel assemblies-rail
5 Fuel Fabrication	8 Waste disposal	750	600 ft^3	85	0	LLW for shallow land burial
6 Reactor	6 Waste disposal	750	600 ft^3	85	0	LLW for shallow land burial
7 Repro-cessing	8 Waste disposal	750	600 ft^3	85	0	LLW for shallow land burial
7 Repro-cessing	8 Waste disposal	750	420 ft^3	60	7 MT	TRU-contaminated LLW for geological repository

[a] Other information:
TRW(j) = 14.4 MT   TRFR* = 2720 BTU/ton-mile (≅ 3000 BTU/MT-mile).

For example,

$$R(5,j,8,7) = \frac{R(5,j,8,0)}{TRCAP(8)} \times 2D(8,j) \qquad (6.71)$$

where R(5,j,8,0) is the total amount of materials in the j^{th} facility MT, and D(8,j) is the distance given in miles from the j^{th} facility to the ultimate disposal site. TRCAP(8) is an average capacity of trucks used in decommissioning (MT).

If mothballing or entombing decommissioning modes[7] are used, Equation 6.71 will be modified to reflect the amount of materials transported offsite.

6.5.2 Transportation Requirements for the Coal EPC

Unlike the case of the nuclear EPC, transportation requirement modeling for the coal EPC is quite complex. Complexity arises from the fact that more than one mode of transportation exists between Stages 2 and 3 (processing site to power plant site), and usage of each transportation mode differs in the eastern coal cycle and the western cycle. A detailed description of each mode is included in Appendix I.

Mode 7,1: Unit Train.[8,9] A typical unit train is devoted to transporting coal to the power plant site. It consists of six 3000-horsepower locomotives, 100 hopper cars having capacities of 100 tons each, and a caboose. One of the chief advantages of a unit train system is its relative speed and ease of loading and unloading.

Mode 7,2: Trucks.[5] The average truck load shipment is 15 to 25 tons. Trucks are usually loaded by shovels or front-end loaders. Typical hauling distances for coal trucks range from 50 to 75 miles; however, in this model, typical processing plant-power plant site distances will be used together with an effective fraction of power plant coal assigned to this model.

Mode 7,3: Water-borne System.[10] This mode of transportation is considered in the eastern cycle. Coal is moved by a train consisting of a tugboat and up to 36 barges. Tugboats are driven by diesel engines of up to 10,000 horsepower.

Mode 7,4: Coal Slurry Pipelines.[9,11-14] In this case coal is pulverized and mixed with an approximately equal weight of water to form a slurry that is pumped through a long-distance pipeline. Data from 1972[15] indicate that less than 5 percent of western coal is transported by the slurry pipeline. For simplicity, this mode of transportation will be excluded from the model; however, it can be included by simple extension of the analysis.

Operations Transportation Requirement (i = 2)

The bulk of the transportation requirement in the operations phase is related to coal. Transportation of process materials is not considered in this derivation. Coal transportation requirements in vehicle-miles for the j^{th} facility are expressed as

$$R(2,j,2,k) = \frac{R(2,j,2,0) \times DELTA(j,k)}{CAP(k)} \times 2D(j,j+1) \qquad (6.72)$$

where R(2,j,2,0) is the coal requirement output of the j^{th} facility MT (See Section 6.1.2). CAP(k) is the k^{th} mode unit capacity in MT; DELTA(j,k) is the fraction of coal transported by the k^{th} mode; and D(j, j + 1) is the distance in miles between the j^{th} and j + 1 facilities sites.

Fuel consumption in BTUs for the k^{th} mode is given by

$$R(2,j,k,3) = 1 + \frac{2\ TRW(k)}{CAP(k)} \times R(2,j,2,0) \times DELTA(j,k) \times TRFR(k). \tag{6.73}$$

Terms in Equation 6.70 carry the same meaning as those in Equation 6.72. In addition, TRW(k) is the k^{th} mode unloaded vehicles weight in MT, and TRFR(k) is the k^{th} model fuel consumption rate in BTU/MT mile. Typical values for the different parameters in Equations 6.72 and 6.73 are listed in Table 6.8.

Construction Transportation Requirements (i = 4)

As in the case of the nuclear EPC, construction materials are transported to the j^{th} facility site from the construction material production (or acquisition) locations. Trucks are considered the only transportation mode utilized in this phase. The normalized number of truck-miles necessary to transport the k^{th} material to the j^{th} facility is given by

$$R(4,j,k,7) = \frac{R(4,j,k,0)}{TRCAP(k)} \times 2D(k,j) \tag{6.74}$$

where k identifies the material type (e.g., 80 for cement, 81 for steel, etc.). D(k,j) is the distance in miles between the k^{th} material initial location to the j^{th} facility site. TRCAP(k) is the amount of the k^{th} material per truck (MT).

As before, the overall truck-miles associated with construction are determined by summing Equation 6.74 over all values of k.

TABLE 6.8

COAL TRANSPORTATION PARAMETERS

Facility (Starting Point) j (Stage)	Transportation Mode k (Primary requirement)	Parameters CAP(k) MT	DELTA(j,k) percent	D(j, j + 1) miles	TRW(k) MT	TRFR(k) BTU/MT-mile
1 Eastern mine	7,2 Truck	23	100	5	14	3000
5 Western mine	7,2 Truck	23	100	5	14	3000
3 Eastern processing plant site	7,1 Unit train	9100	71.6	300	4100[a]	450-600
	7,2 Truck	23	13.0	300	14	3000
	7,3 Waterborne	80000	15.4	300	10300[b]	1100-2750
	7,4 Pipeline					
5 Western processing plant site (or mine)	7,1 Unit train	9100	95.4	300	4100	450-600
	7,2 Truck	23	0.0	300	14	3000
	7,3 Waterborne	80000	0.0	300	10300	1100-2750
	7,4 Pipeline[c]		4.6	300		

(a) Six locomotives, each 150 tons, plus 100 Hopper Cars, each 36 tons, = 4,500 tons (≅ 4,100 MT).

(b) Tugboat 500 tons plus 36 barges, each 300 tons, = 11,300 tons (≅ 10,300 MT).

(c) This mode is omitted in the model for simplicity.

Decommissioning Transportation Requirement (i = 6)

Mathematical treatment of the decommissioning transportation requirement is identical with that of Section 3.5.1, thus

$$R(6,j,8,7) = \frac{R(6,j,8,0)}{TRCAP(8)} \times 2D(8) \qquad (6.75)$$

where all the terms carry a similar meaning to those in Equation 6.71.

6.5.3 Secondary Transportation Requirements

Transportation vehicles are consumed during the conduction of transportation activities. Energy materials and manpower are required to replace the consumed vehicles. This is shown in the transportation requirement tree in Figure 6.1. In this section, formulas used to calculate the number of consumed units are developed; fabrication energy and material requirements for fabrication are also formulated; and the various assumptions underlying the derivation are stated. Manpower requirements and energy requirements to support these activities are covered in later sections (Sections 6.6 and 6.7). Effluents, occupational hazards, and hazards to public health associated with the operation and acquisition of these vehicles are also covered in these sections.

Transportation Equipment (Vehicles) Requirements

In this subsection, expressions for calculating the transportation equipment requirements are derived. Each mode is treated separately, and details of the derivation are described in detail.

Unit Train (k = 7,1)*

In order to estimate the number of unit trains consumed during the 30-year lifespan of the coal EPC, the loaded and unloaded train speeds are assumed to be 25 and 35 miles per hour, respectively. Loading and unloading times are taken to be 2 and 5 hours, respectively. A federal inspection is assumed every 500 miles, and a 15-minute crew change is conducted every 100 miles. Under these assumptions, the time in hours spent per round trip is approximately given by

$$\frac{D(j,\ j+1)}{35} + \frac{D(j,\ j+1)}{25} + 2 + 5 = \{7 + 0.0756\ D(j,\ j,\ +1)\}$$

where D(j, j + 1) is the distance in miles between the j^{th} and j + 1 facility sites.

The amount of coal (MT) transported by a single unit train in a one-year period is given by

$$\frac{8322\ (hrs/yr) \times 10{,}000\ tons/unit\ train}{\{7 + 0.0756\ \ D(j,\ j+1)\} \times 1.1\ (MT/ton)}$$

where 8322 is the number of hours per year, assuming 5 percent down-time for the rail system.

Because the amount of coal to be transported annually to the power plant site is given by R(2,2,2,0) DELTA(k) (k = 7) per unit train, the unit train fleet size can be expressed as

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*The meaning of k = 7,1 is explained in Table 6.8 and is abbreviated as 71 when used.

$$\text{Fleet size} = \frac{1.1\ R(2,2,2,0)\ \{7 + .0756\ D(2,3)\}\ DELTA(71)}{8322 \times 10,000} \times 1.1$$

$$= 1.45 \times 10^{-8}\ \{7 + .0756\ D(2,3)\}R(2,2,2,0)DELTA(71)$$

(Assuming 10 percent reserve of the rolling stock).

After 30 years of operation, the unit train requires replacement with an overall requirement of 2.13 of the initial fleet size. Thus, the number of replacements corresponding to 1 year of operation is given by

$$R(2,j,71,9) = 0.94 \times 10^{-9}\ \{7 + .0756\ D(2,3)\}\ R(2,2,2,0)\ DELTA(71). \quad (6.76)$$

Trucks (k = 7,2)

Trucks are consumed in the transportation activities and require replacement. To calculate the number of replacement units required for any specific transportation activity, the transportation requirement variable (truck-miles) is divided by an estimated unit lifetime of 600,000 miles. Hence, the number of truck replacements associated with coal transportation from the coal processing facility to the power plant site is given in units by

$$R(2,2,72,9) = \frac{R(2,2,2,72)}{TLIFE} \quad (6.77)$$

where TLIFE is the projected truck lifetime of 600,000 miles.[16] The number of trucks associated with transportation of other materials or equipment is calculated in a similar fashion.

Water-Borne Transportation (k = 7,3)

In the following analysis, a "tow" consisting of one towboat and 36 barges is assumed to be used to haul coal. Each barge has a capacity of 1500 tons.

The following additional assumptions are made:[10,17]

Operation-days per year = 360

Upstream speed (including time spent in locks) =
60 to 100 miles/day (about 3.3 miles/hr)

Downstream speed (including time spent in locks) =
220 miles/day (about 9.2 miles/hr)

Barge loading time = 0.5 hour/barge

Barge unloading time = 1 hour/barge

Barge switching time = 0.25 hour/barge

Barge steel content = 300 tons

Towboat steel content = 500 tons

The time for one round trip is therefore

$$\text{Barge cycle time (hrs)} = \frac{D(j,\ j+1)}{3.3} + \frac{D(j,\ j+1)}{9.2} + (0.5 + 1 + 0.25)36$$

$$= 0.41D(j,\ j+1) + 63$$

Where D(j, j + 1) is the one-way water-borne haulage distance. The maximum number of round trips per year per ton is

$$\frac{R(2,j,2,0) \times DELTA(73)}{CAP(73)} .$$

[Note that analysis is approximate. For example, the value of D(2,3) = 300 miles should be divided into two components. Initial transportation is by barge for 250 miles whereas the remaining 50 miles are by truck. This division is expressed by the factor DELTA(K).]

Because the lifetime of the barge is estimated to be 20 years, the required maximum number of trips in 20 years is

$$\frac{20 \times 360(\text{days/yr}) \times 24 \text{ hrs}}{0.41D(j,\ j+1) + 63} .$$

The number of barge replacements associated with transportation of R(2,j,2,0) is

$$R(2,j,73,9) = \frac{\text{Required Tows/yr}}{\text{Max. towload per 20 yrs}} = \frac{\{.41\ D(j,\ j+1) + 63\}}{20 \times 360 \times 24} \times \frac{R(2,j,2,0) \times DELTA(73)}{CAP(73)} \qquad (6.78)$$

Transportation Equipment Fabrication Energy

Fabrication energy for a full-size car is about 1.4×10^7 BTU/ton.[18] In this model, the rate is modified by a factor of 0.85. This factor reflects the fact that full-size car fabrication stresses fine finishing and trimming. In the case of tugboats and locomotives, the rate is unchanged. Fabrication energy for barges and hopper cars is omitted because of insufficient data.

Transportation vehicles fabrication energy is expressed in BTUs as

$$R(2,j,k,9) \times FBE(k) \qquad (6.79)$$

where FBE(k) is the fabrication energy per transportation unit for the k^{th} mode. Table 6.9 shows the calculated values for FBE(k).

Transportation Equipment Materials

Transportation equipment materials are dominated by steel. Aluminum, copper, and other materials are used in relatively smaller amounts. Data about these materials are not currently available. For this reason, the overall weight of a transportation unit will be considered as steel unless otherwise stated.

In the case of rail transportation consideration should be given to the rail units as well as to the transportation units. Rail life depends on several variables, the chief variable being gross tonnage. Other important variables include grade, ground type (sand, rock, etc.), and temperature.

One railroad company observed an average rail life for 60-ton capacity cars (average) of 400×10^6 gross tons on curves and 650×10^6 tons on straightaways.[19] Rail life is expected to decrease with increasing average car capacity. In this study, 500×10^6 gross tons are assumed to represent the average rail life when 100-ton capacity cars are used.

Assuming that the average weight of the unloaded unit train is equal to 4,000 tons, the annual gross tonnage carried by the rails and associated with coal requirement for the power plant results in an amount of steel in replaced rail given by

TABLE 6.9

FABRICATION ENERGY PER TRANSPORTATION UNIT

Transportation Mode	k (Primary requirement)	FBE(k) BTU/Unit	Remarks
Unit train	71	12.6×10^9	six locomotives, each 150 tons
Truck	72	19.0×10^7	
Waterborne	73	7.0×10^9	One tugboat is assumed per fleet of 36 barges

$$1.1 \times R(2,2,2,0) \times DELTA(71) \quad 1 + \frac{8000}{CAP(71)} \times \frac{D(2,3)}{500 \times 10^6} \times 2RWT$$

where D(2,3) is the mileage between the coal processing plant site and the power plant site. RWT is the rail weight (for a single track) in tons/mile. The amount of steel in the replaced rail, therefore, is

$$0.792 \times 10^{-8} \; R(2,2,2,0) \; DELTA(71) \; D(2,3) \; RWT \qquad (6.80)$$

where CAP(71) is taken to be 10,000 tons.

In the case of the western coal EPC, a similar expression is derived giving the amount of steel replacement in the rail as:

$$0.792 \times 10^{-8} \; R(2,7,20) \; DELTA(71) \; D(6,7) \; RWT. \qquad (6.81)$$

The amounts of l^{th} material associated in the transportation equipment requirement for the k^{th} mode are given by the general formula

$$R(i,j,k,l) = R(2,j,k,9) \times TRW(k,l) \qquad (6.82)$$

where R(i,j,k,9) is the number of replacement units for the k^{th} mode. TRW(k,l) is the amount of the l^{th} material per unit in the k^{th} mode. In the case of unit trains (k = 71) discussed above, the amount of steel (l = 82) in the rail must be added to the right-hand side of Equation 6.82 to obtain the overall steel requirement.

Material parameters associated with Equation 6.82 are listed in Table 6.10.

Energy invested in material production and effluents associated with these materials are treated in Section 6.7.

6.5.4 Transportation Manpower Requirement and Associated Hazards

This section includes the formulation of the labor requirement associated with fuel materials transportation and transportation units fabrication. Occupational hazards associated with usage and fabrication of transportation units also are considered. Manpower requirements related to material preparation are considered in Section 6.7.

Manpower Requirement for Transportation Units Usage and the Associated Occupational Hazards

The manpower requirements (in person-years) associated with the use of the k^{th} mode of transportation are given by

$$R(i,j,k,6) = \frac{R(i,j,2,k) \times Z(k)}{THPY \times V(k)} \tag{6.83}$$

where R(i,j,2,k) is the transportation requirements in vehicle-miles for the k^{th} modes used in transporting the fuel material requirement (coal in case i = 2) in a one-year period. Z(k) is the number of crew per transportation unit. V(k) is the average unit speed in miles/hr. THPY is the number of working hours per crew per year (2500 hrs per year). The occupational hazards associated with Equation 6.83 are given by

$$PO(i,j,k,m) = R(i,j,k,6) \times HE(k,m) \times DL(k,m) \tag{6.84}$$

TABLE 6.10

TRANSPORTATION EQUIPMENT MATERIALS DATA

Mode	k (Primary requirement)	Material TRW(k,l) tons: Steel l = 82	Aluminum l = 83	Others l = 89	Remarks
Unit train[a]	7,1				
Locomotives		900			Six locomotives, 150 tons each
Hopper cars		3400			100 hopper cars and a caboose
Total		4300			
Truck	7,2				
Tractor		8		1.5[b]	
Trailer		4.2-4.5	1.5-2		
Total		~12.4	~1.8	1.5	
Waterborne	7,3				
Tugboat		500			
Barge		10800			36 barges, 300 tons each
Total		11300			

(a) Rail contribution is detailed in Section 6.5.3.

(b) 1.5 tons of rubber and plastics.

where PO(i,j,k,m) is the person-days lost by the m^{th} type health effect (m = 1 for injuries, m = 2 for sickness, and m = 3 for mortality). HE(k,m) is rate of occurrence of the m^{th} type health effect per man-year of the k^{th} transportation mode. DL(k,m) is the average person-days lost rate per occurrence of m^{th} type health effect associated with k^{th} transportation mode usage.

The overall person-days lost associated with Equation 6.84 are determined by summation over all values of m, thus

$$PO(i,j,k) = R(i,j,k,6) \sum_{m} HE(k,m) \times DL(k,m)$$

$$= P(i,j,k,6) \times TR\phi(k) \qquad (6.85)$$

where PO(i,j,,k) is the occupational hazards associated with the use of the k^{th} mode. TRϕ(k) is the occupational hazard rate in units of man-days lost/man yr for the k^{th} mode of transportation.

Typical values for the parameters in Equations 6.83 and 6.85 are listed in Table 6.11.

Manpower Requirements Associated with Fabrication of Transportation Units and Related Occupational Hazards

Manpower requirements for fabrication of transportation units are calculated by multiplying the transportation equipment requirement variable for each of the k modes R(2,j,k,9) by the number of man-years invested in the manufacture of a single unit. Similar to the derivation in the last subsection, the occupational hazards are determined by multiplying the manpower requirement by the occupational hazard rate in man-days lost per man-year (productive); thus, the manpower requirement in man-years for fabrication is given by

TABLE 6.11

TRANSPORTATION UNITS USAGE MANPOWER AND RELATED OCCUPATIONAL HAZARDS PARAMETERS

Mode	k (Primary requirement)	Z(k)	V(k)	TRO(k) Man-days lost/ man-year
Unit train	7,1	5	25-50 miles/hr	0.78
Truck[a]	7,2	1	25-30 miles/hr	1.46
Water-borne	7,3	12	150 miles/day	0.75

[a] V(k) for this mode is that for coal, for uranium 40 miles/hr is used.

$$R(2,j,k,6) = R(2,j,k,9) \times TRL(k). \quad (6.86)$$

Occupational hazards in man-days lost associated with Equation 6.86 are thus,

$$PO(2,j,7,9) = R(2,j,k,6) \times WDLR(k) \quad (6.87)$$

where TRL(k) is the manpower invested per transportation unit. WDLR(k) is the occupational man-days lost per productive man-year. R(2,j,k,9) is the number of replacement units for the k^{th} mode defined previously.

