NUREG/CR-0680
FBDU-209-03

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

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Prepared For
U.S. Nuclear Regulatory Commission

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Manuscript Completed: May 1979
Date Published: July 1979

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Prepared for
The U.S. Nuclear Regulatory Commission
Low-Level Waste Branch

NRC FIN No. B1521

NOTICE

ABSTRACT

A comparative analysis of the most viable alternatives for disposal of solid low-level radioactive wastes is presented to aid in evaluating national waste management options. Four basic alternative methods are analyzed and compared to the present practice of shallow land burial. These include deeper burial, disposal in mined cavities, disposal in engineered structures, and disposal in the oceans. Some variations in the basic methods are also presented. Technical, sociopolitical, and economic factors are assigned relative importances (weights) and evaluated for the various alternatives. Based on disposal of a constant volume of waste with given nuclear characteristics, the most desirable alternatives to shallow land burial in descending order of desirability appear to be: improving present practices, deeper burial, use of acceptable abandoned mines, new mines, ocean dumping, and structural disposal concepts. It must be emphasized that the evaluations reported here are generic, and use of other weights or different values for specific sites could change the conclusions and ordering of alternatives determined in this study. Impacts and costs associated with transportation over long distances predominate over differences among alternatives, indicating the desireability of establishing regional waste disposal locations. The impacts presented are for generic comparisons among alternatives, and are not intended to be predictive of the performance of any actual waste disposal facility.

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

1. INTRODUCTION

This report describes an evaluation performed for the U.S. Nuclear Regulatory Commission (NRC) by Ford, Bacon & Davis Utah Inc. (FBDU) of alternative methods for the disposal of low-level radioactive wastes. This chapter provides the background for the report, and summarizes earlier work.[1]

1.1 Background

Radioactive wastes have been disposed of since the beginning of the nuclear age in the 1940's. Wastes from activities involving nuclear materials are considered hazardous because of their radioactivity, and appropriate means of disposal are of international concern.[2] Although radioactive wastes have been handled and disposed of safely for the past 30 years, concern exists for providing even greater levels of public safety in waste management operations.

Initially, the Federal government assumed responsibility for disposal of radioactive wastes. Later, with increased industrial participation in the nuclear industry, commercial radioactive waste disposal services were provided by private industry licensed and regulated by the Atomic Energy Commission (AEC, now NRC) and Agreement States. The Federal government continued to manage and dispose of wastes generated from defense programs at government operated sites. Federal government sites were and continue to be exempt from NRC or Agreement State regulatory control.

Since 1962, low-level radioactive waste has been almost totally disposed of by shallow land burial where packaged wastes are placed in trenches and covered with the previously excavated soil. Disposal sites were initially selected with geologic and hydrologic characteristics which were expected to provide a high degree of assurance that radioactivity would not migrate from the sites. The ion exchange properties of the soils were expected to trap and retain radioactive materials which might be leached from the wastes. No reliance was placed on waste packaging for containment. Packaging was provided only to meet transportation requirements and provide ease in handling the waste when it was received at the site. Although in some cases the containment of wastes has been less than initially expected, no large health hazards to members of the public have resulted from waste disposal operations.

In the past, low-level wastes were also disposed of by ocean dumping at designated sites.[3] Disposal in the ocean was accomplished by dumping the containerized wastes over the side of a ship at specific locations in the ocean and letting the waste packages settle to the ocean floor. In 1960, the AEC began to phase out sea disposal in this country by issuing no new sea disposal licenses and by allowing existing sea disposal licenses to expire. The last U.S. disposal at sea took place in 1970.

Currently, over 60,000 m^3 of commercial low-level waste are disposed of each year at commercial sites and about 35,000 m^3/yr of waste generated in Federal defense programs are disposed of at Department of Energy (DOE) operated sites. The commercial wastes are generated by various sources, including hospitals, industry, educational and research institutions, and nuclear power production facilities. Because of uncertainty in the rate of development of additional nuclear power facilities, projections of future waste volumes are not firm. However, the need for handling low-level radioactive wastes will definitely continue into the future.

Under the Marine Protection, Research and Sanctuaries Act of 1972, the Environmental Protection Agency (EPA) has responsibility for developing criteria and issuing permits for sea disposal of low-level wastes. NRC's authority for licensing land and sea disposal operations is provided in the Atomic Energy Act of 1954, as amended, and the Energy Reorganization Act of 1974. Under Section 274 of the Atomic Energy Act, the NRC may delegate to individual states responsibility for licensing the possession of by-product, source and small quantities of special nuclear materials, including licensing of low-level waste land disposal operations. States that have assumed such responsibility are termed Agreement States.

Under the Atomic Energy Act of 1954, as amended, and the Energy Reorganization Act of 1974, NRC has been given responsibility for ensuring that commercial radioactive waste management operations are performed in a safe and effective manner. DOE has responsibility for developing adequate methods for waste management operations, and EPA is establishing guidelines to assure that the quality of the environment is not compromised.[4]

The NRC is developing regulations for governing the management and disposal of low-level wastes, and preparing for subsequent licensing and regulatory activities.[5] To carry out this responsibility, it is necessary for NRC to consider all reasonable methods for disposal of low-level radioactive wastes. NRC has contracted with FBDU to perform a study of alternate low-level radioactive waste disposal options, to ensure that all viable disposal methods have been considered. This report describes a comprehensive comparative analysis of the most viable alternative disposal methods.

1.2 Scope and Objectives of the Study

The scope of this study includes the investigation of possible alternatives for disposal of low-level radioactive wastes. A comprehensive review of all possible methods which have been identified or proposed for low-level radioactive waste disposal was performed. A systematic methodology for identifying disposal options was used to ensure that no viable choices were overlooked. This included identifying, cataloging and describing possible low-level waste disposal alternatives. Exhaustive listings of minor variations and combinations of approaches were not undertaken because of the generic level at which alternatives are discussed. Consequently, while all major concepts were treated, specific sub-classes and variations, such as differences in locations, operational details, and site-specific parameters, were not elaborated in detail.

A second objective of the study was to evaluate each alternative identified and select those that are the most viable alternatives for disposal of solid low-level waste. 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 was consulted for review and guidance. A formal report of this phase of the study has been published.[1] A list of panel members is included as Appendix A.

Another objective of this study was to evaluate the most viable alternatives using a rigorous and detailed analysis. The alternatives were compared with the base case of solid low-level waste disposal by shallow land burial. The results of this effort are presented in a convenient matrix format.

1.3 Characterization of Low-Level Radioactive Waste

Radioactive wastes can be broadly classed by the intensity of the radiation they emit. For the purpose of this study, low-level wastes are considered to be radioactive wastes other than those specifically categorized as high-level and transuranic wastes, spent fuel, or mine and mill tailings. Low-level radioactive wastes contain lesser amounts of radioactivity per unit volume of waste than do high-level wastes. A more precise quantitative definition of low-level and other waste types is presently under development in another NRC study.[6]

Low-level radioactive wastes are produced from several sources. One source is power reactor operation, where small quantities of fission products escaping from the fuel elements, as well as traces of induced radioactivity, contaminate the coolant and various portions of the plant. The contaminated coolant is routinely treated to remove the radioactive contaminants, which are subsequently solidified. Materials immediately around the reactor core (the 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. Low-level radioactive wastes are also associated with other facilities and operations involved in nuclear power production--e.g., uranium enrichment facilities, reactor fuel fabrication plants, and reprocessing plants. Other sources of commercial low-level waste include discarded radioactive materials used in research, manufacturing, or medical applications.

