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SCREENING OF ALTERNATIVE METHODS FOR THE DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTES

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ABSTRACT

To aid the U.S. Nuclear Regulatory Commission (NRC) in developing regulations for management of low-level radioactive waste, Ford, Bacon & Davis Utah Inc. (FB&DU) is investigating possible waste disposal alternatives. A systematic method for categorizing these disposal alternatives which provides assurance that no viable alternatives are overlooked is reported. Alternatives are categorized by (1) the general media in which disposal occurs, (2) by whether the disposal method can be considered as dispersal, containment or elimination of the wastes, and (3) by the applicability of the disposal method to the possible physical waste forms. A literature survey was performed and pertinent references listed for the various alternatives discussed. A bibliography is given which provides coverage of published information on low-level radioactive waste management options. The extensive list of disposal alternatives identified was screened and the most viable choices were selected for further evaluation. A Technical Advisory Panel met and reviewed the results. Suggestions from that meeting and other comments are discussed. The most viable options selected for further evaluation are: (1) Improving present shallow land burial practices; (2) Deeper depth burial; (3) Disposal in cavities; (4) Disposal in exposed or buried structures; and (5) Ocean disposal.

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1. INTRODUCTION

1.1 Background

From earliest times, mankind has faced problems concerning disposal of waste products which have no further utility. Although disposal of wastes perhaps was not of serious consequence in earlier periods of history, it is now very important because of the quantities and toxicity of wastes requiring disposal. Since the advent of the nuclear age in the mid-1900's, radioactive wastes have been generated which give the waste disposal issue considerable additional significance.

Nuclear wastes, because of their radioactive nature, are generally hazardous, unless properly managed and controlled, and questions concerning long-term isolation or permanent disposal of these wastes are of international concern.(1) However, those responsible for safe waste disposal have managed nuclear wastes since their production began in the early 1940's. Handling of these radioactive waste products presently is carried out at nuclear power production facilities, nuclear facilities at universities and research institutions, and medical facilities using therapeutic radioactive materials. Radioactive waste disposal by burial for low-level wastes has been practiced for more than 25 years. Therefore, considerable experience in disposal of these radioactive wastes is available.

Under the Atomic Energy Act of 1954 as amended and the Energy Reorganization Act of 1974, the U.S. Nuclear Regulatory Commission (NRC) has been given the responsibility of ensuring that commercial radioactive waste management operations are performed in a safe and effective manner. The U.S. Department of Energy has the responsibility for developing adequate methods for waste management operations, and the U.S. Environmental Protection Agency is establishing guidelines to assure that the quality of the environment is not compromised.(2)

The NRC is developing regulations for a national low-level waste management program(3) and preparing for subsequent licensing and regulatory activities. To carry out this responsibility, it is necessary for the Commission to consider all reasonable methods for disposal of low-level radioactive wastes. The NRC has contracted with Ford, Bacon and Davis Utah, Inc. to perform a study of alternate low-level radioactive waste disposal options to ensure that all viable disposal methods have been considered. The purpose of this report is to present the results of the first phases of this study, which include a compilation of alternative disposal methods, a technical advisory panel review, and a screening of the alternatives for selection of those warranting further evaluation.

The scope and objectives of this study, a discussion of the characterization of radioactive wastes and a description of the methodology used to compile the disposal alternatives, are given in Chapter 1. Chapter 2 includes a description of the systematic framework developed to identify and catalog the alternatives, and provides an overview of the alternatives compiled in the study. Chapter 3 provides a summary of the technical advisory panel meeting, and Chapter 4 presents the results of a survey taken to evaluate comparison parameters. The alternatives compiled are summarized in Chapter 5, which gives the basis for selection of those alternatives to be evaluated in detail in the subsequent phases of this project. A revised set of evaluation parameters is contained in Chapter 6 of this report. A summary is given in Chapter 7. References and the bibliography are provided in Chapter 8. The appendixes contain details concerning the technical review panel, and comments from the survey on the evaluation parameters.

1.2 Scope and Objectives of the Study

The scope of this study includes the presentation of possible alternatives for disposal of low-level radioactive wastes. The purpose of this compilation is to aid the NRC in discharging its responsibilities in regulating low-level radioactive waste disposal. To do this effectively, a comprehensive review of possible methods which have been identified or proposed for low-level radioactive waste disposal is presented, based on a systematic methodology for identifying disposal options to ensure that no viable choices have been overlooked.

The first study objective, Task 1 of our effort, included identifying, cataloging and describing the possible low-level waste disposal alternatives using a systematic approach. Exhaustive lists of minor variations and combinations of approaches have not been undertaken because of the generic level at which alternatives are discussed. Consequently, while all general concepts are discussed, specific sub-classes and variations, such as differences in locations, operational details, and site-specific parameters, are not elaborated in detail in this report.

The second objective of the study, Task 2, is to evaluate each alternative identified from the first task and select those that are the most viable alternatives for disposal of solid low-level waste warranting further evaluation. To assure completeness of the initial listing and adequacy of the selection of viable alternatives, a panel of technically competent individuals of recognized waste management expertise has been consulted for review and guidance. A summary of the panel meeting is presented in Chapter 3.

The third objective of this study, Task 3, which remains to be completed, is to subject the most viable alternatives selected to a rigorous and detailed analysis and to compare them with current solid low-level waste disposal operations. These results are to be presented in a convenient matrix format to facilitate use of the results in decisions pertaining to application of viable alternatives in national low-level waste management programs and decisions. The results of this third task will be presented in subsequent reports.

1.3 Characterization of Low-Level Radioactive Waste

Radioactive wastes can be broadly classed by the intensity of the radiation they emit. By regulation, high-level wastes are considered to be those produced from first-cycle chemical processes designed to separate the highly active fission products (produced as nuclear fuel is consumed in a reactor) from the residual useful fuel (a process referred to as reprocessing the irradiated reactor fuel). Low-level radioactive wastes contain lesser amounts of radioactivity per unit volume of waste than do high-level wastes. This study focuses on the alternatives for disposal of low-level radioactive waste.

Low-level radioactive wastes are produced from several sources. One source(4) is power reactor operations, where less than 1% of the fission products escape from the fuel elements and traces of induced radioactivity contaminate the coolant and various portions of the plant. Materials immediately around the reactor (pressure vessel, for example) become radioactive by absorbing some of the neutrons from the reactor. Materials generated in cleaning and maintenance of the reactor plant, in treating the coolant systems, and servicing and replacing worn-out parts and equipment can be considered as low-level radioactive waste. Other sources include radioactive materials used in research or in medical applications. Low-level radioactive wastes are also associated with other facilities and operations involved in nuclear power production; e.g., uranium mines, mills and enrichment facilities, reactor fuel fabrication plants, and reprocessing plants.

Treatment or conditioning of the waste may be desirable before disposal. The waste is often obtained initially as a liquid or slurry. Other components of the waste may be solids or gaseous and airborne particulates. Because the sources of low-level radioactive wastes are so diverse, the chemical and physical forms of the waste are also varied and range from extremely low concentrations of radioactivity possibly mixed with water or air to large, bulky solid materials highly activated and contaminated with relatively high amounts of radioactivity. Disposal of this diverse collection of waste types, sources, and forms requires attention.

Solid and solidified liquid low-level radioactive wastes in the United States are currently disposed of by shallow land burial. To date, about 1.5 million cubic meters of low-level radioactive wastes containing 13 million curies of radioactivity have been buried at disposal facilities,(6) excluding the wastes from uranium mining, milling and enriching operations. In addition, some waste in liquid form is released in compliance with existing standards and regulations as plant effluent. Gaseous and airborne fractions of the waste generally have been discharged to the atmosphere after filtration or decay.

1.4 Methodology

In Task 1 of this study, a systematic approach to identifying potential disposal techniques was implemented. The system prescribes the classification of disposal methods into general broad categories first, and then distinguishing amoung variations in each class to obtain specific options. This systematic approach has allowed verification of the completeness of the list of alternatives derived. The alternatives identified were screened for viability in Task 2.

In this report, the general waste disposal concepts are described and specific pertinent references are given which will allow evaluation of the more detailed aspects of the subclasses and facilitate obtaining additional specific information. The references supplied for each category have been screened and selected to provide as much current, useful information as possible without redundancy. A bibliography of general source documents and listings has been included to provide guidance to more exhaustive reference lists. Sufficient references are specifically listed to provide the information that will be required to perform calculations for comparisons of alternatives.

For the purposes of this study, the waste pretreatments that may be performed before disposal have not been considered except as necessary to explain a specific alternative. The ultimate handling of the radioactive wastes using the alternatives discussed in this report is dependent on the primary waste form. Some alternatives may not be appropriate for disposal of one or more of the possible physical forms of waste as it is generated. The disposal alternative may require converting the primary waste form as generated to a form compatible with the disposal technique. For instance, hydrofracture disposal of low-level wastes would require conversion of the solid wastes to liquid form for injection into the geologic media.

It has been assumed throughout this report that alternatives for disposal of high-level wastes are also technically viable methods for disposal of solid low-level wastes. However, costs and volumetric considerations may make them economically prohibitive in actual practice. The relatively large amounts of information(8) available on high-level waste alternatives, however, do provide much useful information regarding disposal alternatives for low-level waste.

As a part of the initial information-gathering effort, bibliographic source references containing over 8,000 specific references were indentified and made available to personnel assigned to the task. The literature survey included extensive use of the facilities of the Idaho National Engineering Laboratory (INEL) technical library and the University of Utah library.

Two computer search programs were used. One of these programs, DIALOG, from the Information Systems Laboratory of Lockheed Palo Alto Research Laboratory, searched the National Technical Informational System data (listed as Category 6) for pertinent references. A search of Pollution Abstracts (Category 4) from 1970 to September-October 1977, also yielded references under various aspects of radioactive waste.

A second computer search utilized the Department of Energy's computer program RECON. This program searched Nuclear Science Abstracts, volumes 30 through 33, covering the period July 1974 - June 1976. The search was keyed to seven categories contained in the report entitled "ERDA Energy Information Data Base, Subject Thesaurus," TID-7000-42, June 1977. The seven categories searched were: disposal (wastes), ground release, marine disposal, radioactive waste disposal, stack disposal, underground disposal, and radioactive wastes.

In addition to the computer searches, a manual search of books and reports at both libraries was made. This effort was divided into two parts. One effort involved identification of reports which contained bibliographies; approximately 20 documents provided references to over 8,000 other reports on the subject of radioactive waste disposal. These documents are identified in the bibliography in Chapter 7 of this report. For the second effort, specific information on the technical aspects of nuclear waste was sought. In addition, reports also were requested and received from the U.S. Geological Survey, the U.S. Environmental Protection Agency, and national laboratories across the country. To ensure that the activities in foreign countries were considered, information was asked for and received from the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development and from the International Atomic Energy Agency (IAEA).

2. IDENTIFICATION OF ALTERNATIVES

The purpose of this section is to explain the rationale developed to systematically identify low-level radioactive waste disposal alternatives. The identification system was developed to assure that all potential alternatives were identifed. The methodology used also provided a convenient category system whereby the alternatives were cataloged, ordered, and compiled.

A schematic diagram and summary descriptions of the various categories of alternatives are presented in Section 2.2. This presentation provides a list of the disposal alternatives considered and a brief summary of pertinent information.

2.1 Identification and Cataloging

All potential alternatives were identified on the basis of three major characteristics: disposal medium, type of disposal, and applicability to physical waste forms. This approach provides a three-dimensional matrix of possible disposal alternatives into which various disposal options can be classified.

Alternatives for low-level radioactive waste disposal were classified first based generally on the disposal medium and its location with respect to the earth's surface. Six general categories were selected:

(a) Extraterrestrial disposal
(b) Atmospheric disposal
(c) Disposal to waters
(d) Crustal disposal
(e) Structrual disposal concepts
(f) Disposal by conversion

These categories are shown schematically in Figure 2.1. Figure 2.2, the three-dimenional matrix of disposal alternatives, also presents these categories with examples shown of various options included in a given category.

The second dimension used in Figure 2.2 indicates whether or not the disposal method would disperse the low-level radioactive waste, contain the waste in a given location (at least initially), or eliminate the waste. This dimension requires arbitrarily classifying the alternatives, because perfect containment for all time may not be possible (or required). However, even though certain subclasses of alternatives may overlap this artificial boundary, no alternatives are eliminated from consideration by this methodology.

A third dimension involved characterizing the alternatives as appropriate for handling gaseous airborne, liquid, or solid waste forms. In this way it was possible to consider a broad

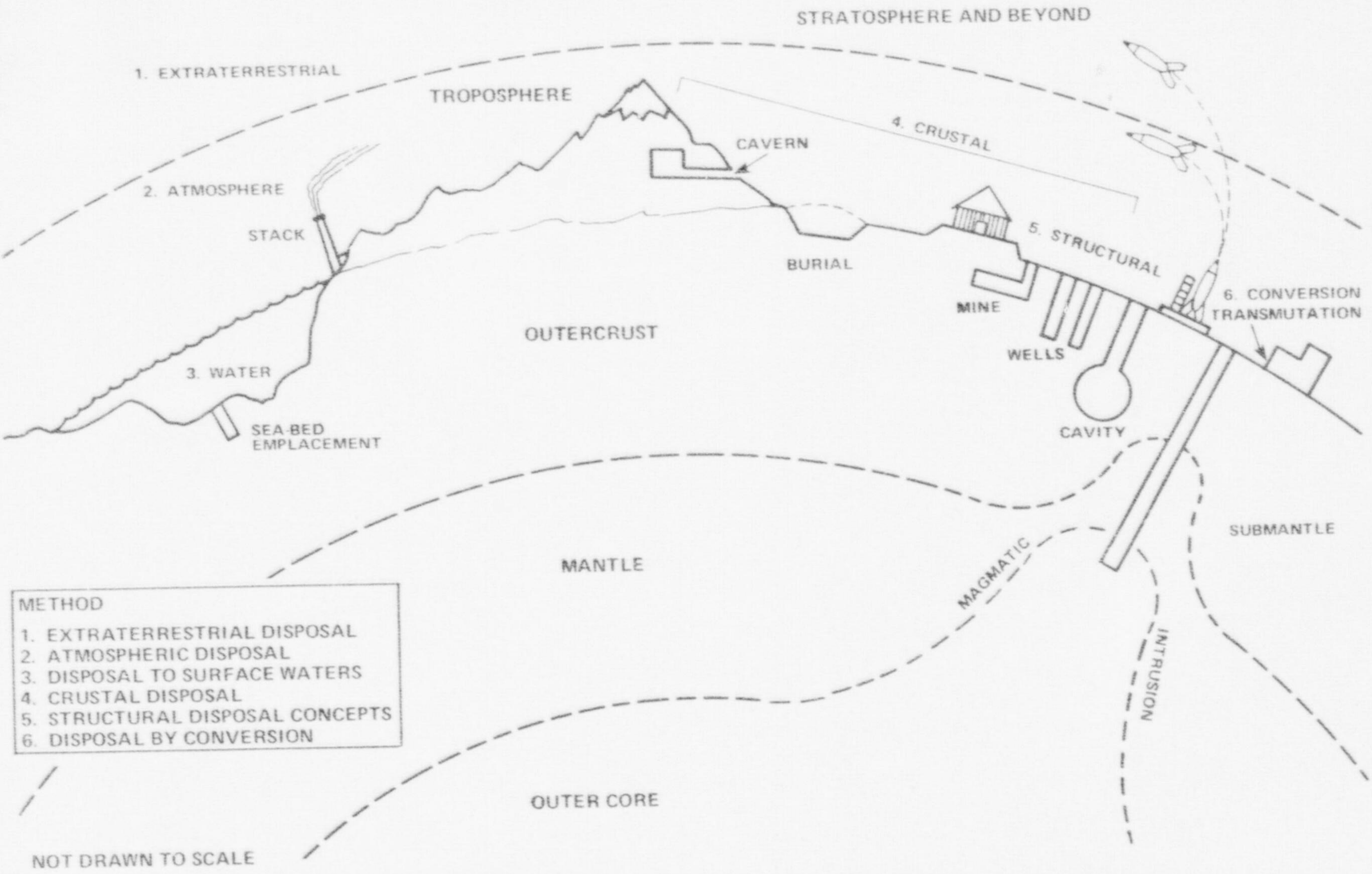


FIGURE 2.1. SCHEMATIC SHOWING THE RELATION OF VARIOUS LOW-LEVEL RADIOACTIVE WASTE DISPOSAL ALTERNATIVES TO THE EARTH AND ITS SURROUNDINGS (ALTERNATIVES ARE CATALOGED ACCORDING TO THE SIX NUMBERED CATEGORIES SHOWN).

spectrum of potential alternatives and distinguish between alternative disposal variations.

The method, illustrated in Figure 2.2, provided an inclusive logical structure to be filled in by a systematic and comprehensive literature search. Each block, or subset, was examined to determine: practicability for low-level radioactive waste disposal, available descriptions of alternative disposal methods in the literature, and new potentially useful alternatives. Using the structure in this way assured that viable alternatives were not overlooked and provided reasonable verification that all alternatives were being considered.

In Figure 2.2, categories containing at least one potentially useful alternative disposal method are marked. As can be seen, in two disposal categories (water and crustal) two mechanisms (dispersal and containment) were both applicable. Elimination applied in only one category: conversion. All three waste forms (gaseous or airborne, liquid, and solid) potentially could be disposed of in four of the categories (atmospheric, water, crustal, and structural). Solid waste forms could possibly be handled in all six categories. By systematically considering each matrix block using the category, mechanism and waste form, the matrix structure is a convenient tool to aid in identification of all possible disposal alternatives.

Included also in Figure 2.2 are partial lists of specific disposal alternatives that pertain to each category. The lists are further expanded in Section 2.2. The boundaries of the categories are noted to be artificial in some cases because various alternatives could be catalogued in two categories (seabed disposal in water and crustal, for example). It is a matter of convenience to maintain the category boundaries as shown in Figures 2.1 and 2.2; these categories are used to organize the alternatives in the balance of this report.

2.2 Summary of Alternatives per Category

This section briefly summarizes the various alternatives that pertain to a given category and lists the alternatives considered. The summary of each category is given below, following the outline provided by Figures 2.1 and 2.2. A detailed description of every possible variation on the alternatives listed was not feasible, particularly since several are related and giving details of each would be repetitive. The summaries that appear are written without references to published material. References for each specific category of disposal alternative are listed in Chapter 5.

Figure 2.3 presents a list of disposal alternatives. An effort was made to determine disposal methods used in the past, currently in use, and methods that are being developed by other countries and include this information in the diagram. A

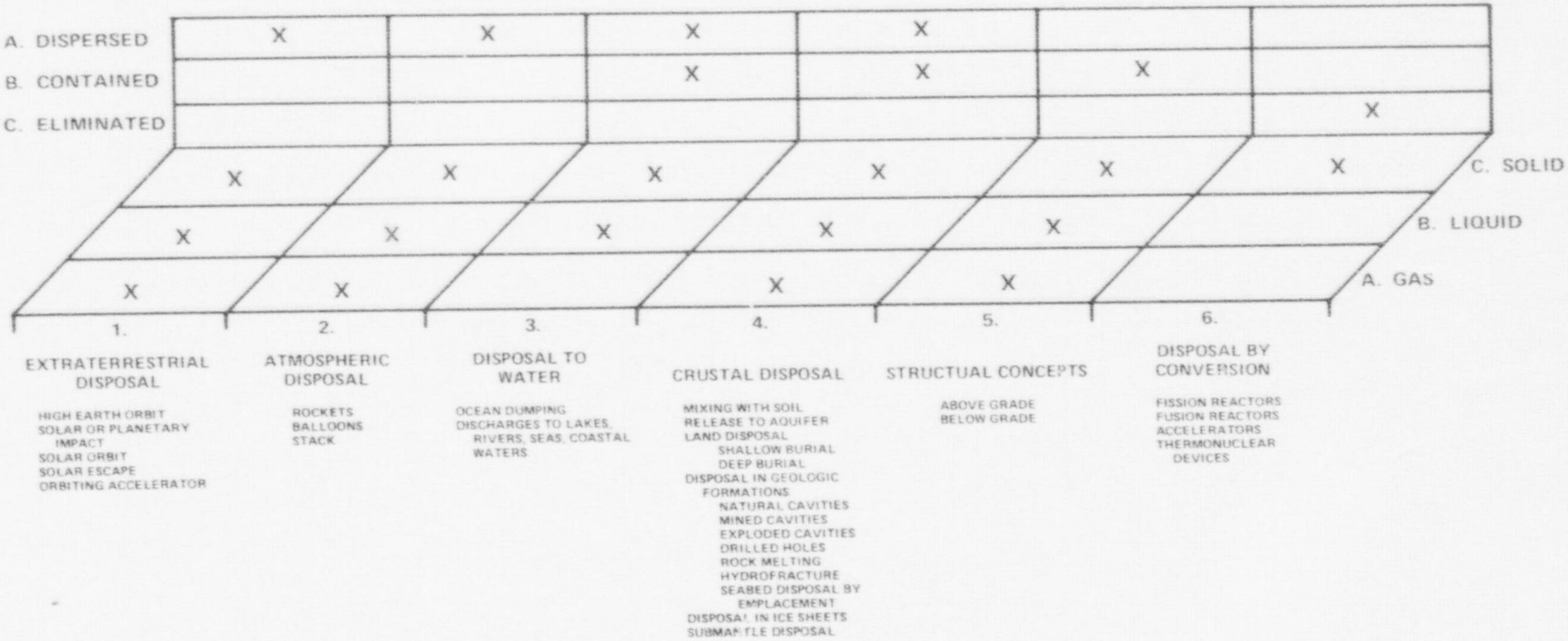
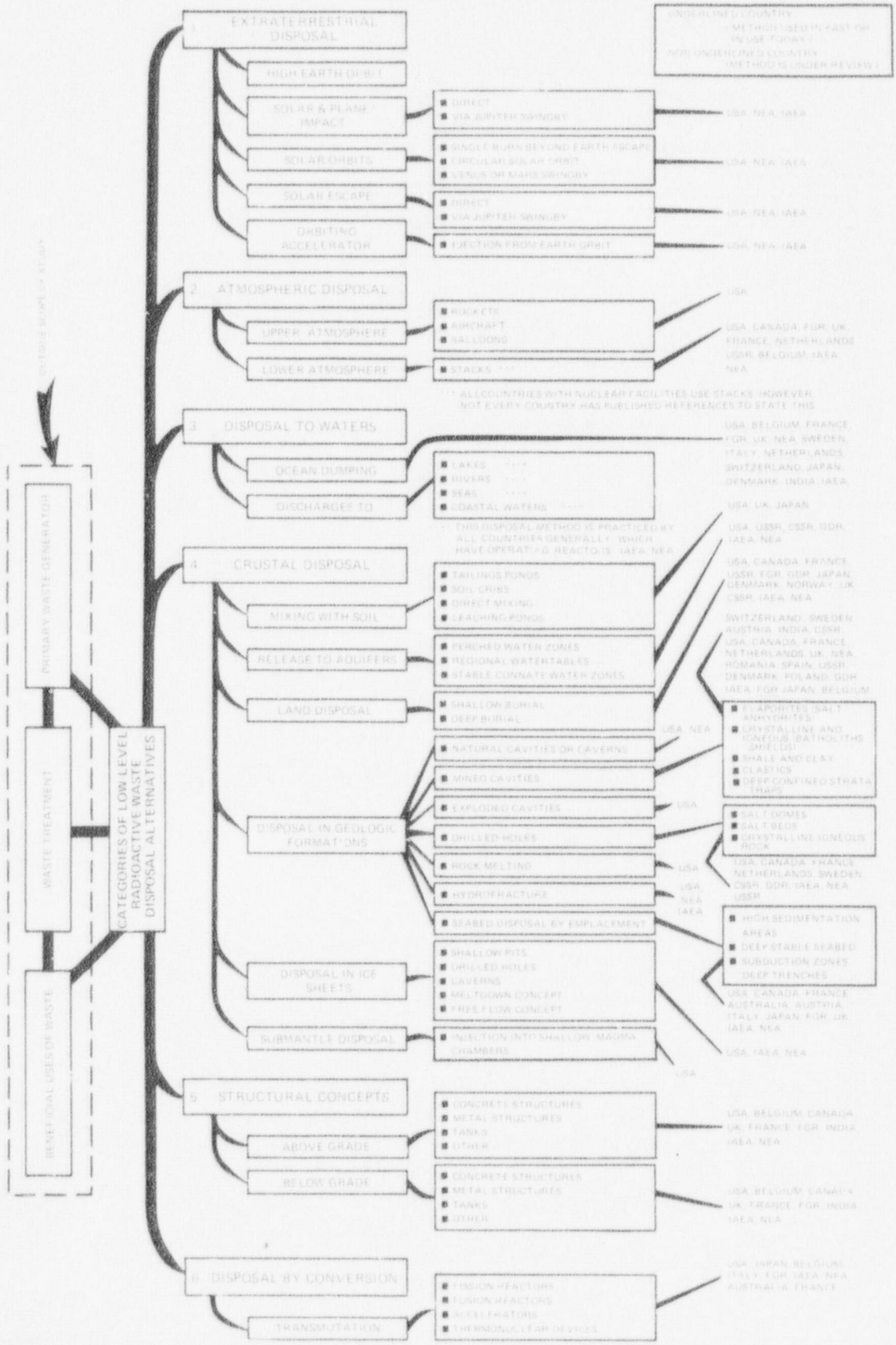


FIGURE 2.2. LOGICAL STRUCTURE WHEREBY LOW-LEVEL RADIOACTIVE WASTE DISPOSAL ALTERNATIVES WERE IDENTIFIED AND CATALOGED

FIGURE 2. 3. CATEGORIZATION OF ALTERNATIVES FOR DISPOSAL OF LOW- LEVEL RADIOACTIVE WASTES



*** ALL COUNTRIES WITH NUCLEAR FACILITIES USE STACKS, HOWEVER, NOT EVERY COUNTRY HAS PUBLISHED REFERENCES TO STATE THIS

**** THIS DISPOSAL METHOD IS PRACTICED BY ALL COUNTRIES GENERALLY, WHICH HAVE OPERATING REACTORS, IAEA, NEA country's past and current use of a disposal alternative is indicated by underlining the name of a country. Listing a country's name without underlining it indicates that the alternative is being studied by the country for possible future application and is not currently in use.