Typical values for the different parameters in Equations 6.86 and 6.90 are listed in Table 6.12.

6.5.5 Effluents Associated with Transportation Units

Pollutants are emitted during the usage of transportation units, during their fabrication, and during their materials production processes. In this section, normal emissions during the use of transportation units are considered. Accidental or uncontrolled emissions are shown in Sections 3 and 4 of this report. Data on emissions during fabrication of locomotives, barges and other transportation units are unavailable at the time of publication. In general, emissions resulting from units usage are the dominant emissions. Effluents from the fabrication process are minor and are likely to be of the same order of magnitude as the emissions associated with the generation of the fabrication energy requirements. It is important to note that effluents from transportation units usage tend to be far less concentrated in nature compared with other sources of emission in the two EPCs treated in this study.

TABLE 6.12

TRANSPORTATION UNITS FABRICATION-RELATED MANPOWER AND OCCUPATIONAL HAZARDS PARAMETERS

Transportation Mode	k (Primary requirement)	TRL(k) man-yrs/unit	WDLR(k) man-days lost per man-year	Remarks
Unit train	7,1			
Hopper car		0.18	1.84	Total = .18 x 101 + 6 x 8.4 100 Hopper Cars 1 Caboose, 6 Locomotives
Locomotive		8.4	0.32	
Total		68.58[a]	50[b]	
Truck	7,2			
Tractor		1.4	0.55	
Trailer		0.62	0.32	
Total		2.02[a]	1.58[b]	
Water-borne	7,3			
Barge		5	1.38	One tugboat and 36 barges in a fleet
Tugboat		5	1.38	
Total		185[a]	255[b]	

[a]Total man-days required for the whole transportation unit.
[b]Total man-days lost per transportation unit.

Emission rates from unit trains can be related directly to the unit train diesel fuel consumption rate, which varies from 2.5 to 3.4 gallons per locomotive per mile. Table 6.13 shows diesel emission rates from the unit train, assuming that the train has six locomotives.

Although some coal dust may be lost routinely from poorly sealed hopper cars or may blow off cars transporting very dry coal, it appears that such particulate emissions do not pose a significant air pollution problem.

Table 6.13 shows the air pollution factors. When these factors are combined with the transportation requirement variables (See Sections 6.5.1 and 6.5.2), the result is overall emissions associated with the tranportation units usage. The formula for the effluent source term is

$$FS(2,j,k,n) = R(2,j,2,k)f(k,n) \tag{6.88}$$

where FS is the amount of the n^{th} effluents in lbs resulting from the use of the k^{th} mode of transportation; f(k,n) is the emission factor for the n^{th} effluent from the k^{th} mode in lbs of the n^{th} effluent per vehicle-mile. R(2,j,2,k) is the transportation requirement variable for the k^{th} mode in vehicle-miles.

TABLE 6.13

AIR POLLUTION EMISSION FACTORS FOR TRANSPORTATION UNITS USAGE

Mode	k (Primary Requirement)	SO_x n = 1	NO_x n = 2	Particulates n = 4	CO n = 4	Hydrocarbons n = 5	Aldehydes n = 6	Organic acids n = 7
		Emission Factors lbs/vehicle mile f(k,n)						
Unit train	7,1	0.86-1.1	6.5-8.6	0.38-0.5	2.6-3.5	1.2-1.6	0.083-0.011	0.011-0.14
Truck	7,2	6.2×10^{-3}	46×10^{-3}	2.9×10^{-3}	63×10^{-3}	10.1×10^{-3}	0.7×10^{-3}	0.7×10^{-3}
Water-borne	7,3	10.5-26.3	110-277		39.3-98.2	20-49.8		

6.6 EQUIPMENT FABRICATION

Numerous pieces of equipment and components are required for the operation of the various facilities in the two EPCs under consideration. Assuming that the effective lifetime of the equipment and components is the same as that of their corresponding model facility, it is possible to define an equipment requirement variable R(i,j,2,9) by normalizing to the annual fuel requirement variable from the model facility output. In order to provide this equipment requirement variable, the support of a number of secondary requirement variables is essential. These secondary requirements are shown in Figure 2 9. Material, energy, transportation, and manpower requirements vary for each piece of equipment. Exact analysis requires the treatment of each facility separately in order to identify the major components and pieces of equipment and determine the partial secondary requirements per component and per facility. For this stage of the analytical model development, data existing in Sections 3 and 4 and Appendix III are used; amounts of materials in the equipment and major components in each facility are used to augment the material requirements in the next section. Energy, manpower occupational hazards, and effluents associated with equipment fabrication are assumed to be equal to those invested in the equipment materials production. Refinement of this crude assumption is a part of the model upgrading.

6.7 MATERIALS REQUIREMENTS

A large quantity of different materials is used in the construction, equipment, and components of each facility of the nuclear and coal EPCs.

Material requirement variables are numerically evaluated for each individual model facility and normalized in the usual manner to determine the magnitude of the variable R(i,j,k,0). R(i,j,k,0) represents the annual requirements (in MT) of the k^{th} type material used in the equipment and construction (i = 3 or 4) of the j^{th} facility.

The process of acquiring the material requirement variable is supported by a number of secondary requirement variables, namely, R(i,j,k,5) for electric energy, R(i,j,k,7) for transportation, and R(i,j,k,6) for manpower, as shown in the requirement tree of Figure 2.8.

The following subsections include the derivation of analytical expressions for these secondary variables, effluent source terms, and occupational hazards associated with material production.

6.7.1 Energy Requirement for Material Production

The amount of energy consumed in BTUs in providing the k^{th} type material requirement variable is given by

$$R(i,j,k,5) = R(i,j,k,0)\ ECR(k) \tag{6.89}$$

where R(i,j.k,0) is the amount of k^{th} material required for construction equipment in the j^{th} facility in MT. The parameters ECR(k) is the rate of energy consumption rate for the k^{th} material in

BTU/MT. Typical values for ECR(k) are shown in Table II.1 of Appendix II.

6.7.2 Transportation Requirement

The transportation requirement variables for construction and equipment materials are calculated using expressions identical to those in Section 6.5.2. For simplicity, the truck is assumed to be the only mode used for material transportation. Secondary requirements related to transportation are also determined in a manner similar to that in Section 6.5.

6.7.3 Manpower Requirement and Occupational Hazards

Manpower requirement for materials production is calculated by multiplying the k^{th} material requirement variable by the number of person-years required to produce a unit weight of material. Thus,

$$R(i,j,k,6) = R(i,j,k,0)\ CRL(k) \qquad (6.90)$$

where R(i,j,k,6) is the manpower required to supply R(i,j,k,0) MT of the k^{th} material. CLR(k) is the manpower consumption rate in units of person-years per unit weight of the k^{th} material.

Estimated average values for CRL(k) are shown in Table II.3. Occupational hazard of the m^{th} type is expressed as

$$PO(i,j,k,m) = R(i,j,k,6) \times HE(k,m) \times DL(k,m) \qquad (6.91)$$

where PO(i,j,k,m) is the number of person-days lost by the m^{th} type health effect ($m = 1$ for injuries, $m = 2$ for sickness, and $m = 3$ for mortality) in the process of producing the k^{th} material requirement, R(i,j,k,0). HE(k,m) is the rate of occurrence of the m^{th} type health effect per person-year in the production of the k^{th} material. DL(k,m) is the average number of person-days lost per occurrence of the m^{th} type health effect associated with the k^{th} material production.

The overall person-days lost associated with all m types of health effects are determined by summing over the m index, thus

$$PO(i,j,k) = R(i,j,k,6) \sum_{m} HE(k,m) \times DL(k,m)$$

$$= R(i,j,k,6)\ RM\phi(k) \qquad (6.92)$$

where RMφ(k) is the overall rate of person-days lost per man-year of productive labor.

Estimated average values for this parameter and for the parameters of Equation 6.91 are listed in Table II.3 of Appendix II.

6.7.4 Material Production Effluent Source Terms

Pollutants are emitted during the material production processes. For simplicity, only air pollutants are considered. The expression of source terms in MT for n^{th} type pollutant emitted during the production of the k type material is given by

$$FS(i,j,k,n) = R(i,j,k,0)\ f(k,n) \qquad (6.93)$$

where FS(i,j,k,n) is the amount of the n^{th} effluent emitted during the production process of the amount of k^{th} material given by R(i,j,k,0), and f(k,n) is the emission factor in MT of the n^{th} effluent per unit weight of the k^{th} material produced.

Estimated average values for f(k,n) are listed in Table II.2 of Appendix II.

6.8 EFFLUENTS DISPERSION AND EXPOSURE MODELS

Effluents source terms were derived in Sections 3, 4, 5, 6 and 7 of this chapter. This section contains a brief outline of the modeling effort that will be used to determine average exposure of the population surrounding each model facility in the two EPCs. No mathematical derivation is given here; however, dispersion calculations will rely on well-established, existing computerized dispersion models.

Generally, an effluent source term has two components. The first is controlled and is associated with normal day-to-day operations of any model facility. The second component is uncontrolled and is associated with accidental failures of control equipment. The normal controlled component usually results in a quasi-steady state low-level concentration of the emitted pollutants in the environment that results in chronic low-level exposure of the population in the neighborhood of the source location. On the other hand, the uncontrolled (accidental) component can be associated with transient high-level concentrations that can produce acute exposure. In general, acute-exposure cause-effect relationships are well understood whereas low-level exposure effects are not (because of lack of data), with some exceptions. As an example, chronic low-level exposure to low-level mine dust eventually will produce definite symptoms of black lung disease in the case of coal miners and silicosis in workers in mineral mines.

6.8.1 Effluents Dispersion Models

Releases from the various facilities are either gaseous, liquid, or solid and radiological or nonradiological. Dispersion models[20,21] depend on the physical form and characteristic properties of each eff[illegible] well as the nature of the release path from the facility.

This work will consider the principal effluents from each facility and identify the most critical pathways associated with these effluents. In the case of gaseous or airborne effluents, a Gaussian Plume diffusion model is adopted.[21] In the case of liquid effluents, a set of appropriate pathways factors will be selected.

6.8.2 Population Distribution

To calculate the population exposure, the model facilities are assumed to be in an urban or rural area. Population densities around the two selected sites are shown in Table 6.14. The urban site is used for the conversion, enrichment, and fuel fabrication facilities and the model LWR (j = 3, 4, 5 and 6, respectively) in the case of the nuclear EPC. It also is used for the coal storage and model coal-fired plant (j =3, 4, 7 and 8) in the case of the coal EPC.

It is recognized that the final results of this study are sensitive to the assumed population distribution. Selection of a specific geographic site and representative population distribution for each facility can be examined in the context of the sensitivity analysis proposed for the analytical model.

Because, in some cases, health effects are related to age, an estimate of the average age distribution for the population is included in Table 6.15. The population distribution is used to calculate the local effects within 88.5 km from the facility. Results of this local model are combined with a global model that emphasizes the exposure to the U.S. population (as in the case of long-lived radioactive emission: C-14, Kr-85 and H-3).

TABLE 6.14

MODEL POPULATION DISTRIBUTION

Distance from Facility (km)	Population Density persons/km^2 Urban[1]	Rural[2]	Total Population Urban	Rural
< 8	37	---	7,400	---
8 - 40	49	0.44	236,500	2,200
40 - 88.5	170	3.65	3,328,500	71,000
		Total	$\sim 3.6 \times 10^6$	~ 73,200

TABLE 6.15

POPULATION AGE DISTRIBUTION

Age Group	Typical Age	Fraction of the Population (Percentage)[a]
Infants (< 1 year)	6 Months	1.79
Children (1 to 9 years)	4 Years	16.47
Teenagers (10 to 19 years)	14 years	19.57
Adults (> 20 years)	~30 years	62.17

6.9 HEALTH EFFECTS

The previous section described in broad terms the method that will be used to estimate population exposure. This section addresses the general features of the health effects estimator that will be integrated in the model.

Dose-effect relationships for each of the identified principal releases and each mode of health impact will be represented by a multiplier.[22] The use of these multipliers means that a linear type dose-effect relationship is assumed. A linear relationship implies that the exposure to pollutants at any concentration always results in some damage to human health. This assumption is widely believed to be conservative and to overestimate the health impact.

The threshold hypothesis is an alternative to the above assumption. It assumes that below a certain exposure level, no effect or health damage occurs. The linear hypothesis is favored primarily for its conservatism and its simplicity. Estimates for the dose-effect multipliers for somatic and genetic health effects are included.[22]

A comprehensive discussion of the health effects and cause-effect relationships is included in Appendix V.

6.10 CYCLE INTERACTION

As described in Section 2 of this report, the coal and uranium cycles interact through their electric energy requirement variables. These interaction parameters may vary with time and location of the various model facilities, and can provide the decision maker with valuable information when used as sensitivity parameters.

SAI has developed a generalized approach that not only treats the coal fired plants and LWRs as a source of electricity, but also treats other energy production cycles that may play a major role in future electricity generation.

The net health effect of electric energy production can be expressed as:

$$\underline{P} = (I-A)^{-1}\ \underline{P}o \qquad (6.94)$$

where

$\underline{P}o$ is an n-tuple vector whose i^{th} component, Po_i, is the health effect associated with the i^{th} cycle when the health impact of electric energy requirements is ignored in this cycle.

$\underline{P}$ is an n-tuple vector whose i^{th} component, P_i, is the total health impact of the i^{th} cycle including the electric energy requirements, and

A is an n x n matrix whose elements are the interaction coefficients.

The elements a_{ij} are the fractions of unit energy consumed in the i^{th} cycle and generated by the j^{th} cycle.

In the special case where the nuclear (i=1) and coal (i=2) cycles are assumed to be isolated from other energy sources, A will b a simple 2 x 2 matrix. The net health effect expressed in terms of the health effects in the two cycles excluding the electric energy requirement is given by

$$\begin{pmatrix} P_1 \\ P_2 \end{pmatrix} = \frac{1}{(1-a_{11})(1-a_{22}) - a_{12}\, a_{21}} \begin{pmatrix} 1-a_{22} & a_{12} \\ a_{21} & 1-a_{11} \end{pmatrix} \begin{pmatrix} Po_1 \\ Po_2 \end{pmatrix} \qquad (6.95)$$

No interaction between two cycles is equivalent to setting $a_{12} = a_{21} = 0$; and in this special case[23]

$$P_1(1-a_{11}) = Po_1$$
$$P_2(1-a_{22}) = Po_2$$

The split of the electric energy requirement between coal and uranium varies with time. As of January 1980 electricity production was 48.4 percent from coal, 11 percent from nuclear, and the remainder from oil, gas and hydro.

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APPENDIX I
TRANSPORTATION

Sections 3 and 4 include partial specification of the transportation requirements for each stage of the two cycles. This appendix sets the framework for assessment of the impact of transportation requirements in the study and, hence, represents an important link in the analyses. This appendix contains a description of the transportation modes used and shows the steps involved in applying the study methodology to transportation. In the following sections, transportation modes, life cycle data, and amounts of materials and energy consumed in the fabrication and use of a representative transportation unit are detailed. Manpower requirements for operating a representative unit are included, as well as the associated occupational hazards. It is recognized that certain information is lacking, especially in the area of public hazards associated with transportation. The public risk is probably much greater from the transportation vehicles themselves than from the contents of the vehicles, but further work is necessary to document this assumption.

I.1 TRANSPORTATION MODES

Principal means of transportation used in the uranium and coal cycles are described in this section. Some of these modes of transportation are unique to the coal cycle (e.g., unit train and slurry pipelines). Other modes (e.g., trucks, barges, and conventional freight train) are common to the two cycles.

I.1.1 Rail

Much of the commerce supporting the two fuel cycles travels by rail. In addition, in the nuclear fuel cycle, about 50 percent of the spent fuel transport is by rail, and all high- and intermediate-level wastes from the reprocessing facility are shipped by rail. Coal is frequently shipped by unit train.

While the definition of a unit train is, for tariff-setting purposes, the result of negotations between shipper and carrier, it is generally "a complete train of dedicated cars operating on a regularly scheduled cycle movement between a single origin and a single destination."[I-1] Unit trains operate over the same track networks as conventional freight and are assumed to carry 60 to 70 percent of the coal used for power generation.

A typical unit train consists of six 3000-HP locomotives and 100 hopper cars having a capacity of 100 tons each. About one such trainload per day would be necessary to supply a 1000-MWe power plant. Locomotive horsepower requirements vary principally with terrain; for especially steep grades, extra locomotives may be added. Hopper cars are used more extensively in unit train operations than in conventional freight. Because unit trains are a relatively new phenomenon, it is not yet known how much more often their cars must be replaced. The economic lifetime of hopper cars has been estimated to be 15 to 20 years.[I-2]

With their uniform weight and length, unit trains set up periodic stress patterns, which tend to concentrate wear and distortion at specific points along the track; lighter-gauge and jointed rail lines often need to be replaced with heavy duty, continuously-welded track.

Unit trains run continuously, with the possible exception of weekends and holidays, stopping only for refueling and for federally-required inspections every 500 miles. Speeds vary considerably, depending upon track conditions and local speed regulations along the line. Average loaded train speeds, including switching and crew-changing, vary from about 20 to 30 mi/hr. Unloaded trains run up to about 50 mi/hr.

One of the chief advantages of a unit train system is the relative speed and ease of loading and unloading the cars. Field observations in Wyoming and Colorado showed that loading and unloading take about 2 and 5 hours, respectively. After crushing and sizing, mined coal is stored on the ground or in silos before loading onto the train. Silo or bin storage provides protection from rain or snow and eliminates the need for secondary handling during loading. Hoppers can be loaded while stationary or moving. Conveyors move coal to the loading point in most ground storage systems whereas silo systems dump directly into the cars.

Two basic unloading systems are employed in coal transport by rail. In the roll-over system, cars are inverted individually or in groups; they may be unloaded individually without uncoupling if each one is equipped with a rotary or swivel couple on one end. Cars are positioned for inversion by the unit train locomotives, a yard locomotive, or by an automatic car positioner. Bottom dumping requires cars equipped with bottom dumps. Standard sawtooth type hoppers require a shaker or vibrator although many new fast unloading hoppers are self-cleaning. Newer cars allow for unloading into track pits while moving at speeds of up to 5 mi/hr.