The physical and chemical forms of low-level radioactive wastes are as diverse as their sources. Low-level wastes can range from slightly contaminated trash to highly activated structural components. They include animal carcasses and other biologic agents, spent ion-exchange resins, evaporator sludges, filters, solidified liquids, contaminated laboratory wares, and any other contaminated materials that may have contacted radioactive substances and are no longer needed. The radioactivity contained in the waste can have half lives that range from a few hours to thousands of years. Activity levels can range from barely detectable to extremely high values requiring extensive shielding to facilitate transportation and handling.[7]

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 both commercial and government disposal facilities,[8] excluding the wastes from uranium mining, milling and enriching operations.

1.4 Summary

The range of potential low-level radioactive waste disposal alternatives was divided into the categories shown in Figure 1.1. The categories were further subdivided to arrive at the specific disposal methods shown in Figure 1.2. After analysis and review, those alternatives warranting further evaluation were selected.[1] The alternatives selected are the basis for this report, and include the base case of typical shallow land burial, improvements to present practices, deeper burial, disposal in mined cavities, disposal in engineered structures, and disposal in the ocean. These alternatives and the subcategories evaluated in this study are listed in Table 1.1.

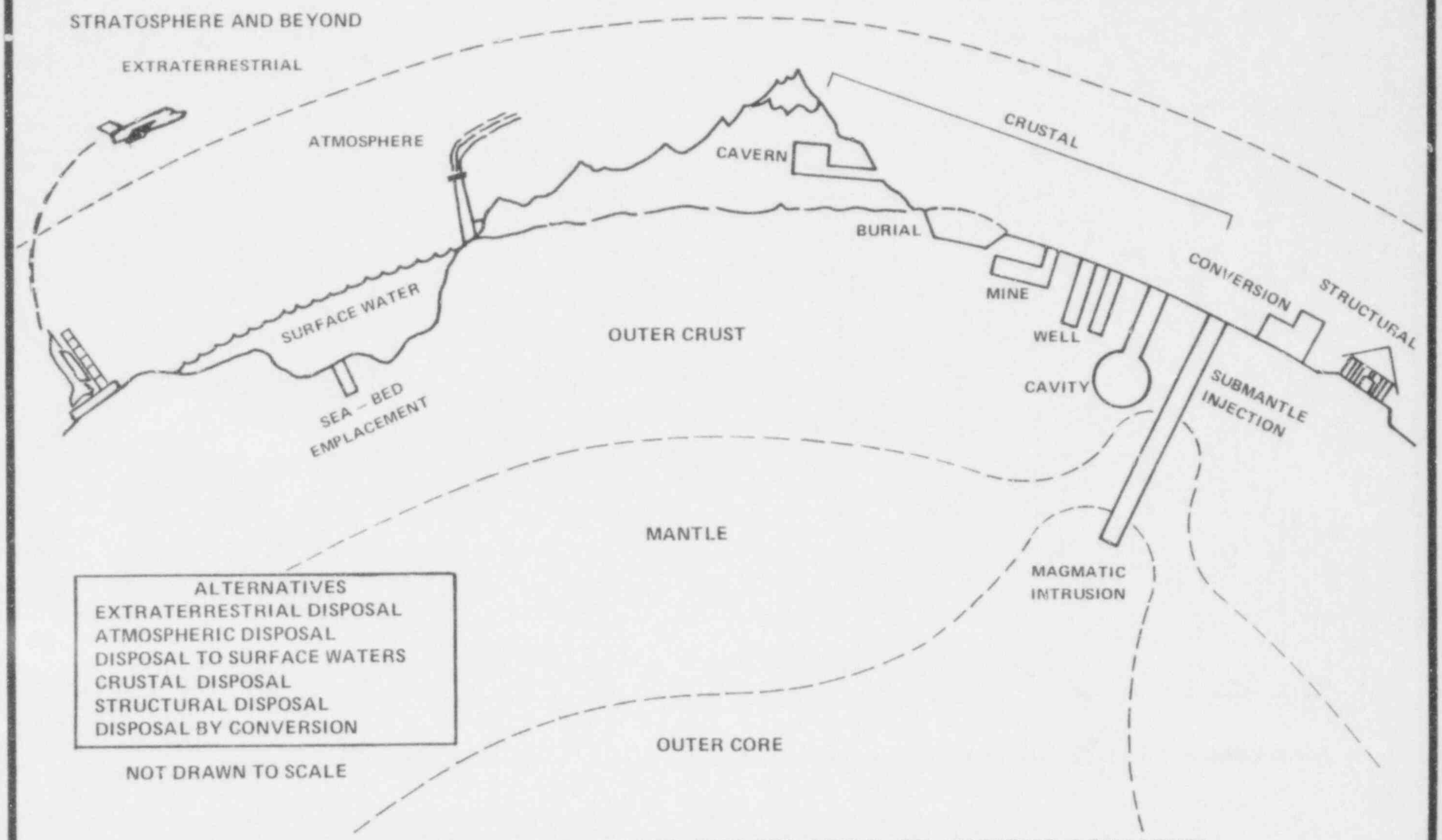

FIGURE 1.1 SCHEMATIC SHOWING THE RELATION OF VARIOUS LOW-LEVEL RADIOACTIVE WASTE DISPOSAL ALTERNATIVES TO THE EARTH

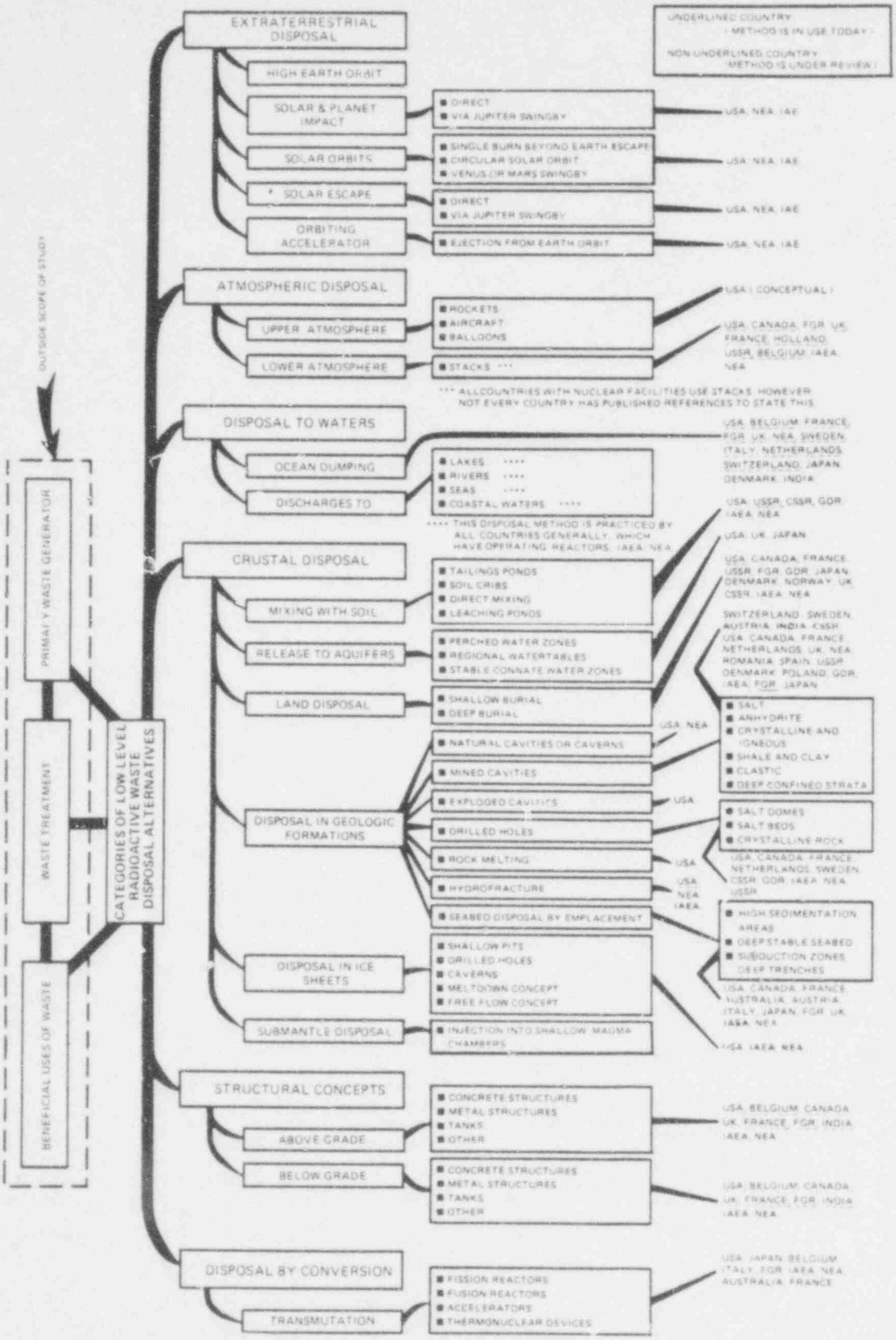

FIGURE 1.2 CATEGORIZATION OF ALTERNATIVES FOR DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTES

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TABLE 1.1

SELECTED ALTERNATIVES FOR LOW-LEVEL WASTE DISPOSAL

(Source: Ref 1)

Major Alternative Concepts and Variations Analyzed

- Shallow Land Burial (Base Case)
- Improvements to Shallow Land Burial
- Deeper Burial
- Mined Cavity Disposal
  - Existing Abandoned Mines
  - New Horizontal Shaft Mines
  - New Vertical Shaft Mines
- Disposal in Structures
  - Above Grade Exposed Structures
  - Below Grade Buried Structures
- Ocean Disposal
  - Direct Ocean Dumping
  - Projectile Disposal

For the generic alternatives selected for further evaluation, several additional factors require specification to allow a meaningful comparative analysis. These factors include the location, size, and type of disposal facility designed for each alternative method. For this study generic eastern U.S. and western U.S. locations and possible ocean disposal sites were assumed to obtain transportation factors, a volume of waste to be accommodated was given, and the disposal facilities were conceptually designed to reasonably accommodate and contain the wastes.

For the reference disposal facility and each alternative method studied, technical, sociopolitical and economic factors are evaluated as the basis of a comparative analysis. Technical factors considered include compatibility of the disposal facility with different waste types, site selection factors, safeguards implications, environmental effects, and availability of the disposal techniques. Sociopolitical factors were divided into considerations of adequacy of present institutional controls for regulation of the alternative disposal facilities and the likelihood of apparent public acceptance of the concept. The economic factors are based on estimated costs for the disposal facilities. They are stated in terms of their impact on consumers of electricity generated from nuclear reactors. A similar impact is assumed for industries generating other radioactive wastes. Each of these considerations is referred to as an evaluation factor in this report.

The evaluation factors determined in this analysis are presented in this report. It should be understood that the performance of any particular waste disposal facility will depend on the conditions that exist at the specific site, which may vary from those assumed for this study. Site- and facility-specific factors, were selected to yield conservatively high estimates of the potential impacts from waste disposal. Calculated values of the evaluation factors are normalized to the base case of shallow land burial prior to the comparative analysis, with values greater than unity indicating less desirability than the base case. Conversely, values less than unity indicate greater desireability. The relative importances of the evaluation factors were estimated and weights assigned (see Section 2.6) to allow an overall comparison among the alternatives.

Based on the weights and factors used in this study, it is concluded that several viable alternatives for low-level waste disposal are available, including improvements to present practices, deeper burial and disposal in mined cavities. Transportation costs and impacts dominate the comparisons between eastern and western sites, leading to the conclusion that regional disposal sites are desireable. Details are found in Chapter 4.