International organizations which have discussed various alternatives in their literature have been indicated by including their names with the lists of countries. Organizations such as the IAEA and NEA are concerned with the development of radioactive waste disposal methods.

2.2.1 Extraterrestrial Disposal

Disposal of radioactive wastes into space is a theoretically attractive option. The option includes alternative trajectories as summarized below:

(a) High earth orbit
(b) Solar or planetary impact
(c) Solar orbit
(d) Solar system escape

There also are various options whereby these destinations are achieved. Studies have included an orbiting accelerator to eject waste into space.

The concept is considered to be dispersive and, because of costs, is applicable to small volumes of concentrated waste. It therefore implies conditioning to separate the most hazardous fraction of wastes from the bulk of the waste volume. This would mean additional processing of the waste which in itself involves some risk. Launch safety and the consequence of waste capsules re-entering the atmosphere are of concern; a very high launch reliability would be essential. The possibility of radioactive waste in space significantly contaminating other terrestrial or stellar environments has been determined to be very unlikely. There are concerns about the economic viability of the concept, and its suitability for future use is being kept under review.

2.2.2 Atmospheric Disposal

Disposal of low-level radioactive effluents, principally airborne wastes and liquids dispersed as vapors, is an option that has and does present practical application particularly with the use of stacks. Alternatives within this category include:

(a) Rocket disposal to the upper atmosphere
(b) Disposal by high-altitude balloons
(c) Disposal using a stack

The destinations of options (a) and (b) would be the stratosphere or ionosphere and may be used for solids and liquids as well as gases by providing a dispersive mechanism such as volatilization by an explosive device. Option (c) pertains to the lower atmosphere and is an alternative presently in use for operating plant effluents.

These disposal concepts are dispersive. Options (a) and (b) may provide means of reducing costs and increasing the volume of disposed waste as compared with extraterrestrial alternatives. Rocket dispersal launch risks are comparable to, but the risk of radioactive contamination of the earth's surface is greater than those of exterrestrial alternatives. Both rocket and balloon disposal in the atmosphere are concepts that have not been studied in great detail. Eventual fallout of the wastes over the earth's surface is the primary drawback to these options. Both concepts therefore require development, even though rocket and balloon technology already exist, should these be considered viable alternatives.

Stack disposal is a viable alternative for gases and airborne effluents released in compliance with existing regulations. Considerable material has been published pertaining to this alternative. The information given in Chapter 5 is a summary of some of the pertinent information from many references.

2.2.3 Disposal to Waters

The disposal alternatives grouped in this category are practiced options and include:

(a) Disposal by ocean dumping
(b) Discharges to seas, rivers and lakes

Both alternatives are currently being practiced for low-level effluents in compliance with existing regulations. Solid low-level wastes are not presently disposed of by either technique in this country.

Concept (a) initially is considered to be "contained" for solid wastes and, as containers eventually become corroded, to be dispersive of the low-level radioactive waste. Concept (b) is dispersive for liquid wastes. High dilution factors, inaccessibility to man, and seabed stability in various areas are the positive features of concept (a), although negative public reaction to ocean dumping may be widespread, and this type of option has been perceived as giving a high risk by the public.

Liquid effluent discharges which are limited in concentrations and volumes to seas, rivers, and lakes are practiced by nuclear facilities where releases meet regulatory effluent standards. These systems are explained and documented in safety and/or environmental analysis reports for the applicable plants.

2.2.4 Crustal Disposal

This category of alternatives for radioactive waste disposal includes numerous options. These alternatives are:

(a) Mixing with soil and leaching ponds

(b) Release to subsurface aquifers into: perched water zones, regional aquifers, or stable connate water zones

(c) Land disposal

(d) Disposal in ice sheets using: drilled holes, a meltdown concept, or a free-flow concept

(e) Disposal in geologic formations in cavities - natural (caves, domes, faults, volcanic), drilled, mined or exploded; or holes drilled into salt domes or formations, argillaceous clayey sediments, intrusive igneous, and metamorphic formations; hydrofracture; seabed disposal by emplacement

(f) Submantle disposal

The several alternatives on or near the surface of the land include both dispersal and containment of gases, liquids, and solids. In practice liquids and solids have been disposed of, while radioactive gas disposal by geological containment is in only the conceptual stage, although it parallels natural gas storage in geological formations. Disposal of nonradioactive wastes and stimulation of natural gas and oil production by industry have led to some of the alternatives listed above.

The popularity of techniques near the land surface is partly due to available technology to emplace the waste, the ability to monitor the emplacement, and for some alternatives the reduced cost of disposal. The depths of the disposal area of the several alternatives vary from natural surface features (caves, for example), to just below ground level (shallow-land burial), to deeper burial, wells and mines in the earth's crust.

2.2.5 Structural Disposal Concepts

Disposal in man-made structures is an alternative that deserves some attention. These concepts are designed to contain the wastes placed within the structures. Structures of metal, concrete, plastic and other structural materials have been reviewed including both above- and below-land surface construction. Tanks are considered to be a subclass of structures. Both new construction built specifically for waste disposal and utilization of existing structures for disposal are possible. This concept thus includes the possibility of using reactor pressure vessels and containment structures in an entombment concept for waste disposal after reactor decommissioning. These concepts are most suitable for solid wastes, but can be designed to contain liquids or gases.

2.2.6 Disposal by Conversion

Two alternatives for handling waste were initially grouped in this category. These alternatives are:

(a) Disposal by transmutation using:

   (1) Fission reactors
   (2) Fusion reactors
   (3) Various accelerators
   (4) Thermonuclear explosive devices

(b) Disposal by putting radioactive wastes to beneficial use

Radioactive isotopes are eliminated by particle bombardment; i.e., one isotope is changed to another isotope, from applying alternative (a). Two properties of radioactive waste, heat and radiation, are taken advantage of beneficially when applying alternative (b). Under concept (b), however, after the period of beneficial use, some disposal of the residual material will still be required. Therefore, beneficial use is not considered to be an actual disposal alternative, and is not discussed further in this report.

Both alternatives are usually associated with separated and concentrated solid forms of radioactive waste, where transmutation generally involves actinide isotopes and beneficial uses involve various fission product and actinide isotopes. Neither alternative applies to all radioactive isotopes. Other disposal alternatives, therefore, are needed to handle the remaining fraction and the residues, once transmutation devices are discontinued or radioactive sources of heat and radiation become ineffective (spent).

3. SUMMARY OF TECHNICAL ADVISORY PANEL MEETING

A technical advisory panel on low-level radioactive waste disposal alternatives was convened in Tucson, Arizona, on March 9, 1978, under the chairmanship of Dr. William C. Taylor of Michigan State University. Mr. Paul Lohaus, NRC, and Mr. Paul Macbeth, FBDU, represented the panel's sponsorship. Dr. William P. Bishop, manager of the NRC's Waste Management program, extended NRC's appreciation to the panel and offered his perspective for guidance. A listing of panel members is given in Appendix 1.

The purposes of convening the advisory panel were threefold:

(1) To discuss the list of disposal alternatives which resulted from the work performed in Task 1 of this study. Each panel member was given an earlier version of Figure 2.3 and asked to comment on whether or not the listing of alternatives was complete.

(2) To discuss the weighting factors determined by the "Delphi" method to be applied to evaluation parameters to provide the bases for intercomparisons between disposal alternatives. The list of evaluation parameters had already been sent to over two hundred persons knowledgable in radioactive waste management to obtain a broadly-based, interdisciplinary assessment of the relative importance of the parameters. Ninety-six responses had been tabulated prior to the meeting and these results were the basis for the discussion. (See Chapter 4 for a discussion of this survey. Specific comments on the weighting factors and evaluation parameters are given in Appendix 2.)

(3) To recommend viable disposal alternatives. Each panel member was asked to rank the five alternatives which he considered to be most viable following the discussions of (1) and (2) above The purpose of this poll was to supplement the more detailed screening presented in Chapter 5.

The meeting began with a presentation of the background of the alternatives study, followed by a brief introduction of the results of the first task including Figure 2.3. Some discussion followed on the specific objectives of the study and definitions used which resulted in clarifying the role of the panel's efforts and setting the ground rules of the discussion. The most important of these were:

(1) Disposal alternatives discussed would be those initially considered appropriate for disposal of routine solid low-level radioactive wastes that are currently being buried. High-level wastes, liquids, gases, mill tailings, and other wastes not currently appropriate for disposal by shallow land burial were recognized as

important, but excluded from the scope of the present study and discussion. The panel recommended that a distinction should be drawn between low-level wastes and reactor effluents, and that this suggestion be reflected in the report. The panel also concluded that, if the need arises later, the study might consider wastes other than solids.

(2) Waste sources and treatments or processing would not be discussed or considered unless required for adequately describing a specific alternative concept.

(3) A precise definition of low-level radioactive wastes is lacking. However, for this study, low-level wastes are taken to be those ranging somewhere between high-level wastes and trash sent to a sanitary landfill. This operational definition is to include generally those wastes currently acceptable for shallow land burial.

(4) The goal of the panel was not necessarily to arrive at a total consensus on all topics that were discussed, but to benefit from the exposure of several opinions in formulating disposal alternatives and evaluation parameters.

(5) Part of the initial effort of this total study is to develop a better justification for pursuing shallow land burial and to identify methods that are as good or better for disposal of low-level wastes if they exist. A ranking of alternatives based on adequacy and acceptability of disposal will result from Task 3 of this study.

The panel discussed the completeness of the list of alternatives presented in Figure 2.3 and offered suggestions for reorganizing the presentation to make the emphasis on important options more consistent. The general consensus of those present was that the systematic approach used for identifying alternatives was adequate and that there were no apparent omissions of important alternative disposal methods. The suggestions for improving the presentation of the alternative concepts have been incorporated in Figure 2.3.

The discussion on the listing of alternatives was facilitated by asking if any credible disposal methods were missing from Figure 2.3. Suggestions from the panel included improving the names of various categories to remove ambiguities and clarify the concepts, and changing a disposal alternative from one category to another to improve the consistency of the presentation. The concept of beneficial use of radioactive waste was moved from the list of disposal alternatives to its present position with waste treatment. It was decided that, in general, beneficial uses of radioactive materials would ultimately result in wastes that must be disposed of in any case; hence, beneficial use concepts are not alternatives to other disposal options.

A diversity of opinion was demonstrated during the discussion on evaluation parameters and the weighting factors to be assigned to the parameters. The diversity was consistent with results drawn from the responses received to the survey on the weighting factors. These results were used as an introduction to this part of the panel discussion. Further details of the survey are given in Chapter 4.

Despite the differences in opinion, the panel provided positive guidance for organizing the evaluation parameters, even though there was some variance on how and if the weighting factors should be applied to the parameters. It was pointed out that the parameters used should be as mutually independent as possible to arrive at a meaningful comparison of disposal alternatives. The initial list of evaluation parameters contained several items that were not mutually exclusive, leading to questions on interpretation of the parameter. Some of the parameters could be considered as yes or no parameters. That is, they represent constraints or minimum requirements that an alternative must meet to be acceptable. Other parameters are variables and can range through different values and still be acceptable. The parameters should be organized to show this fundamental difference. This direction has been followed and the results are discussed further in Chapter 6 on the revised evaluation parameters. The panel initiated an organization of evaluation parameters and discussed in various levels of detail where a given parameter should appear in this organization.

With respect to weighting factors, it was pointed out that if all of the parameters could be quantified and expressed in common units (such as dollars, for instance) then no additional weighting factors would be needed. However, where the units are dissimilar, a method of combining their values for comparison purposes is needed. Assigning the actual calculated value of each parameter for the different alternatives a position on a scale from 1 to 10, applying a weighting factor, and summing over all of the parameters allows comparisons of dissimilar quantities in a straightforward fashion.

As a result of the panel discussion, it was decided to revise the list of evaluation parameters and resubmit the list for further consideration of appropriate weighting. As the discussion on evaluation parameters progressed, it was brought up that engineered improvements of shallow land burial should be considered as an alternative to current shallow land burial. Although improving shallow land burial practices is not a different disposal concept, it is of sufficient importance to deserve further consideration.

The panel then considered the selection of the most viable alternatives to be recommended for further evaluation in Task 3 of this study. There was a general feeling, reflected in the results of a poll taken from the panel, that improving present disposal practices (shallow land burial) was the most reasonable and viable course of action for the country to follow. This study of alternative disposal methods will concentrate on techniques other than shallow land burial, although improvements to the base case of shallow land burial will be incorporated in the comparisons.

A poll was taken to determine the panel's recommendation of viable disposal alternatives for low-level wastes. Each panel member was asked to list the five alternatives he considered most viable in descending order. The panel reviewed the listing of alternatives and screened the alternatives to eliminate choices that were obviously not viable. Some of the alternatives, such as transmutation, were eliminated from further consideration as alternatives for disposal of solid low-level radioactive wastes because of nonapplicability or excessive cost requirements. From the alternatives that remained, each panel member was asked to select five, listing the most preferred first.

The results of the poll of panel members to determine their opinion on the five most viable alternatives for disposal of solid low-level radioactive waste are tabulated in Table 3.1. Concepts other than improvements to shallow land burial practices recommended for further study by the panel include disposal in cavities and man-made structures, ocean dumping, seabed emplacement, drilled holes, hydrofracture, mixing with soils, and injection wells.

Before adjournment, the role of the panel in completing this study was discussed. The task reports remaining (Tasks 2 and 3) will be provided to the panel members for their review, comments and suggestions. A need to reconvene has not been identified at present. However, if the NRC desires, the panel is willing to meet as a body for further deliberations. The suggestions provided by the panel will be considered in completing the subsequent tasks of this study.

TABLE 3.1

POLL OF PANEL MEMBERS ON MOST VIABLE ALTERNATIVES

Alternative Disposal Method	Numbers & Choices	Total Score[a]
Improved Shallow Land Burial	16 I's	80 points
Mined Cavities	1I, 5II's, 4III's, 5IV's, 1V	48 points
Manmade Structures	4II's, 4III's, 4IV's 4V's	40 points
Ocean Dumping	3II's, 2III's, 1IV, 5V's	25 points
Natural Cavities	2II's, 3IV's	14 points
Seabed Disposal	2III's, 1IV, 2V's	10 points
Drilled Holes	3III's 1V	10 points
Hydrofracture	1III (liquids only), 2IV's	7 points
Mixing with Soils	1II, 1III	7 points
Exploded Cavities	1II, 1IV	6 points
Beneficial Uses	1II	4 points
Injection Well	1V (trituim only)	1 point
Release to an Aquifer	1V	1 point
Nevada Test Site	1V	1 point
Not Specified	1V	1 point
Any	1V	1 point

[a] Method of Rating:
I = First Choice = 5 points
II = Second Choice = 4 points
III = Third Choice = 3 points
IV = Fourth Choice = 2 points
V = Fifth Choice = 1 point

4. SUMMARY OF EVALUATION PARAMETER SURVEY AND COMMENTS

Approximately two hundred world-wide experts in radioactive waste management were asked to estimate the weighting factors shown in Table 4.1 and to supply comments. These people were drawn from many agencies and institutions including those of the federal and state governments, national laboratories, universities, private companies, and various individuals. Their disciplines included engineering, science, environmentalism, and many others. Several foreign experts were consulted. Each respondent's weighting factors were normalized to a sum of 100 in order to provide a common basis for correlating the results of the different respondents. The average and standard deviation for each weighting factor were then obtained from the responses as shown in the table.

One hundred twenty-two replies have been received. The trends have been clearly set as shown by the fact that the averages have not changed significantly during the last fifty replies. The standard deviations reflect the diversity of disciplines among the respondents. Nevertheless, a definite difference is discernible in the perceived importance of "Waste Containment" over that of "Energy Consumption," for example, and most of the results have at least a semiquantitative significance. The higher-than-usual average for "Sociopolitical Implications" recognizes the importance of public acceptance apart from technological achievement. The academic community generally has rated "Sociopolitical Implications" higher than have engineers. However, cost-intensive parameters, such as "Economic Costs," "Transportation," and "Energy Consumption," have usually been rated higher by engineers than they have by other groups. Although the canvass bears the imprint of widely different groups, the results are nevertheless felt to be representative of the responses that would be received from a larger cross-section of knowledgeable persons.

The comments received on parameters A to Q have generally described the individual's concept of the parameter and whether or not that parameter overlapped with others. Although such comments are often instructive, they are frequently too esoteric for a general discussion such as this. The comments on R (other parameters felt to be important) have often been of broader significance. Some of the significant comments listed under item R are briefly described below:

(1) Some replies have emphasized that retrievability, etc., should have been considered. This parameter could vary considerably from one disposal alternative to another to reflect differences in retrievability, degree of containment, and isolation from man's environment.

TABLE 4.1

RESULTS OF SURVEY ON APPROPRIATE WEIGHTING FACTORS

Evaluation Parameters	Parameter Weighting Factor[a]
A. Waste Containment	9.3 ± 2.4
B. Public Hazards Protection	9.3 ± 3.0
C. Non-Routine Hazards	6.4 ± 2.6
D. Status of Technology	6.3 ± 2.7
E. Site Availability	6.6 ± 3.0
F. Retrievability	3.1 ± 2.4
G. Resource Commitments	3.7 ± 2.1
H. Environmental Impacts	5.4 ± 2.4
I. Transportation	5.5 ± 2.7
J. Economic Costs	5.3 ± 3.1
K. Environmental Monitoring	6.5 ± 2.7
L. Sociopolitical Implications	6.8 ± 3.8
M. Corrective Actions	6.0 ± 2.6
N. Compatibility with Wastes	5.6 ± 2.7
O. Energy Consumption	3.0 ± 2.1
P. Decommissioning Implications	4.3 ± 2.7
Q. Occupational Exposures	6.7 ± 3.0
R. Others Felt to be Important	
	Sum = 100.0

---

[a] Estimation of appropriate weighting factors (showing relative importance of evaluation parameters) for comparisons of alternatives for low-level radioactive waste disposal. Results are normalized to a total importance of 100. The higher the value, the more important the parameter.

(2) Other respondents have noted the possible need to maintain the disposal site for an appropriate period, e.g., until the hazardous components of the radioactive waste have decayed to innocuous levels. As with many parameters, this one related to another parameter, "Corrective Actions," in this case.

(3) The "waste disposal" of this report refers to the disposal of radioactive waste after it has been given a suitable form by some treatment. However, some respondents justifiably point out the importance of volume reduction in this treatment as it affects the viability of the disposal process. A systems optimization may require considerable reduction in volume before waste disposal.

All of the comments received have been tabulated in Appendix 2. These comments were all considered in revising the list of evaluation parameters. Chapter 6 of the report discusses the revised organization of evaluation parameters.

5. DESCRIPTION AND VIABILITY OF ALTERNATIVES

Based on the perceived ability of the alternatives to properly protect the public health and safety, availability, and economic factors, the concepts shown in Figure 2.2 were screened for selection of the most viable alternatives for disposal of solid low-level radioactive wastes. Where the listed alternative method is not technically feasible for the waste form being disposed, or where costs could likely be prohibitive, the alternatives were eliminated from further consideration at this time. To discriminate further among the remaining alternatives requires quantitative evaluation of the parameters and factors contributing to the constraints used for screening. The Task 3 effort of this study will entail a quantitative comparison of alternatives of this type.

In the subsections that follow, each major alternative is described briefly and reasons given for considering whether or not it deserves further study. All quantitative information readily available was used in making these judgements.

5.1 Extraterrestrial Disposal

5.1.1 Concept Description

This alternative has been considered as "dispersive" because the waste is removed entirely from the earth's atmosphere and ultimately is dispersed into some area of space. Optimum practicality of this class of alternatives would dictate that the waste be highly concentrated in order to achieve high levels of radioactivity disposal per pound of rocket.

Disposal into space would provide the most complete isolation of man's environment from radioactive waste.(5,12,13) Extraterrestrial disposal of high-level radioactive waste has been considered in detail and reported in "High-Level Radioactive Waste Management Alternatives", BNWL-1900, with some additions from later studies.

The basic concept of extraterrestrial disposal includes safely packaging waste material and transporting the material by rocket (manned space shuttle and tugs as depicted in Figure 5.1) to a location off the earth. The concept particularly has merit for consideration as an option to dispose of the longer-lived and actinide fraction of waste.