I.1.2 Water-borne Systems

Large-sized nuclear facility components and spent fuel casks are sometimes transported by barges. In addition, it is estimated that 15 to 30 percent of U.S. coal traffic is moved in barges or other vessels, chiefly in the Ohio and Mississippi River basins.[I-3] Coal is moved as a unit consisting of up to 36 barges. Tugboats are driven by diesel engines that generate up to 10,000 HP. Modern barges have bows and sterns designed to interlock with preceding and following vessels in the tow; friction is thus reduced.

Coal loading facilities are similar to those used for rail transportation. Unloading, however, cannot be conducted with the aid of gravity. Coal is usually scooped out with buckets and transferred to conveyors. New facilities can load and unload barges in 20 or 30 minutes, but the time is usually considerably longer for older installations.[I-4]

Water-borne transportation depends heavily upon the construction and maintenance of channels, dams, and locks. The size of the locks available on river systems is the primary limiting factor because of delays and the impracticality of separating the barges each time a lock is negotiated.[I-3] Delays at some locks can be up to several days.

I.1.3 Trucks

Trucks are the dominant mode of transportation in the nuclear fuel cycle. In addition, about 11 percent of U.S. coal is carried by highway transportation. Trucks used in the uranium cycle can carry shipments of 25 MT and, in some cases, special casks with gross weights of 40 MT or more.

For processed coal, the average truck-load shipping distance to the power plant is 50 to 75 miles. Highway-going trucks, consisting of a tractor and one or two trailers, can carry 15 to 25 tons each. They are usually loaded by shovels or front-end loaders close to the coal seam. Most trucks have bottom openers or dumping capacity.

I.1.4 Coal Slurry Pipelines

Movement of coal as a slurry in a long-distance pipeline is not a new technology. A working model of a slurry pipeline was built in the year 1880, and a 13-mile pipeline in France has operated successfully for over 20 years.[I-5] From the years 1957 to 1963, the Consolidated Coal Company operated a 10-inch-diameter, 108-mile long pipeline from Cadiz, Ohio, to Eastlake, Ohio.[I-2,I-6] The pipeline performed successfully until tariff undercutting by railroads and the approval by the Interstate Commerce Commission of a separate rate structure for unit trains forced its shutdown.[I-7] In August 1970, an 18-inch-diameter, 273-mile pipeline from the Black Mesa Mine in Arizona to the 1580-MW Mohave Generating Station in southern Nevada began operation. Experience with this system has demonstrated that a coal slurry pipeline of the size required to serve a large electric power plant is economically feasible.[I-2,I-7] However, lack of eminent domain legislation for pipelines under railroad right-of-ways has seriously hindered application of this method of transporting coal.

Slurry Preparation

Coal is pulverized at the mine and is then mixed with an approximately equal weight of water. The coal/water ratio depends, among other things, upon the moisture content of the coal. Coal particles must be fine enough to form a homogeneous suspension in the water, yet not so fine that de-watering becomes too expensive. To achieve a distribution in which about 22 percent of the coal transported in the Black Mesa Pipeline is less than 325 mesh (44 μm), and 12 percent is above 30 mesh (590 μm), the Black Mesa system follows dry impact crushing and impact milling with wet grinding and rod milling.[I-8] A pipeline carrying the about four million tons/yr required by a 1-GW-yr power plant would (if 10 percent moisture is assumed) use about 2500 acre-feet of water per year.

In the Black Mesa system, run-of-mine coal is slurried directly; all water used in grinding is used in the slurry. Clay particles and other extraneous materials may clog the centrifuges at the de-watering facility. To preclude this problem and, in certain cases, to reduce the sulfur and ash contents of the coal, coal in future slurry pipeline systems may be "beneficiated" before it is ground and slurried. Beneficiation processes include crushing, sizing, gravity separation, and washing.

Transmission

Pipelines are made of carbon steel. Their diameter depends on several factors, including design velocity, throughput, and type of terrain to be traversed. At low velocities, the uniformity of the coal suspension decreases so that some of the coal particles drag along the bottom; at high velocities energy consumption is greater, and there is a higher possibility of pipeline wear. Practical operating velocities are between 3 and 5 ft/sec, and the Black Mesa slurry runs at 5 to 6 ft/sec.[I-9] Pipes are buried below the frost line to prevent the slurry from freezing. Where rivers are to be crossed, the pipelines are placed in trenches in the stream bottom below the scour level. In some cases, they are protected by concrete casings. Reciprocating, positive displacement pumps at 50- to 150-mile intervals move the slurry. Commercially available pumps for slurry pipeline services are rated up to about 1740 HP, with annual throughput capacities of two- to three-million tons. In the Black Mesa system, 1000 psi are needed to lift the slurry 1300 ft in 22 miles.[I-10]

De-watering

At the receiving end of the pipeline, the coal and water must be separated. The Mohave Generating Station uses centrifuges to remove about

87 percent of the free water (excluding the water inherently bound in the coal) from the slurry.[I-10] Water from the centrifuge, called the "centrate," still has a suspended coal solids concentration of 20,000 to 60,000 ppm by weight. The centrate is added to a "clari-flocculator" tank in which an organic polymer flocculant increases the settling of the coal fines. Because water adheres to the ultrafine coal particles removed as underflow from the clariflocculator, only about 73 percent of the centrate is recovered. The net recovery rate for water reuse is about 64 percent.

De-watering plants for future pipelines may use other processes. Nevada Power Company is considering vacuum filtration. De-watering of coal in the proposed Houston Natural Gas Corporation pipeline would be by centrifugation and/or vacuum filtration in addition to heating, if required.[I-11] It is possible that improved de-watering techniques may increase the water recovery rate.

I.2 IMPACT OF TRANSPORTATION IN THE TWO CYCLES

The health impact of the transportation activities is treated in a manner similar to that used for the cycle stages. The life cycle of each transportation mode also is considered. As shown in Figure I.1, three basic phases of a typical transportation mode life cycle are considered:

- Materials Production

  Production of steel, aluminum, and other materials of which transportation vehicles, pipelines, and ancillary equipment are made.

- Transportation Unit Fabrication

  Assembly of locomotives, barges, and other transportation units and ancillary equipment.

- Transportation Unit Use

  Operation of trains, barges, trucks and pipelines.

Associated with each of these phases are two types of "impacts." The first is requirements (such as manpower and energy). The second is effluents (pollutant emissions) and risk-inducing factors (occupational accidents and public safety hazards). It should be noted that the boundary of any analysis of this type is arbitrary, and that each "impact" identified may result in secondary or tertiary impacts. Consider, for example, the energy required for locomotive fabrication. This analysis has been restricted to quantifying this requirement. However, the analysis could have been extended by estimating the effluents from the power plant used to produce the electrical energy for the locomotive factory; the material requirements for building both the factory and the power plant; the energy required to produce the fuel for that power plant; and so on.

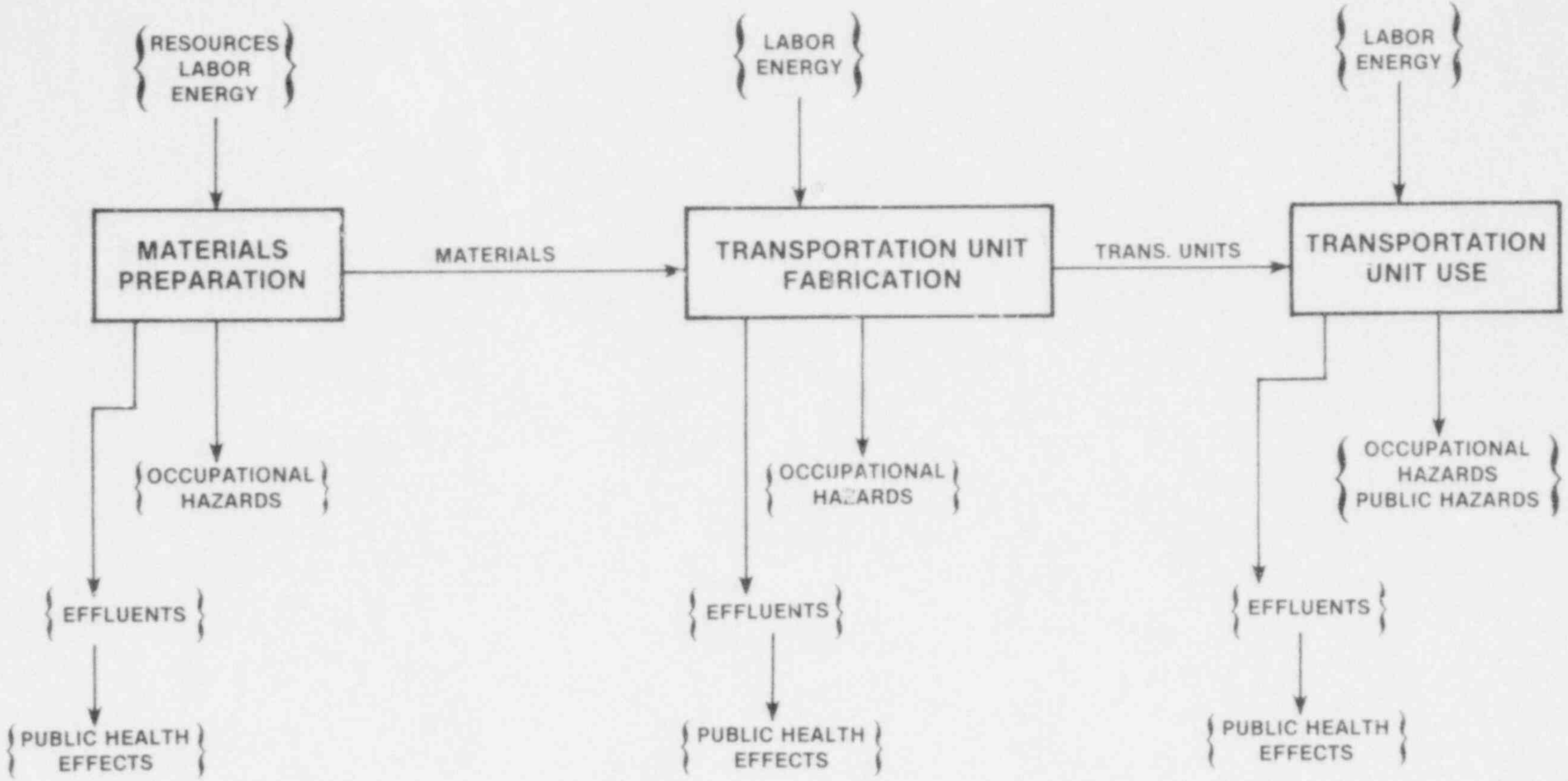

FIGURE I.1. LIFE CYCLE SEGMENTS CONSIDERED FOR A TYPICAL STAGE.

I.3 LIFE CYCLE DATA FOR TRANSPORTATION MODES

In the following subsections, material requirements, fabrication energy, manpower, and transportation unit operational energy consumption, are detailed. This information, coupled with typical transportation mode life cycles, can be used to determine the amounts of effluents and other risk-inducing factors that may impact human health.

The nuclear fuel cycle requires special packages for spent fuel, high-level wastes, and other wastes. These packages are described in the next section of this Appendix.

I.3.1 Rail

As mentioned above, a typical unit train consists of six 3000-HP locomotives, 100 hopper cars (each with 100-ton capacity), and one caboose. Assuming that the bulk of material used is steel and using the data in references I-12 and I-15, it is estimated that each locomotive contains 150 tons of steel, and hopper cars and cabooses weigh about 31 tons.

Although actuarial data for freight cars and locomotives in general service have been compiled,[I-12] no such data are available for unit train service. It is known, however, that the more intensive use of rolling stock in coal unit trains results in shorter vehicle lifetimes than for stock used in general service. Based on discussions with railroad personnel,[I-13] the following arbitrary actuarial table for rolling stock has been constructed:

Age (Years)	Percentage Replaced
14	10
15	60
16	10
17	10
18	10

If U_0 units are needed at the start of year 1, then the purchase and replacement schedule is as follows:

Start of Year	New Units
1	U_0
15	$0.1\ U_0$
16	$0.6\ U_0$
17	$0.1\ U_0$
18	$0.1\ U_0$
19	$0.1\ U_0$
29	$(0.1)(0.1)\ U_0$
30	$[(0.1)(0.6) + (0.6)(0.1)]\ U_0$
Total	$2.13\ U_0$

To estimate steel requirements for rails, it is assumed that no new rail construction would be necessary, and rails would be replaced as needed. Rail life depends upon several variables, with the chief variable being gross tonnage.[I-14] Other important variables include grade, ground type (sand, rock, etc.), and temperature. One railroad company observed an average rail life for 60-ton capacity cars (average) of 400-million gross tons on curves and 650 million gross tons on straightaways.[I-14] Rail life is expected to decrease with increasing average car capacity. Because of a lack of better data, a value of 500 million gross tons has been chosen to represent the average rail life when 100-ton capacity cars are used. The rail replacement rate was thus estimated by the weight of total rail traffic tonnage present divided by 500 million gross tons. Rail is also assumed to weigh 132 pounds per yard or 232 tons per mile of single track.

Information about the amount of energy consumed in fabricating locomotives, hopper cars, cabooses, or rails is not presently available. An estimate of the fabrication energy will be provided in later versions of this report.

Energy consumption in coal transportation is highly route-dependent. As part of a study for the Office of Technology Assessment (OTA)[I-15], General Research Corporation estimated energy intensities ranging from 345 to 540 Btu per net ton-mile. A value of 400 Btu/ton-mile has been assumed as a representative figure. The number of ton-miles per year is calculated by multiplying annual train mileage by 10,000 tons per trainload.

I.3.2 Water-borne System

For coal transportation by water-borne systems, a "tow" is assumed to consist of one tugboat and up to 36 barges. The tugboat has 10,000 HP, and each towed barge has a capacity of 1500 tons.[I-3] Typical upstream fleet speed is 3.3 miles/hr (60 - 100 miles/day),[I-4] while downstream speed averages 9.2 miles/hr (220 miles/day). This average speed includes stoppage in the locks. A tugboat is also assumed to contain 500 tons of steel while each barge contains 300 tons. The lifetime of these vessels is estimated to be 20 years.[I-13] The energy requirement for fabrication of a tugboat or barge is not currently available and will be included in future revisions of this report. The consumption rate of energy for the water system operation is estimated to be 1.4×10^3 Btu/ton-mile.[I-16]

I.3.3 Trucks

The materials required for a truck-trailer combination are detailed in Table I.1. The lifetime of the truck is assumed to be 600,000 miles.[I-17] The fabrication energy of a full-size car is estimated to be about 1.4×10^7 Btu/ton.[I-18] This figure is used to estimate fabrication energy for typical trucks of 14-MT weight. Energy consumed in operating a truck is assumed to be 8.5×10^3 Btu/ton-mile.

I.3.4 Coal Slurry Pipelines

In a coal slurry pipeline system, the chief material requirement is steel for the pipeline, pumping stations, and coal preparation and de-watering facilities.

The pipe weight per unit length can be related to its outside diameter by the following empirical formula:[I-15]

$$\text{Pipe weight (tons/mile)} = 1.52\ (OD)^{1.58}$$

where OD is the outside diameter.

Assuming that T is the annual coal tonnage shipped by the pipeline, the OD can be estimated from the empirical formula:

$$OD = 8.12 \times 10^{-3} \sqrt{T}\ .$$

Combining the above two equations and assuming that (1) D is the shipping distance in miles and (2) the steel used in the pumping station and de-watering facilities is about 2 percent of that used in the pipeline,[I-19] the total amount of steel can be expressed as a function of the annual coal tonnage T shipped by the pipeline:

$$\text{Amount of steel (tons)} = 7.7 \times 10^{-4}\ D\ \text{(miles)}\ T^{0.79}\text{(tons/yr)}$$

TABLE I.1

MATERIAL REQUIREMENTS FOR TRUCKS AND TRAILERS

Material	Tractor[a]	Trailer[a]
Steel (lbs)	16,000	8,500 - 9,000
Aluminum (lbs)		3,000 - 4,000
Rubber[b] (lbs)	2,600	
Fiberglass (lbs)	300	
Upholstery (lbs)	150	

(a) R. Stalley, American Trucking Association, Washington, D.C., Personal Communication, January 3, 1979.

(b) Assuming 18 tires per vehicle.

It is also estimated[I-19] that pipeline construction would require 1.6×10^9 Btu/mile whereas construction of each pumping station would require 2.3×10^{10} Btu. Because there is, on the average, one pumping station per 75 miles, the total fabrication energy can be determined using the formula:

$$\text{Fabrication energy in Btu} = 1.6 \times 10^9\ D + 2.3 \times 10^{10}\ D/75$$
$$= 1.9 \times 10^9\ D$$

Energy consumption for coal slurry pipeline operations is highly route-dependent. An estimated weighted average of the energy consumption rate during operations is 5.9×10^2 Btu/ton-mile.

I.3.5 Labor Requirements and Occupational Hazards

Labor requirements and their associated occupational hazard rates for tranportation units material production and fabrication are included in the material and equipment appendices.

A typical unit train has a five-person crew[I-20] whereas loading and unloading operations require about three persons each. The total amount of labor is based on (1) 360-days/yr operation, (2) the number of unit trains required, and (3) 7 hours for loading and unloading.

A tugboat-barge system is assumed to operate fulltime to haul coal. Each barge system has a 12-person crew.[I-21]

Truck trailers are assumed to operate on a 24-hrs/day, 360-days/yr basis, with one driver per truck.

The Black Mesa coal slurry pipeline has 40 employees working at the slurry preparation facility in Kayenta, Arizona, and six working at the pump stations.[I-22] Assuming 40 more employees are needed for a de-watering facility, a total of 86 employees would be required for a 5-MT/yr, 300-mile pipeline. Also, assuming that the scaling to other pipelines would be linear, a rate of 115 person-hours/10^6 ton-mile for 2000-hour work years is assumed. For the 188-mile, 3.8-MT/yr pipeline (the hypothetical movement assumed here), the labor requirement would be 8.2×10^4 person-hours or 41 person-years. In scaling to much larger pipelines (25 MT/yr, 1000 miles, for example), a labor savings of 30 percent because of scale economies might be achieved.

The occupational hazards (in terms of man-days lost) associated with the use of the transportation systems described above are shown in Table I.2.

TABLE I.2

TRANSPORTATION SYSTEMS OPERATING OCCUPATIONAL HAZARDS

Mode	Lost Workday Rate[a] (lost workdays/person-year)
Rail Transportation	0.78
Water Transportation	2.77
Trucking, Local and Long Distance	1.46
Pipeline Transportation	0.75

(a) U.S. Department of Labor, Bureau of Labor Statistics, "Outlook on Occupational Injuries and Illnesses in 1975," Report 501, 1977.