Further detailed study of specific sites and the most viable options appears warranted. Sensitivity of the analyses to variations in evaluation factor weights, duration of institutional control, and cost factors should be performed to verify these conclusions. Improved methods and models for estimating the impacts from waste disposal, especially those relating to differences between eastern and western locations, should be investigated. Methods for combining short and long-term impacts, including incorporating probabilities of occurrence of exposure events, also deserve further investigation.

A uniform, consistent approach has been taken for all alternatives evaluated in this report. The result is a rational basis for waste management comparisons and allows appropriate evaluation of tradeoffs among disposal options. It should be noted, however, that changing the weights, the site- or facility-specific factors used in determining the evaluation factors, or the methods of combining impacts may change some of the conclusions or relative rankings of alternatives presented in this study. The impacts presented are for comparison of alternatives only, and should not be considered as predictive of the performance of a specific waste disposal option.

2. METHODOLOGY

Reference disposal facilities for each alternative have been designed for performing comparative analyses of the different disposal options. These reference facilities are all based on disposal of a constant volume of waste having a given radioactivity inventory. The conceptual designs of the facilities are based on projections of design criteria for future waste disposal sites. The consequences of disposal of waste in the reference facilities provide a uniform basis for comparing the alternatives, with both costs and nonmonetary effects being appropriate indices for the comparison. The approach taken in this study is detailed in the following sections. It provides a consistent basis for comparing alternatives, appropriate to the preconceptual design stage of development of the reference disposal facilities.

2.1 General Approach

For each of the disposal concepts studied, a reference disposal facility was designed. The reference facilities were designed to reflect the types of disposal facilities that might be used in the future. They conform to reasonable constraints on availability, performance, cost and acceptability. Within these constraints, however, there is considerable flexibility in selecting specific design features. Specific designs for the reference facilities were as generic as possible, to represent the broad range of possibilities within a given alternative and to reflect the design features that might be reasonably expected in practice.

The reference disposal facilities and operations were all sized to accommodate a fixed volume of waste of given nuclear characteristics over the same time period. Some of the conceptual disposal facilities could easily handle more than the specified volumes of waste (ocean disposal, for instance), while others could require a substantial increase in capacity to handle additional volumes at one location. For the bulk of the waste volume, direct handling of the waste containers was assumed to be the method of emplacement in the disposal facility. The ability to accommodate remote handling may vary among the different disposal alternatives.

Assessments of environmental and radiological effects from operations at the reference disposal facilities and evaluation of the technological availability are included as part of the technical evaluations. Sociopolitical factors such as public acceptability and socioeconomic effects are considered for each reference disposal facility. The cost estimates provided are based on the generic reference disposal facility design and other variables, such as relative locations of suitable disposal sites in relationship to existing waste sources. The alternative disposal concepts are compared, based on the results of the analyses and evaluations of the generic reference facility designs.

2.2 Generic Waste Volumes and Characteristics

Reference waste volumes and characteristics were selected to represent low-level radioactive waste typical of that to be disposed of in the future. The sources and characteristics of low-level radioactive waste are extremely diverse. The reference characteristics used in this study, therefore, may not be typical of any single class of radioactive waste, but may represent averages over a broad spectrum of wastes.

The volume of waste to be disposed of was assumed to be 630,000 m^3, which approximates the output of 1,000 typical light-water reactors for one year (1,000 Reference Reactor Years (RRY) of low-level waste).[7] This volume of waste would correspond to roughly 800,000 megawatt-years of electricity production (MW(e)-yr). Wastes from non-fuel cycle sources would also be accomodated in the 630,000 m^3 capacity. The generic reference facilities were assumed to handle this volume of waste in a 20-year operating period.