Several trajectories have been considered:

(a) A high earth orbit of about 150,000 km from earth
(b) Transport to the sun
(c) A solar orbit
(d) Solar system escape

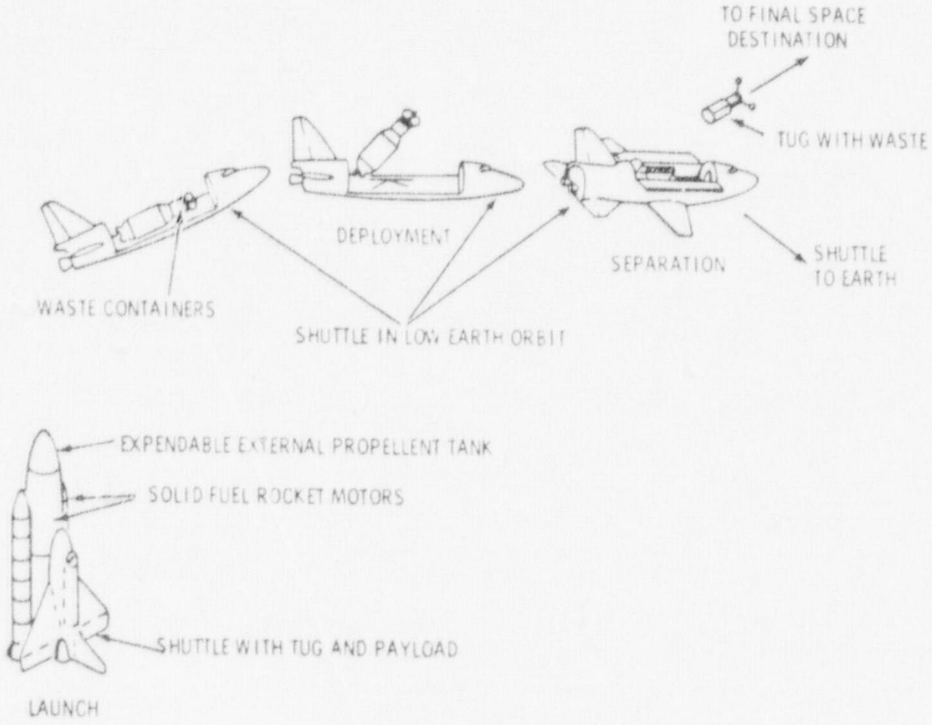


FIGURE 5-1 SHUTTLE LAUNCH DEPLOYMENT SEQUENCE FOR EXTRATERRESTRIAL DISPOSAL

In addition, variations of trajectories for solar orbits, for solar impact, and for solar-system escape have been considered. An orbiting accelerator to eject waste into space also has been studied. The information presented here pertains to solar system excape as the destination considered most likely,(3) but further information on the orbiting accelerator is not given.

5.1.2 Applicability to Low-Level Waste

To apply this option practically to low-level radioactive waste would require treatment and conditioning of the low-level waste to concentrate it to higher levels of activity per unit mass. The implementation of space disposal of the concentrated transuranic waste partitioned from high-level waste could be achieved with current technology which includes the space shuttle and space tug.

A conceptual design of a high-integrity capsule has been considered(13) as a nuclear waste package. Testing would be required to confirm the concept. Other technical development needed includes waste concentrating and partitioning. Development of encapsulation and handling techniques is required. Other needed developmental efforts include disposal trajectory studies, orbit stability studies, special instrumentation, and safety evaluations including evaluations of risks due to mission alerts.

Total estimated costs for solar escape disposal of separated actinides and terrestrial disposal of the remaining high-level waste fraction are 0.34 mills/kWh (e).(13) A later study(14) based on different assumptions, including costs escalated to reflect 1974 dollar values, set the cost of solar escape of the actinides plus salt disposal of fission products at 1.08 mills/kWh(e). This represents a cost increase for high-level waste disposal to the consumer of 3.6%, using a consumer cost of 30 mills/kWh(e) for nuclear-generated electricity. Additional cost for concentrating the wastes would be incurred for disposal of large volumes of low-level waste.(15)

Extraterrestrial disposal concepts would come under provisions of the International Treaty on Outer Space. Any launch operations, mission aborts, or orbit degradations could entail international liabilities under this treaty. The International Conventions on the High Seas and the International Nonproliferation Treaty conceivably also could affect any ultimate disposal concept.

Because the costs per unit volume of waste sent into space and the costs for concentrating and reducing the large volumes of low-level waste to a feasible amount are so high for this concept, extraterrestrial disposal is not felt to be viable for disposal of low-level wastes.

5.2 Atmospheric Disposal

5.2.1 Concept Description

This mode of disposal consists of dispersal to the upper atmosphere such as the stratosphere and lower altitudes attainable with the use of stacks. This method may be used to disperse solids at the upper altitudes; however, the solids return to the earth over a wide area. Otherwise, its principal utility is for disposal of gases and liquids that can be dispersed as vapors without condensation or serious washout for a considerable distance downwind.

There may be a useful middle ground between inexpensive stack dispersal with its limited isolation of radioactive waste from the biosphere and extraterrestrial disposal with its higher expense. Simple dispersal into the stratosphere or ionosphere might successfully achieve this goal. Although little or no material has been published on the latter idea, most of the required technology already exists.

The low-level waste in solid, liquid or gaseous forms could be carried by rocket to an appropriate height where the payload would be forcefully ejected into the rarefied atmosphere. A triggered explosive, for example, might accomplish the ejection. The resulting stratospheric cloud might be similar in shape to that from an atmospheric thermonuclear test.

The region where disposal by rocket would take place is considered to be the earth's rarefied atmosphere above the upper troposphere; i.e., at the begining of the stratosphere (about 10 km) or higher. Bennett has studied the behavior of tritium from the atmospheric thermonuclear tests that were made before the test ban.(15,16,17) The stratospheric residence time of the tritium was about 1 year, and hence the exchange between the Northern and Southern Hemispheres was limited although mixing was considerable within the Northern Hemisphere. The tritium activity that was detected in surface waters of North America disappeared with an apparent half-life of about 3 years (about one-fourth of tritium's natural radioactive half-life).

Rocket dispersal might have merit at a location such that the resultant radioactive cloud initially would pass over uninhabited areas before turbulent atmospheric mixing had become extensive. The choice of locale should be determined by demographic geography and long term meteorologic data bases. International politics would inevitably be involved because of uncontrolled movement of air masses over international boundaries. Differences in national criteria and standards of acceptability could cause conflicts between adjacent countries over which contaminated plumes pass. International agreement on acceptability of this mode of waste disposal would be difficult to obtain.

The "fallout" from rocket dispersal would be over thousands of square kilometers rather than tens of square kilometers as with stack dispersal. The larger dispersal would possibly allow the dispersal of larger amounts of radioactivity.

The design of a rocket specifically suited to this mission might be worth examining. Also, recovery of the rocket after use to affect a saving in cost might be possible. These matters are beyond part of the state of the art of rocketry.

In addition, related ideas such as the possible use of a high-altitude balloon deserve consideration. A conceptual design of a captive (recoverable) "hot-air" balloon with continuous dispersal is sketched in Figure 5.2. The dispersed waste could have greater loft by an order of magnitude than a stack could offer. This implies roughly two orders of magnitude less maximum exposure downwind at the ground level versus a stack for the same wind speed.(18)

Futher knowledge about fallout patterns would be needed if either rocket or balloon dispersal to the upper atmosphere were pursued. Considerable effort should be expended to find the location and conditions that would result in least exposure of the public to the fallout radioactivity. The problems of not exceeding established radioactivity concentration guides could be acute, because rocket dispersal takes place over a short period. Long term models of the interactions between the stratosphere and troposphere would have to be developed. The total development for the balloon concept might be more expensive than that of the rocket but the ultimate cost per kilowatt-hour could be less. Balloon usage obviously would require conformance with the Federal Aviation Administration requirements and might be restricted to certain areas of the country. Sufficiently reliable operations would require careful attention to meteorological conditions and ground operations. Even so, the operations probably would be allowed only in restricted areas of the country, as is the case with rocketry.

The use of a stack to dilute and disperse harmful materials has been used extensively since the advent of the Industrial Revolution. Stacks similarly were used in the Manhattan Project to reduce the exposure of the populace to radioactive off-gases. An increase in knowledge on the radiation effects on humans ensures the continued use of stacks in some capacity unless they are replaced as more effective techniques are implemented.(18)

In dispersing radioactive wastes to the atmosphere, the effects on the surrounding population as well as on water supplies, crops, cattle, and other pathways to man must be considered carefully. In addition to having some kind of exclusion area, there must be a constant regard for meteorology and climatic variabilities. For example, rain and snow would have to be

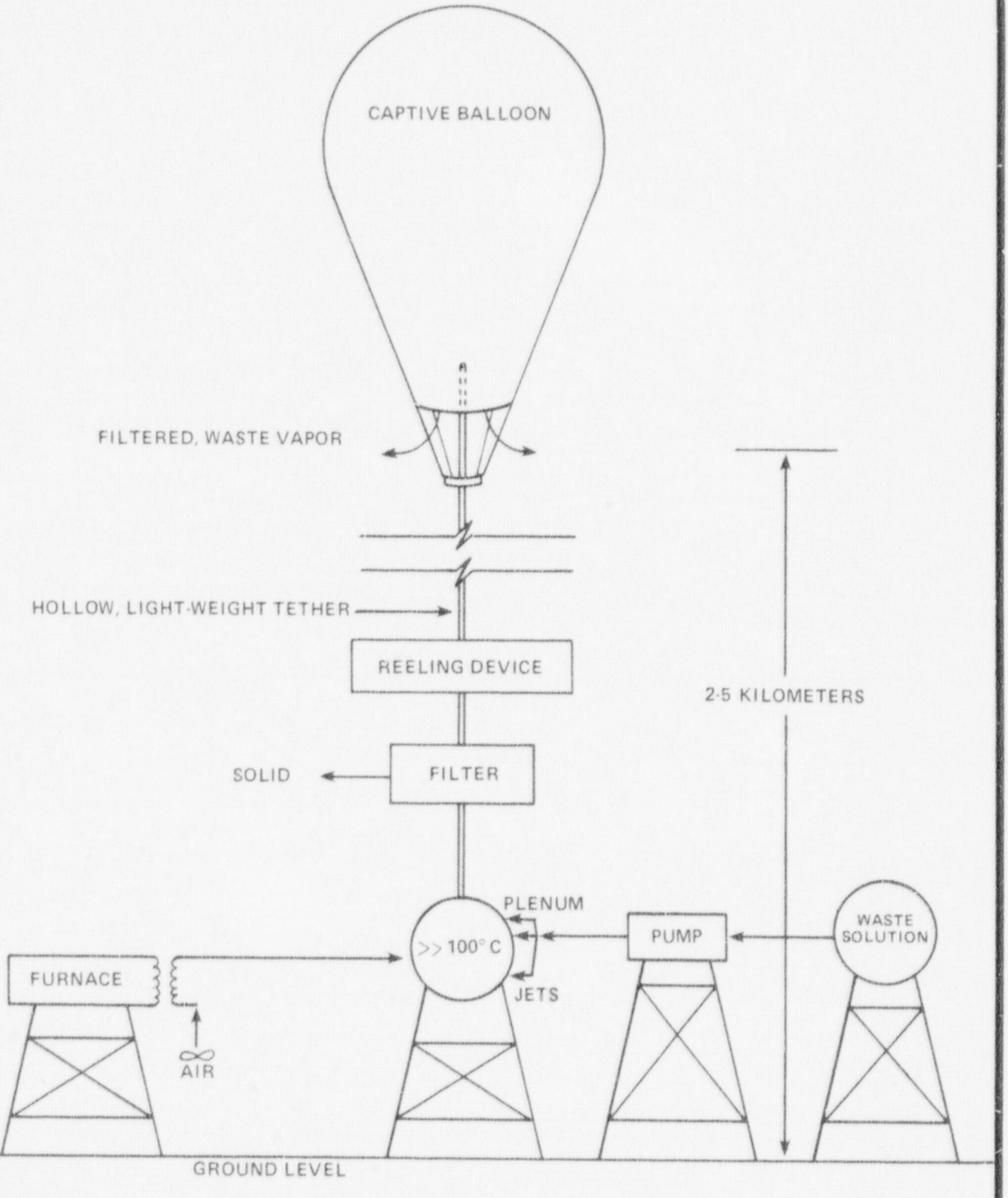


FIGURE 5·2. CONCEPT OF CONTINUOUS DISPERSAL BY BALLOON avoided for some distance downwind in order to forestall downwind scavaging.(19,20) The dispersion of radioactive waste as vapor to the atmosphere could be accomplished more readily and economically when there is a brisk wind and favorable diffusion parameters. Stack sitting, local terrain, and meteorology are of great importance,(21) but a general treatment of these is beyond the scope of this article.

5.2.2 Applicability of Atmospheric Disposal to Low-Level Waste

Although atmospheric dispersal is now practiced for discharges of controlled volumes and concentrations of airborne radioactivity from operating plant effluents, it is not considered viable for disposal of solid low-level wastes. Dilution and dispersion of the bulk of the low-level wastes is not considered to be environmentally sound by this method. The required volatilization of the wastes would be economically prohibitive. It is highly inefficient to collect the solid wastes, volatilize them, and then disperse them after expending effort to collect, concentrate, and minimize the volume of contaminated material. Disposal to the atmosphere is not consistent with present goals of the nation's waste management program.

5.3 Disposal to Waters

5.3.1 Concept Description

5.3.1.1 Discharge to Waters

Liquid radioactive effluents often are discharged directly into bodies of water if the levels of radioactivity are sufficiently low. Similar dispersive effect is expected to occur ultimately with packaged wastes dumped into water bodies although the packaging is expected to remain intact for some time after dumping. These concepts usually are applicable to solid or liquid wastes, but not the gaseous or airborne fractions without solidification.

Seas, rivers and lakes have been a disposal option for radioactive liquid effluents.(22,25,26) When radioactive effluents are discharged they are diluted until the concentrations of the constituents are within Federal limits and dispersed. Of importance also has been the concern that the radioactive constituents not return to man's environment due to reconcentration pathways which then may cause either external or internal radiation doses exceeding the recommended maximum permissible levels.

5.3.1.2 Ocean Dumping

Ocean dumping has been used for disposal of large volumes of low-level radioactive waste.(22) The United States carried out ocean disposal of radioactive wastes from numerous sources under AEC license and by AEC contractors between the years 1946 and 1970.(23) In November 1972, the United States signed the International Ocean Dumping Convention, formally called the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.(24) The Convention was ratified in April 1973, and became a treaty and was implemented August 30, 1975. The United States has not conducted ocean disposal since 1970.(23)

From 1946 to 1970 more than 86,000 containers with an estimated total activity of 94,673 curies were dumped by the United States. About 80,000 curies were dumped into the Atlantic Ocean and 15,000 curies into the Pacific Ocean.(23) Two of the major radioactive waste disposal sites in the Pacific are located near the Farallon Islands 66 km off San Francisco at 900- and 1700-m depths. The Atlantic site is approximately 192 km off the Maryland-Delaware coast at a 2,763-m depth. The EPA has surveyed these sites.(27) The surveys represent the first successful attempts actually to locate the drums of radioactive wastes, some of which have been in place for almost 30 years.

Similar operations were carried out by the United Kingdom in the Atlantic Ocean from 1951 through 1966, representing disposal of a total activity of approximately 40,000 curies.(28,29) Some other minor operations also may have been carried out during this period. Since 1967, surveys were completed by a number of European countries under international arrangements authorized by the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development.(12) A total of 45,970 metric tons (dumped weight) of packaged solid or solidified radioactive waste of relatively small radionuclide content (total approximate activity was 293,000 curies) were involved. These operations represented eight ocean-disposal campaigns from 1967 to 1976, all located in the northeastern Atlantic at an average depth of 5,000 m.(28)

5.3.2 Applicability to Low-Level Waste

5.3.2.1 Discharge to Waters

The nuclear power program produces substantial quantities of liquid effluents that are very dilute in radioactivity.(35,36) These low-level wastes often are disposed of in seas, lakes and rivers. The treatment of these wastes to concentrate the activity for storage is not always economically viable,(37) and dispersal into the environment under carefully controlled conditions, therefore, is practiced.(38) This disposal of effluents ultimately to the oceans (or lakes) is distinct from the concept of ocean disposal of solid low-level wastes, however. Dispersion of collected solid wastes into large volumes of water is not consistent with present waste management goals.

Dispersal to water under carefully monitored and legally regulated conditions is practiced routinely for operating plant effluents. Consequently, these systems are explained and documented in safety analysis and/or environmental reports for every nuclear power plant. To be applicable to solid low-level wastes, however, the collected wastes would be dispersed to the water body. Dispersal of the collected wastes is inefficient and is not an environmentally sound practice.

5.3.3.2 Ocean Dumping

The technical feasibility of the concept has been demonstrated. This disposal alternative has been applied directly to low-level wastes (the only radioactive wastes disposed of in this manner to date). The assumption underlying this form of disposal as currently practiced is eventual dilution and dispersion of the radioactivity in the marine environment. In practice, waste packages can be designed to remain intact for some time after dumping. The release of radioactivity from the waste and the possible consequences for man and the environment have been assessed resulting in limits on wastes to be dumped and of total site tonnage proposed by the International Atomic Energy Agency (IAEA).(24) The IAEA proposals also include specific recommendations for operational control of ocean dumping and include waste conditioning, site selection, and ship selection.

Technical development requirements include the development of models for oceanographic transport of radionuclides.(30) Fallout from weapons testing has contributed to the oceans' measurable amount of most of the nuclides of concern, and has offered the most general basis for modeling and subsequent prediction of nuclide behavior whenever released to the ocean environment.(31) Nuclide movement is complicated and difficult to model, particularly to describe certain short-term processes, and requires change in some of the simplistic assumptions of oceanic modelers. Thus, great care should be taken not only in the setting of any dumping limits but also to assure periodic review of the scientific basis of any computation.

The cost of sea dumping and the need to maintain doses as low as reasonably achievable, particularly for personnel carrying out the operation, may constitute obstacles to large-scale application of ocean disposal techniques. The bases for acceptable ocean disposal developed for a high-level waste feasibility study(32) may also be applicable to low-level wastes. The reasons to consider the oceans and seabeds for disposal include the size of the oceans, inaccessible areas, stable seabed areas, containment characteristics of sediments, and opportunity for international cooperation.

Ocean disposal generally is regarded as an expensive option. Representative cost figures are not easy to establish since they depend on many factors such as: type of ship used; port charges, which vary significantly; weather conditions, which may influence the duration of unloading at sea; insurance; and installation of costly navigational equipment. In 1975 the average cost of ocean disposal was about $30 per metric ton of packaged waste. This figure includes only the ocean shipping costs (hire of the vessel and port charges), insurance, navigation aids, and unloading at sea. Handling, loading, and ground transport costs are not included. Implementation of this concept will require construction of ships and loading ports. The high total cost for this option is one of the main reasons it has not been adopted on a wider scale in the United States and France.(28)

Under the Ocean Dumping Act of 1974 (P.L. 92-532), the EPA has regulatory responsibility over ocean disposal.(23) The EPA has instituted a domestic criteria and standards development program beginning with criteria as published in the Federal Registar of October 15, 1973 (Title 40, Chapter 1, September 11). These statements include a policy of placing in containers all radioactive wastes contemplated for disposal, and a requirement that the materials decay to environmentally innocuous levels within the lifetime of the container and/or its inert matrix. The purpose of the EPA's survey of ocean disposal sites was to develop more specific regulations and criteria based on pertinent measured data.

Internationally, the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matters covers all types of pollution.(24) The IAEA adopted specific recommendations for the application of the Convention to radioactive wastes in 1974. All nuclear waste-producing countries have not ratified the Convention, nor do they abide by NEA rules.(33) Therefore, uniform and effective regulation of radioactive waste disposal at sea is lacking both nationally and internationally, although a legal framework is available.(34) Low-level waste disposal at sea faces progressively more restrictive legal requirements. Containment as opposed to dilution and dispersal, and prior proof of safety as opposed to retroactive proof of harm or no harm to man or environment, are frequently receiving serious considerations as overall guidelines.(34) Radioactive waste disposal in oceans is also a politically sensitive practice. Packaging of the wastes for containment and use of the water as an isolation barrier is a feasible alternative warranting further evaluation.

5.4 Crustal Disposal

The several disposal techniques on or near the surface of the land encompass both dispersal and containment of radioactive wastes. Radioactive gases may be disposed of by containment methods. The popularity of "near the surface" techniques is partly due to their ready accessibility to man in emplacing the waste and in monitoring it. The first two alternatives in this category (mixing with soil, and discharge to subsurface ground waters) are dispersive.

5.4.1 Dispersal by Mixing into Soil and Leaching Ponds

5.4.1.1 Concept Description

The use of soil as a dispersive and diluting medium for radioactive wastes has been practiced widely in the past, ranging from the deep-plowing of solid surface contamination into the soil to disposal of contaminated liquids into leaching ponds or soil cribs,(39,40) although the use of this type of disposal mechanism has been officially discouraged,(41) it nevertheless is considered as a possible disposal option. Extensive use of this type of disposal technique presently continues in the uranium mining and milling industries.

The mixing of low levels of radioactivity with soil by direct mixing (plowing a contaminated surface layer to mix it with clean soil) or by discharge of liquid wastes to seepage ponds or soil cribs for leaching into the soil (where the radioactivity percolates or leaches into the soil lining or forming the pond or crib) provides a degree of isolation and localization of the wastes. Under properly controlled situations, direct human access to disposed wastes can be prohibited. Cribs (covered leaching ponds) for instance, isolate discharged liquid wastes from wildlife and human intrusion. Through the ion-exchange and sorptive properties of the soil in which the wastes are mixed, the radioactivity can be bound to allow for decay.

These disposal concepts entail the mixing of radioactive wastes with the upper layer (soil) of the exposed land surfaces of the earth. This soil layer of the earth's crust, the lithosphere, is the area most accessible to man's activities. The relatively shallow depths envisioned for these disposal concepts imply an accessibility of the disposed wastes to future intrusions. Because these concepts are dispersive (waste products are distributed through a relatively large volume of soil), with little effort initially expended to contain the wastes, site-specific ground water flow patterns, climatology, meteorology, and population distributions are important in evaluating the impacts from disposal.

5.4.1.2 Applicability to Low-Level Wastes

Much experience has been gained concerning retention of wastes in the ground. For instance, study of the 1.8-billion-year-old "fossil nuclear reactor" zones of the Oklo Mine in the Republic of Gabon shows that many of the elements produced by fission have been almost completely retained, as evidenced by proper budgets of stable daughter elements. Plutonium, ruthenium, the rare earth elements, zirconium, and palladium have been retained effectively while most sulfide-forming elements exhibit some degree of remobilization. The alkali and alkaline earth elements have migrated to varying degrees, but their presence in gangue affected by younger periods of alteration suggests redistribution not far removed from sites of formation. More important, such migration may not have started until some 25 million years after the reactor shut down. The noble gases, xenon and krypton, escaped with apparent ease during the 500,000 years the reactor was operative, and iodine seems to have been mobile. The Oklo reactor ores occur in shale infilled into a fracture system in organoargillaceous sandstone. Retention of so many of the fission-produced elements in this shale along with evidence that most others may have been only locally redistributed lend support to considering shales in geologically stable areas for radioactive waste disposal.(42)

Low-level liquid wastes have been discharged to leaching ponds at government-operated reactors for more than 25 years. Tailing ponds (impoundment basins) have been traditionally used in the uranium industry for the disposal of tailings (radioactive waste), which consist of a slurry of sand, slime, and liquid. All uranium ore concentrator plants in the United States(43) use the same method for disposal of tailings; i.e., the use of a tailings pond for containment of the solid waste. Liquid disposal is accomplished by natural evaporation and seepage from the pond.(44)

An evaluation of the use of sludge(45) containing plutonium (^{239}Pu) as a soil conditioner for food crops was made by Lawrence Livermore Laboratories in order to assess the possible adverse health implications associated with it. Sludge containing ^{239}Pu at a dry weight concentration of 2.8×10^{-6} µCi/g was used on a test garden. The average concentration of resuspended ^{239}Pu in the dust cloud was 2.4×10^{-8} µCi/g, and the average dry-weight concentration of the vegetables grown in the sludge-amended soil was 3.8×10^{-11} µCi/g. The maximum potential 50-year radiation doses associated with both the inhalation and ingestion were calculated. It was concluded that the hazard associated with the use of the sludge as a soil conditioner is not significant. Physical and chemical characteristics of the plutonium in existing contaminated soils and sediments have been studied by Tamura.(46)

Although use of mixing with soil has been safely performed in the past for some liquid wastes, these dispersive concepts are not appropriate for the bulk of solid low-level wastes. The wastes would have to be finely divided and dispersed into relatively large volumes of soil to ensure that resultant concentrations do not exceed acceptable values. Simple burial of the bulk wastes is more technically feasible.