I.4 NUCLEAR PACKAGE DESCRIPTION AND MATERIALS REQUIREMENTS

Radioactive materials in a wide variety of physical and chemical forms must be transported between facilities that are situated in diverse geographic locations. Materials such as uranium ore concentrate, uranium hexafluoride, fresh LWR fuel, spent LWR fuel, plutonium, and many forms of radioactive waste have been shipped routinely in the United States for many years. Other materials that are expected to require transportation on a commercial scale in the future are solidified high-level waste, cladding hulls, and radioactive gases. Although these materials have not yet been packaged and shipped on a commercial scale, development of appropriate transportation systems is not expected to pose significant technical difficulties.

In the United States, radioactive materials in the nuclear fuel cycle are transported primarily by truck or rail. To simplify this presentation, either truck or rail is selected as the dominant mode for discussion; however, the choice is essentially an economic one. Furthermore, only legal weight truck shipments are assumed in order to reduce the complexity of the discussion. In practice, a significant fraction of overweight shipments is made for economic or logistics reasons. Likewise, intermodel shipments (e.g., both truck and rail) are not discussed here. In this presentation, barge or sea transport has not been considered although in many cases they are viable, economic alternatives for domestic transport and a practical necessity for many international shipments. Air transport is not considered economical for commercial shipments in the fuel cycle.

I.4.1 Uranium Oxide Powder

Fresh UO_2 and ThO_2, recycled ThO_2 stored 10 years, and reprocessed UO_2 that has been through two purification cycles (<200 mrem/hr) can be handled similarly. Typically, UO_2 is packaged in steel containers within an inner gasketed steel cylinder, which is contained in a double-high 55-gal steel drum. About 0.11 MT of UO_2 is packaged per drum. Almost all shipments of UO_2 are made by truck. Normally, 40 drums are loaded per vehicle, with a net weight of 4.4 MT of UO_2 per shipment.[I-23] Fifty-five gallon drums have a tare weight of about 23 kg.[I-24]

Uranium may be recycled (1) by transporting UF_6 to the enrichment facility, (2) by transporting UO_2 to the fuel fabrication facility, or (3) both. To simplify subsequent discussion, uranium is assumed to be recycled as UF_6 and transported from the reprocessing facility to the enrichment facility.

I.4.2 Uranium Hexafluoride

Uranium hexafluoride is a highly reactive material that reacts chemically with water, most organic compounds, and many metals. UF_6 does not react with oxygen, nitrogen, or dry air, and it is sufficiently inert with aluminum, copper, Monel, and nickel that they can be used in a UF_6 environment without excessive corrosion. At room temperature, UF_6 is a white, volatile solid. The UF_6 is placed in its shipping container under pressure as a liquid at about 90°C (200°F) and then is cooled to room temperature to form a solid before shipment.

Four containers are available for shipping UF_6 for the various fuel cycles: (1) the 5A cylinder containing 25 kg, (2) the 30B cylinder containing 2½ tons,* (3) the 48X cylinder containing 10 tons,* and (4) the 48Y cylinder containing 14 tons.* Fifty 25-kg cylinders, two 10-ton cylinders, one 14-ton cylinder, or five 2½ ton cylinders can be transported on a truck trailer. Four 10-ton cylinders, four 14-ton cylinders, or sixteen 2½-ton cylinders can be transported on a railroad flatcar. The 25-kg cylinder is not normally transported by

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*The "2½-ton" cylinder has a nominal capacity of 2.28 metric tons; however, the nomenclature is common practice. The same is true for the "10-ton" (9.5MT) and "14-ton" (12.5MT) cylinders.

rail. Special cradles and tiedowns are used to secure the cylinders to the transport vehicle.[I-25]

The maximum enrichments are 5, 4.5, and 4.5 wt% ^{235}U for the 2½-ton, 10-ton, and 14-ton cylinders, respectively. Cylinders containing UF_6 enriched to greater than 1.0 wt% ^{235}U must be shipped in protective outer packages (called overpacks) to ensure criticality prevention and to protect the cylinders from accident environments. Usually such shipments constitute a Type-B quantity of radioactive material under NRC regulations. Type-B protective overpacks for the 2½- and 10-ton cylinders have been designed to satisfy the accident test criteria of 10CFR71. These overpacks are boxes or cylinders with about 6 inches of foam between steel plates. Neoprene pads or rubber cradles inside the inner steel liner cushion the UF_6 cylinder. Truck shipment of UF_6 in 2½-ton cylinders with overpacks is generally used for the level of U enrichment needed for current LWRs.

I.4.3 Fresh Fuel

Fresh fuel assemblies are usually enclosed in a plastic bag and shipped in a container that supports the fuel assembly along its entire length (sometimes called a strongback). Typically, two PWR or two BWR fuel assemblies are packaged within one container. Containers for PWR fuel consist of a steel cradle and an outer steel container and weigh from 2500 to 4800 kg when loaded.[I-26] BWR fuel assemblies can be shipped in a modified PWR container or a special BWR container consisting of a steel cradle and an outer wooden container weighing about 1270 kg.[I-26] Six PWR containers (12 fuel assemblies) or 16 BWR containers (32 fuel assemblies) are shipped on a truck trailer using simple tiedown techniques. For simplicity of the treatment here, a universal, all steel container will be assumed that contains either two PWR or four BWR fuel assemblies, that has a tare weight of 3600 kg, and that are shipped six to a truck trailer.

I.4.4 Spent Fuel

Spent fuel contains uranium, plutonium, other transuranic radionuclides, and highly radioactive fission products. The radioactive decay processes of these materials also generate a large amount of decay heat. The spent fuel assemblies usually are stored at the reactor at least 120 days to allow radioactivity and heat generation levels to decrease before transport. After 120 days, the typical LWR spent fuel assembly contains about 2×10^6 curies and generates about 8.4kW.[I-27] Current casks are licensed for spent fuel cooled as short as 120 to 180 days; however, the current practice is to let the spent fuel cool much longer

Spent fuel shipping casks are designed with a thick layer of steel, lead, or depleted uranium for gamma shielding and with a water or solid hydrocarbon layer for neutron shielding. Steel liners provide structural strength and additional gamma shielding. Heat removal is usually accomplished by natural convection and conduction inside the cask and by natural convection and radiation from numerous fins on the exterior of the cask. Although not required for safety, mechanical heat removal systems are sometimes provided to reduce cask cool-down times, thus reducing turn-around times and thereby reducing shipping costs. All these factors make spent fuel shipping casks massive.

Spent LWR fuel has been shipped both by rail and truck in the United States for many years, and several types of shipping casks have been designed. Table I.3 lists information about casks currently available or proposed for domestic use.

About 50 percent of the reactors currently operating or under construction do not have rail sidings, thus precluding the use of rail casks at these sites.[I-28] The other factors influencing the choice of rail or truck transport are largely economic ones: (1) the cask payload, (2) the loading and unloading time, (3) the travel time, and (4) cask availability. Rail shipments have payload and

TABLE I.3
LICENSED OR PROPOSED SHIPPING CASKS FOR CURRENT-GENERATION LWR SPENT FUEL

Cask Designation	Number of Assemblies PWR	Number of Assemblies BWR	Loaded Cask Weight, MT	Usual Transport Mode	Shielding: Gamma	Shielding: Neutron	Cavity Coolant	Maximum Heat Removal, kW	Status
NFS-4 (NAC-1)	1	2	23	Truck	Lead and steel	Borated water and antifreeze	Water	11.5	Licensed
NFS-5	2	3	25	Truck	Uranium and steel	Borated water and antifreeze	Water	24.7	SAR submitted in U.S.
NLI 1/2	1	2	22	Truck	Lead, uranium, and steel	Water and antifreeze	Helium	10.6	Licensed
TN-8	3		36	Truck[a]	Lead and steel	Borated solid resin	Air	35.5	Licensed
TN-9		7	36	Truck[a]	Lead and steel	Borated solid resin	Air	24.5	Licensed
TN-12	12	32	97	Rail	Steel	Borated solid resin	Air	135	Licensed in Europe only
IF-300	7	18	63	Rail[b]	Uranium and steel	Water and antifreeze	Water or air	76[c]	Licensed
NLI 10/24	10	24	88	Rail	Lead, uranium, and steel	Water and antifreeze	Helium	97[d]	Licensed

(a) Overweight permit required.

(b) Truck shipment for short distances with overweight permit.

(c) Licensed decay heat load is 62 kW.

(d) Licensed decay heat load is 70 kW.

loading/unloading time advantages, but current shorter truck travel times at least partially compensate for these advantages. Utilities have purchased both types of casks. Existing reprocessing facilities have receiving facilities designed for specific cask types, and extensive truck shipments may restrict operations to less than full design capacity because of limited overhead crane capacity.[I-29]

For purposes of computing the materials requirements, 50 percent of the spent fuel is assumed to be transported in a truck cask carrying one PWR or two BWR assemblies. Fabrication of the truck cask would require 3000 kg of steel and 20,000 kg of lead.[I-30] The other 50 percent is assumed to be transported by rail in a hypothetical cask representing an average between the seven PWR/eighteen BWR cask and ten PWR/twenty-four BWR cask. The fabrication of such a rail cask would require 26,000 kg steel, 65,000 kg lead, and 5000 kg depleted uranium.[I-30] A composite truck/rail cask is assumed to have a tare weight of 60 MT; consisting of 14.5 MT steel, 42.5 MT lead, and 2.5 MT of depleted uranium.

Other waste materials, such as replacement components from the various fuel cycle facilities, may be transported in spent fuel casks or the more heavily shielded low-level waste packages if radiation levels are high.

I.4.5 Low-Level Waste

Low-level wastes include (1) resins and filters from liquid cleanup systems at reactors, AFRs, and fuel storage pools in reprocessing facilities; (2) HEPA filters; (3) a wide variety of radioactive trash from all facilities, including failed or obsolete equipment, plastic bags, gloves, and other protective clothing; and (4) miscellaneous combustible and noncombustible trash. The waste generally is shipped in 210-liter (55-gal) drums, in plywood boxes, or in disposable metal containers inside a reusable metal package containing some shielding material. Low-level waste usually is able to meet a licensing classification called "low specific activity" (LSA), and the packaging usually needs to be only a strong, tight container such as a plywood box. The 55-gal drums usually used for LLW meet the next most-r strictive classification, "Type A". Proposed DOT regulations that would require LSA shipments to be made in Type A containers would impact that portion of waste now being shipped in boxes.[I-31] While the percentage of LLW shipped in boxes is low overall, the percentage could be as large as 65 percent for some facilities.[I-32]

A typical metal transport package for reactor wastes such as resins might require shielding of the equivalent of several inches of lead. The resins are contained in a disposable steel liner, inside a reusable shield. Although the resins are generally shipped as LSA material, the reusable package may meet Type A or even Type B (the next most-restrictive classification) specifications to provide more versatility.

Type A packages with up to 8 inches of lead shielding are available for transport of LLW. If Type A radionuclide quantities are exceeded, a Type B overpack to a Type A package can be used to take advantage of the shielding provided by the Type A package. Alternatively, a Type B package alone could be used.

As discussed in Reference I-44, the large number of different reactor LLW packages used can be represented by 55-gal drums (73%), 4 x 4 x 8 foot plywood boxes (10%), and by resin casks (17%). For non-TRU reprocessing wastes and fuel fabrication waste the 55-gal drum is used almost exclusively. A typical reactor shipment of boxes and drums would contain 600 ft^3 of waste and require 725 kg wood and 1475 kg carbon steel of disposable material. A typical reactor resin shipment would contain 200 ft^3 of resins and would require 1106 kg of stainless steel of disposable material. Thus a single, composite reactor LLW shipment would consist of 530 ft^3 of waste and would require 600 kg of wood, 1225 kg of carbon steel, and 190 kg of stainless steel as disposable material. Typical reprocessing and fabrication facility LLW shipments would contain about 600 ft^3 of waste and require 1875 kg of carbon steel as disposable material.

Reprocessing facilities also generate LLW that is TRU-contaminated and must be disposed of in a deep geological repository. A typical shipment consists of 420 ft^3 in 55-gal drums and is transported inside a reusable steel container. The disposable material requirement is 860 kg of carbon steel. Fabrication of the reusable steel container would require about 7 kg of steel.[I-30]

1.4.6 High-Level Waste

High-level waste is the primary waste generated when spent fuel is reprocessed. The waste is solidified in borosilicate glass in stainless steel containers and includes (1) essentially 100 percent of the fission products from the fuel, excluding noble gases, tritium, iodine, and bromine; (2) essentially 100 percent of the transplutonic actinides from the spent fuel; and (3) about 0.5 percent of the uranium and plutonium originally in the spent fuel. For a LWR, about 0.085 m^3 (3 ft^3) of waste is produced per metric ton of heavy metal charged.[I-30] Radioactive by-product gases generally are not collected and transported.

High-level waste currently is not being commercially solidified. Casks designed specifically for shipment of solidified high-level waste have not been built yet; however, when built, they are expected to resemble the casks currently available for truck and rail shipment of spent fuel. It is expected that rail shipment will be used exclusively because of the higher payload per shipment. The most likely cask appears to be a 75 MT cask accommodating six 30 cm (12 in.) diameter, 3 m (10 ft) long canisters. The payload per canister would be 6.28 ft^3 of glass.[I-44] The payload per shipment is 37.7 ft^3 containing the vitrified waste from processing 12.6 MTHM. The cask construction is estimated to require 18,000 kg of steel and 50,000 kg of lead.

The radiation level and heat generation rate of the HLW may vary significantly among the various fuel cycles. For Pu recycle, the neutron source is about 30 times larger[I-33] than the present UO_2 waste, and the heat generation rate may be 20 to 100 percent higher than for present UO_2 waste at the same cooling time.[I-34]

I.4.7 Cladding Waste

Cladding waste is the term denoting solid residues from fuel reprocessing operations in which fuel bundles have been sheared into short lengths, and the fuel pellets have been leached from the cladding with acid. The residues include short lengths of fuel cladding with some residual fuel, end fittings, fuel support grids, assorted springs, spacer elements, and fuel-bundle support rods. The radioactivity of cladding wastes arises both from neutron-induced isotopes and from the fission products and actinides present in the small amount of fuel that remains with the cladding.

Cladding wastes generated to date in commercial fuel-reprocessing operations have been disposed of by onsite burial. Casks designed specifically for rail or truck shipment of fuel-bundle residues have not been built. When built, these casks are expected to resemble casks currently available for shipment of spent fuel, but should be somewhat simpler in design because heat removal requirements would be reduced and neutron shielding would not be required. Casks would require no neutron shielding and only a few inches of gamma shielding. Heat loads are low enough that cooling fins probably would not be required. The maximum disposable container dimensions are not yet established but will be dictated by requirements of the federal repository handling equipment. A variety of disposable container sizes have been proposed, which to a certain extent depend on whether the hulls are noncompacted, mechanically compacted, or compacted by melting. For this presentation, hulls are not assumed to be compacted; thus, the residue from reprocessing 4.7 MTHM is shipped per cask.

Reference I-45 describes a cask which can be transported on a legal-weight truck or three casks on a railcar. Three 55-gal drums would be transported in each cask. Since HLW shipments to a repository are by rail, it is assumed that cladding hulls are transported by rail. Thus, 63 ft^3 of hulls, the volume resulting from reprocessing about 4.7 MTHM, would be transported in each shipment. About 540 kg of sand would be placed in the drums to partially fill the void spaces and thus, reduce the fire potential. The cask fabrication would require about 72,000 kg steel.

A summary of the material require nts for the reusable packages described above is given in Table ı . In addition to the reusable packages, some shipments require disposable materials as listed in Table I.5. Table I.6 contains a listing of the reusable package lifetimes and an estimate of the number of times a year the package would be used for a shipment.

TABLE I.4
SUMMARY OF TRANSPORTATION REUSABLE PACKAGE PARAMETERS

Origin	Destination	Commodity	Package	One-Way Miles	Mode	Packages/ Shipment	Materials/ Shipment
Mill	Conversion	Yellowcake	55-gal drum	1000	Truck	40	920 kg steel
Conversion	Enrichment	UF_6	14-ton cylin.	750	Truck	1	2359 kg steel
Enrichment	Fabrication	UF_6	2½-ton cylin.	750	Truck	5	3175 kg steel
			Overpack	750	Truck	5	3950 kg steel and small amounts of rubber and foam
Fabrication	Reactor	Fuel Assembly	Strongback	1000	Truck	6[a]	21600 kg steel and small amounts of neoprene
Reactor	Reprocessing (or Disposal)	Spent Fuel	Cask	1000	Truck/Rail[a]	1[a]	14500 kg steel 42500 kg lead 2500 kg depleted uranium
Reprocessing	Disposal	HLW	Cask	1000	Rail	1	25000 kg steel 75000 kg lead
		Cladding Hulls	Cask	1000	Rail	1	72000 kg [illegible]
		TRU LLW	Overpack	1000	Truck	1	7000 kg steel
		UF_6	14-ton cylin.	1000	Truck	1	2359 kg steel

(a) See text for description of composite package.

TABLE I.5

DISPOSABLE MATERIAL REQUIREMENTS

Shipment	Disposable Material Per Shipment
Reactor Low-Level Waste	600 kg wood, 1225 kg carbon steel, and 190 kg stainless steel (assuming 73% drums, 10% boxes, and 17% resin casks)
Other Low-Level Waste	1875 kg carbon steel
High-Level Waste	2560 kg glass and 2550 kg stainless steel per shipment
Cladding Hulls	540 kg sand and 230 kg stainless steel per shipment

TABLE I.6

TRANSPORTATION PACKAGE REQUIREMENTS

Commodity	Package	Lifetime[a]	Shipments/Year
Yellowcake	55-gal. drum	12 shipments	55
Natural and Reprocessed UF_6	14-ton cylinder	20 yr.	2[a]
Enriched UF_6	2.5 ton cylinder	20 yr.	3[a]
Fresh Fuel	Strongback	20 yr.	55
Spent Fuel	Cask	10 yr.	30
HLW	Cask	10 yr.	30
Cladding Waste	Cask	10 yr.	30

[a] Personal communication with S. A. Dupree, Sandia Laboratories, January 1980.[I-46]

I.5 HAZARDS FROM TRANSPORTING NUCLEAR MATERIALS

The hazards from transporting nuclear materials can be categorized as: (1) radiological and/or chemical hazards due to accidents; (2) hazards due to accidents that do not involve the cargo; (3) radiological dose to the public along the route during normal (accident-free) transport (because the radiation levels cannot be reduced to zero); and (4) accident-free occupational doses.

I.5.1 Non-Cargo Related Hazard

The rail accident rate is 1×10^{-5} accidents per mile, but because not all rail cars are involved in most train accidents, a rate of 1.5×10^{-6} rail car accidents per rail car mile is recommended.[I-35] The common carrier truck accident rate is 1.5×10^{-6} accidents per mile,[I-35] and with 0.03 fatalities/truck accident,[I-36] the truck fatality rate is 1×10^{-7} fatality/truck mile. This fatality rate is thought to be appropriate for accidents not related to the cargo and is by more than a factor of 100 the most hazardous of the nuclear material transportation hazards discussed below.