The routine low-level waste containers that arrive at the disposal facility are generally assumed to be relatively contamination-free on the outer package surfaces to facilitate direct handling. Because 55-gallon (208-liter) drums are the most commonly used package in this country at present, this container was selected for use in the analyses. Choice of different container types and sizes is possible, but these differences are relatively unimportant to the conclusions of this study because, in general, no credit is taken for the containment provided after disposal by the primary packaging, and all disposal facilities are expected to accomodate similar wastes.

Based on experience in waste disposal,[7] 90% of the waste to be handled is assumed to have low radiation levels measured at the outside surfaces of the containers. However, the other 10% of the waste (mainly ion exchange resins and evaporator bottoms) is assumed to contain higher concentrations of radionuclides, which necessitates increased shielding and more remote handling to preclude unacceptable worker exposures. The reference waste inventory used for this study has been adjusted to reflect both radiation levels.

Table 2.1 lists the major radionuclides expected to be present at the time of disposal of the wastes. The nuclide concentrations are given for both the low and the higher radiation level fractions of the inventory. This inventory is derived from several sources,[7,8,9,10,11] and anticipates future low-level

TABLE 2.1

CHARACTERISTICS AND INVENTORY OF LOW-LEVEL RADIOACTIVE WASTES USED FOR COMPARISONS

Nuclide	Halflife (yr)	Concentration in Low-Level Waste (90% Fraction)(a) (Ci/m^{3})	Concentration in Higher Radiation Level Waste (10% Fraction)(b) (Ci/m^{3})	Total Site Inventory(c) (630,000 m^{3} total waste volume) (Ci)
^{3}H	12.3	0.12	--	6.8x10^{4}
^{14}C	5730	3.8x10^{-3}	--	2.2x10^{3}
^{51}Cr	0.08	4.3x10^{-2}(d)	65	4.1x10^{6}
^{54}Mn	0.86	2.5x10^{-2}(d)	40	2.5x10^{6}
^{55}Fe	2.7	4.3x10^{-1}	--	2.7x10^{4}
^{58}Co	0.19	4.3x10^{-2}(d)	65	4.1x10^{6}
^{59}Ni	8x10^{4}	1.3x10^{-3}(d)	--	7.4x10^{2}
^{60}Co	5.27	0.13(d)	200	1.3x10^{7}
^{63}Ni	100	0.24(d)	--	1.5x10^{5}
^{90}Sr	29	4.8x10^{-3}	--	2.7x10^{3}
^{99}Tc	2.1x10^{5}	3.2x10^{-5}	--	1.8x10^{1}
^{125}Sb	2.73	5.3x10^{-3}	--	3.0x10^{3}
^{129}I	1.6x10^{7}	6.4x10^{-6}	--	3.6
^{134}Cs	2.06	4.8x10^{-2}(d)	70	4.4x10^{6}
^{137}Cs	30.2	8.6x10^{-2}(d)	130	8.2x10^{6}
^{152}Eu	13	4.8x10^{-5}	--	2.7x10^{1}
^{226}Ra	1600	1.2x10^{-4}	--	6.8x10^{1}
^{230}Th	7.7x10^{4}	7.1x10^{-5}	--	4.0x10^{1}
^{232}Th	1.4x10^{10}	8.4x10^{-7}(d)	--	4.8x10^{-1}
^{235}U	7.0x10^{8}	3.2x10^{-6}(d)	--	1.8
^{237}Np	2.1x10^{6}	4.6x10^{-8}	--	2.6x10^{-2}
^{238}U	4.5x10^{9}	7.1x10^{-5}(d)	--	4.0x10^{1}
^{238}Pu	87.8	3.2x10^{-4}	--	1.8x10^{2}
^{239}Pu	2.4x10^{4}	4.3x10^{-5}	--	2.5x10^{1}
^{240}Pu	6540	6.7x10^{-5}	--	3.4x10^{1}
^{241}Pu	15	1.6x10^{-2}	--	9.1x10^{3}
^{242}Pu	3.9x10^{5}	2.4x10^{-7}	--	1.4x10^{-1}
^{241}Am	433	3.0x10^{-5}	--	1.7x10^{1}
^{243}Am	7370	2.1x10^{-6}	--	1.2
^{243}Cm	28	6.0x10^{-7}	--	3.4x10^{-1}
^{244}Cm	17.9	1.9x10^{-4}	--	1.1x10^{2}
	Totals	1.2	570	3.7x10^{7}

(a) Based on Table 1, Ref 9
(b) Based on Refs 7 and 10
(c) Activity at time of disposal
(d) 10% of value from Table 1, Ref 9

radioactive wastes from both nuclear power production facilities and non-fuel cycle functions.

Measured and derived concentrations of radionuclides in typical commercial low-level waste[9] are used as the basis for the lower radiation level fraction of the waste, assumed to be 90% of the total volume of waste handled. Some of the reported values for specific nuclides (Ref 9) have been divided by a factor of ten to account for the assumed concentrations of the higher radiation level wastes, and to correspond more closely to the values reported in the other references.[7,8,10,11] The nickel inventory in Ref. 9 accounts for eventual disposal of activated structural components from decommissioning of reactor facilities, while this source of waste is not generally included in the other referenced inventories. Because of uncertainties in ultimate methods of decontamination, decommissioning, and disposal, however, lower estimates of average nickel concentrations in low level waste are used in this generic inventory.

The higher radiation level fraction of the waste was assumed to be generated at nuclear power plants. The total concentration of energetic gamma emitting nuclides was assumed to be 570 Ci/m^3 in this fraction of the waste.[7] Because this waste is produced in nuclear power reactors, the isotopic production ratios for these activation and fission products were used to allocate the total activity.[10] Only those nuclides that emit quantities of radiologically important gamma rays are included in the higher radiation level inventory. The average concentration values for the other nuclides are taken to be applicable to the total 630,000 m^3 volume of waste.

The radionuclide concentrations in the waste are important because radiological impacts from waste disposal operations are directly proportional to the amounts of radioactivity handled. That is, if the concentrations are higher than those assumed, the calculated doses would be correspondingly higher. If the composition of future waste changes, the relative impacts from the various alternatives for disposing of that waste will vary. The comparisons of impacts presented in this study are based upon this specific inventory and may change if substantial changes in waste concentration are encountered.

It is assumed that the wastes will be packaged and shipped to the disposal site in compliance with established regulations and requirements in effect at the time. It is further assumed that any liquid wastes will be absorbed or solidified prior to transport to the disposal facility. Other potentially hazardous materials such as pyrophorics, explosives, toxins and biological agents are also assumed to be properly identified and reacted prior to shipment to the waste disposal facility. These assumptions and the radionuclide inventory given provide the basis for the analyses involving waste characteristics and handling operations.

2.3 Technical Evaluations

Based on the conceptual designs of the generic reference disposal facilities and the characteristics of the wastes described in the preceding subsection, the different options were analyzed to determine the technological feasibility, impacts on resources, and other short- and long-term effects from implementation of waste disposal operations. Specific requirements on waste form or packaging necessitated by given alternatives are identified. The relationships between site climatology, meteorology, hydrogeology, mineralogy and demography were generically investigated for the various alternatives. Safeguards and security (ability to prevent unauthorized use) requirements for the waste were assessed and the long- and short-term environmental effects calculated. (Essentially, the short-term effects are those arising before and during the operational phase of the facility, while long-term effects arise during the post-operational period.)