5.4.2 Release to Aquifers (Perched, Watertable, and Connate)

5.4.2.1 Concept Description

Radioactive wastes discharged into subsurface aquifers generally are diluted and dispersed until the concentrations in the waste become too low to be of concern.

The basic method used for disposal of liquid wastes or effluents has been pressure or gravity injection into known aquifers through properly located and constructed injection wells. To ensure that no unacceptable migration of contaminants beyond established requirements occurs, monitor wells usually are located on the downgradient side to measure the migration rate and concentration from the injection wells. Additional monitor wells should be located upgradient and laterally as necessary to establish background values and injection impacts on natural groundwaters.

Information to be considered in selection of a suitable aquifer follows:(1)

(a) Dimensions of the aquifer zone

(b) Depth to the aquifer zone

(c) Composition of the aquifer zone (sediment/water)

(d) Hydrologic characteristics of the aquifer zone (determined by pumping or injection tests)

(e) Structural and seismic history of the area

(f) Evaluation of existing drill hole information

(g) Current and potential use of the aquifer for culinary irrigation and other human needs, and regulatory constraints and requirements

Aquifers in shales, mudstones, and claystones in areas of little or no structural deformation with low fracturing and seismic risk are most promising for this method.(47) Also, salt domes are considered good candidates for injection because of self-healing and appropriate fracture characteristics, but questions have been raised concerning tectonic stability, salt dissolution and long-term reliability.(48)

Prime areas of concern for the injection method of disposal are ground water and surface water contamination, tectonic subsidence, generating earthquake movement (e.g., U.S. Army disposal of gas at the site near Denver, Colorado, which caused magnitude 5.5 quakes in area), and mineral resource pollution.(49)

An aquifer is defined as "a geologic formation or structure that transmits water in sufficient quantity to supply pumping wells or springs".(50) Another definition states that "an aquifer is a lithologic unit (or combination of such units) which has an appreciably greater transmissibility than adjacent units and which stores and transmits water commonly recoverable in economically usable quantities".(51) Extending the definition further, the term also applies to water-bearing zones contained in shallow subsurface soil media and deep-seated connate (fossil) water zones which are capable of storing and/or transporting water.(52)

Movement of ground water is from areas of greater to areas of lesser hydrostatic head. Gravity is the prime moving force, but other forces such as natural gas pressure and fracture patterns contribute to the hydrostatic head. Movement of the water and storage capacity of an aquifer are controlled primarily by permeability and porosity. In addition, the occurrence, movement and storage of ground water in an aquifer, are influenced also by lithology, thickness, and structure of the rock formations or soil layers.(51)

Where a localized, saturated, permeable zone exists above the main water table (piezometric surface), the zone is called a perched aquifer or water table. Perched zones are created when a permeable layer existing above the main water table is underlain by an impervious formation such as a shale, mud, silt, or claystone which prevents or reduces downward migration of ground water. Perched or isolated aquifers also are created when a confined bed is horizontally pinched-off stratigraphically or by geologic structure (fault, joint, or fold) interference.

There is a need for comprehensive hydrologic studies in order to establish firmly the viability of using aquifers as potential disposal zones for low-level radioactive wastes. Obviously, the overall homogeneity, isotropy, and nature of laminar flow must be well understood so that the best disposal methods can be developed. Several areas of the United States have quite complete information on ground water conditions. Other areas have either sporadic data bases, or none.

5.4.2.2 Applicability to Low-Level Wastes

The injection concept for low-level radioactive waste disposal has been utilized in several cases. Technology was initially developed in the petroleum and water well drilling industries. Considerable data are available as to aquifer definition, injection rates and pressures, well construction, maintenance, longevity, and costs.(53-57) Some data also are available pertaining to impact of injected low-level waste effluents on the ground water regime, especially in aquifer zones where sufficient monitor wells exist.(52,58) Although there has been much work on this aspect, the current state of the knowledge is not entirely adequate.(49) Costs are estimated to range between \$5 and \$80/m^3 of liquids injected, exclusive of costs for well placement and transport to the disposal site.

It appears that injection into deep-seated aquifers or permeable zones where connate waters may exist may be a practical solution for large quantities of tritium-bearing water from reactors and fuel processing plants, but additional research is needed to determine safe and effective application.(59)

Adequate, proven techniques exist to establish aquifer conditions and estimate ground water flows and velocities,(5,14-16) but these techniques need to be fortified by more refined modeling techniques. However, even if a sufficient amount of information were available, a well-designed injection and monitor system must be employed to ensure adequate evaluation of contaminant migration or of excessive buildup in concentration. State and federal regulations either exist(17-19) or are being formulated for protection of subsurface waters. The Safe Drinking Water Act of 1974 and subsequent regulations covering disposal by injection specifically require complete evaluation of all hydrologic and ground water quality conditions of all liquid waste injection programs prior to, during, and after operation.

In summary, the basic injection technology exists for evaluation of the concept, but formulation of stringent regulations will require extensive background and impact monitoring studies to ensure that implementation on a macroscale would result in minimal adverse environmental impact. Restoration of the ground water quality must be accounted for, should monitoring data indicate or prove excessive radioactive levels. Associated costs to develop adequate restorative techniques could prove economically unfeasible. Nevertheless, the general injection concept is feasible for liquid effluents and the liquid fractions of low-level waste. However, for the bulk of the low-level wastes, which are solid, the necessary liquification and dispersive nature of the disposal concept make injection unfeasible.

5.4.3 Land Disposal

5.4.3.1 Concept Description

Land disposal or "burial" as used in this section refers to the placement of waste at relatively shallow depths in earth materials, with no intended provision for ready retrievability at a later date. Low- and intermediate-level solid radioactive wastes have been disposed in burial grounds for over three decades during which dozens of reports, symposia, and even textbooks describing the practice have been published.(5,65-67) Burial at deeper or intermediate depths (up to 15 or 20 m deep) is a possible variation or alternative to shallow land burial.

Shallow land disposal has been used since the inception of the nuclear weapons research program in the 1940's. Initially, only AEC laboratories and contractor facilities handled and disposed of radioactive waste. Burial grounds were operated at each facility for the disposal of waste generated by weapons development and other nuclear research programs. Radioactive wastes generated by private industry were initially disposed of at the AEC-operated burial grounds.

In 1962 the first commercial burial facility was opened in Beatty, Nevada. This burial ground, licensed by the regulatory branch of the AEC, provided an alternative to both sea disposal and the AEC facilities. A similar site was opened shortly thereafter in Morehead, Kentucky. In May 1963 the AEC discontinued its policy of accepting radioactive wastes from private industry. In the following years additional commercial sites were opened in other states, and by 1971 six commercial burial grounds were licensed for handling and disposal of radioactive waste.

Disposal operations are similar to conventional sanitary landfill operations, with the additional handling precautions requisite to radioactive materials. Burial in open, unlined trenches is the common practice, with each trench containing a mixture of radionuclides and waste forms. Water is the principal medium by which the radioactive materials can migrate from the burial trench, either by dissolution in subsurface water, or by erosive processes. Thus, site investigation and selection procedures involve extensive studies of the hydrogeology of prospective sites. Similarly, efforts are made to exclude water from the waste following burial. Less than half of the existing burial sites have detected the movement of radioactive materials away from the buried waste and none of these releases has posed any hazard to the public health.

Open trenches are used at all sites as the primary burial facility. Generally trench design is similar in all facilities, ranging in physical dimensions from 60 to 260 m long, 4 to 20 m wide at ground surface, and 3 to 8 m deep. At some sites large pits are used for the disposal of large bulk items. Wastes routinely are covered daily for two reasons. One is to limit the contact of precipitation with the waste, and the other is to minimize the risk from fire.

Techniques to cover and seal waste in trenches vary with the local climate, soil, and ground water conditions. Up to 3 m of soil is mounded and graded over the top of the waste. At some sites special impermeable soils such as clay are used in constructing the cover. A vegetative cover usually is established over completed trenches and pits to control surface erosion.

All burial ground sites have special handling and burial procedures for high-activity beta-gamma wastes. Because of the radiation problem, such wastes are generally not buried in the same trench or pit as bulk low-level wastes. A majority of the sites use dry wells for the high-activity waste, which generally is contained in small volumes.

Permanent trench markers are required within 1 year of the closing of the trench. These consist of concrete posts located either at the ends of the trenches or corners of pits. Information contained on the markers include the trench number, date opened, date closed, survey data on trench location, and summary data on the wastes contained.

Commercial burial grounds have been located on the basis of regional requirements for waste disposal facilities. Site selection has involved the survey of several prospective sites, with the final decision based on hydrogeological and economic factors. Costs for commercial waste disposal range from \$100 to \$200/m^3 of low-level waste buried.

The single most important factor affecting the containment capability of a burial ground is the degree to which ground and surface water can contact the waste and subsequently cause migration of the radionuclides. As a result, a hydrologic assessment is required as a portion of the licensing procedure for each site. In effect, these studies provide: an estimate, prior to the use of the burial ground, of the degree to which ground and surface water will contact the waste following burial; the pathways of the water away from the burial site; the ion-exchange or adsorptive capability of the materials along the path; and the extent to which the radionuclide content of off-site ground and surface waters will be affected by the burial grounds. Solid waste burial usually is located at shallow depths, in the transition zone between surface soil materials and subsurface geology. This zone has not received much geologic study, and the uncertainties related to hydraulic subsurface conditions, such as pertinent water velocities, gradients, and permeabilities, within a given burial ground reflect this lack of attention.

Descriptions of the existing burial grounds have been reported many places in the literature.(5,65-67) The alternatives involving improving present burial practices and deeper depth burial warrant further evaluation to compliment the base case disposal method of shallow land burial.

The most commonly used disposal alternative for low-level radioactive wastes in this country currently is shallow land burial. However, there are many potential problems associated with placement of wastes only a few feet under the ground surface, including possible land reclamation, ground water leaching and transport, and surface erosion scenarios. These types of problems could largely be avoided in a properly designed deeper land burial incorporating a final covering of 10 to 20 m of clean soil over the waste burial trenches. The deeper covering would make any inadvertent or unintentional encounters with the buried waste quite unlikely, would reduce the amount of percolating water available to infiltrate the waste, and would increase the time required for erosion to expose the wastes long enough to allow decay to greatly reduce the residual activity.

Deeper land burial would provide these additional containment advantages over shallow land burial with minimal adverse penalties. There would be a slight increase in time that workers would be exposed to earth moving hazards, and slightly more dust. However, there would be the possibility of productively reclaiming old strip mines or other poor terrain by the use of additional depths of cover. The cost increases for deeper burial are expected to be only a small fraction of the total disposal costs. Future surveillance and maintenance costs would probably be reduced in comparison to shallow land burial. These factors justify further investigations and analysis of this type of alternatives for low-level radioactive waste disposal.

5.4.3.2 Applicability to Low-Level Waste

Shallow land burial is currently the most widely practiced low-level waste disposal option in this country. Although some relatively small releases of activity have been detected at some waste burial sites, no unacceptably high radiation exposures have resulted. With proper design and institutional controls, shallow land burial can be expected to provide adequate waste confinement to be be considered an acceptable waste disposal method. Improvements to current shallow land burial practices and deeper burial at the 10 to 15 m depth are also viable waste disposal alternatives deserving further evaluation.

Burial trenches are or could be designed to contain critical nuclides for several hundred years.(68) This design can be accomplished through numerous engineering features and utilization of some of the physical aspects of wastes and burial sites. Site selection criteria could be imposed and detailed studies undertaken to identify potential locations for new burial grounds. It is conceivable that a thorough and systematic search will produce areas of the country that possess all of the suitable qualifications necessary to allow the continued use of shallow land burial. Improvements to present practices, such as better trench capping, deeper burial, or waste conditioning, for disposal of low-level wastes are viable alternatives.

After a site selection and suitability study has been performed and a site selected, there are many engineering modifications which possibly could enhance the suitability of the site and provide additional factors of safety. Site drainage and water sealing improvements, trench layout and filling optimization, and possibly structural covers during operations are examples of factors that could improve performance. Similarly, an aggressive program to improve the conditioning of the waste before disposal by incineration or encapsulation, for instance, can provide an additional margin of safety if it were shown to be necessary.

Both shallow land burial as it is now practiced, and engineered improvements to shallow land burial are considered to be viable alternatives warranting further evaluation.

5.4.4 Disposal in Geologic Formations

5.4.4.1 Disposal in Cavities or Drilled Holes

5.4.4.1.1 Concept Description

Disposal of radioactive waste in geologic formations has the potential of isolating the waste from man's environment for millions of years. Geologic environments exist which have been physically and chemically stable for millions of years, are isolated from man's environment, and have the potential to provide effective barriers between the waste and man's environment for the time periods required.

The basic requirement for any geologic environment to be suitable for disposal of radioactive waste is the capability to isolate safely the emplaced radioactive material until decay has reduced the radioactivity to nonhazardous levels. The geologic environment should: be adequately far removed from man's environment, not permit waste transport readily, remain relatively stable over geologic time periods, and adequately contain a highly immobile waste form. Relative to other terrestrial locations, a large amount of information is available on the geology of the United States.

A geologic formation can be penetrated and altered in several ways to provide a repository for low-level radioactive wastes. It is assumed that geologic disposal alternatives are directed toward the management of these low-level wastes, including the long-lived radionuclides, without preconditioning or partitioning. This survey considers the use of drilling, mining (mechanical and dissolution), and exploded cavity. Many combinations of potential environments and methods of penetration, along with methods for placement of waste within these systems, were surveyed in an attempt to cover the broad range of potential possibilities. Most geologic disposal concepts will require basically the same waste management steps; that is, the solid waste must be transported to the disposal site; following site preparation, the waste is emplaced in the disposal site, and the disposal site is sealed from man's environment.

While the primary purpose of this survey is to identify alternative methods of disposing of low-level solid radioactive wastes, several of the geologic alternatives are suited for disposal of either liquid or gaseous wastes. Bulk liquid or gaseous waste would be emplaced directly into the geologic formation, and the disposal site would be sealed from man's environment and monitored.

Two primary disposal geometries for disposal of low-level solid radioactive wastes in geologic formations were examined in this survey. These geometries are cavities and drilled holes. Several means for forming cavities exist and are examined separately for their suitability. The depth of the drilled hole also has a bearing on the disposal technique and therefore is examined briefly.

The first geologic disposal concept is based on the placement of waste packages in cavities formed by nature or by conventional mining techniques, the second considers cavities created by explosive devices, and the third considers the drilled holes with all operations being performed from the surface. There can be a combination of concepts; e.g., shallow drilled holes in the floors of cavities could be utilized for those wastes that might require a degree of shielding.

The mined cavity concept employs rooms or tunnels that have been excavated in the geologic formation. This generic concept includes the bedded-salt complex that presently is being studied by the Department of Energy as a repository for long-lived solid radioactive wastes.(69) Excavation and shaft costs range from \$25 to \$50/m^3 of space for existing or new mines respectively. The exploded cavity concept would utilize an unlined, rubble-filled cavity formed by either a nuclear or conventional explosive. The cavity size would be determined by the size of the explosive device and type of geologic formation. (The explosive device could be designed to provide an elongated cavity with a vertical axis.) After creation of the cavity it would be connected to a surface facility by two sealed and cased holes. One hole would contain monitoring instrumentation while the other hole would be used to lower waste packages. If nuclear explosives were used, the waste packages would have to be automatically unhooked since this concept would not allow man to enter the cavity because of high induced radioactivity. Once the cavity is filled with waste, the cavity could be backfilled. Cavity-forming techniques using nuclear devices were established in the Plowshare project.

The drilled hole concept employs established drilling techniques. The method of placing wastes in appropriate geologic formations is based on lowering waste packages into an array of holes drilled into the formation from the land surface. As with the exploded cavity concept, the primary feature of the drilled hole concept is that all operations are conducted from the surface. Salt domes, argillaceous, intrusive igneous, and metamorphic formations are other examples of geologic candidates for the drilled hole concept. The concept is currently envisioned as being appropriate for depths ranging from about 50 to 1000 m. Drill equipment capable of drilling holes 3 m in diameter, 1700 m deep exist. Surface facilities consist of a handling facility (waste container unloading and temporary storage space), drill rig, and charging vehicle. A sealant and/or backfill can be added after a hole has received a specified amount.

Provided that a geologic candidate with an absence of moisture is found, the drilled hole concept provides a significant degree of isolation. Many such areas exist in the conterminous United States. Provided that the holes can be satisfactorily sealed, this technique by reason of the distance of the waste beneath the surface would provide greater protection from percolating waters than is provided by the shallow land burial technique.

The Special Projects Branch of the U.S. Geological Survey has performed a study for the AEC specifically to evaluate geologic formations.(70) In addition to the general geohydrologic considerations summarized here, the USGS briefly evaluated and identified the U.S. geohydrologic environments that they consider as possibly suitable for the various geologic disposal concepts.

Of the various geohydrologic factors that must be considered in the selection of optimum waste disposal sites, the most important is hydrologic isolation to assure that the wastes will be contained safely within a small radius of the emplacement zone. To achieve this degree of hydrologic isolation, the host rock for the wastes must have very low permeability and the site must be virtually free of faults. In addition, the locality should be:

(a) In an area of low seismic risk where the possibility of large earthquakes rupturing the emplacement zone is very low

(b) Where the possibility of flooding during the period that the wastes remain hazardous is very low

(c) Where a possible return of glacial or pluvial climate will not cause potentially hazardous changes in surface or ground water regimens during the period that the wastes remain hazardous

(d) Where danger of exhumation by erosion is nil

The geographic location for an optimum site has low population density, is far removed from major drainages, lakes and ocean, and has gentle topographic relief in order to avoid steep surface water drainage gradients that would allow rapid distribution of contaminants in case of accident.

The most suitable media for the drilled hole and exploded cavity concepts appear to be crystalline rocks, either intrusive igneous or metamorphic, because of their potentially low permeabilities and high mechanical strengths. Salt (either in thick beds or stable domes), tuff, and possibly shale appear to be suitable for mined chambers and cavities with manmade access structures. Salt appears to be suitable because of its very low permeability, high thermal conductivity, and natural plasticity. Tuff and shale appear suitable because of their very low permeabilities and high ion-exchange capacities. Sedimentary rocks other than shale and volcanic rocks, exclusive of tuff, are generally unsuitable for waste emplacement because of their potentially high permeabilities.

Areas considered to be unsuitable for waste disposal are those where seismic risk is high, where possible sea level rise would inundate potential sites while the wastes remain hazardous, where high topographic relief coincides with high frequency of faults, where there are unfavorable ground water conditions, and where no suitable rocks are known to be present to depths of a few thousand meters, and where these strata contain either large volumes of ground water or have high oil and gas potential.

Geohydrologic environments that are concluded to be potentially suitable for waste disposal should be further evaluated to pinpoint the most suitable locations. The localities should then be: mapped in detail and seismically monitored to delineate active fault zones and areas of crustal unrest, surveyed by geophysical techniques (where applicable) to locate buried faults and to define accurately the subsurface conditions, and drilled and hydraulically tested to locate the zones having the lowest permeabilities. Finally, the drill core should be analyzed physically and chemically in order to predict the nature of the rock-waste interaction.

All the geologic waste disposal concepts considered in this survey involve emplacing waste in the earth's crust or shell of the earth. The crust of the earth ranges in thickness from about 5 km in some places under the ocean to more than 50 km under high mountain ranges, such as the Sierra Nevada. These thicknesses are obviously adequate for disposal of low-level radioactive wastes.

5.4.4.1.2 Applicability to Low-Level Waste

All wastes are expected to be conditioned before packaging for geologic disposal. The volume of waste should be reduced because of the relatively high cost per unit volume of space within geologic formations. Only slight but obvious variations in waste handling techniques exist for the three concepts of geologic disposal considered in this survey. All three would require a surface facility to unload and temporarily store the waste. Appropriate equipment would be required to lower the waste packages into the cavity or hole.

The engineering ability exists to place any one of these concepts into operation. The technical feasibility rests with the answer to the following question: Can the concept provide the potential for confining or eliminating the waste over the time period of concern? Studies to date indicate that technology permitting the emplacement of solid, liquid or gaseous waste either is, or can be, established and that candidate formations exist in geologic environments which have the potential to provide confinement for the time periods necessary to allow decay to reduce the radioactivity in low-level wastes to harmless levels. No significant breakthroughs in technology are required for concept design and no uncommon construction mining, or operational problems are anticipated.

Although all concepts of geologic disposal were found to be technically feasible, they all have research and development needs, especially in the evaluation of events that would impair confinement integrity. Substantial experimental and evaluative efforts are currently under way concerning the development of a mined cavity repository in bedded salt. There has been much less effort associated with other potential geological environments, and considerably less is known about their suitability for waste disposal.

Public reaction to the fact that the waste is isolated from man's environment by meters of "rock" could be favorable. On the other hand, the concern for the ability to maintain containment for long periods of time, especially in case of a major geologic event, will always be present.

The alternatives classified under geologic disposal concepts are compatible with existing federal policies and programs. In fact, these alternatives are being complemented under the Planned program for the management of federally-generated transuranic and high-level radioactive wastes.

5.4.4.2 Disposal in Hydrofractured Geologic Strata

5.4.4.2.1 Concept Description

Hydrofracturing involves fracturing geologic media around a borehole in order to dispose of wastes or stimulate gas and oil production. The technology is available as a commercial service (Hydrafrac). It has been used in at least 100,000 wells mostly for stimulation of gas and oil production, but sometimes for waste disposal instead. Typically, the technique of disposal has three stages:

(a) A viscous fluid containing a gelling agent and a propping agent such as silica sand is pumped under pressure into the well until it fractures the chosen geologic region.

(b) A fluid containing a gel-breaking agent is pumped in and the fluids are then drained out, leaving behind the propping agent to keep the fractures open.

(c) The waste fluid containing grouting agents such as cement and diatomaceous earth is pumped into the fracture. The grouting agents subsequently harden leaving the wastes fixed in the fractured geologic structure.

The study of hydrofracture for the disposal of intermediate-level radioactive waste began in 1959 at ORNL at which it has become a routine operation.(21,71-74) Their waste solutions have contained up to 0.5 Ci/l, thus necessitating the concrete shielding of the hydrofracture plant. However, low-level liquid wastes, particularly those dominated by tritium activity, would require much less shielding. The solutions from the ORNL are conveyed to the site by means of a pipeline.

The injection has been made into more or less horizontal layers of impermeable geologic strata, such as the argillaceous shale at ORNL.(21,74) A single well has been used there with injections into the shale at depths of 200 to 300 m, well below the level of the aquifer. Site-proof studies must be made before a site can be further considered for this technique. Such studies have been completed for a second injection well at ORNL(75) as well as an initial one at West Valley, New York. Permissible depths of injection depend upon the specific geology, but cannot be made safely beyond certain depths because of increasing danger of vertical fractures and loss of radioactivity toward the aquifers and the ground level. Desirable depths have generally been envisaged to be in the range of 150 to 500 m.(73) At ORNL there is thought to be no danger of vertical fracture for depths less than 760 m, the pumping pressure usually being in the range of 100-170 bars.(21) Costs were estimated in 1970 to range between \$50 and \$90/m^3 of liquid wastes injected.(21,72)

The set grout is monolithic but rather porous. Hence the need for impermeability of the employed strata is particularly desirable when the principal hazards of the radioactive waste are from nuclides that migrate with water.