I.5.2 Accident-Free Radiological Hazard

The maximum individual dose from transporting radioactive material is likely to be received by a truck crew member transporting irradiated fuel. Although the maximum allowable radiation dose in the cab of an exclusive-use truck carrying radioactive material is two mrem per hour, experience indicates that dose rates are usually less than 0.2 mrem per hour because of the distance from the cask and shielding by intervening material.[I-37] Dose rates at 1 meter from an irradiated fuel cask are regulated to a maximum of 33 mrem per hour, but in practice are more likely to be about 25 mrem/hour.[I-37] Assuming that a crew member spends 20 hours per trip in the cab and a total of 1 hour at a distance of 1 meter from the cask, his maximum dose per trip is 73 mrem. Assuming 30 trips per year would produce 2.2 rem. A similar calculation summed over a "standard shipment" scenario (which includes fuel cycle, medical, and industrial shipments) produces 2580 man-rem per year for the crew dose in the cab and a maximum dose to an individual member of the public (a cargo handler) of 500 mrem.[I-37] The maximum annual population dose summed over (1) the crew, (2) persons traveling along the same routes, (3) persons living on frequently traveled routes, and (4) while in storage is 4361 man-rem.[I-37] These dose values are several orders of magnitude larger than for a similar rail shipment scenario. These values can be put into perspective when compared with the 9.7 million man-rem population dose and the 100 mrem individual average dose from natural background radiation.[I-37]

I.5.3 Radiological Hazards From Accidents

Several reports have addressed the risk of transportation accidents between the various facilities in the nuclear fuel cycle; however, none have addressed either all of the transportation steps or all of the most hazardous steps. Therefore, a consistent set of quantitative results are not available. Workers at Battelle Pacific Northwest Laboratories have produced a number of reports (plutonium by truck,[I-38] rail,[I-39] and air,[I-40] UF_6,[I-41] and spent fuel[I-42]), but future assessments for low- and high-level wastes and cladding hulls would be expected to provide important contributions to the risk. Science Applications, Inc., (SAI) studies have addressed the shipment of (1) spent fuel by truck and rail, (2) PuO_2 by truck, (3) high-level waste by rail, (4) cladding wastes by rail and truck, and (5) low-level waste by truck.[I-43] The SAI studies have not included UF_6, which has an insignificant radiological risk, but whose chemical toxicity risk is about a factor of 10 greater than PuO_2 transport by truck for the high-probability/low-fatality event.[I-41] The SAI results are given in Table I.7, and the accident categories are defined in Table I.8. Note that the largest value for fatalities per mile--PuO_2 by truck--is about 100 times smaller than the fatality rate for accidents that are generally not related to the type of cargo. The risk for PuO_2 shipment is based on the 6M container, but current

TABLE I.7

RISK SUMMARY TABLE FOR RADIOLOGICAL TRANSPORTATION ACCIDENTS

Transportation Step					Consequences		Risk					
Description	Category	Probability/Mile	Probability/Trip	Total Curie Release	Total Person-rem	Total Latent Cancer Fatalities	Person-rem/Mile	Latent Cancer Fatalities/Mile	Person-rem/Trip	Latent Cancer Fatalities/Trip	Person-rem/GWe-year	Latent Cancer Fatalities/GWe-year
Spent Fuel by Rail	2	9×10^{-9}	9×10^{-6}	8×10^{-2}	1×10^{-6}	1×10^{-9}	9×10^{-15}	9×10^{-18}	9×10^{-12}	9×10^{-15}	4×10^{-11}	4×10^{-14}
	3	4×10^{-10}	4×10^{-7}	8×10^{3}	1×10^{-1}	1×10^{-4}	4×10^{-11}	4×10^{-14}	4×10^{-8}	4×10^{-11}	2×10^{-7}	2×10^{-10}
	4	2×10^{-12}	2×10^{-9}	8×10^{3}	2×10^{3}	2×10^{-1}	4×10^{-9}	4×10^{-13}	4×10^{-6}	4×10^{-10}	2×10^{-5}	2×10^{-9}
Spent Fuel by Truck	2	2×10^{-8}	2×10^{-5}	2×10^{-5}	5×10^{-9}	9×10^{-11}	1×10^{-16}	2×10^{-18}	1×10^{-13}	2×10^{-15}	1×10^{-12}	2×10^{-14}
	3	2×10^{-10}	2×10^{-7}	8×10^{2}	1×10^{2}	1×10^{-5}	2×10^{-12}	2×10^{-15}	2×10^{-9}	2×10^{-12}	2×10^{-8}	2×10^{-11}
	4	2×10^{-12}	2×10^{-9}	8×10^{2}	6×10^{2}	6×10^{-2}	1×10^{-9}	1×10^{-13}	1×10^{-6}	1×10^{-10}	1×10^{-5}	1×10^{-9}
PuO_2 by Truck	1	6×10^{-9}	1×10^{-6}	3×10^{-2}	2	2×10^{-14}	1×10^{-8}	1×10^{-12}	2×10^{-6}	2×10^{-10}	2×10^{-6}	2×10^{-10}
	2	2×10^{-13}	4×10^{-11}	3×10^{-1}	20	2×10^{-3}	4×10^{-12}	4×10^{-16}	8×10^{-10}	8×10^{-14}	8×10^{-10}	8×10^{-14}
	3	3×10^{-10}	6×10^{-8}	3×10^{2}	2×10^{4}	2	6×10^{-6}	6×10^{-10}	1×10^{-3}	1×10^{-7}	1×10^{-3}	1×10^{-7}
High-Level Waste by Rail	2	5×10^{-9}	1×10^{-5}	30	7×10^{2}	2×10^{-2}	4×10^{-6}	1×10^{-10}	8×10^{-3}	2×10^{-7}	3×10^{-3}	7×10^{-8}
	3	3×10^{-11}	6×10^{-8}	4×10^{2}	6×10^{3}	6×10^{-1}	2×10^{-7}	2×10^{-11}	4×10^{-4}	6×10^{-8}	1×10^{-4}	1×10^{-8}
Cladding Wastes by Rail	2	2×10^{-11}	4×10^{-8}	4×10^{2}	20	4×10^{-3}	4×10^{-10}	8×10^{-14}	8×10^{-7}	2×10^{-10}	3×10^{-6}	6×10^{-8}
Cladding Wastes by Truck	2	5×10^{-12}	1×10^{-8}	4×10^{2}	20	4×10^{-3}	1×10^{-10}	2×10^{-14}	2×10^{-7}	4×10^{-11}	7×10^{-7}	1×10^{-10}
Low-Level Waste from Power Plant	1	1×10^{-7}	1×10^{-4}	2×10^{-1}	3	2×10^{-4}	3×10^{-7}	2×10^{-11}	3×10^{-4}	2×10^{-8}	8×10^{-3}	5×10^{-7}
	2	6×10^{-10}	6×10^{-7}	5×10^{-1}	9	8×10^{-4}	5×10^{-9}	5×10^{-13}	5×10^{-6}	5×10^{-13}	1×10^{-4}	1×10^{-9}
	3	1×10^{-11}	1×10^{-8}	50	7×10^{2}	6×10^{-2}	7×10^{-9}	6×10^{-10}	7×10^{-6}	6×10^{-10}	2×10^{-4}	2×10^{-8}
Low-Level TRU Waste from Fuel Facilities	1	1×10^{-7}	2×10^{-4}	2×10^{-2}	7	1×10^{-3}	7×10^{-7}	1×10^{-10}	1×10^{3}	2×10^{-7}	2×10^{-2}	2×10^{-6}
	2	6×10^{-10}	1×10^{-6}	1×10^{-1}	40	5×10^{-3}	2×10^{-8}	3×10^{-12}	4×10^{-5}	6×10^{-9}	3×10^{-4}	5×10^{-8}
	3	1×10^{-11}	2×10^{-8}	1	4×10^{2}	5×10^{-2}	4×10^{-9}	5×10^{-13}	8×10^{-6}	1×10^{-9}	7×10^{-5}	9×10^{-9}
Transportation Risk											3×10^{-3}	3×10^{-6}

TABLE I.8

RADIOLOGICAL RELEASE CATEGORIES FOR TRANSPORTATION ACCIDENTS

Categories	Release
Spent Fuel	1. Loss of neutron shielding.
	2. Loss of gases from the inner cavity.
	3. Loss of gases from the inner cavity, 50 percent cladding damage due to breakage, no overheating.
	4. Loss of gases from the inner cavity and some semi-volatiles, all cladding fails and fuel overheats in excess of 1240°F.
PuO_2[a]	1. Release fraction of 10^{-6}, which could result from: a. Leak from one container, and failure of outer drum and van, or b. Failure of one container, leak from outer drum and van failure, or c. Failure of one container, outer drum failure and normal van leakage.
	2. Release fraction of 10^{-4}, which would result from: a. Failure of one container, outer drum leakage and van failure, or b. Failure of one container, outer drum failure and normal van leakage.
	3. Release fraction of 0.01, which could result from failure of all barriers of one container.
	4. Release fraction of 0.2, which would require the complete failure of all the barriers of half the containers in the shipment.[b]
High-Level Waste	1. Loss of neutron shield.
	2. Release to the atmosphere and breakage of one waste canister.
	3. Release to the atmosphere and significant canister overheating.

TABLE I.8 (Continued)

Categories		Release
Cladding Hulls	1.	Loss of gamma shield.
	2.	Loss of hull containment and zirconium fire.
Low-Level Wastes	1.	One drum spill, contents outside of overpack.
	2.	Twenty-one drum spill, contents outside of overpack.
	3.	Twenty-one drum spill, contents accompanied by fire that volatilizes 50 percent of the contents.

(a) Assumed to be shipped in a 6M container.

(b) R. J. Hall, et al., "An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train," BNWL-1996, February 1977.

restrictions for shipping special nuclear material will probably lead to a package design for commercial quantities that will be much stronger than the present 6M containers.[I-32] Therefore, the fatality rate would be lower than that given in Table I.7. This shipment of PuO_2 powder would occur only in the recycle of plutonium, which is not one of the two options considered in this report.

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APPENDIX II
MATERIAL PRODUCTION

II.1 INTRODUCTION

Large amounts of materials are required for the construction and operation of the various model facilities within the two cycles. As indicated in Figure 2.8 structural materials, materials for equipment and machinery, and materials for transportation vehicles should be investigated to assess their potential health impacts from both a public and occupational viewpoint.

Figure II.1 shows a simplified material production cycle. This cycle comprises three typical segments; ore acquisition, processing, and production, with transportation links between the segments in the cycle. Some of the materials have an all-domestic cycle while others are complicated by the presence of imports and recycle. This fact adds complexity to the calculation of energy requirements and health impacts associated with the cycle.

Full treatment of the materials impact for the coal and uranium fuel cycles is an overwhelming task, as it has not been treated adequately in the published literature. Therefore, in view of the resource constraints imposed on this study, simplifications and approximations are unavoidable. Thus, it is the goal of this appendix to provide an appreciation of the relative magnitude of health impacts associated with some of the dominant materials in the two cycles. The selected materials are iron and steel, concrete, and aluminum. Iron, steel and concrete were selected due to the magnitude of their requirements while aluminum was singled out due to the amounts of energy invested in its production. Other materials like copper, zircalloy, lead, etc. were judged to play a less significant role and will not be treated at this stage of the study.

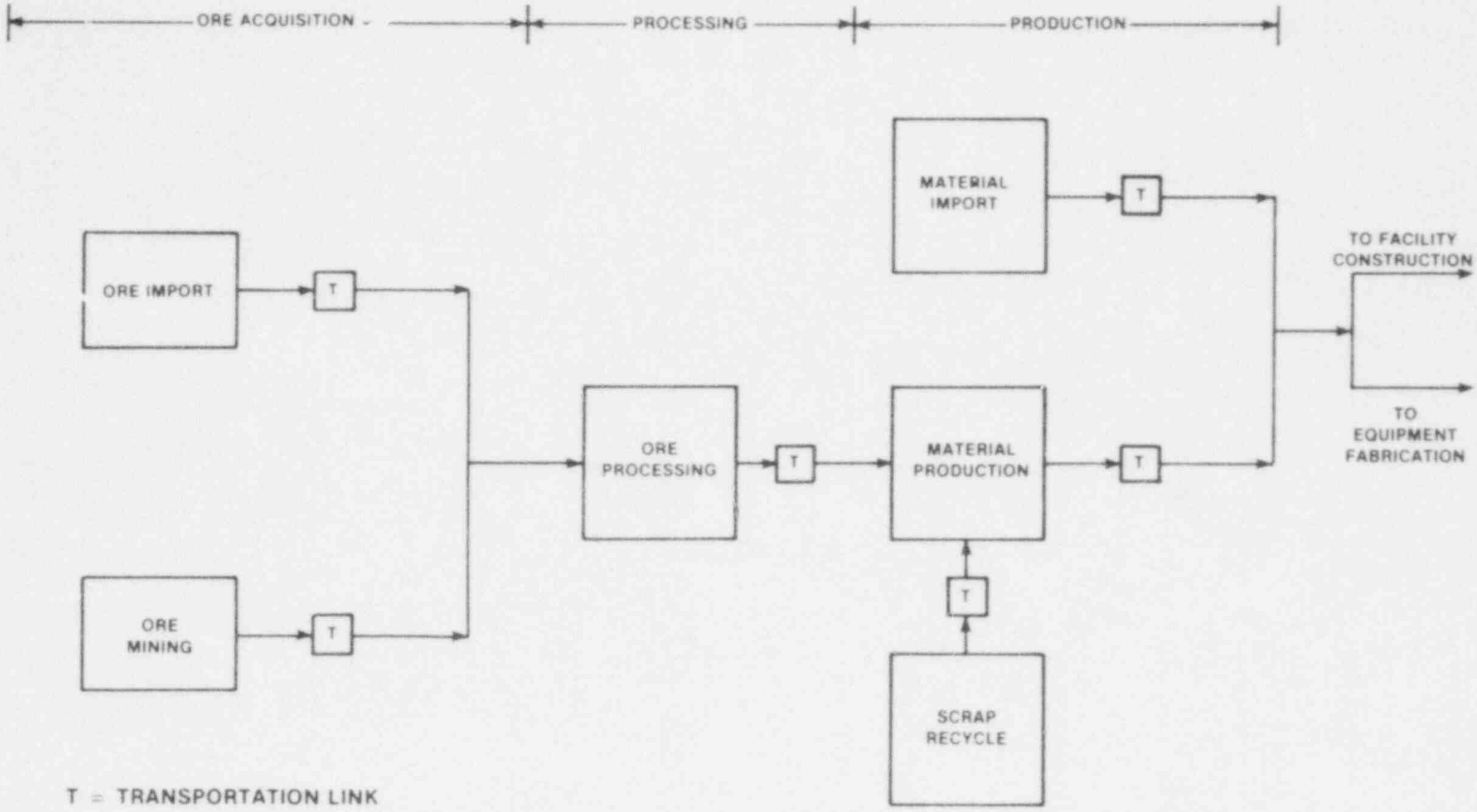

FIGURE II.1 SIMPLIFIED MATERIAL PRODUCTION CYCLE

The treatment of iron, steel, and aluminum includes a fair amount of detail about their respective production cycles. One exception is the occupational hazards data, where more refined details and more original data are required.

The concrete production cycle* is not included due to time constraints. Approximate values for the occupational hazards rates were calculated though. An overall injury rate of about 0.43×10^{-4} injuries/MT of concrete produced was based on non-metal mining, cement manufacture, and concrete production data. Illness and death rates were crudely estimated to be 0.3×10^{-6} illnesses/MT concrete produced and 1.6×10^{-7} deaths/MT of concrete produced, based on reported data for broad industrial categories and not on the specific cement-concrete industry for which no data were reported.

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*1 cubic yard of concrete has an assumed weight of approximately 2 tons including 1300 lbs. sand, 1800 lbs. stone, and 515 lbs. cement.

II. IRON AND STEEL

Iron and steel are the major metallic materials used in the various model facilities of the coal and uranium cycles. They are used extensively in facility construction, and in the manufacture of equipment, machinery and transportation vehicles.

The steel production process follows the material production cycle shown in Figure II.1. The production process consumes iron ore, steel scrap, coal and coke, limestone, dolomite, a variety of alloying elements, as well as other fuel and non-fuel materials. The following subsequences briefly address the stages of the production cycle.

II.2.1 Iron Ore Mining[II.1]

The U.S. crude iron ore comes mostly from large open-pit mines where high productivity can be achieved. In 1977, 49 out of the 56 operating iron ore mines were open-pit mines, which contributed more than 95% of the ore production. About 80% of the ore production in the United States is concentrated in the Lake Superior district.

At most of the open-pit mines large quantities of waste rock and/or overburden must be stripped in order to expose the crude ore. The quantity stripped usually ranges between one third to three times the tonnage of the crude ore produced. The average ratio of waste to ore is about one to one. Open-pit mining utilizes large power shovels and trucks. Blast hole drilling is achieved either by down-the-hold percussion, or rotary or jet piercing machines depending on the physical characteristics of the ore deposits.

II.2.2 Ore Processing (Beneficiation and Agglomeration)[II.1]

Most of the mined ore produced is beneficated to achieve higher concentration of iron and more uniform chemical and physical properties in the ore.

Benefication includes crushing, screening and washing using gravity, magnetic floatation, or other methods. Iron ore consisting of small particles (less than ¼" in size) is usually agglomerated before being charged to the blast furnace. This process will improve permeability of the furnace burden and prevents loss of ore fines up the stack. Fine ores are also agglomerated to improve the transportation and handling characteristics. The principal methods of agglomeration are sintering and pelletizing. Sintering is usually done at the blast furnace site while pelletization is done at the mine sites. The average iron content of sinter consumed by the blast furnaces is approximately 54 percent. Finished pellets contain 62-65 percent iron, with an average of about 63 percent iron. In 1976, iron pellets made up 62% of all the iron ore consumed in the U.S.

The final ore product of the mining operation, whether it results from directly shipping the ore, or it is the product of extensive processing, is referred to as usable ore. The average grade of usable ore has increased from about 50 percent in 1952 to about 62 percent in 1977. However, the tonnage of crude ore required to produce one ton of iron in the ore has increased by 75 percent during the same period. In 1977 an average of about 1.8 tons of crude ore was mined for each ton of usable ore produced, compared with 2.2 tons of crude ore in 1976 and 1.5 tons of crude ore in 1957.

II.2.3 Ore Production Data and Productivity[II.1]

The United States production of iron ore has averaged 56 x 10^6 tons (of contained iron) annually during the ten year period 1966-1976. Imports in the same period averaged about 30 x 10^6 tons (of contained iron).

In 1977 the estimated number of workers in the iron ore mining and beneficiation industry was 21,000. An average of about 16 MT of usable ore and about 10 MT of iron in ore was produced per individual per eight hour shift.