The current status of disposal technology required to satisfactorily implement each alternative was also assessed. Viable technology exists for implementing the disposal concepts addressed in this document. As new technology emerges, additional disposal concepts may be considered as viable alternatives. This study considers only choices for waste disposal which are presently available.

The environmental effects are divided into non-radiological and radiological impacts. The non-radiological effects include impacts on construction and waste management workers, and to the public along transportation routes. These impacts are based on estimated construction and operations crew sizes and comparisons with accident statistics for comparable industries.[12] Injury and fatality rates for the comparable industries used for the projections in this study are presented in Table 2.2.

Radiological impacts include direct radiation exposures to workers and the public along the transportation route and in the area of the disposal facility. The transportation routes are generalized into typical eastern and western U.S. categories. Table 2.3 summarizes transportation distances. An average population density of 300 persons per square mile along the transportation route[13,14] was used. A hypothetical eastern site is assumed to be located an average distance of 400 miles from the waste generators for both the burial and structural disposal concepts. A map showing locations of existing nuclear power reactors was used to provide average transportation distances from waste generators to potential disposal sites. For the eastern sites, a central location would average approximately 400 miles from the nearby waste generating facilities. Generation of non-fuel cycle wastes is assumed to be distributed reasonably uniformly across the country, so that transportation

TABLE 2.2

FATALITY AND TOTAL INJURY RATES FOR COMPARABLE INDUSTRIES (per 10^6 workhours)

(Source: Ref 12)

Industry	Total Fatalities and Permanent Disabilities	Total Injuries and Disabilities
Construction	0.17	14.7
Surface Mining	0.13	9.8
Non-Coal Mining, Underground	0.53	25.3
Storage and Warehousing	0.00	6.7
Transit	0.05	40.5

TABLE 2.3

SUMMARY OF TRANSPORTATION DISTANCES

Alternative	Average Distance to Generic Disposal Site (mi)	Annual Rail Car Mileage (one way) (mi/yr)
Shallow-Land Burial--Eastern Site	400	528,000
Shallow-Land Burial--Western Site	1,400	1,848,000
Improved Burial--Eastern Site	400	528,000
Improved Burial--Western Site	1,400	1,848,000
Deeper Burial--Eastern Site	400	528,000
Deeper Burial--Western Site	1,400	1,84[illegible]000
Adandoned Mine--Eastern Site	600	7[illegible]2,000
Abandoned Mine--Western Site	1,600	2,112,000
New Horizontal Shaft Mine--Eastern Site	600	792,000
New Horizontal Shaft Mine--Western Site	1,600	2,112,000
New Vertical Shaft Mine--Eastern Site	600	792,000
New Vertical Shaft Mine--Western Site	1,600	2,112,000
Above Grade Structure--Eastern Site	400	528,000
Above Grade Structure--Western Site	1,400	1,848,000
Buried Structure--Eastern Site	400	528,000
Buried Structure--Western Site	1,400	1,848,000
Direct Ocean Dumping	1,600	2,112,000
Ocean Projectile Disposal	1,600	2,112,000

distances are based on average distances from fuel cycle facilities. Because fewer power reactors and other nuclear waste sources are located in the west, the average transportation distance to a western disposal site would be greater than to an eastern site. An average distance of 1400 miles is used in this study for both land burial and structural disposal concepts at western sites.

Using the same transportation distances for the land burial and structural alternatives implies that suitable locations for both burial and structural disposal facilities involve similar average transportation distances. Even though an advantage of structural disposal facilities may be less restrictive requirements on the meteorological, geological and hydrological features of the site, the hypothetical nature of the potential disposal sites studied and the use of average distances to central locations does not justify any differentiation between the methods.

Because suitable locations for mined cavities are assumed to be more remote than those acceptable for shallow land burial, average distances are increased by 200 miles for both the eastern and western hypothetical sites. The average distance to deep sea shipping port with loading facilities for the low-level wastes (two on the East Coast, two on the West Coast, and one on the Gulf of Mexico) was determined to be 1600 miles, assuming that existing facilities in use for nuclear powered military vessels may be used.

Transportation costs and risks presented in this report are based on shipment of the waste to the disposal site by rail. Radiological risks are incurred only while the rail cars are loaded with wastes, although non-radiological accidents with injuries or fatalities are possible for the entire round trip. Current practice by most waste generators is shipment by truck, as smaller volumes of waste can be more efficiently accommodated. It is expected that future waste shipments will be made in the most cost- and risk-efficient manner, based on analyses of the specific sites and transportation routes involved. The selection of rail shipments for this study is intended only to facilitate meaningful comparisons among the alternatives. Use of this transportation method does not greatly change the associated shipping costs.[15] Risks for rail transport are slightly less than for trucks,[11,12,13,16] but either shipping method would result in the same relative order of impacts for the various alternatives. Use of train transport is therefore consistent with the objectives of this comparative analysis.

The meteorology, hydrogeology and climatology used in evaluating environmental effects are presented in Table 2.4. As shown in the table, eastern sites receive more rainfall than do western ones. The aquifers, assumed to be 10 m below the bottom of the shallow burial excavation and structural disposal facilities in

TABLE 2.4

SUMMARY OF ASSUMED METEOROLOGIC* AND HYDROGEOLOGIC FACTORS

Alternative	Depth to Underlying Aquifer (m)	Productivity of Aquifer (m^3/yr)
Shallow-Land Burial--Eastern Site	10	3.6×10^6
Shallow-Land Burial--Western Site	20	3.6×10^6
Improved Burial--Eastern Site	10	3.6×10^6
Improved Burial--Western Site	20	3.6×10^6
Deeper Burial--Eastern Site	10	3.6×10^6
Deeper Burial--Western Site	20	3.6×10^6
Adandoned Mine--Eastern Site	>100	N.A.(c)
Abandoned Mine--Western Site	>100	N.A.(6)**
New Horizontal Shaft Mine--Eastern Site	>100	N.A.
New Horizontal Shaft Mine--Western Site	>100	N.A.
New Vertical Shaft Mine--Eastern Site	>100	N.A.
New Vertical Shaft Mine--Western Site	>100	N.A.
Above Grade Structure--Eastern Site	10	3.6×10^6
Above Grade Structure--Western Site	20	3.6×10^6
Buried Structure--Eastern Site	10	3.6×10^6
Buried Structure--Western Site	20	3.6×10^6
Direct Ocean Dumping	N.A.	N.A.
Ocean Projectile Disposal	N.A.	N.A.

---

*Pascal Stability Class F with 1.56 m/sec wind speed, $_y = 7$ m and $_z = 3.5$ m at the directly downwind site boundary (160 m from point source) were used for airborne accident release calculations.

**N.A. = Not Applicable

the east, and 20 m in the west, probably would vary in productivity but have been sized to yield the same quantities of water for the purpose of uniform comparison. The mined cavities are assumed to be located in geologic formations far removed from productive aquifers. The potential environmental pathways to human radiation exposure from the various alternatives are based on the values listed in Tables 2.3 and 2.4. Appendix B contains a summary of these parameters for the existing low-level waste disposal sites in this country for perspective on the reasonableness of the values used in the comparative analysis.

The exposure pathways analyzed may not represent all the possible mechanisms for human exposure at each site. However, they provide a consistent basis for comparing the alternatives and represent the most important impacts. The pathways used for the comparative analysis are those shown to be most significant in Ref 6.

Short-term radiological effects include direct gamma exposure to workers and the public along transportation routes, accidents causing airborne contamination, and small airborne releases occurring as a consequence of normal operations. Long-term effects may result from attempts at reclamation which involve direct contact with the waste in the future, and migration and contamination of ground water systems that could be used to supply drinking water.