5.4.4.2.2 Applicability to Low-Level Wastes

The principal uncertainties in applying this alternative appear to be in the following areas:

(1) It has been estimated that 30-35% of the continental United States is underlaid by shale that may be

suitable for disposal by hydrofracture. However, comparatively few areas may have adequate thickness of shale to contain large volumes of low-level waste or to be otherwise suitable.(47) The disposal technique requires areas where containment will be ensured, requiring appropriate thicknesses and lateral extents or continuous shale, with proper plastic deformation characteristics.

(2) It is difficult to predict beforehand how much waste can be disposed of by hydrofracture per square mile of land. However, the facility at ORNL disposed of a total of 1,860,000 liters for the years 1972 and 1975.(73)

(3) There is a chance that the hydraulic fracturing will stimulate seismic activity which would open up pathways to man's environment. The latter has been observed in the petroleum industry. However, it is believed that this can be entirely avoided in the injection of radioactive waste by proper site selection and injection techniques.(76) Seismic activity should be covered in the routine environmental impact statement along with the usual considerations.

(4) The production of vertical fractures is common in crystalline rock and the petroleum industry. Vertical fracturing obviously could be harmful in radioactive waste disposal. This danger is considered to be readily avoidable because of the natural proclivity of horizontal shale to fracture horizontally as well as the use of the aforementioned proper ranges of depth and pumping pressure.

(5) The issuance of the recent environmental impact statement for ORNL(77) and the several years of safe operation of that organization's facility should bolster public acceptance of the technique. This concept would require liquefaction of the bulk of the solid low-level wastes, however, and will not provide definite containment. Therefore, this concept is not a viable alternative for solid low-level wastes.

(6) This concept would require extensive surface handling facilities for liquefaction of the solid waste and injection. The requirement for these facilities could limit the utility of this concept.

5.4.4.3 Seabed Disposal

Various seabed areas appear to have the potential for long-term isolation. These areas include subduction zones (deep-sea trenches), stable deep-sea floor areas, and areas with relatively high sedimentation rates. In all cases, the waste packages would be emplaced in the basement rock below the sediments to ensure isolation of the radioactivity from man's environment and to take advantage of the high ion-exchange capacity of the sediments as backup protection.

This disposal concept consists of the collection of previously conditioned and packaged waste at specialized embarkation ports, transport by suitable ships to the seabed site, and waste emplacement at the site from either a drilling ship or a semi-submersible drilling platform. Disposal is accomplished by the emplacement within the basement rock or sediment, and isolation is maintained by natural behavior within oceanic crustal layers after sealing of the emplacement drill holes; or in one concept, isolation is ensured by further natural burial as a result of the geologic nature of the site.

5.4.4.3.1 Concept Description

The three concepts studied for high-level radioactive wastes technically are suited equally for the disposal of low-level and intermediate-level wastes.(13,78) These concepts are categorized according to the type of seabed area as discussed below and depicted in Figure 5.3.

Deep-sea trenches, most of which are now considered to be subduction zones, occur at the margins of certain oceanic plates. Depths of water in these areas are 7 to 10 km. In this concept, the waste canisters would be transported by ship and placed in previously drilled holes in the zones where seabed material is being subducted by the under-thrusting of oceanic plates under other continental plates. After a hole is filled to the desired level with waste canisters, the top of the hole would be sealed by cementing it closed. The hole in the sedimentary layer would be closed by backfilling with sediments or other sealants. This concept could provide permanent disposal of waste by transport into the lower crustal zone of the earth. Calculations indicate that with a subduction zone 10 km wide, the time required for earth plate subduction of the wastes into the earth's lower crust could take from 1 to 10 million years. In the meantime, isolation would depend largely on the sealant and the slow sedimentation rate above the waste canisters.

For disposal in stable deep-sea floors, waste packages would be emplaced in previously drilled holes in abyssal plain areas. Abyssal plains are considered to be relatively stable areas in the framework of geologic time. They are nearly featureless areas, built of continental margin sediments carried into the basin areas by turbidity currents. These sediments bury the pre-existing topography under large quantities of coarse material. The drill holes would be sealed as described previously. Depths of water in the abyssal plain areas are 4 to 6 km;

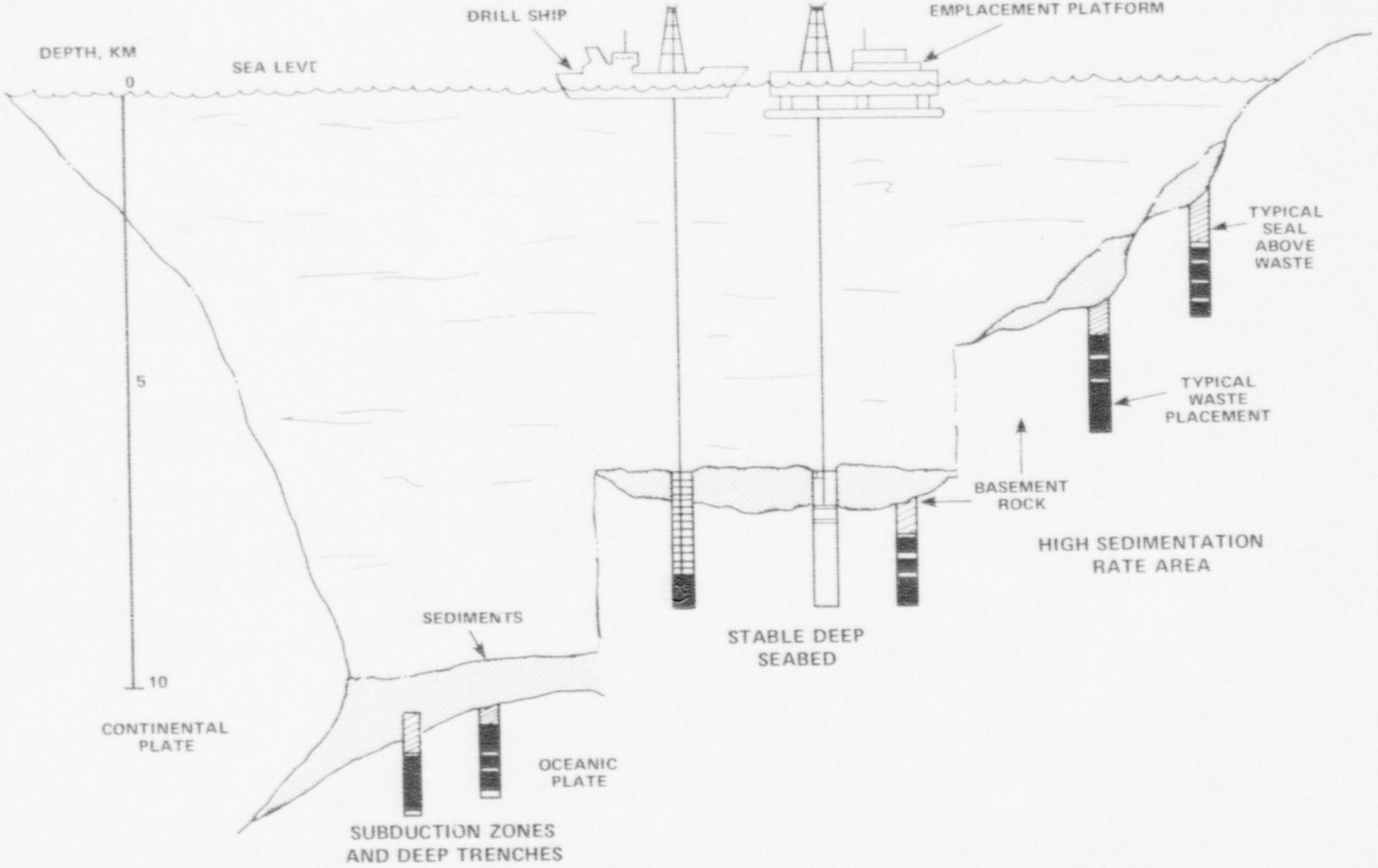


FIGURE 5-3. CONCEPTS FOR DISPOSAL OF RADIOACTIVE WASTE IN THE SEABED

sediment thickness averages 0.5 km in the Pacific Ocean and about 0.5 to 2 km in the abyssal plains of the Atlantic Ocean. The sediments are generally more consolidated than in trench areas.

Other important stable deep-sea floor areas are the geologically stable centers of the ocean basins. The depth of water is about 6 km and the sedimentary cover is thin and firm. Currents are thought to be slow and biological activity low. The deep ocean basins also offer the advantage of being generally far from land. Stable deep-sea floor areas are some of the most geologically inactive areas in the world.

The concept for disposal in high-sedimentation-rate areas takes advantage of relatively rapid natural burial. These areas usually occur in deltaic settings at the mouths of major rivers such as the Mississippi, Amazon, Ganges and Indus.

Other potential sites for disposal, also connected with major rivers, are the fans or cones of sediments found farther off shore in deeper water. These cones of sediment are found at the foot of the continental slopes at depths of 2 to 4 km. Details of this part of the seabed are unknown, but sediments are estimated to be 1 to 5 km in thickness.

The term "seabed" is considered to mean the dense basement rock surface of the earth's crust which forms the ocean basin, usually overlaid by unconsolidated sediments. The seabed, however, may be directly in contact with the ocean water. The sea floor, or ocean bottom, can be divided into three principal provinces: continental margins, ocean basin floors, and mid-oceanic ridge.

The continental margin consists of the continental shelf, inland seas, margin plateaus, continental slope, landward slope of trenches, and the continental rise. These make up the most dynamic part of the ocean where the range of seasonal water temperature changes is the greatest, chemical and biological processes are most active, and geology is complex. Surface material of the continental margins may vary from rock to gravel to clay within distances of a few kilometers.

The ocean basin floors contain the abyssal plains, abyssal hills, oceanic rises, and trenches. These floors comprise nearly 30% of the earth's surface and contain the deepest parts of the ocean areas, from 4.5 to 11 km in depth. Deep trenches, 7 to 11 km, occur in parts of the ocean basin floors, frequently forming the landward boundary of the abyssal hills or occurring seaward of some continental slopes. Most of these trenches are considered to be zones of subduction where oceanic crust is destroyed; i.e. where oceanic crust is being overridden by continental crust. Associated with the trenches usually on the landward side are arcuate groups of islands and volcanos, known as island arcs. Earthquakes occur frequently in these trench areas, triggering submarine slides and promoting volcanic activity.

The mid-oceanic ridge is a sea floor spreading center, about 40,000 km long, that nearly circles the earth. A seismicly active rift valley, 2 to 3 km deep, is located in the center of this ridge. From this rift valley new crustal material is constantly being extruded and moved symmetrically to both sides. This ridge represents the youngest part of the ocean.

5.4.4.3.2 Applicability to Low-Level Waste

All low- and intermediate-level solid wastes are expected to be conditioned before they are packaged for seabed disposal. All wastes must be subjected to volume reduction and, where appropriate, chemically separated. Following conditioning and packaging, waste containers would be stored until a full shipload could be accumulated, then transported to the disposal area, and finally emplaced in the seabed.

If the stability of the seabed can be verified, safe containment of waste forms for periods on the order of 1 million years or more is possible. Therefore, separation of actinides or long-lived fission products may not be required. However, costs inherent in the system concerning the transportation, logistics, and operations at the potential disposal site may suggest some separation of waste products. Cost estimates for seabed disposal of high-level wastes are about \$200,000/m^3 of waste implanted.(13) The actinides and long-lived fission products should be consigned to disposal systems that have a high potential for safe long-term containment. Costs for emplacement of low-level wastes would be lower because of lesser shielding and handling requirements.

Actual site preparation would begin after evaluation and final selection of the disposal site were accomplished. Site preparation would require precise positioning on a repetitive basis. The drilling ship or semisubmersible drilling platform would be on location for several months and possibly for as long as 3 years before disposal operations could begin. The drilling platform would be positioned, supplied, equipped, and rigged for drilling. Markers or sonar beacons used on the sea floor would be put in place and tested. Holes would be drilled ahead of the disposal operations, and funnels would be installed above drill holes for re-entry as would riser or conductor pipes through the unconsolidated sediments.

Transportation from the waste-generating facility to the disposal site would be accomplished in two stages. The first stage would consist of transport by truck, rail or possibly barge to port of embarkation. Waste packages would be carried in specially constructed transport casks. At the port of embarkation the packages would be removed and stored temporarily before shipping to the disposal site. The second stage of transport would be by special ship from the embarkation port to the disposal site. At the disposal site, transfer would be made to the drilling/emplacement ship or semisubmersible platform by positive handling after "firm" docking. The transport ship could travel an 11,000 km round trip in about 25 days. With allowance for such factors as loading, unloading, fueling, bad weather, and maintenance, a net average trip of 90 days is believed to be reasonable.

Once the waste package is approved for disposal, the package would be emplaced using one of the several techniques. For example, the cask containing the waste package could be positioned over the drill hole and opened at the bottom, allowing the package to fall through the drill pipe; or it could be lowered on a wire line. Alternative methods of emplacements not involving drilled holes are guided-fall along anchored cables, free-fall from a cable at a predetermined depth, and free-fall from the transport ship or emplacement barge. These methods all would require waste containers specifically designed to obtain maximum penetration of the sediment on the sea floor.

Waste disposal in the seabed environment in general offers potentially favorable features such as:

(a) Relative remoteness and isolation from man's environment

(b) High ion-exchange capacities of seabed sediments as backup protection

Unfavorable general features or unknowns concerning seabed disposal are:

(a) Difficulty in monitoring and retrieval

(b) Extended sea transport

(c) Possible mobility of seawater, saturated sediments, sediment porewater, and uncertainty of sediment interactions with waste or waste packages possibly leading to indefinite containment

(d) Possible concentration of waste by biological mechanisms

(e) Relatively slow rates of sedimentation and movement of crustal plates

Primary problem areas presently recognized in the feasibility of seabed disposal are stability and isolation with respect to the human environment, maximum drilling depth, means of emplacement, rate of burial or disposal by natural sedimentation, and high costs associated with underwater activities. Rates of natural sedimentation are unfavorably slow. Some means of emplacement other than merely lowering the waste packages to the seabed seems desirable to assure isolation of the waste from man's environment.

Deep trenches and subduction zones frequently are associated with earthquake activity that could cause submarine landslides and slumping, and conceivably could destroy shallow placement sites. However, it also has been suggested that earthquake activity could loosen consolidated sediments enough that waste containers would sink through them into deeper sediments.

The disposal of radioactive waste in the seabed can be considered technically feasible, subject to certain limitations. The limitations are due mainly to lack of definite knowledge of the seabed and of the geologic and biological processes at work in the oceans, particularly at great depths. For example, the existance of subduction zones has not been fully demonstrated specifically for the three seabed waste disposal concepts; deep ocean trenches are relatively unstable areas and would require more investigation into the nature and thickness of the sediments; and high-sedimentation rate deltaic areas, which are subject to various high-rate geologic processes, may make them unstable over relatively short geologic periods of time.

The present state of knowledge of seabed conditions and materials is inadequate and would need considerable research of the type being done in the Deep Sea Drilling Project. Research and Development needs primarily concern the properties of the sea and seabed and those concerning drilling and emplacement equipment. Overall time requirements are estimated to be 25 to 30 years. Modern drilling equipment would need some additional development, design, and modification to be capable of the emplacement operations considered here, but these should present no insurmountable problems. Early primary effort would be design and testing of drill pipe with sufficient strength to drill as an unsupported string in deep sea locations and sufficient diameter to be used as a conductor for emplacement operations.

The overall question of public attitude toward the disposal of radioactive waste in the seabed can, in part, be answered by the fairly wide-spread negative reaction to ocean dumping of these wastes. After a brief introduction to four generic disposal schemes, seabed disposal was ranked next to the highest perceived risk level.(13) Seabed disposal generally was perceived as having unfavorable characteristics regarding protective measures believed achievable in event of leakage; similar reactions were recorded for retrievability, detectability and overall safety once the waste was in place. It was rated relatively safe with respect to distance and population density.

A number of existing treaties and agreements impose restrictions on the use of the oceans for dumping and disposal of radioactive material. Such policies would require revisions before seabed disposal could be used. These factors are important not only because use of the seabed for disposal would require international agreement but also because, once agreed to and demonstrated as feasible, the seabed could become an international repository. The United States Marine Protection, Research, and Sanctuaries Act of 1973 restricts high-level waste disposal. An Environmental Protection Agency permit would be required for low-level waste disposal before the United States could implement this alternative. The 1958 Convention on the Continental Shelf provides for the protection of the seabed and subsoil submarine areas adjacent to continental coasts and might restrict the seabed disposal concept.

For solid low-level wastes, the relatively large volumes involved and the small advantages over direct ocean dumping, make this concept economically unfeasible. Much additional development is needed before this concept becomes practical and acceptable.

5.4.5 Disposal in Ice Sheets

5.4.5.1 Concept Description

The potential for the disposal of radioactive wastes in ice sheets was recognized as early as 1958 when Bernhardt Philbirth(79) was issued a German patent entitled, "Storage of Radioactive Decay Products in Polar Ice". In 1974 a comprehensive documentation of this alternative as a method for the disposal of high-level radioactive waste was reported by BNWL.(13) Subsequently, these data were updated and summarized in ERDA-76-43.(5)

The principal thrust of the work to date stresses the disposal of high-level solidified radioactive wastes in ice sheets. No record has been found of this alternative being considered for liquid or gaseous wastes. In theory, the continental ice sheets could provide a disposal site for all levels of solid radioactive wastes. Ice sheets on several different occasions during the last 2 to 3 million years have covered up to 30% of the Earth's surface and theoretically constitute the world's largest fresh water reservoirs.

The problems with the disposal of low- and intermediate-level radioactive wastes in ice sheets will parallel those for high-level wastes.

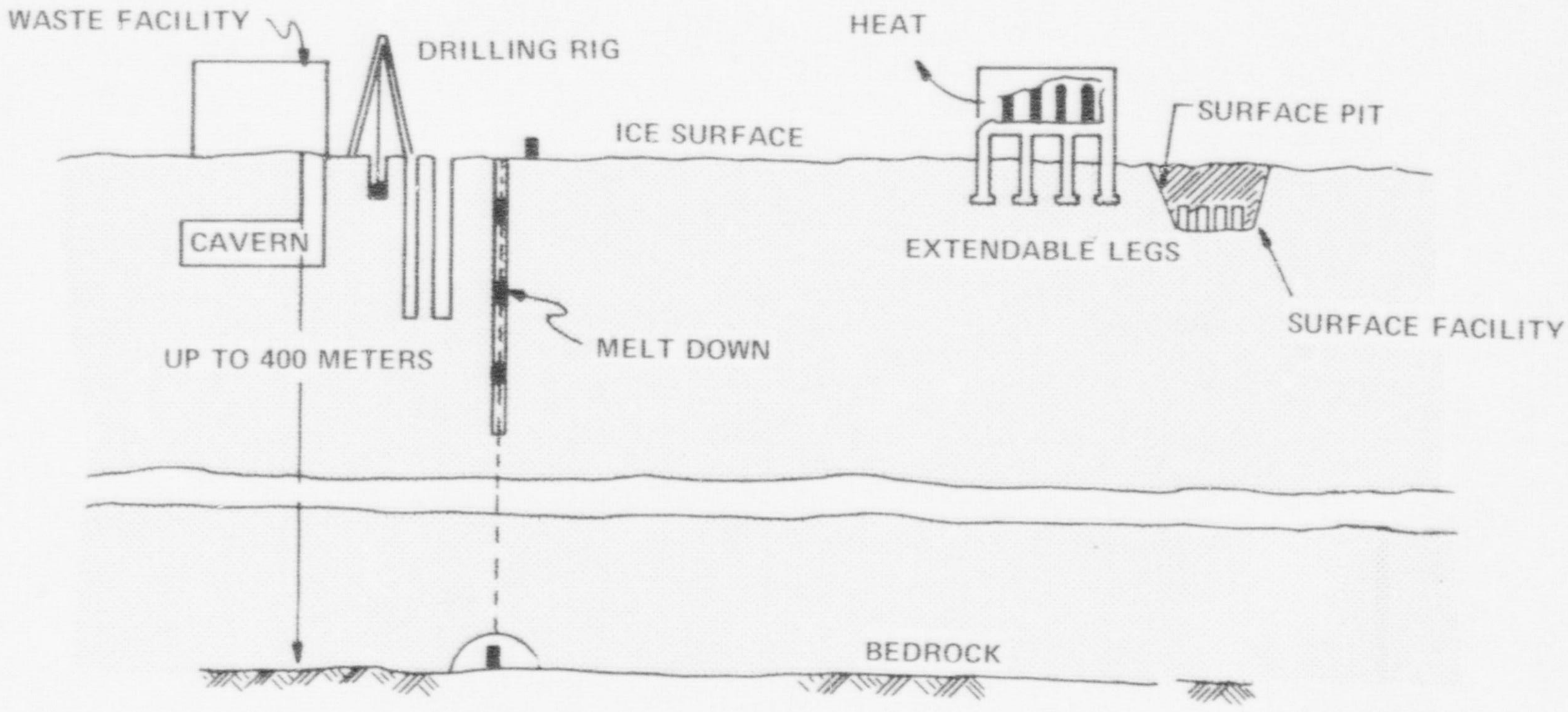
The drilled hole technique, as shown in Figure 5.4, would parallel the proposed "Meltdown or Free Flow" technique for high-level wastes. In this concept, the waste containers would be placed in previously drilled holes. It is unlikely that containers of low- or intermediate-level wastes would approach the thermal heat generation of high-level wastes. Depending on the heat generation, the containers might remain where placed or melt down to some lower level. A depth of 100 m would provide sufficient shielding for surface operations. If heating were a problem, the rate of meltdown could be controlled by limiting the thermal output of the waste containers during packaging. Container shape would be designed so that a vertical path from surface to bedrock could be assured. The potential problems that could result from pressure and possible saline water at the base of the ice sheet would be considered in choosing a container design and materials.

Placement in caverns or in shallow pits carved in the ice sheet also are possible techniques of disposal and are depicted in Figure 5.4. Both the cavern and pit techniques closely parallel the similar established concepts applicable to ground disposal.

The snow on all but the periphery of the ice sheet areas is deposited as a powdery, dry noncohesive aggregate. After deposition, intergranular bonds form between the grains, and the snow becomes firm and cohesive. As a result of the snow accumulation on the surface of the ice sheet, each layer becomes buried deeper and deeper beneath the surface as time progresses, and the pressure on it steadily increases. As the snow is compressed, the density and intergranular bonding increase. At depths of 50 to 100 m, the air spaces become sealed, a process that is the transition from snow to ice. The process of transformation from snow to perennial ice occurs where environmental conditions are such that more snow is deposited than is dissipated by melting or evaporation.

The surface area of the Greenland ice sheet is about 1.72 x 10^6 km^2. The mean thickness of ice cover is 1,515 m. Average annual accumulation for the ice sheet is about 36.7 cm of water equivalent. Climatological data suggests that the Greenland ice sheet has a slight positive mass balance; that is, ice is slowly accumulating. The Greenland ice sheet covers about 83% of the land area. The coastal areas surrounding the ice sheet are largely ice-free. The bedrock configuration is reasonably well known. The central part of Greenland is depressed, and approximately 31% of the area underlying the ice is below sea level.