II.2.4 Iron and Steel Production[II.2]

Production of iron from usable ore is achieved by smelting in a blast furnace to produce pig iron or by reduction to metal for direct usage in steel production or foundry iron products. Iron and steel scrap is also an important raw material in both of steel manufacture and foundry production. In the ten year period 1967-1976, scrap consumption remained approximately at the same level as pig iron consumption. In case of steel manufacture, the proportion has been 43-46 percent scrap, while in case of steel foundries and iron foundries it was 95-98 percent and 83-87 percent respectively. Iron and steel scrap is classified as home scrap, prompt industrial scrap and obsolete scrap, with the last two classes referred to as purchased scrap. Home scrap constituted 52-61 percent of the total scrap consumed in the period 1967-1976. Purchased scrap consists of roughly equal amounts of prompt industrial and obsolete scrap.

Pig iron, scrap, or directly reduced iron, or a mixture of these feeds the steel production process. The production process involves lowering the impurity content, controlling the carbon and silicon content, and addition of some alloying elements. The open-hearth process was the dominant steel making process until 1979. However, presently the dominant steel making method is the Basic Oxygen Process (BOP). In 1977, 62 percent of the U.S. raw steel production used the BOP method, about 22 percent was produced by the electric arc furnace, and the remainder was produced by the open-hearth process.

Molten steel produced by any of the above methods is then poured into ingot molds or into a continuous casting machine. Ingots then pass through various degrees of processing (e.g., rolling and forging) depending on the type of end product required. As an example, structural beams and bars are rolled on grooved rolls in several passes, with the final pass giving the product its required shape.

Iron and steel foundries produce castings by pouring molten metal into molds. The casting process is versatile and can produce a variety of complex parts and a wide range of part sizes and shapes.

II.2.5 Production Data and Productivity[II.2]

Raw steel is converted into steel mill products by forming and shaping processes in which approximately 30% of the steel becomes scrap and is recycled. Steel mills produce several hundred types of steel which are designed for different uses. In the ten year period 1968-1977 the average annual production of raw steel in the United States was about 132×10^6 tons. The average annual finished iron and steel production was about 94×10^6 tons and the average annual import was 16×10^6 tons in the same period. Foundry shipments of iron and steel castings in the 1968-1977 period had an annual average of 16×10^6 tons and 1.8×10^6 tons, respectively. In the same period, the average net annual consumption was about 122×10^6 tons and the average amount of steel mill products which were exported was about 3.8×10^6 tons.

The steel industry had an average employment of about 452,400 workers in 1977. The production of 125×10^6 tons of raw steel required 121×10^6 tons of iron ore and agglomerates, 73×10^6 tons of coal, 69×10^6 tons of home and purchased scrap, 28×10^6 tons of fluxes, and 251 billion cubic feet of oxygen.

II.2.6 Transportation[II.1, II.2]

In this study, it is assumed that the crude iron ore is carried to the processing facilities by trucks. Most of the trucks that are currently used in the open pit mines have haulage capacities of 40-120 tons. However, the present trend is to increase the usage of larger capacity trucks (130-170 tons). Two of the largest U.S. tactonite mines use trains to haul ore to the crushers. The train consists of 9 to 17 cars of about 100-tons capacity each and is automated to allow operation by one man.

Unit trains continue to haul iron ore from most of the large mines to shipping ports and consuming centers. Usable ore produced in the Lake Superior district is transported by large ore carrying vessels. The present trend is to expand the usage of vessels with carrying capacities of about 59 x 10^3 long tons (66 x 10^3 tons) of iron ore pellets. These vessels are of the self-unloading type with discharge capacity of about 10,000 long tons or more per hour.

Calculations of the transportation requirements will be conducted in a preliminary fashion. Lake Superior district will be assumed as the mine location. Crude ore is assumed to be transported from the mine to the processing facility by 100 ton trucks for a distance of 5 miles. Unit trains will transport the usable ore for an estimated distance of 50 miles to the shipping port. Usable ore is then loaded in great lake vessels of the type described above, and shipped to a Southern great lake port about 750 miles away. Unit trains then carry the ore to the steel mills for an average distance of 50 miles. Other transportation requirements in the production cycles, like the movement of coal, scrap, and fluxes will be assumed to be carried on unit trains for an average distance of 50 miles. Some of these assumptions are crude; however, they are only used for preliminary calculations.

II.2.7 Energy Requirements[II.4, II.6]

Calculation of the amount of energy invested in the production of one ton of steel requires consideration of all aspects of the steel production cycle. Energy consumed in each stage of the cycle should account for the direct consumption of energy in the stage, transportation from the stage, and energy consumed in the production and transportation of process materials like limestone and coke. The energy accounting study by Sample[II.6] describes each component of the energy requirements in detail and it will be used in most of the following discussions.

The amount of energy required to mine and transport one ton of iron ore is estimated to be 874 x 10^3 BTU. Limestone requires 178 x 10^3 BTU/ton for mining and transportation, while the coke production cycle including transportation requires an average total of 3.42 x 10^6 BTU/ton. The correct portions of these three materials are loaded into the blast furnace which consumes about 20.2 x 10^6 BTU/ton. The overall amount of energy consumed per ton of pig iron produced is approximately 24 x 10^6 BTU.

The open-hearth furnace requires 4.04 x 10^6 BTU/ton of steel produced while the electric furnace and basic-oxygen furnace require 8.54 x 10^6 and 1.35 x 10^6 BTU/ton, respectively. Based on the industry production in 1977 and the ratio of pig iron to scrap in each furnace[II.2], a ton of steel requires 6.15 x 10^6 BTU plus about 2.1 x 10^6 BTU for oxygen and other materials. A hot roll milling requires 16.16 x 10^6 BTU/ton, whereas a cold rolling mill requires 5.7 x 10^6 BTU/ton. Adding the last four figures yields about 40.1 x 10^6 BTU required per ton of steel produced.

Additional amounts of energy are required to produce stainless steel and alloy steels. The amounts of energy required to produce a pound of the different kinds of steel and other non-ferrous material are shown in Table II.1.

II.2.8 Environmental Effects and Effluents[II.1, II.2]

As described above, iron ore mining involves substantial amounts of waste rock, overburden and tailings. Large amounts of processing water are also used. Open-pit mining and ore crushing and grinding operations involve the release of dust and high levels of noise. There is also a concern that the presence of asbestiform fibers in the tailings discharge may constitute a potential health hazard in Lake Superior. Detailed treatment of the impact of these pollutants is generally lacking.

TABLE II.1

ENERGY REQUIREMENTS FOR MATERIAL PRODUCTION

Material	Energy Consumption (BTU/lb)[a]
Carbon Steel	21,000
Stainless Steel	34,000
Alloy Steel	22,800
Aluminum (Rolled/Drawn)	110,000
Cast Aluminum	10,000
Copper	65,700
Zinc	45,500
Lead	22,000
Glass	13,000
Rubber	36,900
Plastics	25,000
Lubricants	7,000

[a] D.K. Samples, "Energy in the Automobile," Presented at the Energy Seminar, University of Michigan Institute of Sciences and Technology, August 1974, and R.G. Hudson, "The Engineers Manual," Second Edition.

Steel mills and foundries produce solid, liquid and gaseous effluents with potentially adverse effects on human health. Slags from iron and steel furnaces, and flue dust are the principal solid wastes. Non-recyclable slags are either used for railroad ballast, in concrete, or as land fill material. Flue dust includes iron oxides and other impurities which may prevent recycling. Liquid effluents include process water, sulphuric and hydrochloric acids, oil, and grease, all with potential harmful effects. Gaseous effluents from steel furnaces, sintering plants, blast furnaces and coke ovens present one of the most difficult environmental control problems. Effluents include sulfur dioxide, organic compounds, tar vapours, particulates, and fumes. Pollution control devices such as cyclones, electrostatic precipitators, bag houses, and wet scrubbers are currently used to minimize releases to the atmosphere.

II.2.9 Occupational Health Effects

Detailed calculations of the components of the steel production cycle occupational health effects is a lengthy, complex task. It requires an adequate statistical treatment of the published occupational data, and in many cases requires handling the source data. Finely-structured occupational data related to each step in the production cycle are not readily available. As an example, injury data exist for broad categories like metal mining and steel products. Illness and death rates have large fluctuations and are tabulated for broader classes of industries. For these reasons calculations in this section are preliminary and require further refinement. However, these calculations can be used to assess the relative occupational impact of materials as compared to other health effect components.

Based on the data in references (II.5, II.7 - II.10) and the productivity data above, the average injury rate per metric ton of usable ore produced was estimated to be 17×10^{-6}. The injury rate for steel production is about 46.8×10^{-5} injuries/MT of steel. Estimates of the illnesses are based on reference II.5, and the values for mining are 29×10^{-6} illnesses/MT of usable ore produced and 21×10^{-6} illnesses/MT of steel produced. The estimates of the number of deaths for mining and steel production were 0.164×10^{-6} deaths/MT of usable ore mined and 3.48×10^{-7} deaths/MT of steel produced.

With the assumption that no ore or finished steel is imported and that 34% of the steel comes from scrap, the following values result: 0.48×10^{-3} injuries/MT of steel produced, 21×10^{-6} illnesses/MT of steel produced, and approximately 0.52×10^{-6} deaths/MT of steel produced.

With the assumption that ore imports and finished steel imports are 35 percent and 15 percent of the demand, respectively, the above figures will change to 0.41×10^{-3} injuries/MT of steel produced, 8×10^{-6} illnesses/MT of steel produced and 0.41×10^{-6} deaths/MT of steel produced. These values represent the health effects to U.S. workers only. These figures include neither the occupational effects associated with the steel production cycle transportation nor the effects of acquisition and handling of the amounts of process materials like coal (coke), limestone, etc.

II.3 ALUMINUM

In the coal and uranium cycles, aluminum is used in facility construction and in the manufacture of the various electrical and mechanical equipment, machine parts, and transportation vehicles. Although the amounts of aluminum used are small compared to iron and steel, aluminum requires large amounts of energy or its production and hence may have a non-negligible contribution to the materials-related health impact.

II.3.1 Mining and Processing

Presently, bauxite is the main source of aluminum both domestically and abroad. The U.S. bauxite deposits are mainly in Arkansas, with smaller deposits in Alabama and Georgia. Open-pit mining accounts for over 90 percent of the mined domestic bauxite. The stripping operations include the usage of draglines, scrappers, shovels and trucks. Stripping ratios of as much as 13 feet of overburden to 1 foot of ore have been reported. Bauxite processing includes crushing, washing and drying. Crude bauxite contains 5-30 percent free moisture. Dried bauxite is prepared by heating the ore up to 600°F. Typical dried ore includes 45-60 percent Al_2O_3.

Alumina is extracted from the bauxite by the Beyer process, which involves a causti leach of the ore at elevated temperature and pressure. The leaching process is followed by separation of the resulting sodium aluminate solution and selective precipitation of aluminum as hydrated aluminum oxide.

II.3.2 Primary Aluminum Production

Primary aluminum is produced by electrolysis of alumina in a molten bath of natural or synthetic cryolite which serves as an electrolyte as a solvent for alumina. Molten al[illegible] removed periodically from the cells and is then blended i a [illegible] furnace with other batches. The mixture may be fluxed and alloyed and cast into different forms or transported molten to fabrication plants.

II.3.3 Production Data and Productivity[II.3]

The U.S. has long been the leading world consumer of aluminum. In the ten year period 1968-1977, the average annual U.S. production of aluminum in bauxite was about 466 x 10^3 tons. The amount of aluminum in bauxite mined in 1977 was 460 x 10^3 tons. The United States imports the major portion of the bauxite needed for aluminum production. The 1976 imports of aluminum in bauxite was 3330 x 10^3 tons. The 1977 production of aluminum in alumina and primary metal was 3450 x 10^3 tons and 4539 x 10^3 tons, respectively. The 1976 imported metal in alumina and primary metal imports were 1880 x 10^3 tons and 749 x 10^3 tons, respectively.

The aluminum production cycle includes scrap recycle. In 1976, the amount of metal in recycled, old scrap was estimated to be about 485 x 10^3 tons, while the secondary recovery from purchased scrap was estimated to be 1470 x 10^3 tons.

An estimated 200,000 to 250,000 people are employed by the aluminum industry in the United States. The estimated labor invested in the production of alumina required to produce one ton of metal is 3-5 man-hours, while 8-15 man-hours are required to produce one ton of metal from alumina by the prebaked method (10-20 man-hours by the Soderberg method).

II.3.4 Transportation

Shipping distances between the bauxite mines and the processing facilities are assumed to be about 5 miles. The transportation modes used are assumed to be truck or train. Such the current trend is toward producing alumina near the bauxite mines, a shipping distance of about 20 miles will be assumed.

The current tendency is to locate the aluminum metal plants in areas of abundant, low cost energy. For simplicity, an average shipping distance of 300 miles by 25 ton trucks will be assumed. Imported bauxite and alumina are assumed to be shipped on similar size trucks for an average distance of 300 miles to the metal production facilities.

II.3.5 Energy Requirements[II.4,II.6]

As described in Section II.3.3, an average of 4.5 tons of bauxite are required to produce about 2 tons of alumina which are required for the production of one ton of metal. The metal production process consumes about 0.6 tons of carbon electrodes.

The mining process consumes 2.51×10^6 BTUs, and alumina production requires about 11.0×10^6 BTUs. The carbon electrodes and electrolysis require about 2.11×10^8 BTUs. Rolling or drawing a ton of primary aluminum requires 26.1×10^6 BTUs and all of the transportation requirements consume an average total of 3.6×10^6 BTUs. The estimated overall total is about 2.54×10^8 BTUs per ton of rolled aluminum. This value may be compared with the reference II.5 estimate of 2.44×10^8 BTUs/ton.

In 1976 purchased scrap represented approximately 26% of the aluminum supply. Assuming that a ton of secondary metal requires on the average 12.0×10^6 BTU[II.5], the average energy requirement per ton of aluminum, including recycle, is about 1.91×10^8 BTUs. Assuming an extra amount of 30.0×10^6 BTU/ton for rolling or drawing and transportation, the total amount of energy for rolled/drawn aluminum is about 2.2×10^8 BTU/ton.

II.3.6 Environmental Effects and Effluents

Large amounts of overburden are produced during the bauxite mining operations. The red muds generated in the alumina production process are usually impounded in large mud lakes, adjacent to the alumina plants. Overburden and waste rock are used for land fills. Red mud has to be treated before it is used for such purposes.

Fluorine-containing gases evolve from alumina production cells. High fluorine concentrations in the air at the reduction plants or in the areas immediately surrounding the plant can be a potential hazard to life. About 40-60 pounds of flucrine in gas and as particulate matter is evolved from alumina reduction cells per ton of primary aluminum produced[II-3]. An additional 15 to 25 pounds of fluorine is absorbed by the cell or pot lining and 1-5 pounds is lost in handling[II-3].

II.3.7 <u>Occupational Data</u>[II.3,II.5,II.7,II.8,II.9,II.10]

Calculations of the occupational impact of the aluminum production cycle present the same difficulties discussed in the case of the steel production cycle. No information was found showing the occupational hazards associated with alumina production; therefore, illness and death data were based on reported data for broad industrial categories. Preliminary calculations of the occupational effects associated with the production of one metric ton of aluminum metal (including recycle) showed 0.55×10^{-3} injuries/MT of aluminum produced, 24×10^{-6} illnesses/MT of aluminum produced and 8.6×10^{-7} deaths/MT aluminum produced. However, if we consider the bauxite, alumina and metal imports, these rates (for U.S. workers only) change to 0.43×10^{-3} injuries/MT, 20×10^{-6} illnesses/MT, and 3.7×10^{-7} deaths/MT of aluminum produced. These figures include neither the contribution of processing materials acquisition and handling, nor the transportation of the domestic and imported aluminum carrying materials.

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II.2 D. H. Desy, "Iron and Steel Mineral Commodity Profiles," MCP-15, July, 1978.

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II.9 National Safety Council, Accident Facts, 1979 Edition.

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APPENDIX III
EQUIPMENT FABRICATION IMPACT

A substantial amount of manpower and energy is invested in the manufacture of equipment and major components in each facility of the two cycles. Moreover, the heavy requirement for transportation results in accelerated equipment wear and requires frequent replacement.

At this stage of the work, information about energy consumption, manpower requirements, and occupational hazards related to component fabrication is lacking. Tables III.1 and III.2 present available information for some industrial products and transportation units.[III-1,III-2]

TABLE V.2

ESTIMATED EXCESS MORTALITY RATES FROM THE MODEL COAL- OR OIL-FIRED PLANT

Fossil fuel type[a,b]	Average population density (persons/km^2)		Estimated excess annual mortality rate (deaths/10^6 persons)		Remarks
	Rural	Urban	Rural	Urban	
Eastern high sulfur coal (12,000 BTU/lb, 3% sulfur, 12% ash)	59	101	2.8	12.6[c]	Particulate control and flue gas desulfurization assumed
Interior eastern coal (11,000 BTU/lb, 3.6% sulfur, 10.3% ash)	30	78	2.8	8.2	Particulate control assumed
Western coal (8,750 BTU/lb, 0.8% sulfur, 8.4% ash)	4.3	7	2.3	7.1	Particulate control assumed
Low sulfur oil			0.8	1.1	Particulate control assumed

(a) U.S. Nuclear Regulatory Commission, "The Environmental Effects of Using Coal for Generating Electricity," NUREG-0252, June 1977.

(b) TEKNEKRON, Inc., "Activities, Effects and Impacts of the Coal Fuel Cycle," Draft Report, Contract Number NRC-03-78-076, June 1979.

(c) L. D. Hamilton, "Health Effects of Air Pollution," Proceedings of the Conference on Computer Support of Environmental Science and Analysis, Brookhaven National Laboratory, 1975.

TABLE III.2

LABOR REQUIREMENTS AND OCCUPATIONAL HAZARDS FOR FABRICATION OF TRANSPORTATION UNITS

Component[a,b]	Labor Requirement (person-year/unit)	Lost Workday Rate (lost workdays/person-year)[c]
Locomotives (166)	8.4	0.32
Hopper Cars (278)	0.18	1.84
Tractor (933)	1.4	0.55
Trailers (933)	0.62	1.31
Barges (79.2)	5	1.38
Towboats (2.2)	No data	---
Pipe (20,000 ton)	No data	---
Rail (23,000 ton)	No data	---

(a) U.S. Department of Labor, Bureau of Labor Statistics, "Outlook on Occupational Injuries and Illness in 1975," Report 501, 1977.

(b) Numbers in parentheses are number of units required or weight of pipe and rail required for 30 years.

(c) The product of the number of components, the labor requirement, and lost workday rate gives the number of lost workdays of the 30-year period.

REFERENCES

III-1 H. Inhaber, "Risk of Energy Production," AECB-1119/Rev. 2, November 1979.

III-2 U.S. Department of Labor, Bureau of Labor Statistics, "Outlook on Occupational Injuries and Illness in 1975," Report 501, 1977.