Some exposures to radiation are bound to result from waste disposal activities because no shielding or filtering system will be 100% effective. The pathways for potential short-term exposures to radiation considered to be most important in this comparative analysis are: direct exposure to ionizing radiation from the waste packages; extremely small, ongoing releases of contamination to the air from contaminated package surfaces and undetected leaks; and airborne contamination from accidents or spills. Because the waste disposal operations are similar for many of the different alternatives, these short-term consequences will also be similar. Personnel requirements for waste disposal operations will be similar for most concepts because the same standard volume and type of waste container are assumed to be handled. (Construction crew sizes would differ for the different alternatives, reflecting the different construction difficulties.)

Institutional control over disposal sites by regulatory agencies and their contractors is assumed to be maintained for 150 years after operations cease.[6] Any future site reclamation efforts would occur after that time period. Sabotage and other intrusions into the waste before 150 years have elapsed have not been considered in this analysis. The probabilities are low for this type of event, and the consequences would probably be similar for the various alternatives, because the wastes contacted are assumed to be the same.

The current generation of ground water migration models does not differentiate between differences in rainfall amounts. The underlying aquifers are assumed to be of the same productivity at both eastern and western sites for consistency in the comparison. Although the conditions assumed could be matched at actual sites, western sites would more likely be drier and present less opportunity for migration of nuclides by ground water contact. Efforts to more accurately model the effects of unsaturated flow conditions, percolation, evapotranspiration, and geometric distributions of waste within the disposal site are currently under way.[17]

The details of the calculations concerning transport pathways to human exposure are presented in Appendix C. The results presented in Section 3 are based on the equations and methodologies given in this appendix.

2.4 Sociopolitical Implications

There are many persons in this country who are vitally concerned with questions relating to radioactive waste disposal, and these issues have received much public attention. Several recent meetings[18,19,20,21] have been specifically held to discuss the non-technical aspects of nuclear waste management. The sociopolitical implications arising from the disposal alternatives studied in this project have been assessed, based on their apparent public acceptability and resultant requirements for changes in domestic or international institutional controls and agreements. The items considered in this analysis in quantifying the sociopolitical and other implications of the various alternatives are shown in Table 2.5.

Much of the assessment of sociopolitical implications is somewhat subjective. However, available published research and information on the topic[22,23] have been used for guidance. Additionally, many of the social acceptance issues depend on adequate demonstration that the technological problems have been appropriately solved. Assuming that the disposal alternatives meet the minimum constraints of being technically sound, the sociopolitical issues hinge mainly on requirements for governmental agreement and control, as is the case with ocean disposal in international waters. These issues are considered in the weighting factors used in the comparative analysis.

Sociopolitical factors in this country occasionally appear to have at least as much importance in selecting among various alternatives as do technical issues. However, it is not clear that this should be reflected in a basically technological evaluation of alternatives. There is also relatively little experience in soliciting public opinion and other sociopolitical factors concerning alternatives for low-level radioactive waste. This study subjectively quantifies the sociopolitical

TABLE 2.5

ITEMS CONSIDERED IN EVALUATING SOCIOPOLITICAL IMPLICATIONS

Public Acceptance	Major Concerns
• Acceptability of Risk	Compatibility of low-level radioactive waste disposal with criteria for disposal of other hazardous wastes. Consistent formulation and assessment of risks from radiation. Comparison of risks from other energy source wastes.
• Perception of Risk versus Hazards	Adequate information and understanding of risk assessment and cost-benefit tradeoffs. Definition of acceptable risks to public health and safety and the environment.
• Ethical and Moral Issues	Morality of leaving "legacy" of concentrated hazardous wastes for future generations. Credibility of sources of information, especially in light of conflicting views among experts. Problem of appropriately transmitting descriptive information concerning waste disposal sites to future generations.
Institutional Controls	
• Domestic Regulatory Controls	Adequacy of published regulations. stated philosophies and licensing requirements to provide framework of regulatory controls covering health and safety, site selection, and operational criteria. Accident response procedures. Environmental protection standards. State versus federal ownership and control of disposal sites. Long-term monitoring and surveillance responsibilities. Institutional stability.
• International Controls	Appropriateness of international involvement in territorial disposal operations. Established standards and guidelines. International agreements for world-wide disposal criteria and practices.

implications arising from implementing various waste disposal alternatives.

2.5 Cost Analyses

The economic evaluation performed in this study is based on disposal of a given volume (630,000 m^3) of low-level radioactive waste, 10% of which will contain sufficient ionizing radiation to require special handling and shielding for personnel protection. The conceptual designs for the alternatives were analyzed to arrive at order-of-magnitude costs associated with construction, operation and surveillance of the given disposal concept.

The following items provide the basis for a consistent set of cost estimates for comparison purposes:

- The costs for the alternative concepts are estimated in 1978 dollars with provisions for escalation and inflation during the period of operation.
- Costs for capital investment return, time value of money and profit are included.
- None of the costs common to all waste generators and borne by them (such as purchase of shipping containers, waste treatment for packaging or biological shielding required prior to waste disposal) are included except for costs associated with additional steps required by a specific disposal concept. (For instance, the cost of projectiles is included in the ocean disposal estimate.)
- Estimates are generic, not based on specific sites. However, anticipated average distances for transportation are included. Differentiation is made between eastern U.S., western U.S. and sea disposal sites.
- Institutional control over all land disposal sites is assumed to continue for 150 years following termination of waste disposal activities. This is the period of time for which monitoring and surveillance costs are estimated.

- Costs are reported for several broad categories for each concept, including rail transportation to the disposal site, to allow meaningful comparisions of the alternatives. Costs for final stabilization activities at the sites are included in the capital cost estimates.

More specific details concerning the cost estimates are provided in Appendix D describing each alternative.

2.6 Comparative Analyses

After the technical, sociopolitical and cost evaluations are completed for each concept, the major factors relating to each of these areas are quantified. Some of the items important in comparing alternatives can be quantified only by subjectively ranking one concept against another. Care is exercised to assure that the different alternatives are uniformly assessed. The foregoing sections of this report have described the approaches taken to assure uniformity and consistency in the evaluations.

Once the important evaluation factors have been quantified for each of the disposal alternatives, the factors and the alternatives are displayed in matrix format to facilitate comparison. (see Chapter 4). The values for the evaluation factors determined by the analyses are normalized with the corresponding factor for the base case (shallow land burial). Values greater than unity indicate less desirability or poorer performance than the base case, while those less than one reflect better anticipated performance.

One additional requirement for meaningful comparison is an estimate of the relative importance (weighting) of the evaluation factors. For instance, the question of how heavily costs should be considered in relation to sociopolitical issues will influence the comparison.

Table 2.6 lists the evaluation factors quantified and the weights assigned to each factor. The weights shown are based on a survey of the Technical Advisory Panel listed in Appendix A. It should be noted that the panel members were not in close agreement about the weights to be used and those shown in Table 2.6 only represent the average of the weights suggested. The use of these weighting factors allows quantitative comparison of the alternatives. Other weights may be more appropriate for different circumstances. Both the weighted and unweighted values for the evaluation factors are displayed in Chapter 4 in the comparison matrix format. Therefore, other weights can be assigned as desired.

TABLE 2.6

EVALUATION FACTORS AND THEIR WEIGHTS

Evaluation Factors	Relative Weight or Importance (%)
Technological Status	
• Compatibility with Waste	7.5
• Site Selection	12
• Safeguards	6.5
• Environmental Effects	11
• Availability of Techniques	10
Sociopolitical Acceptability	
• Institutional Control	11
• Public Acceptance	16
Economic Feasibility	
• Individual Consumer Costs	14
• Industrial Costs	12
	100%

It should be noted that certain evaluation parameters in Table 2.6 can be highly correlated. In particular, safeguards and environmental effects can be directly related to costs; improvements in safeguards and reductions in environmental effects can be achieved through higher expenditures. It is felt that reasonable assumptions have been made regarding procedures for safeguarding the waste and reducing environmental effects and that these are reflected in the costs calculated in this study.