The surface area of the ice sheet in Antarctica is about 14 x 10^6 km^2. The land-based ice sheet is up to 4,250 m. Along most of the Antarctic coast, no land is visible. The continental or shelf ice terminates abruptly in vertical cliffs of 15 to 45 m. Crevasses may be found in any part of Antarctica but are more common near the coast, close to the mountains and isolated bare rock areas. The crevasses are often bridged by snow and difficult to identify. Their width can vary from a few meters (a common width is 10 m) to more than 100 m. Zeller, et al,(80) have identified a tentative depository area in the central region of the East Antarctic ice sheet where ice thickness ranges from 1,000 to 3,000 m, the annual precipitation



BNWL - 1900

FIGURE 5-4. ICE SHEET DISPOSAL CONCEPTS

is generally less than 10 cm of water, and the average annual surface temperature ranges from -50°C to -60°C.

The motion of the continental ice sheets has been treated theoretically, but until recently, most of the measurements were of surface movement within range of fixed bedrock features. Recent utilization of high-altitude orbiting satellites and radio-echo sounding techniques have expanded experimental data. As a result, the presence of lakes beneath parts of the Antarctic ice sheet, including one in the area of the repository proposed in Reference 80, have been detected.(5)

5.4.5.2 Applicability to Low-Level Waste

The facts that ice sheets are in remote parts of the earth and have very hostile meteorological conditions pose serious logistics problems to this alternative method of disposal. The lack of accessibility to the Arctic, Antarctic, or to Greenland during a large part of the year would require that all wastes be shipped on a campaign basis over about a 1- to 4-month period.

No information has been found that precludes the technical feasibility of radioactive waste disposal in continental ice sheets. All systems required for waste management, transportation, logistics support, and emplacement are available or could be developed through existing technology. The potential for a long-term containment and disposal system exists. However, today's limited knowledge of ice sheet physics and history makes prediction of the stability of the ice sheets for periods greater than a few thousand years uncertain. Verification of the theories that support ice sheet disposal will require many years of extensive new data collection and evaluation.

From the limited data presently available, it appears that the ice sheet disposal concepts could offer potentially favorable features such as:

(a) Geographical isolation

(b) Relative isolation and containment of wastes by the ice in the event of leakage or package failure

(c) Low temperatures and high heat dissipation capacity

(d) Relative safety from damage by storms, sabotage, and other hazards once the waste is emplaced

Potentially unfavorable features for ice sheet disposal in general are:

(a) Extensive new data on all facets of ice sheet physics will have to be obtained.

(b) The harsh environment and unpredictability of conditions on ice sheets will present severe problems in establishing safe operations.

(c) Ice sheet areas are inaccessible during much of the year (6 to 11 months) because of storms, long periods of winter darkness, and freezing of surrounding areas.

(d) Monitoring and evaluating waste disposal operations would be difficult.

(e) Recovery from an unforeseen occurrence during transport would be difficult.

(f) The use for the planet's largest theoretical reservoir of fresh water may not be acceptable to worldwide public.

The research and development requirements for ice sheet disposal can be divided into those associated with obtaining basic information on the ice sheet and those related to the handling, transport, and emplacement of the waste.

The primary research need for ice sheet disposal of radioactive waste is for information on the rates of movement of the ice, its long-term stability, and the characteristics of the ice-bedrock interface. At present, little quantitative information is available on motion within the ice sheets. Stability of the ice is of prime importance in assessing the suitability of the ice as a means of isolating and containing the wastes for the time periods required. The characteristics of the ice-bedrock interface of Arctic, Antarctic, or Greenland ice sheet are almost unknown.

The need for further development of the transportation system for ice sheet disposal is primarily in the transporting of the wastes from the edge of the ice sheet to the disposal site. Existing ships could be adapted by installation of the necessary safety, cooling, and handling facilities to provide transportation to the ice sheets. Operations would be limited to 3 to 4 months or less each year because of the climate and accessibility to the ports at the ice sheets.

Transportation to the disposal sites, either by air or on the ice surface, would require some development in vehicles and methods. Aircraft have replaced surface vehicles to a large extent in Antarctica, but would require additional modifications in cargo capacity, fuel load, and navigational equipment for reliable operation during unfavorable weather conditions. Even during the operational season, air transport would be at times impossible due to fog, blowing snow, and winds.

Surface transport of wastes would require considerable development to be put into a practical and dependable system. Load capacity, fuel needs, speed of travel, and capability to traverse rough surfaces and some grades would need consideration. Tracked vehicles have proved practical, although slow. Surface effect vehicles (SEV's) or air cushion vehicles need further testing and development before they would be capable of routine use for transportation of waste over the ice sheets.

Public attitudes regarding nuclear waste disposal are obviously of enormous importance Large-scale projects simply cannot proceed without some degree of public acceptance and favorable attitudes on the part of key decision makers who are responsive to public feelings.

A number of treaties and agreements exist that could affect the use of the ice sheets for disposal of radioactive waste. Because Greenland is Danish territory, it was not considered with respect to policy restrictions. Disposal of radioactive waste in Antarctica is specifically prohibited by the Antarctica Treaty of 1959, of which the United States is a signatory.

Because of the high transportation and on-site handling costs, and the required technological developments to make this a practical alternative, it is considered unviable at the present time.

5.4.6 Submantle Disposal

5.4.6.1 Concept Description

The disposal into the earth's magma would be impossible for gases or aqueous wastes. It could be attempted for solids, however, with appropriate consideration of possible volatilization.

The concept of disposal of low-level radioactive wastes by injection into molten magma deposits deep within the earth's crust has received some recent interest. This interest is primarily due to the potential and relative success of exploring relatively shallow magma chambers with advanced drilling technology. The technology has been basically improved through geothermal exploration designed to assess the potential of utilizing magma heat/steam as an energy resource.(81)

Injection of low-level wastes would be accomplished through partly or fully cased holes drilled from either the land surface or from locations within an ocean basin where shallow magma chambers are known to exist. The deepest drill hole on record in the United States is located in the West Texas Oil Field at a depth near 10 km.(82) Therefore, the potential of advancing a borehole utilizing new drilling techniques(83) into some of the shallowest known magma chambers(84) (near 20 km in depth), such as in the Katmai volcanic range of Alaska or into deep sea volcanic ridges is possible. Other than drilling technology, factors critical to the success of a magma injection project is the ability of engineering materials to survive the high temperature magma environment.(85-87) Material compatibility studies to date show that materials are available that will perform under these conditions.(86-88)

The problem of overcoming magma gas pressures to permit injection has not been addressed or studied. The success of a liquid waste injection technique would be dependent on overcoming this key factor. To date, most of the research being done is directed towards penetrating the high-pressurized chambers to allow steam/gas escapage and capture for heat sources.(89,90)

Another major problem relating to the success of the concept is maintaining the integrity of an injection hole. The integrity is affected by the apparent mobility of the upper zone of the magmatic deposit as a result of pressure changes due to collection, inner transport, release and subsidence of molten materials.(88,91-94) It is further reported that instability of the partially molten layer in upper rock mantle is continually experiencing low-velocity movements due to shifting along the mantle.(95) Both lateral and upward movements occur which cause extrusions of magma and create ridges along the ocean floors.(96,97)

A magma is defined(98) as "naturally occurring mobile rock material, generated within the earth and capable of intrusion and extrusion, from which igneous rocks are considered to have been derived by solidification. It consists of a liquid silicate-melt phase due to the high temperatures attained, a number of solid phases of suspended mineral crystals and in certain instances a gas phase may be present". An additional definition(99) states that "magma is a hot mobile rock material generated within the earth from which igneous rock results by cooling and crystallization. It is usually conceived of as a pasty or liquid material, or a mush of crystals together with a noteworthy amount of liquid phase having a composition of silicate melt". Steam and other volatile constituents are usually present which greatly influence the complex behavior between the magma and the pre-existing rocks with changes of temperature and pressure.

The source of the molten magmatic material is generally believed to be from the earth's core. Almost all currently known magma chambers are identified from geothermal-volcanic activities within the earth's upper crust.(100-104) Considerable effort has been and is now being expended towards identification, evaluation and development of geothermal-magmatic heat sources.(105-110)

Definition of the magma chambers as to depth, thickness area, and heat extraction feasibility is being accomplished by remote sensing,(111) geophysical logging(112) and drilling programs.(83,88,90,91,93)

The mobility of the molten masses and the composition of the flows at distances away from the source fissure are also being studied.(85) Permeability of the upper magma reservoir is reported as higher than at depths in the lower zone. Likewise, the temperatures are reported as varying between upper and lower zones and between liquid and solid phases.

In conclusion, significant research has and is being conducted towards understanding magma deposits. However, the technology needed to inject low-level radioactive wastes successfully into magmatic areas is only in the infant stage. Other factors concerning the feasibility of using a magma chamber as a long-term disposal medium are discussed in the following paragraph.

5.4.6.2 Applicability to Low-Level Waste

A review of the available reference data indicates that the technical feasibility of the concept has not been demonstrated nor attempted. Factors to be considered, other than those previously mentioned, to develop the technical feasibility of the magma injection concept are as follows:

(a) Environmental impacts (ocean floor/water, ground water geothermal steam, and explosion to the atmosphere by volcanic action)

(b) Stability relationships(97) (migration by extrusion into the fractured mantle, migration along crustal plate boundaries, upward migration along deep-seated active seismic zones)

(c) Subsidence and swell

(d) Volume of magma chambers

(e) Interaction of injected effluents with magma constituents

(f) Monitoring the disposition of injected media

(g) Overcoming internal chamber pressures to allow injection

(h) Costs for exploration, transport, drilling, injecting, sealing and monitoring

(i) Converting all wastes into liquid or slurry to facilitate injection

(j) Obtaining political acceptance of the concept

Finally, prevailing regulations would have to be adhered to should technology be developed to approach concept feasibility. This concept is therefore not viable at this time.

5.5 Structural Concepts

5.5.1 Concept Description

The disposal of low-level radioactive waste by placement in manmade structures(5) can be considered. The structures obviously must be designed to provide containment for the hazardous life of the wastes. Advantageous characteristics of the structural disposal method are:

(a) Ease of monitoring the environment and detection of radiation leakage

(b) The ability to locate the facility almost anywhere

(c) The ease of accomodation of waste containers of essentially all sizes and shapes

(d) The ease of accessibility for inspection of the containers

(e) Year-round operations

(f) Ease of environmental control to protect the containers

This alternative features the potential use of several types of structures. The generic types of structures for indoor disposal of solid, low-level radioactive waste consists of reinforced concrete and metal structures. Several typical construction methods are available; namely precast concrete, cast-in-place concrete, concrete block, and metal-frame buildings. Tanks, for the purpose of this survey, are considered to be a special form of building. Tank usage generally is associated with the retention of liquid and gases. Since gases and liquids are very mobile when not confined, their disposal must be in structures designed to provide a high degree of containment over their hazardous lifetimes for disposal on or near the surface of the earth to be considered viable.

While the prime concept of this alternative will be structures constructed above ground, there is some merit in also considering below-grade or partially buried structures. For example, below-grade storage would provide greater resistance to storms earthquake, vandalism, and sabotage. However, below-grade excavations may be slightly more expensive than placing a similar structure at grade level. One consideration is that, except for the concrete structures, other building materials will be more susceptible to degradation or corrosion if buried below grade. Since the same type of concrete building constructed above grade would meet minimum criteria for earthquakes and other requirements for radioactive waste disposal, the only substantial advantages of below-grade storage would be the excellent radiation shielding and additional protection against adverse events. Costs for disposal in concrete structures may range up to \$500/m^3 for low-level wastes.

The use of precast, prestressed concrete panels in construction of low-cost permanent buildings is an established engineering practice. Disposal of waste would take place as in routine warehousing operations. The waste would be delivered to the warehouse in appropriate containers, and stacked using conventional material handling equipment. Depending upon the location of the structure, the local environment, and the structural-life integrity of the waste containers the atmosphere inside the building could be controlled within temperature and humidity limits. The building could possibly be filled with an inert gas, if desired, and sealed after the building is filled with waste to reduce container corrosion. Air sampling capabilities could be used for monitoring. This type of building is exceptionally strong and relatively low in cost. It is also adaptable to modular construction so that additional units can be added by utilizing common walls for adjacent building units.

The cast-in-place concrete structure is similar to the precast concept. It is generally more expensive than other types of concrete buildings. It would exhibit the same operating characteristics described for the precast building. Fire resistance is excellent and it is possible to make it quite impermeable to water.

The third basic type of concrete structure is similar to the previous two, except the walls are laid with concrete block. Cement block construction would be somewhat more difficult to seal, and structurally it is much inferior to the precast building.

There are several types of metal frame buildings commercially available. Building styles, prices and quality vary considerably. These buildings are fire resistant and structurally inferior to the concrete buildings, especially under adverse meteorological conditions. The precast concrete building is probably the only building that could be built to withstand the maximum creditable tornado; but, it is doubtful that this type of building could be built to survive, without violation of its integrity, a direct impact (crash) by an aircraft.

5.5.2 Applicability to Low-Level Waste

The major question regarding the applicability of this alternative for disposal of low-level waste surrounds its ability to confine the waste under all conditions for the periods of time that are required. Above-ground structures are subject to severe meteorological conditions and highly vulnerable to sabotage attempts. The underground structures greatly reduce some of the adverse conditions prevalent with the above-ground buildings. Unless some means of eliminating oxygen from within the building is provided, there always will be a certain fire potential. If fire is a concern, the wastes could be reduced to noncombustible form as by incineration and placed in noncombustible waste containers.

There are no major technical obstructions to this alternative, but because of the wastes' immediate proximity to man's environment for long time periods, it may not be a popular alternative. Long-term monitoring could be facilitated by this type of disposal concept, however, and ameliorative actions taken, if necessary.

5.6 Disposal by Conversion

The conversion of objectional isotopes to unobjectionable ones is an acceptable disposal alternative. Conversion of gases requires high pressure equipment to get useful rates of reaction, making this concept nonfeasible for gaseous waste forms. Tritium could not be readily converted in a thermal reactor, but might be disposed of using other nuclear processes. Generally the isotope to be removed would need to be in a condensed, concentrated form.

5.6.1 Transmutation

The concept of isotopic transmutation is valid when considering alternative waste disposal methods. The objective of transmutation is to use nuclear processes to accelerate the conversion of nuclides with long-term risk potential to shorter-lived nuclides of a lesser risk potential.(5) The conversion is achieved by bombarding waste nuclides with photons or other subatomic particles. Transmutation is generally defined as any process whereby a nuclide absorbs or emits radiation and is thereby changed into another nuclide.(13) A case in point has been the recycling of plutonium experimentally in thermal reactors.

5.6.1.1 Concept Description

The concept first proposed by Steinberg et al.(113) in 1964, indicates that special purpose high-flux burner reactors be used to transmute fission products ^{85}Kr, ^{90}Sr, and ^{137}Cs. Gregory and Steinberg(114) later considered the use of spallation accelerators. Claiborne(115) studied neutron-induced transmutation of high-level waste, emphasizing actinide recycle in light water reactors. Leonard(116) and Steiner(116) suggested that fusion reactors be used in transmutation and studies were made of this approach.(116,117)

Transmutation concepts and other concepts suggested through 1973 are presented in detail in a BNWL study report.(13) Accelerator devices discussed in the report are:

(a) Direct bombardment by charged particles from accelerators having energies of tens of MeV

(b) Acceleration of the beta decay process by Coulomb excitation

(c) Use of two processes of photon transmutation: electron bremstrahlung and stimulated gamma emission

(d) Use of a high energy ($\geq$1 BeV) proton accelerator to produce by spallation an intense source of neutrons for transmuting radionuclides

Thermonuclear explosive devices, fission reactors, and fusion reactors as neutron sources also were discussed.

Transmutation studies subsequent to BNWL-1900 considered a ^{233}U-^{232}Th reactor as a burner for actinide wastes,(118) actinide recycle in liquid metal fast breeder reactors,(119,120) and recycling of plutonium and other transuranium elements in power reactors.(121,124) Reports giving the status of neutron cross-sections and measurements required for many of the actinides(125-127) were made available during 1975.

Additional transmutation studies have been reported since the 1976 ERDA report.(5) The studies include performance calculations of fast reactor actinide recycle,(128) a linear-accelerator/fission-product transmuter,(129) and actinide transmutation in fission reactors.(130)

Favorable concepts for transmutation that have emerged from the studies reported are:

(a) Actinide transmutation in fission reactors, both thermal and fast

(b) Fission-product plus actinide transmutation by means of spallation and neutron accelerators

The transmutation of long-lived fission products (i.e, the spallation accelerator) is not considered feasible within the limits of current or near-term technology.(131) Thus, actinide transmutation by fission reactors is the most favorable concept for transmutation.

In the fission reactor concept,(13) specific constituents in spent fuel coming from the reactor are recovered during reprocessing and partitioning and are sent to a fuel fabrication facility. There they are incorporated into rods for subsequent insertion in the reactor. Of merit in this case of actinide recycle is that they may represent an increase in fissile resources. The concept results in the elimination of the actinides, except those which are residue, once fission reactors are discontinued. This residue and the other fraction of radioactive waste must be disposed of by other means.

5.6.1.2 Applicability to Low-Level Waste

The theoretical feasibility of the concept, in terms of nuclear physics, has been established. The recycle of plutonium experimentally in thermal and fast reactors has been demonstrated. Calculations(123,124) indicate that fast reactors would be more efficient actinide burners than thermal reactors. In practice, however, the success of the scheme would be critically dependent on the development of new processes to achieve adequate levels of conditioning of the several actinides from the multiplicity of wastes in which they appear. Applying transmutation to the disposal of low-level radioactive waste requires low-level waste to be highly concentrated.

In addition to the requirement of developing actinide conditioning, there are other developmental requirements that must be met. One requirement is good neutron cross-section data for all the actinides with a half-life greater than about 1 day.

A detailed analysis of the risk of the total concept, including the disposal of final residual actinide wastes and the various partitioning and recycling operations, would help to assess the value of the concept. Consideration of the radiation exposure to workers involved may be of particular importance. To be worthwhile, the concept must offer a significant reduction in risk compared with that associated with the more conventional shallow-land and geologic disposal alternatives. More research and development work is needed before a conclusion can be reached on the merits of the concept.

Concepts costs were reported in BNWL-1900.(13) In the case of transmutation, the cost given included the cost of transmuting the actinides and of terrestrial disposal of the remaining fractions of the high level waste. This estimated cost was 0.5 mills/kWh(e) and compares to 0.046 mills/kWh(e) for solid waste emplacement of high-level waste in a mined cavity with no fluid cooling or melting. The cost of 0.5 mills/kWh(e) was approximately 1.5% of the cost of nuclear-generated electricity. A subsequent study(14) took into account partitioning strategy costs, recycle of the actinides to fission power reactors, and salt disposal of the fission products. An estimated cost of 0.99 mills/kWh(e) was given as the cost for the total management system. This cost was approximately 3.3% of the cost of nuclear generated electricity. In the case of low-level wastes, these estimated costs do not include the cost of conditioning these wastes, which must be added.

As far as policy considerations are concerned, the transmutation concept is compatible with existing governmental policies and programs.(13) However, the costs for conditioning the low-level wastes and partitioning out the actinides makes this concept nonfeasible at this time.

6. EVALUATION PARAMETERS FOR COMPARING ALTERNATIVES

The task of summarizing radioactive waste disposal criteria or evaluation parameters into a reasonable, workable format is complicated by the wide variety of scientific, technical, economic, sociopolitical and institutional factors that are closely interrelated with varying degrees of importance. This complexity requires a logical systematic approach to assure that all considerations are subjected to a consistent and comprehensive analysis.

The evaluation parameters discussed at the technical advisory panel meeting (see Chapter 3) and reported in Chapter 4 do not provide the degree of independence and logical organization necessary for optimum utility. Comments from the panel and the survey on these original parameters were combined with other information(10,11) to revise the set of evaluation parameters.

To compare different disposal alternatives, certain criteria must be used to assure that the comparisons are objective and truly reflect the viability of a given concept. Before any concept is implemented, it will necessarily conform to certain constraints, such as technological feasibility, sociopolitical acceptability and economic feasibility. The factors that make up these constraints, however, can vary through a range of values as long as the combined effects are acceptable. Figure 6.1 schematically shows the three major constraints and subordinate parameters that go into each category. Following the figure is a brief description of the factors that are included in each of the terms in the third tier.

The parameters listed under each constraint have been selected to be somewhat independent to facilitate comparisons. Note, however, that costs are reflected in almost every parameter. By changing the costs spent on an alternative, most of the other parameters can be changed. For a given design of a specific disposal alternative (implying certain costs), however, certain calculable effects will obtain. Therefore, costs and results can both be used in making comparisons, recognizing that changing the costs will also change the resultant effects, by establishing a reference or base case design for the given alternative. The reference designs will be based on good engineering judgement to provide minimum costs and still meet reasonably expected criteria for waste disposal. The evaluation parameters will then be quantified based on this reference design for each alternative being evaluated.

In using this set of evaluation parameters to compare alternatives, detailed analyses will be performed to quantify each of the parameters for each alternative. Weighting factors reflective of the importance of each parameter will then be applied prior to summing to arrive at the figure of comparison. Obviously, if the parameters can be expressed in the same units

EVALUATION PARAMETERS FOR COMPARING ALTERNATIVES

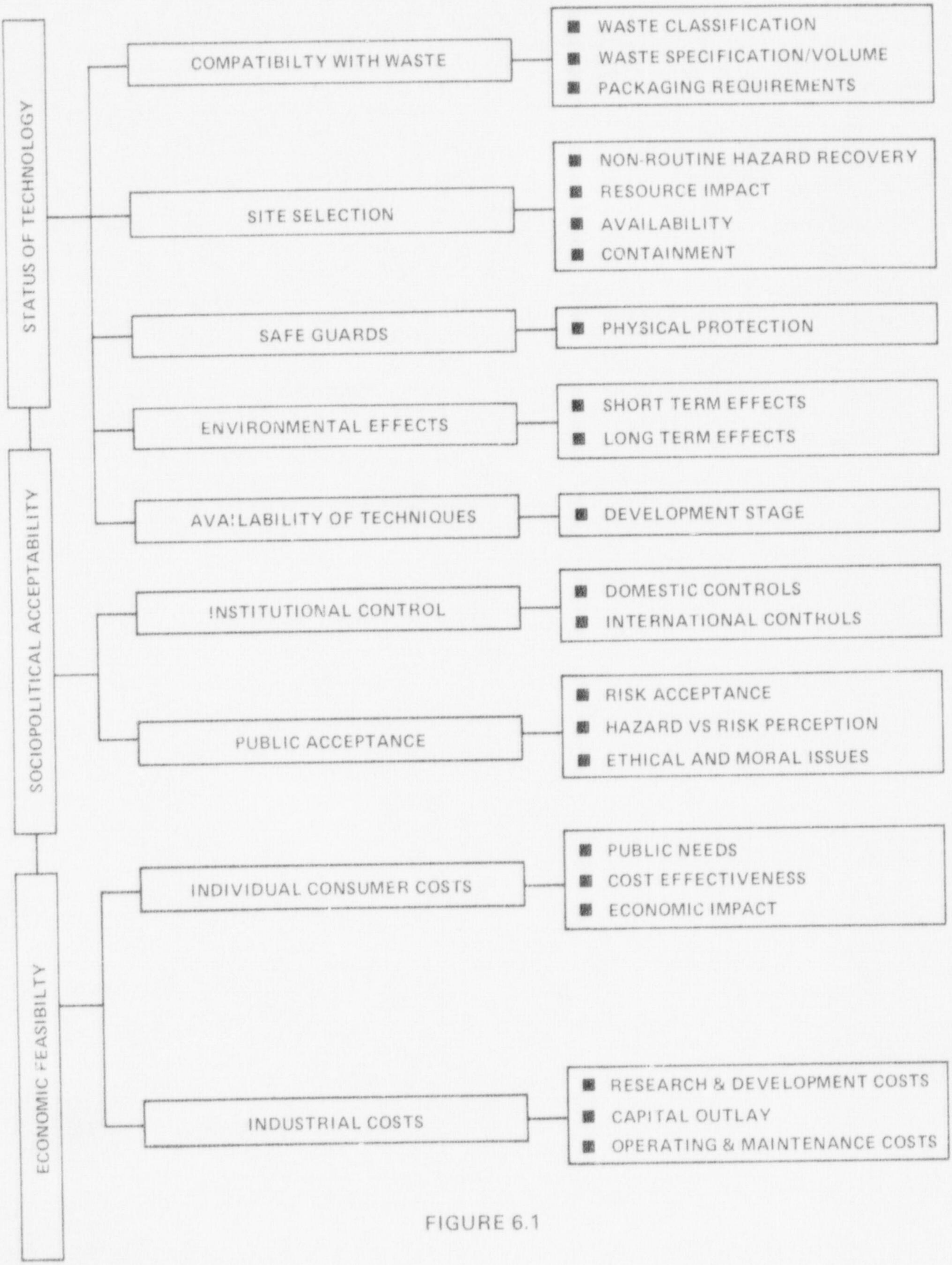


FIGURE 6.1

DEFINITION OF TERMS USED IN FIGURE 6.1

Waste Classification	alpha, beta or gamma; TRU's, or FP's; long- or short-lived.
Waste Specification/Volume	solid, liquid or gas; radioactivity per unit volume.
Container Requirements	containment capability, shielding needs; size limitations; retrievability.
Non-Routine Hazard Recovery	time lapse from "upset" to detection; time for upset to affect population.
Resource Impact	locations of affected resource; value of resource rendered inaccessible.
Availability	technical criteria; degree of isolation; legality of acquisition; accessibility.
Containment	extent of barriers; probably duration of containment; retrievability.
Physical Protection	protection against the diversion of waste, accessibility to "nuisance" intruders or other man-made threats including sabotage.
Short-Term Environmental Effects	risks in transport and operation; routine and non-routine releases; aesthetic appearance.
Long-Term Environmental Effects	the long-term results of isolation and natural catastrophes on the biosphere.
Development Stage	whether or not the technique is at the conceptual, laboratory, demonstration or production stage.
Domestic Controls	federal, state and institutional.