APPENDIX IV
EFFLUENTS: THEIR HEALTH EFFECTS AND DISPERSION MODELS

IV.0 INTRODUCTION

This appendix includes a brief discussion of the various effluents from the two EPC model facilities. Generally, these effluents have an adverse impact on the environment, on the human food chain, and on human health. There is a large number of effluents with variations in physical and chemical form. This study is mainly concerned with those effluents with proven adverse health impacts. These health effects are discussed qualitatively in this appendix. Appendix V includes a survey of the models used to quantify these effects, and Section 6 includes the analytical details of the models chosen to compute the health impact.

In general, airborne and liquid effluents from a model facility are dependent (1) on the type of processes at the facility, (2) on the type of fuel used, and (3) on the efficiency and type of emission controls available in the facility. Estimation of the environmental and health impact of these effluents requires knowledge of the chemical and physical nature of the effluents and their interaction with the physical environment into which they are introduced. This knowledge is used to determine their dispersal or dilution profiles and to estimate typical dosages to the exposed population.

In Chapter 2 of this report, chronic exposure to low levels of pollutants was differentiated from short-term, high-level exposure to effluents released by the model facilities. High-level exposure is associated with the occurrence of malfunctions in the effluent controls (or accidents). Large, uncontrolled releases may occur in both cycles; however, they are of greater concern in the case of the nuclear EPC. Some of the accidents postulated for the nuclear facilities may result in high-level radiation exposure. High radiation doses are known to cause early sickness and fatalities, mainly through irradiation of the bone marrow with resultant reduction in blood white cell production. It is also recognized that certain groups of the population with chronic bronchitis, chronic infections, people with wounds and burns, and fetuses are especially sensitive to increased radiation.

Short-term, high-level exposure to normal effluents from coal-fired plants can also occur in association with adverse or stagnant weather patterns. High-level pollution episodes have occurred historically[IV-1,IV-2,IV-3] and are likely to be repeated, especially in industrial areas. These episodes are known to cause a significant increase in fatalities or to aggravate illnesses of persons with lung diseases or heart and circulatory diseases. Long-term chronic exposure to pollutants has been shown to lead to irreversible damage to lung tissues and can lead to cancers in the lung as well as in other organs.

The next sections include a brief discussion of the various effluents and the health impact of chronic low-level exposure to these effluents. The dispersion models are also discussed in general terms.

IV.1 FOSSIL FUEL EFFLUENTS

This section includes a brief survey of airborne effluents from fossil fuel combustion. Because of the nature of this study, the main emphasis in the discussion is on coal combustion products. Effluents unique to other fossil fuels and with proven adverse health impacts will also be addressed.

IV.1.1 Sulfur Oxides and Sulfates

Coal generally contains sulfur in the form of organic compounds, as pyrite particles or as iron or calcium sulfates. Coal combustion products released to the atmosphere include sulfur, mainly in the form of sulfur dioxide (SO_2). Sulfur dioxide interacts with the particulates in the fly ash, atmospheric moisture, and photochemical smog pollutants to produce sulfuric acid aerosols and sulfate salts.

Airborne SO_2 has an adverse effect on the environment. It affects vegetation through acid formation on wet leaves, and it tends to penetrate plant tissues where sulfates, sulfites, and bisulfates are formed.[IV-1] Sulfur dioxide is also a major contributor to the phenomenon of acid rain previously discussed in Chapter 5.

Sulfur dioxide is a well-known pulmonary irritant. It causes respiratory distress by constricting air passages in the bronchial system. Sulfur dioxide combines with moisture in the respiratory tract to form sulfuric and sulfurous acids. A massive dose can result in a severe respiratory reaction whereas low-level exposure can lead to chronic obstructive lung disease.[IV-1]

Recent studies on animals provided an indication that sulfate aerosols (such as zinc sulfate and zinc ammonium sulfate) and sulfuric acid play a primary role in pollution toxicity.[IV-1,IV-3] This suggests that the adverse health impact of SO_2 emissions may be because of their interaction products or possibly because of synergistic effects with other agents in the atmosphere (e.g., ozone (O_3)). However, further analysis is needed to identify the principal agents causing respiratory irritation.

IV.1.2 Nitrogen Oxides

Nitrogen oxides are emitted in significant amounts from combustion of coal and other fossil fuels. Most of the nitrogen emissions are in the form of nitrogen monoxide (NO) which is relatively harmless to human health. However, NO is oxidized in the atmosphere to nitrogen dioxide (NO_2), which plays an important role in smog formation and is known to have an adverse impact on human health.

Nitrogen dioxide interacts with the moisture and particulate matter in the atmosphere to form nitric acid and nitrate aerosols. Peroxyacyl nitrates (PAN), formed photochemically in a series of interactions involving NO_2 and organic particulate matter, are known eye irritants.[IV-2] Studies with animals, and in some cases humans, indicated that high concentrations of NO_2 and NO_2 atmospheric interaction products have an adverse impact on the respiratory functions and can be linked to increases in asthma attacks. However, further investigations are required to quantify the impact of NO_2 and nitrate aerosols on human heath.

IV.1.3 Particulates

Impurities in coal include compounds like aluminosilicates, inorganic sulfides, trace metals, and organic compounds. During the combustion process, the organic compounds are oxidized or decomposed to produce chemicals of varying volatility. The aluminosilicates, on the other hand, have very high vaporization temperatures and, therefore, tend to survive more or less intact as fly ash and slag.[IV-4]

The size range of the particulates in fly ash extends from about 0.01 to 10 microns. Some of the smaller particulates act as condensation nuclei for volatile compounds and trace elements. Secondary particulates are also formed from post-combustion interactions of gaseous products and sunlight. Among these are sulfates, nitrates, and hydrocarbons. The typical size of these particulates is in the range 0.01 to 1 micron.[IV-4]

Particulates act as carriers of many trace elements and hydrocarbons. Among the metallic elements, lead, tellurium, mercury, arsenic, selenium, cadmium, nickel, chromium, and vanadium are known to be toxic.[IV-4] Moreover, nickel, chromium, beryllium, and arsenic are recognized carcinogens.

The effect that airborne particulates have on human health thus depends on their composition, their size, and their period of residence in contact with sensitive tissues. Smaller respirable particles are generally more toxic than larger ones. They are capable of reaching the pulmonary region of the lung and lodging there for extended periods of time.

IV.1.4 Hydrocarbons

Coal is known to contain aromatic carbon compounds and heterocyclic compounds that are not completely oxidized during combustion. Organic compounds are thus emitted to the atmosphere, possibly with inorganic particles acting as carriers. Organic compounds tend to be released in larger amounts during transient operations that result in incomplete combustion.[IV-4] These compounds include aliphatic and aromatic hydrocarbons and aldehydes that are known lung and eye irritants, carcinogens, or potential carcinogens. Among these hydrocarbons benzo(a)pyrene has been established as a carcinogen.

IV.1.5 Carbon Monoxide (CO)

Carbon monoxide is a product of incomplete combustion of coal and other fossil fuels. It is produced in larger quantities during transient operations that result in inefficient combustion. It is also noted that control of nitrogen oxide emissions from coal-fired plants by combustion modification involves reduction in combustion temperatures and increased oxygen that enhance CO production.

Carbon monoxide affects human health by combining with the blood hemoglobin to form carboxyhemoglobin, which has a very long residence time in the blood. An increased CO level in the blood is known to affect patients with cardiovascular diseases.[IV-4]

IV.1.6 Synergism

Controlled laboratory studies using a given dose of a pollutant (e.g., SO_2) showed smaller responses when compared to field epidemiological studies involving the same dosage of the pollutant. Field studies involve the pollutant under study as well as a number of unspecified agents and unmeasured effluents. These agents and unmeasured effluents are probably acting additively or synergistically with the studied effluents and, hence, result in a more severe response than that observed in the laboratory. Field studies, therefore, revealed the existence of synergism although the studied effluent is used only as an index for the combination of effluents in the atmosphere.[IV-4] Sulfur dioxide and particulates were the initial choices for air pollution indices, but sulfates may be a better candidate for an air pollution index. However, a more complete study is required to justify the choice of sulfates or any other pollutant as the main causative agents for mortalities and sickness induced by air pollution.

It is important to note that the uncertainty about synergism makes the published epidemiological data unsuitable for use in this study. These data were derived from measurements with poorly controlled sources, and they are site specific. Model facilities in this study are equipped with the latest abatement devices, and their effluents may have a smaller health impact.

IV.2 RADIOLOGICAL EFFLUENTS

The study of radioactive effluents from the coal and nuclear EPC model facilities is complicated by the fact that over four hundred different radioactive isotopes can be emitted in a variety of chemical and physical forms. A detailed discussion of all of these effluents is beyond the scope of this study. However, previous investigations[IV-5, IV-6, IV-7, IV-8, IV-9] indicated that this complex situation can be simplified by considering a number of principal radionuclides that are recognized to contribute significantly to the radiation dosage received by the model facilities' workers and by the general public. The selection of these radionuclides is based on a number of criteria, including the magnitude of their half-lives and the amounts released from the different facilities. Some of these isotopes, their half-lives, their principal discharge and exposure modes, and the critical organs affected by them are shown in Table IV.1.

The principal modes of exposure to radiation from these isotopes include inhalation, ingestion, submersion, and irradiation from radioactive deposition. The health effects of exposure to a certain isotope depend on many factors, among them (1) the isotope release characteristics (such as amount and duration of the release), (2) its half-life, (3) the type and energy of the emitted radiation, (4) the mode of exposure, and (5) the chemical characteristics and the metabolic behavior of the isotope in the human body. Generally, alpha and beta emitters induce more internal damage when compared to gamma emitters whereas gamma rays are capable of deeper penetration into the body tissues. Some of the ingested isotopes concentrate in certain organs or glands whereas others tend to distribute uniformly in the human body.

Exposure to radiation can cause somatic or genetic abnormalities. Somatic effects can be early or latent. Early somatic effects are usually observed following large acute doses of radiation and can result in early mortalities and morbidities within days or weeks after

TABLE IV.1

RADIONUCLIDES AND THEIR EXPOSURE CHARACTERISTICS

Radionuclide	Half life $T_{½}$	Principal Discharge Modes	Principal Exposure Modes	Critical Organ	Remarks
Radioiodines					
I-131	8.05 d	Airborne or water	Ground deposition	Whole body	Radioiodines are released
I-132	2.3 h	Airborne or water	Air inhalation	Thyroid gland	in both the elemental and
I-133	21 h	Airborne or water	Drinking water	Thyroid gland	organic forms
I-134	52 m	Airborne or water	Consumption of contaminated food	Thyroid gland	
I-135	6.7 h	Airborne or water	o Consumption of contaminated milk	Thyroid gland	
I-129	1.59×10^7 y	Airborne or water		Thyroid gland	Principally of global concern
Noble Gases					
Kr-85	10.8 y	Airborne	External irradiation	Whole body	Noble gas of greatest regional and global concern
Kr-85m	4.4 h	Airborne	External irradiation	Whole body	
Kr-87	76 m	Airborne	External irradiation	Whole body	
Kr-88	2.8 h	Airborne	External irradiation	Whole body	
Xe-133	5.3 d	Airborne	External irradiation	Whole body	
Xe-133m	2.3 d	Airborne	External irradiation	Whole body	
Xe-135	9.2 h	Airborne	External irradiation	Whole body	
Xe-135m	15.6 m	Airborne	External irradiation	Whole body	
Xe-137	3.9 m	Airborne	External irradiation	Whole body	
Xe-138	17.5 m	Airborne	External irradiation	Whole body	
Nuclides with Low or Intermediate Volatility					
Cs-134	2.05 y	Airborne, water	External irradiation	Whole body	
Cs-137	30.0 y	Airborne, water	External irradiation	Whole body, liver, Spleen, muscle	
Te-132	77 h	Airborne	External irradiation	Whole Body	Contributes to I-132 exposure
Mn-54	303 d	Water	External irradiation	Whole body	Released in liquid form
Fe-55	2.6 y	Water	Drinking water	Spleen	
Fe-59	45.0 d	Water	Drinking water	GI, spleen	
Co-58	71.3 d	Water	Drinking water	Whole body, GI	
Co-60	5.26 y	Water	Drinking water	Whole body, GI	
Sr-89	52.0 d	Water	Drinking water	Bone	
Sr-90	28.1 d	Water	Drinking water	Bone	
Y-91	58.8 d	Water	Drinking water	Bone, GI	
Zr-95	65.0 d	Water	Drinking water	Whole body, GI	
Nb-95	35.0 d	Water	Drinking water	Whole body, GI	
Ru-103	39.6 d	Water	Drinking water	GI	
Ru-106	367.0 d	Water	Drinking water	GI	
Ce-141	33.0 d	Water	Drinking water	GI, liver, bone	
Ce-144	284.0 d	Water	Drinking water	GI, liver, bone	

TABLE IV.1

(CONTINUED)

Radionuclide	Half life $T_{1/2}$	Principal Discharge Modes	Principal Exposure Modes	Critical Organ	Remarks
H-3	12.3 y	Airborne, water	Ground deposi on, inhalation, and ingestion	Whole body Thyroid gland	Has global effect
C-14	5730 y	Airborne	Inhalation, ingestion	Fat, Whole body	Has global effect
Naturally Heavy Elements					
Pb-210	22.3 y	Water	Ingestion	Kidney, wholebody	
Bi-210	5 d		Ingestion	GI, kidney	
Po-210	138 d		Ingestion	Spleen, kidney	
Rn-222	3.8 d	Airborne	Inhalation	Lung	Daughter products are hazardous
Ra-226	1600 y	Water	Ingestion	Bone	Majority of heavy elements are bone seekers
Ra-228	5.75 y	Water	Ingestion	Bone	
Th-228	1.9 y	Water	Ingestion	Bone	
Th-230	7.7×10^{4}y	Water	Ingestion	Bone	
Th-232	1.4×10^{10}y	Water	Ingestion	Bone	
Th-234	24 d	Water	Ingestion	GI, bone	
Pa-231	3.2×10^{4}y	Water	Ingestion	Bone	
U-232	72 y	Water	Ingestion	GI, bone	
U-233	1.58×10^{5}y	Water	Ingestion	GI, bone	
U-234	2.44×10^{5}y	Water	Ingestion	GI, bone	
U-235	7×10^{8}y	Water	Ingestion	GI, kidney, bone	
U-236	2.34×10^{7}y	Water	Ingestion of water or contaminated food	GI, bone	
U-238	4.47×10^{9}y	Water	"	GI, kidney	
Np-237	2.14×10^{6}y	Water	"	Bone	
Pu-238	87.8 y	Water	"	Bone	
Pu-239	2.44×10^{4}y	Water	"	Bone	
Pu-240	6540 y	Water	"	Bone	
Pu-241	15 y	Water	"	Bone	
Pu-242	3.87×10^{5}y	Water	"	Bone	
Am-241	433 y	Water	"	Kidney, bone	
Am-243	7370 y	Water	"	Kidney, bone	
Cm-243	28 y	Water	"	Bone	
Cm-244	17.9 y	Water	"	Bone	

POOR ORIGINAL

the exposure. They also include deaths and illnesses that occur within a year or so. The latent somatic effects include latent cancers (e.g., leukemia) as well as benign thyroid nodules. Fatalities and sicknesses can occur after a latency period ranging from 2 to 30 years.[IV-6] Genetic abnormalities result from breakage of a chromosome and subsequent rearrangement of genetic materials to induce mutation. Genetic effects manifest themselves in the descendants of the exposed person and, hence, affect future generations.

Radiation effects of high and low doses differ significantly. As mentioned above, high doses can induce early sicknesses and sometimes death. This occurs principally by bone marrow irradiation and subsequent interference with blood cell production and by irradiation of the gastrointestinal tract producing bacterial septicimia. Cataracts, growth retardation, and sterility are also known to be induced by high-level exposures. It is recognized that these high exposures are primarily associated with large scale accidents and are primarily limited to persons in or in the immediate neighborhood of the facility responsible for the release.

Latent somatic and genetic effects may result from low radiation levels. The occurrence rate of these effects is estimated to be very low and is subject to uncertainties because of the lack of conclusive scientific evidence. For this reason, latent effects of low exposure levels are treated as random phenomena, and probabilistic techniques are used to estimate the likelihood of their occurrence.

IV.3 DISPERSION MODELS

Sections 3 and 4 of this report include estimates of the amounts of airborne and liquid pollutants released from each model facility. The dispersion models discussed in this section are used to describe the spatial and temporal distribution of these effluents following their release. Normal releases are essentially continuous. The concentration of the pollutants at points along the dispersion paths generally reach equilibrium values. These equilibrium values are usually established some time after the model facility start-up. In some cases, this time interval may be quite large, but equilibrium values are expected to prevail during most of the productive lifetime of the facility. Time independence cannot be assumed for short-term accidental releases. The concentration of the various contaminants along the various dispersal paths tends to build up to a maximum value shortly after the release and decreases steadily thereafter. A small change in the time behavior may have a significant impact on the population exposure.[IV-6]

Dispersion models are used to calculate the concentration of the various contaminants on local, regional, and global basis. Local concentrations are evaluated up to 80 kilometers from the point of emission whereas regional concentrations extend beyond this limit. Global dispersion models are used in association with either long-lived radiological effluents or those nonradiological releases with potential worldwide impact.[IV-10,IV-11,IV-12] Typical of the releases of principal concern in this study are H-3, C-14, and Kr-85 of the radiologic effluents and CO_2 of the nonradiologic effluents. For example, C-14 introduced into the troposphere as carbon dioxide becomes a part of the global carbon cycle and moves continuously from its inorganic reservoirs (different atmospheric and oceanic layers) to living systems in the biosphere and back again. Global variations in the concentrations of C-14 or CO_2 can be quantified using a global dispersion model.[IV-10,IV-11] This model is basically a multi-reservoir exchange model. A number of exchange rates are estimated to define the pollutant transport within and among the different reservoirs. These estimated rates are selected to approximate the mechanics of the pollutant transport in nature. Currently, a number of computerized global dispersion models are in use to calculate the world burden of these effluents. However, the results from these models are still imprecise.

IV.3.1 Atmospheric Dispersion Models

Time-and space-dependent distribution of airborne effluent concentrations around the source of emission is generally evaluated by computerized models. The model most widely used, the Gaussian plume model, assumes a normal distribution of the contaminants in the vertical and horizontal directions perpendicular to the plume centerline. The Gaussian plume model is usually modified to account for factors like plume rise, particle deposition, radioactive decay of the short-lived isotopes, atmospheric chemical interactions, and seasonal variations in weather conditions.

In the case of normal, long-term effluents, the dispersion model uses the release rates to estimate the pollutant concentrations (in curies per unit volume or gm per unit volume for radiological and nonradiological contaminants, respectively) at a number of specified spatial points. In the case of short-term (accidental) releases, the model is used to establish the time-integrated concentration at the same set of points. These points are generally selected within 80 kilometers from the emission source, near ground level.