It is expected that the comparison of disposal alternatives will be based on weighted sums of the evaluation factors. However, it is possible that a method or site can be rejected because the value of one or more evaluation factors is unacceptable, regardless of what the weighted sum may be. In other words, there are implied acceptability constraints that society may choose to place on any of the evaluation factors, and if those constraints are exceeded, the method will be rejected. The constraints are not presently well-defined and tend to be stated only on a case-by-case basis.

The comparative analysis demonstrates that selecting the best or optimum alternatives for low-level radioactive waste disposal involves complex tradeoffs among many factors. It also shows that there is more than one appropriate method for handling low-level radioactive wastes. However, going from the generic concepts studied in this project to specific designs at real sites will lead to important differences in the values of the evaluation parameters. This comparative analysis should, therefore, be used primarily for guidance in comparing disposal methods.

3. DESCRIPTION OF SELECTED ALTERNATIVES

The alternative disposal methods selected by the NRC for detailed investigation include a base case of shallow land burial, improvements to present burial practices, deeper burial, disposal in mined cavities, disposal in engineered structures, and ocean disposal.[1] In the following sections, each of these disposal concepts is described, and the technical evaluation, assessment of sociopolitical implications, and cost estimate are reported.

Because it is not possible to treat all variations within each of the alternative disposal concepts, generic designs have been used for this analysis. This study is not intended to be a detailed analysis of all possible disposal options, but a comparative analysis of the generic alternatives that are most feasible; however, some variations on representative cases have been analyzed briefly.

3.1 Shallow Land Burial

Shallow land burial was the original radioactive waste management practice adopted by the Atomic Energy Commission. The concept consists of emplacing the radioactive waste in trenches dug into the native soil at depths ranging from 3 to 6 m and covering the waste with about 1 m of soil. Burial grounds were generally located in areas that were relatively remote from population centers, on land that was otherwise considered of little value.

The waste was received in a variety of containers. Cardboard cartons, wooden boxes, steel drums and cement pipe were used, depending upon the nature of waste and the distance it had to be shipped. The burial ground operators, as well as the federal regulators, generally viewed the soil surrounding the burial trench as the containment mechanism once the waste had been emplaced in the trench. Little care was taken to preserve the integrity of the container during the "dumping" operation.

It was recognized that most soils make very efficient ion exchange beds and that ground water containing dissolved radioactive isotopes would generally deposit those isotopes in the soil in exchange for more soluble minerals such as sodium, calcium and magnesium. Although radionuclides have been found outside of some burial grounds, the releases have not posed a threat to public health and safety.

In the past, some small quantities of nuclides have been released from burial grounds mainly due to rainwater or snow melt accumulating in an open waste trench and washing the nuclides out onto the ground surface, ground water overflowing from disposal trenches, workers carrying off useful but contaminated articles found in the waste, and locating trenches in areas where the underlying soil or strata was not suitable for good containment.[24] It is believed that current burial ground operating procedures and regulations will greatly reduce the potential for these types of releases.

3.1.1 Description of Reference Shallow Land Burial Disposal Facility

A reference Shallow Land Burial Facility (SLBF) has been described in an earlier report.[6] Potential releases from the SLBF have been calculated. This generic facility provides the base case for this study. A schematic of the SLBF is shown in Figure 3.1. The SLBF is not necessarily a typical burial facility, nor is it an average of existing burial site parameters. It is rather a model shallow land burial facility whose parameters were determined to be representative of what may be generally expected from such burial facilities. Appendix B contains details of the major existing disposal facilities in this country for perspective. Future site selection criteria may eliminate or greatly reduce the consequences of some of the potential environmental exposure pathways from this SLBF. However, the SLBF shown in Figure 3.1 will be used for this comparative analysis.

An aquifer is assumed to lie 10 m below the bottom of the burial trenches and the water in this aquifer flows at a rate of 100 m/yr toward a large river located 1 km away. These values are representative of typical values at existing disposal sites. (See Appendix B.) The SLBF disposal capacity is 6.3×10^5 m^3 of waste, discussed in Section 2.2. Table 3.1 contains the key parameters relating to the SLBF.

3.1.2 Technical Evaluation

It is assumed that the disposal alternatives will all conform to certain minimum standards of performance and compatibility with the waste. However, there are no presently established quantitative criteria, and "acceptable" performance may vary over a relatively broad range. However, this generic analysis is performed to aid in comparing the different waste disposal alternatives. The result is a set of quantitative measures of performance for each alternative.

3.1.2.1 Compatibility with Waste

Some disposal alternatives may be better suited to receive and handle specific radioactive waste forms than other options. However, important differences between generic alternatives are not expected in the present study, because the waste inventory, physical form and packaging are assumed to be the same for each

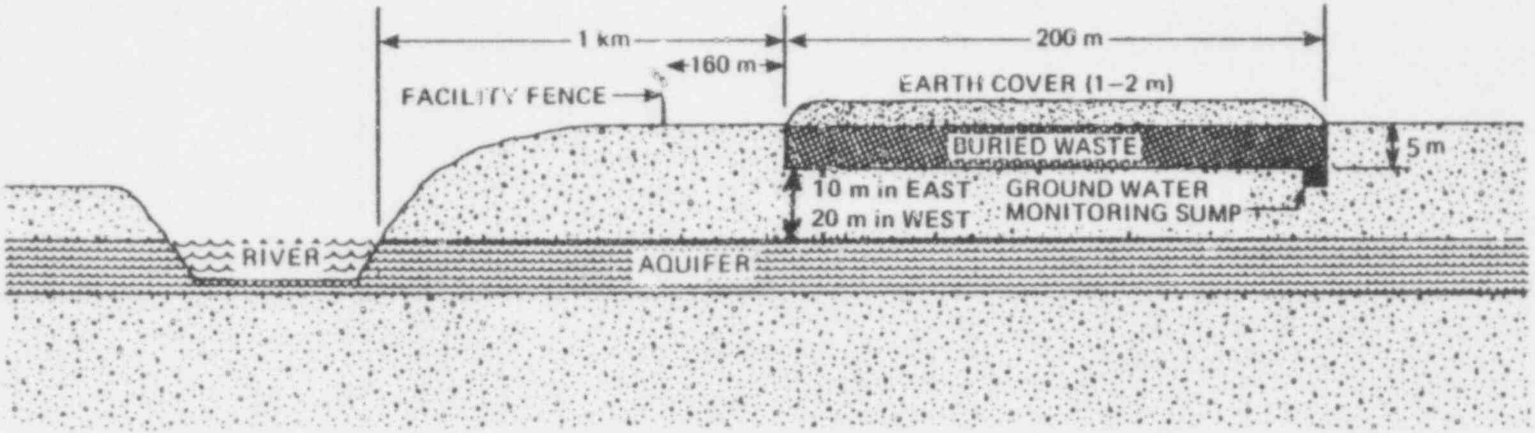

FIGURE 3.1 SCHEMATIC OF REFERENCE SHALLOW LAND BURIAL FACILITY

TABLE 3.1

REFERENCE SHALLOW LAND BURIAL FACILITY PARAMETERS

Parameter	Value
Number of Disposal Trenches	315 (100m x 8m x 6m)
Site Plan Area	2.0 X 10^6 m^2
Site Capacity for Waste	6.3 x 10^5 m^3 (10^3 RRY of nuclear power or 800 GW(e)-yr of electricity)
Minimum Distance to Site Boundary	1.6 X 10^2 m
Distance - Trench Bottom to Aquifer	10 m
Water Velocity - Trench Bottom to Aquifer	1.0 m/yr
Distance - Site to Surface Water (River)	10^3 m
Water Velocity - Aquifer	10^2 m/yr
Dispersion Coefficient*	1.0 m^2/yr
Minimum Earth Cover Over Waste	1.0 m
Fraction of Trench Volume Occupied by Waste	0.5
River Flow Rate	5.0 X 10^2 m^3/s

*Shown in Ref 6 to be a relatively unimportant parameter for the ranges of sorption coefficients used in this study.

alternative, and the reference disposal facilities are all designed to handle the reference waste types and volumes. The differences in difficulty in handling the waste at the different reference facilities are expected to be small compared to the overall inherent difficulty of any given waste disposal operation.