DEFINITION OF TERMS USED IN FIGURE 6.1 (Cont)

International Controls	treaties; world-wide agreements and organizations (e.g., IAEA).
Risk Acceptance	the public's acceptance of the risks as it perceives them.
Hazard vs. Risk Perception	how well the public understands the hazards and risks.
Capital Costs	the total costs from conceptual design to operation, including R&D, site acquisition and preparation, licensing, construction and support facilities.
Operation & Maintenance Costs	the costs from start-up throughout facility life, plus costs of decommissioning, implementing long-term care, transportation, additional treatment, and energy consumption.
Public Needs	sociopolitical implications of expenditure of funds by or for public, addressing whether public perceives need for costs.
Cost Effectiveness	what benefits are accrued by expenditure of funds by or for the public.
Economic Impact	what effects do disposal costs have on consumer costs, taxes, and other economic penalties or incentives for individual members of the public.

(such as dollars) the weighting factors are unity. Therefore, the weighting factor is truly meant to be the relative importance of the parameter compared to the other parameters, using the assumption that the three main constraints will be met by any given alternative, and that the units in which they are expressed may be different. Table 6.1 lists additional factors and considerations that contribute to the evaluation of the parameters listed in Figure 6.1. The compilation of all criteria that have been identified into a logical framework provides objectivity to this study. Some of the listed criteria, however, such as waste definition and treatment, may not be relevant to this project, but have been included in the table for completeness.

TABLE 6.1

LOW-LEVEL RADIOACTIVE WASTE DISPOSAL EVALUATION PARAMETERS

- 1. STATUS OF TECHNOLOGY
  - 1.1 COMPATIBILITY WITH WASTE
    - 1.1.1 WASTE CLASSIFICATION
      - 1.1.1.1. STANDARD DEFINITIONS
        - a. NO PERCEIVED RESOURCE OR PRODUCT VALUE
        - b. CONTAMINATED WITH RELATIVELY LOW LEVELS OF RADIOACTIVITY
      - 1.1.1.2. SOURCES OF RADIOACTIVE WASTE
        - a. NATURALLY OCCURRING RADIOACTIVE ELEMENTS IN ROCKS, SOILS, AND WATER WHICH ARE CONCENTRATED/ EXPOSED BY HUMAN ACTIVITY
          - i. PHOSPHATE MINING/MILLING TAILINGS
          - ii. URANIUM MINING/MILLING TAILINGS
        - b. DENTAL/HOSPITAL FACILITIES
        - c. RESEARCH LABORATORIES
        - d. NUCLEAR FUEL CYCLE ACTIVITIES
          - i. FUEL CONVERSION
          - ii. FUEL ENRICHMENT
          - iii. FUEL FABRICATION
          - iv. REACTOR OPERATIONS
          - v. REPLACED/FAILED EQUIPMENT
          - vi. FUEL REPROCESSING
          - vii. DECONTAMINATION/DECOMMISSIONING
        - e. WEAPONS MANUFACTURING
        - f. COMMERCIAL ISOTOPE PRODUCTION
        - g. MILITARY PROPULSION SYSTEMS
      - 1.1.1.3 AMOUNTS/QUANTITY/CONCENTRATION
      - 1.1.1.4 CHEMICAL/PHYSICAL CHARACTERISTICS
        - a. HALFLIFE
        - b. HEAT PRODUCTION
        - c. CHEMICAL FORM
    - 1.1.2 WASTE SPECIFICATION/VOLUME
      - 1.1.2.1 MINIMIZE AMOUNTS OF WASTES
        - a. VOLUME REDUCTION
      - 1.1.2.2 SEGREGATION BY HALF-LIFE
      - 1.1.2.3 HANDLING/STORAGE OPERATIONS
      - 1.1.2.4 TRANSPORTATION FOR DISPOSAL
    - 1.1.3 PACKAGING REQUIREMENTS
      - 1.1.3.1 SOLIDIFICATION
      - 1.1.3.2 PRODUCT SPECIFICATIONS
        - a. RADIOACTIVE CONCENTRATION
        - b. LEACHABILITY
        - c. THERMAL STABILITY
        - d. TEMPERATURE LIMITS, ETC.

- 1.2 SITE SELECTION
  - 1.2.1 NON-ROUTINE HAZARD RECOVERY
    - 1.2.1.1 RETRIEVABILITY OF WASTES
    - 1.2.1.2 REPAIRS/CORRECTIVE ACTION
  - 1.2.2 RESOURCE IMPACT
    - 1.2.2.1 ENERGY CONSUMPTION
    - 1.2.2.2 PACKAGING MATERIALS
  - 1.2.3 AVAILABILITY
    - 1.2.3.1 SITE CHARACTERISTICS
      - a. HYDROLOGY
        - i. LOW GROUND WATER PENETRATION
        - ii. FLUID FLOW FACTORS
      - b. GEOLOGY
        - i. DISTRIBUTION OF ROCKS/SOIL
        - ii. LOW EROSION RATES
        - iii. LOW MIGRATION RATES
      - c. METEOROLOGY
        - i. LONG-TERM SEISMIC STABILITY
        - ii. EARTHQUAKE FREQUENCY AND INTENSITY
      - d. CHEMISTRY/GEOCHEMISTRY
        - i. MINERAL CONTENT OF WATER
        - ii. SORPTION PROPERTIES OF MEDIA
    - 1.2.3.2 DESIRABLE SITE CRITERIA
      - a. LOW MINERAL RESOURCES
      - b. LOW BACKGROUND AREA
      - c. RELATIVELY INACCESSIBLE
      - d. SAFEGUARDABLE
      - e. DEFENSIBLE FROM SABOTAGE
    - 1.2.3.3 MULTIPLE SITES
      - a. USE EXISTING GOVERNMENT SITES
      - b. OTHER LOCATIONS NEAR WASTE SOURCES
    - 1.2.3.4 LONG-TERM CARE
      - a. DECOMMISSIONING
      - b. RESTORATION
      - c. LAND USE PLAN
    - 1.2.3.5 SITE DISPOSAL OPERATIONS
      - a. OPERATIONAL STANDARDS/PROCEDURES
      - b. ADEQUATE RECORDS
      - c. MONITORING DURING DISPOSAL
      - d. GOOD HOUSEKEEPING/CARETAKING
      - e. SITE MAINTENANCE REQUIREMENTS
  - 1.2.4 CONTAINMENT
    - 1.2.4.1 PHYSICAL/NATURAL
    - 1.2.4.2 INSTITUTIONAL
      - a. MONITORING
      - b. MITIGATING ACTIONS
    - 1.2.4.3 ENGINEERED/TECHNICAL
- 1.3 SAFEGUARDS
  - 1.3.1 PHYSICAL PROTECTION
    - 1.3.1.1 NUISANCE ACCESS
    - 1.3.1.2 DIVERSION OF WASTE
    - 1.3.1.3 ACCESS TO MAN-MADE THREATS
    - 1.3.1.4 SABOTAGE

- 1.4 ENVIRONMENTAL EFFECTS
  - 1.4.1 SHORT-TERM EFFECTS
    - 1.4.1.1 POTENTIAL PATHWAYS TO MAN/AIR, WATER, FOOD
      - a. SHORT-TERM IMPACTS
        - i. SHORT-TERM/OPERATIONAL PERIOD
        - ii. POTENTIAL DOSE TO INDIVIDUALS/ POPULATIONS - PRESENT AND FUTURE
        - iii. INTRUDER PROTECTION
        - iv. MINIMIZE IRREPARABLE HARM
        - v. MINIMIZE ADVERSE HEALTH IMPACTS
      - b. SITE CHARACTERISTICS
      - c. RADIATION SOURCE
      - d. PROJECTED EFFECTIVENESS OF BARRIERS
      - e. POTENTIAL ENVIRONMENTAL IMPACTS
      - f. PROBABILITIES OF RELEASE OF RADIOACTIVE MATERIALS
      - g. SABOTAGE/ATTACK
      - h. ACCIDENTS/UNPLANNED RELEASES
        - i. TRANSPORTATION
        - ii. OPERATIONAL PARAMETERS
      - i. NATURAL/CATASTROPHIC EVENTS
      - j. SIZE OF AFFECTED AREA
    - 1.4.1.2 UNCERTAINTY IN RISK ASSESSMENT METHODOLOGY AND MODELS
  - 1.4.2 LONG-TERM IMPACTS
    - 1.4.2.1 PATHWAYS TO MAN
- 1.5 AVAILABILITY OF DISPOSAL TECHNIQUES
  - 1.5.1 DEVELOPMENT STAGE
    - 1.5.1.1 CONCEPTUAL STAGE
    - 1.5.1.2 LABORATORY SCALE
    - 1.5.1.3 DEMONSTRATION SCALE
    - 1.5.1.4 PRODUCTION SCALE
      - a. POSSIBLE FOR FUTURE IMPROVEMENTS
      - b. FUTURE WASTE MATERIALS
      - c. AUTOMATION OF WORK
      - d. STATE-OF-THE-ART TECHNIQUES
      - e. CONCEPT AVAILABLE BY 1985

2. SOCIO-POLITICAL ACCEPTABILITY
- 2.1 INSTITUTIONAL CONTROL
  - 2.1.1 DOMESTIC CONTROLS
    - 2.1.1.1 REGULATIONS/LICENSING/ALARA/ALAP
      - a. HEALTH AND ENVIRONMENTAL CRITERIA AND STANDARDS WASTE MANAGEMENT CRITERIA APPLICABLE TO ALL FORMS OF EXISTING AND FUTURE RADIOACTIVE WASTE MATERIAL
      - b. SITE SELECTION AND APPROVAL CRITERIA
      - c. ACCIDENT RESPONSE/CONTINGENCY PLANS
      - d. OPERATIONAL CRITERIA & STANDARDS
    - 2.1.1.2 STATE VERSUS FEDERAL CONTROLS
      - a. PRIVATE OR GOVERNMENT OWNERSHIP OF DISPOSAL SITES
      - b. PERPETUAL SURVEILLANCE/LONG-TERM CARE/ INSTITUTIONAL STABILITY

- c. COORDINATED INTERAGENCY EFFORT BETWEEN EPA, DOE, AND NRC
- 2.1.1.3 DELEGATION OF AUTHORITY AND RESPONSIBILITY
  - a. INVOLVEMENT OF PUBLIC AND LOCAL/STATE/ REGIONAL GOVERNMENTS
    - i. INCREASED PUBLIC PARTICIPATION
  - b. IMPROVE OUR DECISION-MAKING PROCESS
    - i. TECHNOCRATS/BUREAUCRATS/PUBLIC
  - c. ANSWERABLE TO THE PUBLIC
    - i. ECONOMIC IMPACT OF CONTROLS
    - ii. COST-BENEFIT ON LEVELS OF CONTROL
- 2.1.2 INTERNATIONAL CONTROLS
  - 2.1.2.1 INTERNATIONAL IMPLICATIONS/CRITERIA/ POLICIES
- 2.2 PUBLIC ACCEPTANCE
  - 2.2.1 RISK ACCEPTANCE
    - 2.2.1.1 COMPATIBLE WITH OTHER HAZARDOUS WASTE CRITERIA
    - 2.2.1.2 RISK ASSESSMENT IN PUBLIC ARENA
      - a. CONSISTENT PROBLEM FORMULATION AND RISK ASSESSMENT OF RADIATION HAZARDS
      - b. RISKS TO PUBLIC FROM RADIOACTIVE WASTE VERSUS RISK FROM OTHER ENERGY WASTE
  - 2.2.2 HAZARD VS RISK PERCEPTION
    - 2.2.2.1 ADEQUATE AND ACCURATE KNOWLEDGE OF RISKS AND BENEFITS TO ILLUMINATE INCONSISTENCIES
      - a. ACCEPTABILITY OF PUBLIC HEALTH AND ENVIRONMENTAL CRITERIA
  - 2.2.3 ETHICAL AND MORAL ISSUES
    - 2.2.3.1 CONFLICTING VIEWS
      - a. SCIENTIST/ENGINEERS
      - b. INDUSTRY
      - c. SPECIAL INTERESTS
      - d. GOVERNMENT AGENCIES
    - 2.2.3.2 CREDIBILITY DILEMMA
    - 2.2.3.3 LEGACY QUESTION
      - a. TO FUTURE GENERATIONS
      - b. FROM PREVIOUS GENERATIONS
      - c. PROVIDE FULL INFORMATION TO FUTURE GENERATIONS
- 3. ECONOMIC FEASIBILITY
  - 3.1 INDIVIDUAL CONSUMER COSTS
    - 3.1.1 PUBLIC NEEDS
    - 3.1.2 COST EFFECTIVENESS
    - 3.1.3 ECONOMIC IMPACT
  - 3.2 INDUSTRIAL COSTS
    - 3.2.1 RESEARCH AND DEVELOPMENT COSTS
    - 3.2.2 CAPITAL OUTLAY
      - 3.2.2.1 ACQUISITION COST
      - 3.2.2.2 SITE PREPARATION
      - 3.2.2.3 LICENSING COSTS
      - 3.2.2.4 CONSTRUCTION COSTS
      - 3.2.2.5 SUPPORT FACILITIES

- 3.2.3 OPERATING AND MAINTENANCE (O&M) COSTS
    - 3.2.3.1 FACILITY O&M
    - 3.2.3.2 SURVEILLANCE
    - 3.2.3.3 ENERGY/RESOURCE CONSUMPTION
    - 3.2.3.4 SAFEGUARDS
    - 3.2.3.5 ADDITIONAL TREATMENT COSTS
    - 3.2.3.6 TRANSPORTATION COSTS
    - 3.2.3.7 DECONTAMINATION/DECOMMISSIONING
    - 3.2.3.8 RETRIEVABILITY COSTS
    - 3.2.3.9 PERPETUAL CARE COSTS

7. SUMMARY

The alternatives listed in this report are felt to completely span the options available for low-level waste disposal. Those selected for further evaluation are the most feasible and suitable for implementation at this time. However, other options or variations could become more attractive in the future as waste disposal technology develops. Selection of the apparently most viable alternatives at this time does not preclude consideration of other choices if they become reasonable candidates for disposal of low-level radioactive wastes.

The suggestions from a technical advisory panel review have been implemented in preparing this report.

Based on a screening of alternatives on technical and economic factors, the following concepts appear to deserve further consideration:

1. Ocean disposal
2. Land disposal
3. Disposal in geologic formations
4. Structural disposal concepts

Under land disposal, deeper burial is an alternative to shallow land burial, and will be analyzed and compared to the base case of shallow land burial. Under disposal in geologic formations, cavities and drilled hole disposal concepts appear promising. Above and below grade structures, both newly built for disposal and reused for disposal purposes, deserve investigation. These selected alternatives are generally consistent with the poll of panel members reported in Chapter 3.

As recommended by the technical advisory panel, improvements to shallow land burial will also be studied in the Task 3 effort.

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APPENDIX 1

LIST OF ATTENDEES AT PANEL MEETING ON DISPOSAL ALTERNATIVES, TUCSON, ARIZONA - March 9, 1978

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APPENDIX 2

RESPONDENTS' COMMENTS ON PARAMETERS A-Q AND ADDITIONAL PARAMETERS (R) IN TABLE 4.1

Respondent No./ Parameter	Comments
1/General	Why not assess present methods for handling these wastes, then devise better methods where present methods are not suitable, if they are not? Assume you are aware that LLW are to be reposited ultimately in a government-owned facility which is underground.
2/A	I assume modern containment technology is adequate.
/E	Many adequate sites are available. See S.
/G	See S & T.
/H	See S & T.
/I	See S & T.
/S	Public perception of hazard vs. total risk.
/T	Risk to public of radioactive wastes vs. risk to public of other energy sources.
3/G	For land only.
/L	Question unclear.
6/B	Should be analyzed on basis of long-term, integrated population dose commitment.
8/I & P	The safety and economic consideration of items I and P need to be separated.
/General	Most of these parameters naturally fall into three main categories which I would rate (with regard to their importance to successfully coming up with workable disposal definitions) as follows: 1. Safety (absolute minimum) 90-100. 2. Economic (absolute, then ALARA) 40-60.

Respondent No./ Parameter	Comments
	3. Political/Emotional (public acceptance) 90-100. I haven't spend a lot of time on these but feel it's representative of reality.
10/A & D	A & D are very closely linked.
/A	Excellent packing available now.
/B	Depends largely on site selection.
/C	Some risk in any operation
/E	Should be selected with great care - really key to problem.
/F	Not considered feasible.
/I	Largest potential exposure to general population.
11/M	Must be immediate and planned alternatives available.
/P	Should be considered in E.
12/R	Safeguards: needed even though LLW.
13/F	85 for first 100 years.
/K	Temporary (100 years).
/M	85 for first 100 years.
14/R	Courage for decisions.
/R	NEPA reform.
/General	My bias shows, but without the last two items having emphasis, I'm not sure the rest of the points are very meaningful.
15/A	Includes design and operating features to preclude water entry.
/I	Costs principally.
/K	Not over 100 years, maybe only 50.

Respondent No./ Parameter	Comments
16/A	Must consider short-term and long-term period.
/B	Answer is based on omitting the word "operations".
/E	Answer is go (any site available) or no go (no site available).
/G	Answer is either go (few resources needed) or no go (much excessive resources needed).
/H	Statement is not clear. My answer is a wild guess.
/I	Costs 10; hazards 90. Note difference in 2 categories.
/J	Cost of almost any technique is very low relative to cost of electricity.
/K	Indefinite answer - monitoring should not be necessary more than about 100 years.
/L	These will really control the whole decision.
/M	The rating on whether any corrective action at all could be taken is controlling and would be about 80.
/N	Compatibility is only important if some wastes could not be handled at all.
/O	My % is % of net electrical energy generated; this is a go, no-go basis.
/P	Note difference in 2 categories; a more basic question is "Can it be decommissioned?"
/Q	Basically go, no-go. If exposures are acceptable, importance is very low, approximately zero.
17/A	Depends on waste and avenues of loss.
/B	Paramount.
/C	The public hazard undefined.

Respondent No./ Parameter	Comments
/D	We don't need immediate action except for political reasons.
/E	Really talking about addition sites.
/F	For properly chosen sites.
/G	Not likely to be major commitments.
/H	Can't see major impact.
/I	No real problem.
/J	Won't affect power cost much.
/K	See H.
/L	Subject political, not technical problem.
/M	Should never occur.
/N	You've defined LLW as subject.
/O	Can't be major factor.
/P	See F.
/Q	Should be very low.
18/F	Assumes disposal, not storage.
/H	Excluding health hazards noted under B.
/N	Parameter not clear - if not compatible certainly would not use for disposal.
21/R	Standards (Cf. 24/R and 50/R).
22/J	Costs to whom?
23/A	Doesn't B insure A?
/D	Can be forced to high degree.
/F	Assuming negligible beneficial uses.
/J	Assuming small change in cents/kwhr.
/P	Assuming very long-lived facility.

Respondent No./ Parameter	Comments
/R	Immunity to sabotage.
24/B	Heavily site-dependent.
/F	Probably heavily option-dependent.
/M	Again option-dependent.
/R	Site Evaluation (no Maxey Flats, please!) (Cf. 7/R and 57/R.)
/R	Operational Standards (these could be limiting). (Cf. 21/R and 50/R).
27/O	Shows up in costs.
/R	Disposal Criteria, e.g. waste form, site characteristics. (Cf. 24/R and 57/R.)
28/D & E	I weighted these at 100 as I don't believe an alternative is an alternative without them.
/R	Reliability (independent of local government control, license renewals, strikes, etc).
/R	Profitable to Private Industry.
29/R	Perpetual Care Programs. (Cf.37/R.)
/R	Site Impacts and Costs as Compared to Waste Volume Reduction Programs.
30/General	Assumed low-level is non-transuranic, beta-gamma waste.
33/A	This is the name of the game.
/B	B = A.
/D	If the technology is not reasonably achievable, the option is not there.
/I	Very important hazard; cost should be a separate consideration.
/J (?)	Costs are not important; the availability of a technology is.

Respondent No./ Parameter	Comments
/N	Classification of waste forms is a necessary step.
/P	True decomissioning to really allow unrestricted use is probably impossible.
/Q	Exposures can be controlled in practically any option.
34/F	Reflected in part in M.
/G	Does this include energy-related resources?
/I	Should separate costs from hazards.
/J	Does this include costs of monitoring?
/M	Closely related to F.
/O	Reflected in part in J.
35/General	I have some problems with the survey as indicated below. In general, I disagree that all of the factors are subjective. Dose-to-man, costs/mrem, availability of sites, etc. are not subjective. It would help if initial conditions were stated, i.e. all options will meet EPA requirements, and the evaluation is based upon how much better one option is than another, but all are acceptable. It won't get licensed if it is an unsafe practice, so why consider it.
/A	Assuming containment is adequate, the degree of additional containment is not important.
/B	Question is not clear. After disposal, question A covers this. If disposal operations is the issue, it's very important.
/C	Depends upon initial concentration of waste and toxicity/time. If low, then not too important (20). If high, very important (80).
/D	We will get what we want.
/E	Don't understand. If sites are not available, why consider option?