It is recognized that all dispersion calculations possess some inaccuracies. The local topography, local turbulance, and buildings in urban areas are among the factors that can influence ground level pollution concentrations. Moreover, interactions among pollutants originating from different sources (e.g., transportation vehicle and power plant emissions) may contribute to these inaccuracies. However, it is important to note that the model facilites responsible for the emissions are generic in nature and are chosen to be independent of specific topographical or demographical details since they are intended for general comparison.

IV.3.2 Dispersion Models for Liquid Effluents

Toxic compounds and radionuclides released with liquid effluents from the model facilities can reach the general public by a number of pathways. These pathways include (1) ingestion of drinking water, (2) ingestion of aquatic and marine food, (3) ingestion of vegetables irrigated by contaminated water, (4) ingestion of meat or milk from animals that previously ingested contaminated water or vegetables, and (5) submersion in contaminated water.

Dispersion models for liquid effluents are based on the definition of a number of dilution factors and transfer coefficients. The dilution factors allow for the reduction of contaminant concentration before consumption by the public. Transfer coefficients relate human intake to the contaminant concentration in water. It is important to note that the role played by a specific pathway and the dilution coefficients for the various pathways are sensitive to geographic location and are very site specific.

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APPENDIX V
DOSE-EFFECT MODELS

V.0 INTRODUCTION

Dose-effect relationships correlate the amount of exposure to radiological or nonradiological toxicity with their potential health impacts. Results of a number of dose-effect relationship studies have been published. Some of these are widely accepted whereas the majority are still controversial and their validity is uncertain. The next two sections include models chosen for the health impact assessments in this study.

V.1 RADIOLOGICAL DOSE-EFFECT MODELS

The health effects of radiation exposure were discussed qualitatively in Appendix IV. A distinction was made between low-level exposure (which is either chronic from normal effluents or temporary from accidental releases) and acute exposure (which is associated with high exposure rates from accidental releases). Low-level exposure will mainly affect the local population, with minor potential effects on the national scale. Exposure to low-level radiation may result in a number of latent somatic and genetic effects. On the other hand, high-level exposure is limited to the immediate vicinity of the facility that is the source of the release. High-level exposure can induce early as well as latent effects.

The quantitative models discussed in this section are based on the principal assumption that the radiation health effects constitute random phenomena whose likelihood of occurrence for a particular individual is some function of the dose received. The number of occurrences of a certain effect is evaluated as the product of two parameters. One is an estimate of the effective population dose (in person-rems), and the other is an estimate of the rate of occurrence of this effect (cases per person-rems). The functional relationships used to estimate the occurrence rates for the different possible health effects are discussed in the next two subsections.

V.1.1 Low-Level Dose-Effect Model

There are considerable differences of opinion among experts concerning the human response to low radiation dosages. Effects of high radiation dosages are well documented. However, it is not yet clear whether one may legitimately extrapolate linearly from the effects observed at these high levels to lower, near-normal-background radiation levels. Estimates of the rates of induced cancers and genetic effects caused by low radiation dosages are seriously affected by the manner in which the extrapolation is postulated. Figure V.1

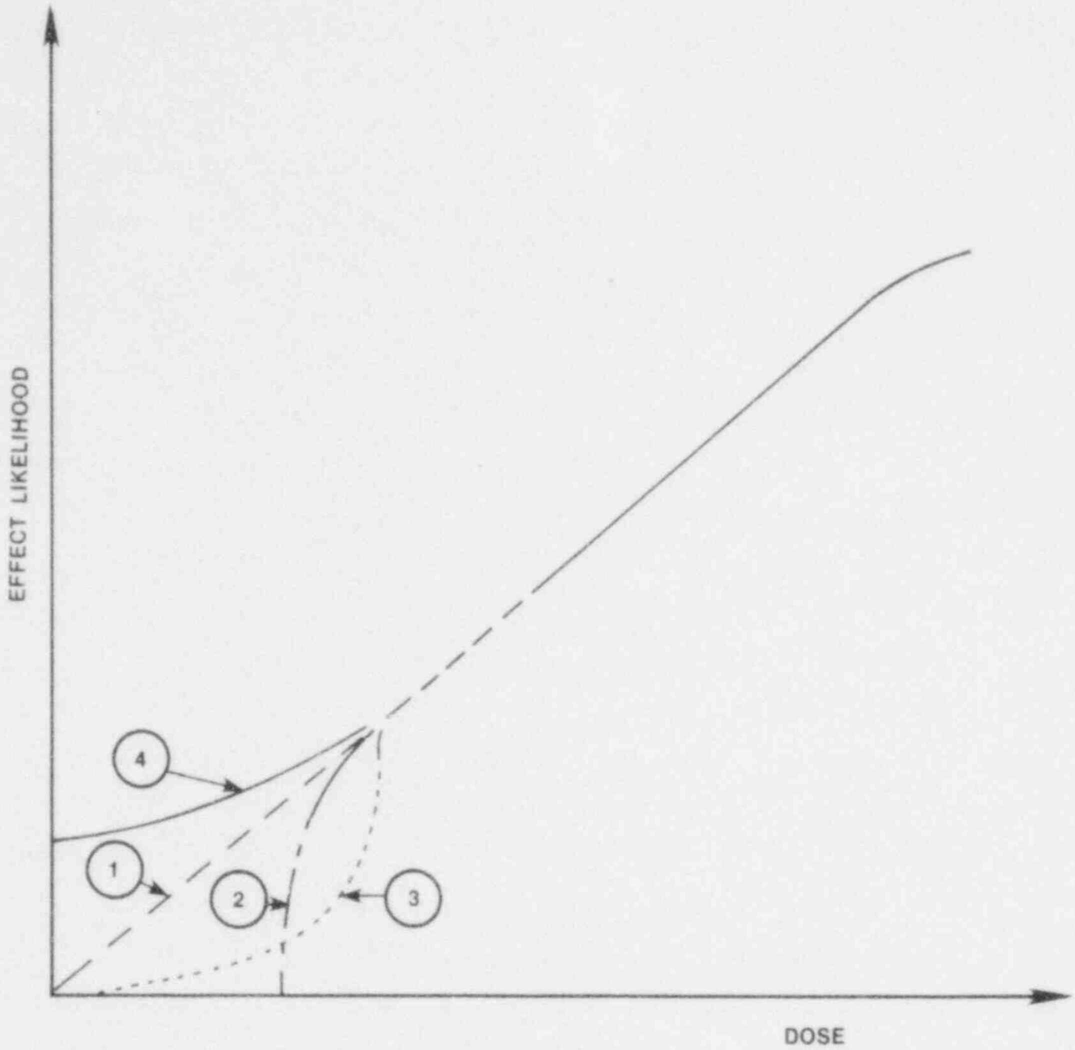

FIGURE V.1. TYPICAL PROFILE FOR DOSE-EFFECT RELATIONSHIPS shows the four possible means of extrapolation. Support can be found for each method of extrapolation, but there is no conclusive evidence on which a choice can be made. Curve 1 assumes that the effect probability is directly proportional to the dosage. This extrapolation method is referred to as the linear hypothesis. Some researchers believe that a threshold exists below which no effect can be observed. Curve 2 represents such a dose-effect curve. However, the value of this threshold may vary with the age and the health of the people under study. Other investigators contend that the health effect likelihood is lower (Curve 3) or higher (Curve 4) than that predicted by the linear hypothesis. The linear hypothesis embodying some degree of conservatism currently has wide acceptance. This study adopts this hypothesis. Typical values for the slope of the linearly extrapolated segment of the dose-effect relationships are shown in Table V.1, giving the rates of the occurrence of various health effects.[V-2,V-3,V-4,V-5,V-6,V-7,V-8]

A study[V-9] of 38 published dose-response curves involving animal and plant material subjected to treatment with carcinogenic chemicals and low linear-energy-transfer ionizing radiation showed that all the responses satisfactorily fit the equation $f = (D^n)/(K^n+D^n)$, where f is the fraction of subjects affected; D is the dose applied raised to the n^{th} power; and K is a constant characteristic of the carcinogen or treatment. The values of n that were found ranged between 0.33 and 3.13 with a value close to 1 (linear at low doses) in only three cases. Because only one set of data on human exposure was included in this study, the more complex relationship was not adopted in the present study.

V.1.2 Acute Dose-Effect Models

For acute doses the dose-response curve is generally accepted to be sigmoidal, with an effective threshold below which early effects do not occur. The dose-response curves for early fatalities and morbidities are reasonably well known and agreed upon. If all parts

TABLE V.1

ESTIMATED OCCURRENCE RATES FOR RADIOLOGICAL EXPOSURE

Target Organ	Rate of Occurence per 10^6 person-rem[a,b] Mortalities	Morbidities	Remarks
Breast	25.6	65	
Lung	22.2	18	
GI tract	17	45	
Bone	6.9	5	
Leukemia	28.4	20	
Thyroid	13.4	130	Thyroid cancers and benign nodules
Others	21.6	198	
Total Body	135	471	

Specific genetic effects	158
Defects with complex/etiology	100
Total genetic effects	258

(a)U.S. Nuclear Regulatory Commission, "Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors," NUREG-0002, August 1976.

(b)National Academy of Sciences, "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation," Report of the Advisory Committee on the Biological Effects of Ionizing Radiation, November 1972.

of the body were uniformly exposed, a dose equivalent of 300-350 rem over a short time will result in 50 percent mortality in the absence of medical treatment. With supportive therapy, 50 percent mortality might be reached at 500 rem. At such doses, death usually occurs in weeks; much larger doses are required to cause death within hours (90 percent at 770 rem). Figure V.2 shows such cause-effect relationships.[V-10]

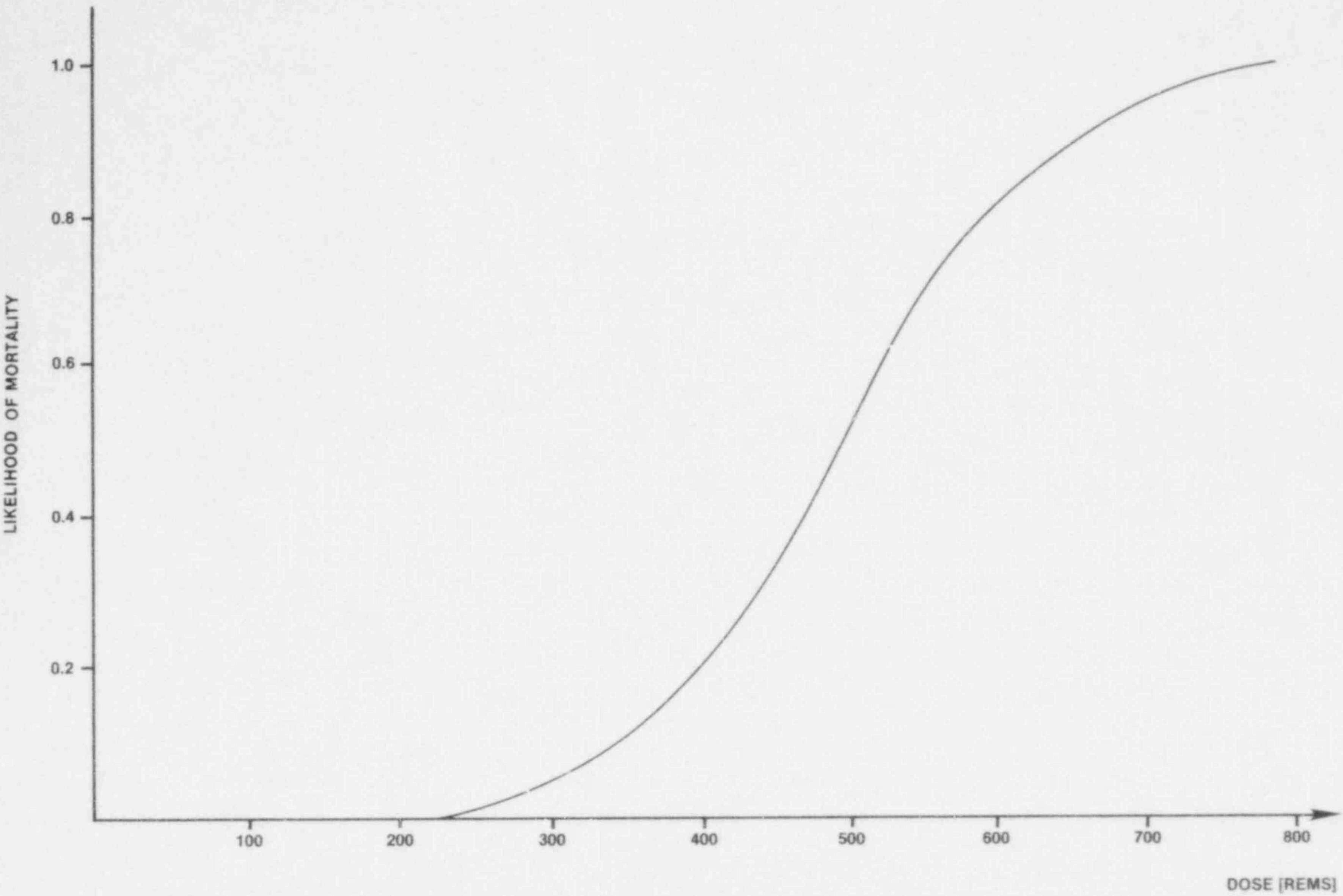

FIGURE V.2.TYPICAL ACUTE DOSE-RESPONSE CURVE

V.2 HEALTH EFFECT MODEL FOR COAL-FIRED PLANT EFFLUENTS

A brief discussion of the health effects of airborne releases from coal combustion was included in Appendix IV. An adverse health impact was linked to the emission of sulfur oxides, nitrogen oxides, particulates, and hydrocarbons as well as the products of their chemical interactions in the atmosphere. Current knowledge is insufficient to relate each pollutant independently to some health impact; however, there is general agreement that certain health effects such as aggravation of asthma and cardiopulmonary symptoms occur at or below the current emission standards. Increases in mortality rates from chronic bronchitis and emphysema can also be linked to increases in pollution levels. In general, the health impact of air pollution depends on (1) pollutant concentration distribution, (2) demographic distribution, (3) age distribution in the population, and (4) the percentage of people in this population who are particularly vulnerable to air pollution.

As with radiation effects, the cause-effect relationships for coal combustion effluents may have a threshold above which the effect is observed. Evidence for the presence of these thresholds is quite inconclusive. These thresholds, if they exist, probably vary with age, smoking habits, health conditions, and possibly with other factors. For this reason, the current trend is to use the linear hypothesis (Figure V.1, Curve 1) for health impact assessment. Researchers[V-11,V-12,V-13] have maintained that even if the linear hypothesis were not completely valid, the increments in pollutant concentrations contributed by the model power plant do not fall far outside the linear portion of the dose-response curve. (The work assumed a constant SO_2-SO_4 conversion rate and provided estimates for the mortality rate based on the model developed by Winhelstein,[V-14] corrected for the sulfate percentage in the particulate emissions.)

Table V.2 includes estimates of the mortality rates per 10^6 persons residing within an 80 kilometer distance from the power plant.

TABLE III.1

MANPOWER REQUIREMENTS AND OCCUPATIONAL HAZARDS OF EQUIPMENT FABRICATION AND CONSTRUCTION ACTIVITIES

Production or[a] Construction Related Activity	Labor Requirement (man-days/MT)	Man-Days Lost (man-days/MT)		Death Rate (deaths/MT)
		Injury	Illness	
Fabricated Metal Products	18.6	6.7×10^{-2}	2.0×10^{-3}	67.0×10^{-7}
Plumbing	146	41.0×10^{-2}	1.4×10^{-2}	1.3×10^{-4}
Electrical	7.0	1.5×10^{-2}	3.3×10^{-4}	4.9×10^{-6}
Roofing & sheet metal	20.3	13.0×10^{-2}	2.0×10^{-3}	3.4×10^{-5}
Miscellaneous contracting	14.3	7.4×10^{-2}	1.0×10^{-3}	2.4×10^{-5}

(a) H. Inhaber, "Risk of Energy Production," AECB-1119/Rev. 2, November 1979.

Estimates are provided for the type of coal and population densities typical of three different geographic locations. Data[V-15,V-16] in this table are modified to reflect the mathematical availability of particulate and flue gas desulfurization controls, the efficiency of respirable particle (<2 microns) collection, and the plant capacity factor.

Table V.3 details morbidity rates[V-17,V-18] corrected to reflect model power plant rating and capacity factors. However, criticism of these data[V-17] points out that these estimates could be low by a factor of 2 or high by a factor of 10.

Air pollution episodes have undeniable adverse health impacts, especially on the elderly and others with respiratory problems. Within a period of 5 years, episodes lasting 2 days or longer with extreme pollution exposure conditions occurred in 11 out of 62 monitoring locations (most of them in the West) in the continental United States.[V-19] The total number of such episode-days in 5 years is as high as 71 in Wyoming and 52 in Oregon. The average number of episodes per year in these eleven locations is estimated to be 1.

To provide a rough estimate of the number of fatalities attributable to pollution episode occurrences, a number of assumptions are made. Using episode data and assuming no geographical dependence, the likelihood of occurrence of an episode per year can be estimated as (11/62) or 0.18. Moreover, if it is assumed that an area with an 80 kilometer radius around the model plant is an urban area with 2.1×10^6 population and that 1 percent of this area is affected by the episode, then the number of people residing in the affected area is 2.1×10^4. Under the assumption that there is only one power station in the neighborhood of the affected area, and that 10 percent of the population is vulnerable to the episode, the number of people to be affected by the episode per plant year is about 370. If the probability of death for this vulnerable segment of the population

TABLE V.3

ESTIMATED MORBIDITY RATES FROM THE MODEL COAL-FIRED PLANT

Health effect	Estimated morbidity rates[(a-d)] Rural	Urban
Cases of chronic respiratory disease	32,700	54,800
Persons-days of aggravated heart-lung disease symptons	338,700	551,400
Asthma attacks	67,700	113,900
Cases of children's respiratory disease	7,900	13,400

(a) National Academy of Sciences/National Academy of Engineering/National Research Council Commission of Natural Resources, "Air Quality and Stationary Source Emission Control," prepared for Committee of Public Work, U.S. Senate, 1975.

(b) C. C. Comar and L. A. Sagan, "Health Effects of Energy Production and Conversion," Annual Review of Energy 1, pp. 581-599, 1976.

(c) Assumes the total population within a distance of 80 kilometer from the plant to be 1.2×10^6 and 2.1×10^6 for eastern rural and urban areas respectively.

(d) Data corrected for plant power rating and capacity factor.

ranges between 10^{-3} and 10^{-2}, then the expected mortality rate per plant year because air pollution episodes has an upper limit of about 4. It is important to point out that most of the above assumptions are rather crude. However, it can be concluded that air pollution episodes do produce a non-negligible health impact that can become significant with expanded use of coal for electricity generation. More detailed data and modeling are required to refine these calculations.

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