Respondent No./ Parameter	Comments
/F	Assuming containment, this is not important.
/G	I don't think the alternatives will be that much different.
/H	Do we want electricity or forests?
/I	Only variable should be distance and change of hazard is small.
/J	Again, it depends upon degree. If cost change is large, then important (75). If cost change is small, then not important (15).
/K	Essential
/L	On a technical basis, not important (5). On a political basis, important (90).
/M	Important.
/N	I have no idea what this means.
/O	Unimportant.
/P	Why unrestricted use? Unimportant.
/Q	Assuming standards are met, not important.
36/B	High need to quantify.
/D	Can be developed.
/E	Can be located.
/R	Waste Treatment Needs (degree or costs of sophisticated waste treatment required to generate acceptable physical and chemical forms).
37/A	Suggest degree of containment be one parameter (100) and duration of containment be a second parameter (100).
/C	Consequences of non-routine hazards need to be correlated with frequencies of non-routine hazards.

Respondent No./ Parameter	Comments
/H	Assume sites would be located where relatively few people would be impacted.
/M	See R1.
/P	Restricted use of site may be acceptable.
/R1	Possibility of Remedial Action (if containment unacceptable).
/R2	Site Maintenance Requirements (not just surveillance, but requirements both during operation and after closure of site). (Cf. 29/R.)
38/General	Two of us assigned numbers to your weighting factors independently; we agree that we can't do your questionnaire justice without a better understanding of the ground rules. We think we've got some valid inputs to your study; in fact, we have probably given more thought to this general subject than anyone else around. If the protocol of NRC/DOE interactions will permit, we should talk about this face-to-face.
40/R	(unspecified)
42/B	This is the end goal! All other factors influence, ultimately, this one.
43/A, B & C	Can't answer. Would depend on site characteristics.
/F	Not for low level.
/K	For limited period.
/P	Depends on site.
44/A, B & C	These are really the same.
/N	Also part of A, B & C.
/P	Incompatible with "disposal".
45/A	Should be multi-barrier.
/C	Considered during site selection process.

Respondent No./ Parameter	Comments
/F	Should not be relied upon for design considerations.
/G	Should be comparatively small.
/K	Only required for short term.
/L	This could be most important parameter for many sites.
/Q	Should follow ALARA considerations.
46/A,B,C,D & G	Quantative factor: failure to meet minimum values unacceptable, but values greater than upper range not important.
/General	I must explain what these weighting factors mean to me. For waste containment, public hazards protection, non-routine hazard, status of technology, resource commitments, environmental impacts, transportation, economic costs, sociopolitical implications, corrective actions, compatibility with waste, energy consumption, decommissioning implications and occupational exposures each has a range of values which is relevant in the design criteria. At one end of this range, the values represent a threshold and any of these values if outside the range at this end would be unacceptable. If, for example, waste containment were non-existent, such a scheme of waste management would not be acceptable and at the other boundary by proper design, values of these parameters can be established which in turn make the value of improvement trivial so that we may have at one end a value of 100 which we would say is a go/no-go situation and at the other end a value of zero. Now my weighting factors don't weight the relative importance of these, but represent my opinion of which end of the scale we are now able to anticipate in a reasonable facility design. In other words when I put economic costs down as values of 10, that means I believe that the cost of any of the reasonable well designed disposal schemes would be very small compared to the total cost of the energy generated in the fuel cycle. It does not mean that costs are not important, but that they will be low in relation to other fuel cycle costs. Other

Respondent No./ Parameter	Comments
	factors were judged similarly. In my evaluation of socio-political implications, for example, I believe that this is a major problem close to a critical value of 100. I hope that this interpretation is responsive to your evaluations and I really believe that we should discuss this to some extent before you place much importance on the results of your survey.
47/B	Hazard should be ALARA.
/D	Tech must be available; question is how good is it?
/E	Ditto tech observation.
/L	Major factor.
48/A	Excludes non-routine hazards.
/K	Difference in short- and long-term.
/P	What are you going to dispose of? Any transuranics?
49/A	Composed of degree of containment and isolation.
50/A	Solidification 200 years after burial.
/B	Routine spillage.
/C	Packaging for transportation.
/D	Volume reduction and solidification technology.
/E	Inspection, plant design and transportation.
/G	Land for burial.
/H	Not many.
/I	Routine expenses, costs and accidents.
/J	Overall fuel cycle costs.
/K	Know how to do.

Respondent No./ Parameter	Comments
/L	Related to E.
/M	Good site selection important.
/N	Animal carcasses and organic surface leaching.
/O	Transportation.
/Q	Trench utilization vs. dose tradeoff.
/R	Automation of work.
/R	Solidification and volume reduction (Cf. 52/R.)
/R	Criteria for Disposal Based on Treatment and Transportation (Cf. 21/R and 24/R.)
51/C	100 if the hazard has high consequence.
/E	"Go/no-go" parameter.
/H	Other than public health (see B).
/K	Meaningful monitoring required.
/N	"Go/no-go" parameter.
/R	Need for alternative ("go/no-go" parameter that in these should be a meaningful volume of waste which can be disposed of to the alternative being considered).
52/R	Volume Reduction (Cf. 50/R.)
/R	TRU Leachability.
55/A,B, & C	These items might not be different (from) each other from a radiological safety aspect.
/D	Required technology for LLW disposal has been developed well.
/E	If site is not available land burial of waste is impossible.
/G	Valuable site for resources should not be used as disposal site.

Respondent No./ Parameter	Comments
/Q	Occupational exposure could be reduced easily by protective apparatus.
56/R	A probabilistic analysis of comparative hazards of high probability - low consequence events and low probability - high consequence events.
57/M	Cost.
/R	Criteria.
/R	Site Characterization. (Knowledge of geology, hydrology, meterology, chemistry, etc. of site in use or proposed for use.) (Cf. 24/R and 27/R.)
59/R	Effect of Design on Ultimate D & D Costs.
60/C	Half-life dependent.
/D	For an alternative to be viable, the technology must exist.
/F	Non-TRU, not very long $t_{1/2}$.
/H	Aesthetics of little consequence.
/M	Depends on definition of unacceptable.
/R	Definition of low-level waste.
/R	Water Management (depending on site and alternative.)
62/General	As you will note, I have changed your form to reflect my proposed solution to certain difficulties that I had with the use of the form. My main point is that there are some "threshold characteristics" that any alternative must satisfy in order to be considered at all. Any such threshold characteristic is obviously of paramount importance. However, once that characteristic is satisfied, the factor may have little or no bearing in a comparison with another alternative which also satisfies such characteristic. In other words, in comparing between alternatives that satisfy threshold characteristics, undue weight should not be given to excessively

Respondent No./ Parameter	Comments
	meeting certain requirements. For example, if shallow land burial satisfies "containment" requirements for LLW, it should not be unduly penalized because it is not geological disposal. Accordingly, I have revised your form to contain, in essence, two separate lists: one which identifies what I considered to be "threshold characteristics" that must be satisfied, and another which weighs the importance of each characteristic assuming that all threshold characteristics have been satisfied. My comments on some of these factors are also attached to the form.
/A Threshold	I realize that you acknowledge an overlap between various factors, but I think that clearer definitions might avoid some confusion and duplication. As Dr. Leddicotte, et al., have discussed in their paper at the NRC-EPA Conference in Atlanta (May 1977) and in their forthcoming paper at Tucson (March 1978), there are two goals of interest: "containment" (keeping materials at or near the place where they were originally put) and "isolation" (placing material in such a place that intrusion by man or nature is unlikely). In my view, your factor A should reflect the foregoing definition of "containment" and should obviously encompass any "public hazard" arising from the degree and duration of containment provided. Your factor B should exclude the foregoing hazards, should be entitled something like "Operational Hazards" and should refer to hazards from routine operations (e.g. effluents from incineration) or from expected accidents (e.g. spills during handling). Your factor C should exclude the foregoing "containment" hazards and "operational hazards" and should be limited to long-range problems such as natural catastrophes, changes in environmental conditions, etc. In addition, a new factor "S" should be added (entitled "Isolation") which would reflect the above definition of "isolation". I have used my revised definitions in filling out the form. As you will note, I believe that "A", "B" and "C" (as I define them) are threshold characteristics, i.e. an alternative must satisfy certain basic requirements to be considered.

Respondent No./ Parameter	Comments
	This does not mean, for example, that "containment" must be absolute, but only that resulting releases would be within acceptable limits. As you will note, I do not view factor "S" ("isolation") as a threshold characteristic.
/B Threshold	See comment under A.
/C Threshold	See comment under A.
/D Threshold	In order to be considered, an alternative should involve technology which is either available or clearly able to be developed.
/E Threshold	This does not mean that an unlimited number of sites must be available but that at least some sites must be.
/F Non-Thr.	---
/G Non-Thr.	Unlikely to be significant for LLW.
/H Non-Thr.	I think environmental impacts are unlikely to be significant for LLW, but any alternative that does have such impacts should be penalized.
/I Non-Thr.	For LLW, transportation hazards are unlikely to be significant. Transportation costs should be reflected in factor "J" which should include all economic costs.
/J Non-Thr.	Assuming that threshold characteristics are met, alternatives should be encouraged that minimize occupational exposure and economic costs.
/K Non-Thr.	---
/L Non-Thr.	An alternative that satisfies the threshold characteristics should not face overwhelming problems pertaining to social, political and institutional acceptance.
/M Non-Thr.	Not likely to be necessary for LLW.
/N Threshold	If an alternative is compatible with many types of wastes, it would tend to reduce the number of alternatives that must be implemented.

Respondent No./ Parameter	Comments
/O Non-Thr.	---
/P Non-Thr.	---
/Q Non-Thr.	See comment under J.
/S Non-Thr.	Isolation (although "isolation" is not required for LLW, it is an important consideration).
63/D	Need good techniques for volume reduction.
/E	Very important, but good sites are available.
/F	Almost impossible.
/G	Doesn't need much.
/H	Trivial except for B.
/K	Short term; should not depend on monitoring forever.
/L	Most important.
/M	It won't be too late.
/N	Providing all is LLW.
/P	This will be important for old reactors, etc.
64/General	I find great difficulty in replying to your letter. My knowledge of the status of the 17 parameters is not broad enough to give a comprehensive reply as you request. I use the word "status" because if the status of a parameter is such that most problems are solved, that parameter probably is of less importance than another where many problems are still unresolved.
/L	This I do know: the not-knowledgable, poorly informed group of well-intentioned intervenors have brought nuclear power development almost to a halt. The most acceptable alternative for radwaste disposal will be one that can best be sold to these people. Consequently parameter "L" is ranked high above all others.

Respondent No./ Parameter	Comments
67/General	I left the waste business for the the solar business several years ago. My opinion is not that of a waste expert.
/J & O	The cost of doing the job right is minute compared with total power costs in the nuclear cycle.
/R	Partitioning to provide storage appropriate to varying life time (My personal belief is that sorting out the isotopes which have essentially infinite life and treating them as such is essential.)
68/P	Unrestricted utilization is unrealistic.
71/B	Why not "risk"?
/C	Why not "risk"?
/D	Does this include treatment?
/F	Disposal implies no retrieval.
/R	Volume Reduction (affects several other parameters).
72/General	I have serious reservations about using weightings as a basis for selecting among alternative sites. There are a number of theoretical concerns in using linear scoring and making functions that should be considered before adopting such an approach.
73/R	Waste Segregation and Volume Control during Generation of Waste (this holds promise for significant economic, public and resource conservation advantage).
75/H	Long term.
80/R	Public Acceptance.
82/R	
83/C	Institutional control major factor.
/H	Public health major factor.
/L	Unfortunately this is always controlling.

Respondent No./ Parameter	Comments
84/General	The key of selecting optimum alternatives is to choose the least annual cost of disposal system operation. However, the potential health effects resulting from each assumed system should always be maintained below innocuous levels at any time and at any space (sic). To evaluate the total system cost, all of the parameters listed in the table, except perhaps retrievability, state of technology and the social implications, should be considered. This evaluation of each parameter contains either 100 or 0 as they represent those to be or not to be considered.
85/R	(Unspecified)
88/P	There will be no decommissioning.
89/I	Should not consider "costs" and "hazards" together in one parameter.
/General	The relative importance of some of the parameters could be very much affected by whether one does or does not assume that the waste includes significant quantities of long-lived alpha contamination (TRU waste). I have assumed it does not.
90/General	One problem with these factors is that they can't all be specified with the same degree of certainty. Relative weighting of the importance of these for a disposal option under consideration is also made difficult in that some are qualitative and others can be quantitative to a certain extent.
91/A	Same as B!
/B	Key to the whole business.
/C	Scenarios dependent.
/D	If no technology available, item should not be considered.
/I	If we believe NUREG 0271.
/K	Related directly to J.

Respondent No./ Parameter	Comments
91/L	Public relations included.
/M	Related to F as a next step? Related to J directly.
/N	Don't consider if not compatible.
/O	Relates to J.
/P	Depends on extent of D & D contemplated as necessary.
92/R	(Unspecified)
94/C	A high value for A seems to imply C!
/D	Can normally be developed.
/R	Solubility or Vapor Pressure of Waste Forms.
95/P	Not applicable to disposal.
/R	Hydrogeology if not included in A. Retardation capacity if not included in A.
96/D	Dependent on time frame and urgency.
/J	Economics should not be dictating factor at expense of others.
/P	By definition, isn't disposal permanent rather than temporary, thus precluding decommissioning.
97-102/A	The waste is assumed to be packaged or geologically contained.
/D	The word "technology" is understood to mean proven technology.
/E	The word "sites" is understood to mean acceptable sites.
/N	Clarification needed, e.g. regarding nuclear or non-nuclear types or segregation within the nuclear type.

Respondent No./ Parameter	Comments
/P	Decommissioning is only important if storage is considered retrievable or temporary. If site is considered to be permanent storage, no effect should be given to decommissioning.
/R	Waste Generation Rate Implementation and Satisfaction of NEPA Requirements.
103/R	Public Perception.
105/E	Appropriate site!
/M	Why just costs? Why not question possibility of response of West Valley.
/General	Many of the above categories are facets of the same problem and merely getting numbers to identify their importance is not going to move you nearer to (a) understanding or (b) solution. I personally think that what you are doing is a waste of time and $$.
108/A & B	These should be based upon realistic considerations.
/C	Low probability; therefore, low importance.
/G	Should be in perspective with real - not perceived - hazards.
/I	Important as this is probably a greater accident potential here.
/K	Best sites/methods may be the most difficult to monitor to "prove" effectiveness.
/O	Unless excessive.
109/A	The major overriding concern, although zero release is not a prerequisite.
/B	Interrelated with A and of equal importance. Containment will be defined in terms of public hazard.
/C	An important consideration. However, there is a limit on what can be foreseen, and all predictions will ultimately rest on opinions/ assumptions of probability. Consequently, while important, must be ranked lower than B due to speculative nature of studies.

Respondent No./ Parameter	Comments
/D	Well advanced for many alternatives, so options are available and this is not a primary consideration.
/E	Sites exist for all options. Principally affects cost and safety of transportation.
/F	A frivolous issue if containment is adequate. A + F = 100.
/G	Small concern for any option.
/H	An important consideration, but must be viewed in perspective.
/I	Most studies show that transportation represents the major concern in minimizing public hazard.
/J	There is only a finite amount of money to spend, so cost must be carefully examined. J + H = 100.
/K	Proper disposal should not require a significant effort. B + K = 100.
109/L	Acceptance is a necessary prerequisite to any disposal alternative.
/M	Cost is no object if this is necessary. The need for this is influenced principally by non-routine events, therefore C + M = 100.
/N	The best alternative for one waste type may not be the best for other wastes. It is appropriate to be fully aware of the implications of trying to impose a "universal solution".
/O	Waste Disposal will never be a significant drain on energy resources.
/P	Principally a cost issue that has to be considered to assure the public that the total implications of any solution have been addressed. Totally unrestricted reuse of the area may not be possible for some alternatives.

Respondent No./ Parameter	Comments
/Q	In principal, this is as important as public hazards, although in practice the importance is tempered by: (a) Workers acknowledgement of risks. (b) Use of monitoring procedures that are not practical for the general public.
/R	Waste Management Practices. (It is important to consider waste generation processes from the standpoint of minimizing the volumes of wastes for disposal, through recycle and reuse, as well as improved administrative practices and technology.)
112/N	Don't understand this factor.
/P	Not obvious what decommissioning really means in this context.
/R	Time Factor for Availability.
117/R	Waste Criteria.
/R	Site Quality Control
/R	Site Selection.
121/A	As distinguished from B.
/H	(Non-human health impacts.)
/L	If you can't do it, you won't. Don't worry about this otherwise.
/O	Except as contribution to cost.
/Q	Workers' health is just as important as anyone else's.
125/A	Packaging containers are useful during handling prior to disposal only.
/D	If it is not available, sources for readily containing it should be.
/E	Not necessarily on site where the waste is generated.

Respondent No./ Parameter	Comments
/R	Compatibility with a Variety of Programs.
/R	Adaptability to Waste Previously Generated or Identity of What Waste Is Being Considered Here.
126/A	These are two different factors, degree and duration, and should be separated.
/B	This overlaps - - + half the others.
/C	What is meant by hazards? Low level radiation doses to a few people or actual health effects?
/F	This is part of item M.
/I	(Transportation may be resolved into) costs and hazards which are part of other factors listed.
/J	(He rates the weighting factor at 10) assuming that no reasonable alternative will significantly affect cost of nuclear power.
/K	What is long term?
/M	Available technology? This is relevant to retrievability.
/O	Part of item G.
/P	(Decommissioning Implications may be resolved into) costs and risks which are two different things.
/R	At least, a scale of 1 to 10 is realistic, and possibly only 1-5 for this kind of exercise.
128/General	The submitted questions were examined by our team in charge of our program on waste disposal in geological formations. It appeared that in some cases quite different quotations were assigned to some criteria. However, after discussion it was clear that these differences were due to shades in the interpretation of the description text. Finally there was a general agreement on the

Respondent No./ Parameter	Comments
	answers as presented in the joined questionnaire. It is unfortunately not possible to give here all the comments which were brought forward during our discussions. Meanwhile we wish to clarify our position with regard to the following points.
/H	Biota--for whom the problem needs in priority an acceptable technical solution as far as health hazards are concerned.
/I	Hazards--the quotations 100 and 0 were ruled out because it was assumed that all mentioned criteria have at least to be considered and no one can be taken individually.
/M	Costs--even for low-level waste, the acceptability of a disposal site can be a function of the total waste volume foreseen, its chemical form and the half-life of some radionuclides.

GLOSSARY

Abbreviations/Terms	Definitions
aquifer	subsurface geologic formation which has sufficient permeability to store and transmit useful amounts of water.
argillaceous	containing or consisting of clay, a term commonly associated with the names of rocks.
buried channel	an active or abandoned subsurface water course.
conditioning	the treatment of a radioactive waste in order to facilitate its subsequent disposal.
connate water	fossil or ancient water stored below the zone of the active water table.
containment	the holding of the substance in question in a confined, well-defined location for a very long time, perhaps permanently.
Curie (Ci)	measure of radioactive decay, 3.7×10^{10} disintegrations per second.
diapiric	anticlines in which a mobile core, such as salt, has injected the more brittle overlying rock.
dispersal	the dilution and widespread distribution of the substance in question in a chosen medium.
disposal	as employed here the removal of radioactive materials from many environs by some means.
effluent	fluid releases (airborne or liquid) from operating facilities that may contain very low levels of radioactivity in compliance with existing regulations.

GLOSSARY (Cont)

Abbreviations/Terms	Definitions
fault	fracture in the earth's crust on which there has been displacement along the line of the break.
fission products	radioactive materials resulting from the fission process, a major contributor of activity to low-level radioactive wastes.
fractionation	the separation of short- and long-lived fission products or transuranics from one another.
glacial shield	an area of extreme glaciation where unconsolidated glacial deposits overlie highly impervious, older bedrock.
high-level waste (HLW)	high-level radioactive waste typically from the first stage of the fuel reprocessing cycle.
hydrofracture	the fracturing of a geologic stratum around a bore hole to dispose of fluids or to stimulate the production of gas, oil or water.
injection well	a drilled well of the desired diameter and depth for the injection or emplacement of waste.
ionosphere	the part of the earth's atmosphere beyond the stratosphere in an approximate range of 40 to 400 km from the earth and composed of charged particles.
kCi	the kilocurie = 10^3 Ci
leaching pond	a lined or unlined basin designed to allow chemical concentration of dissolved constituents by percolation or evaporation.
lithosphere	the outer part of the earth having rock like that at the surface.

GLOSSARY (Cont)

Abbreviations/Terms	Definitions
Low-level Waste (LLW)	for present purposes, low-level is defined to be those waste forms containing less radioactivity than HLW.
magma	the molten rock within the earth from which igneous rock results by cooling and solidification.
mantle	the rock layer between the earth's crust and the core. The crust is usually defined as between 10 and 35 km thick, and the mantle as 2900 km thick.
MPC	maximum permissible concentration of a radioisotope as given in 10CFR20, Jan. 1, 1976.
μCi	the microcurie = 10^{-6}Ci
nCi	the nanocurie = 10^{-9}Ci
partitioning	the separation of fission products from transuranics.
perched water	subsurface water existing or trapped in a restricted aquifer above the active water table.
playa basin	a level or nearly level area occupying the lowest part of a closed basin that is covered intermittently with water. The basin consists of stratified beds of fine-grained sediment containing high percentages of soluble salts.
pCi	the picocurie = 10^{-12}Ci
piezometric surface	the resultant groundwater level influenced by hydrostatic and atmospheric pressures as measured in drill holes penetrating an aquifer zone.

GLOSSARY (Cont)

Abbreviations/Terms	Definitions
salt dome	a domal structure above or below the surface resulting from the upward movement of a salt mass; e.g. gypsum or sodium chloride.
scavenging	the "washout" of radioactivity from a stack's discharge by precipitation; e.g. rain or snow.
seepage basin	an unlined waste storage basin designed to allow seepage of effluent of reduced radioactivity to the substrata.
shale	a stratified, fissile sedimentary rock in which the constituent particles are predominantly clays.
sink hole	a funnel-shaped depression in the land surface generally occurring in limestone regions as a result of the collapse of a cavern roof and usually interconnected with deep subsurface liquid flow.
solution cavity	a solution-filled, otherwise empty void resulting from the dissolving of gypsum or other salt deposit.
stratigraphic/structural trap	a geologic feature within the earth's crust which can act as a solution reservoir (such as an anticline, syncline or fault zone).
stratosphere	a portion of the earth's atmosphere rarely having clouds and in which temperature varies little with altitude. It begins roughly 11 km from the earth depending upon the season and other factors.

GLOSSARY (Cont)

Abbreviations/Terms	Definitions
subduction zone	a zone being slowly drawn beneath the rock from a deep trench in the seabed.
substrata	geologic formations within the earth's upper crust but below the surface.
tailings, mine	the processed mine ore stripped of the desired component.
tailings pond	a pond built up from mine tailings on the periphery impounding associated water in the middle.
transuranics	materials appearing after uranium on the periodic table having atomic values of greater than 92. Plutonium is a major transuranic of concern in radioactive waste management.
troposphere	the part of the earth's atmosphere beneath the stratosphere.

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A systematic method for categorizing waste disposal alternatives which provides assurance that no viable alternatives are overlooked is reported. Alternatives are categorized by (1) the general media in which disposal occurs, (2) by whether the disposal method can be considered as dispersal, containment or elimination of the wastes, and (3) by the applicability of the disposal method to the possible physical waste forms. A literature survey was performed and pertinent references listed for the various alternatives discussed. A bibliography is given which provides coverage of published information on low-level radioactive waste management options. The extensive list of disposal alternatives identified was screened and the most viable choices were selected for further evaluation. A Technical Advisory Panel met and reviewed the results. Suggestions from that meeting and other comments are discussed. The most viable options selected for further evaluation are: (1) Improving present shallow land burial practices; (2) Deeper depth burial; (3) Disposal in cavities; (4) Disposal in exposed or buried structures; and (5) Ocean disposal.

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