The evaluation factor for compatibility with waste is assigned a value of unity for the reference SLBF. Other disposal concepts will be ranked based on their compatibility with the waste forms planned for shallow land burial.

3.1.2.2 Site Selection Factors

Site availability is an important consideration in comparing alternatives. Factors important in locating a shallow land burial facility include distances to ground and surface water systems, meteorology and climatology of the area, degree of remoteness, geologic stability, proximity to the sources of waste, competing uses of the land, and ownership for long-term control.

Shallow land burial could be acommodated in many areas of the country. Ideally, precipitation at the potential site should be low; the distance to any aquifers should be long; aquifer flows and utilization should be low; and underlying strata should be neither highly fractured nor contain voids and flow channels. These characteristics are generally found more frequently in the arid Western U.S.

The native soil at the disposal site should have good ion exchange and sorptive properties, which usually accompany fine-textured material. In Europe, however, burial in coarse sand has been successfully practiced by placing a layer of fine sand over the coarse trench bottom.[24] Water penetrating the waste and fine sand will not penetrate into the coarse sand because of the stronger capillary attraction in the fine sand layer. Thus, the migration of nuclides in water stops at the interface between the fine and coarse sands. This technique, of course, is effective only where the ground is not saturated with water.

There are many land areas in the country where no known subsurface resources would be considered attractive, and competing uses of the lands are not contemplated. Because shallow land burial is the base case, to quantify the site selection evaluation factor, a value of unity is assigned for the eastern SLBF site. For the western site, a value of 0.9 is assigned to reflect the greater availability of suitable land in the west. The other alternatives will be rated relative to the suitability and availability of eastern sites for shallow land burial.

3.1.2.3 Safeguards

In this study, safeguards is defined to include considerations of maintaining physical protection of the wastes from unauthorized uses. Shallow land burial provides some assurance that disposed wastes will not be disturbed, and that any unauthorized attempts to dislocate the wastes will be easily detected by inspection of the ground surface. Although it is not likely that the buried wastes will be dug up, it is assumed that security coverage of the site will be maintained for 150 years. Intrusion alarms and security fencing are assumed to discourage unauthorized attempts to obtain access to the wastes.

The evaluation factor for the reference SLBF concerning safeguards is assigned a value of unity. The other alternatives will be assessed and assigned appropriate values for this factor based on their relative accessibility and ease of unauthorized use of wastes compared to the reference SLBF.

3.1.2.4 Environmental Effects

Because the land on which a shallow land burial facility would be sited is assumed to be generally undesirable for other uses and relatively remote from population centers, the nonradiological impacts from constructing a waste burial facility would be small. Routine hazards to construction workers would be comparable with those encountered in the general construction and surface mining industries. Although about 2 million m^2 (500 acres) of land would be purchased to provide a buffer zone around the waste disposal operations, only about 25% of the site would be disturbed. If the trenches are 100 m long and 6 m deep, filled to 1 m from the top with waste, with a 50% efficiency, there would be 315 trenches 8 m wide in the reference SLBF, covering 252,000 m^2 of area. Assuming that roadways, structures and spacing between trenches occupy an equal area, about 500,000 m^2 (125 acres) of surface would be disturbed. Construction of worker change, clean-up and eating facilities, garage space for equipment, and security fencing would not result in consequential hazards. Excavation of trenches would conform to existing safety standards and requirements, minimizing hazards to workers. Train crews would be subjected to normal occupational hazards in shipment of the wastes to the disposal sites. A summary of the estimated non-radiological impacts is given in Table 3.2. The total effect for the comparative analysis is obtained by summing the projected injuries with ten times the projected fatalities. The fatalities are weighted more heavily than injuries to reflect the more serious nature of loss of life. Construction crew sizes are estimated, based on dividing estimated capital costs by a single factor for labor. This method gives a slight difference between eastern and western sites, although the normalized differences are not significant.

TABLE 3.2

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR SLBF

Transportation	Eastern Site	Western Site
Average Transit Distance to Disposal Site (mi)	400	1,400
Total Train Car Miles (round trip)	21,100,000	73,900,000
Total Projected Accidents[a]	3.0	10
Total Projected Injuries[b]	8.0	28
Total Projected Fatalities[c]	0.60	2.0
Construction Phase		
Average Crew Size (man-years)	20	17
Comparable Industry[d]	Construction/ Surface Mining	Construction/ Surface Mining
Total Projected Injuries	0.61	0.52
Total Projected Fatalities	0.01	0.01
Operational Phase		
Crew Size (man-years)	265	265
Comparable Industry[d]	Construction/ Storage and Warehousing	Construction Storage and Warehousing
Total Projected Injuries	8.1	8.1
Total Projected Fatalities	0.09	0.09
Total Overall Effect for Comparison[e]	23.7	57.6
Normalized Effect[f]	1.0	2.4

(a) Based on 1.4×10^{-7} accidents/car mile from Ref 13.
(b) Based on 2.7 injuries/accident from Ref 13.
(c) Based on 0.2 fatalities/accident from Ref 13.
(d) From Table 2.2, for rates used for statistical injury and accident projection data. (Highest projected frequencies for given categories were used in the calculations.)
(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted more heavily than injuries to account for the more significant loss of life.)
(f) Normalized to reference SLBF eastern site case.

The environmental effects during and subsequent to the operational phases at the SLBF include radiological hazards from handling the low-level radioactive wastes. All waste management operations are expected to be conducted under the philosophy of maintaining exposures to radiation to both workers and the public at levels "As Low As Reasonably Achievable" (ALARA). Actual operations will be subjected to extensive and comprehensive safety reviews and analyses to assure that no unacceptable exposure is likely to occur, and that appropriate preventative and mitigating measures are incorporated into the facility design.

To assess the magnitudes of the short-term effects for the reference SLBF, the environmental pathways analysis methodology developed in detail in Ref 6 was utilized. For direct exposures to ionizing radiation, both the exposed population along transportation routes and the waste management workers are important. Exposures along transportation routes for low-level radioactive wastes shipped in compliance with existing standards have been presented in other reports.[13,14,16,25] Transportation exposures are estimated by assuming that wastes would have to be shipped an average distance of 400 miles to an Eastern U.S. site, and an average distance of 1,400 miles to a Western U.S. site, and using typical population densities along the routes.

Shipping the 630,000 m^3 of low-level radioactive wastes by rail to the reference SLBF would result in exposures to the population and train crews along the route of about 9.5 manrem/yr for an Eastern site and about 33 manrem/yr for a Western site. These values will be the same for the other alternatives involving shipment over the same distances. These exposures are based on 1.8×10^{-5} manrem/car mile as developed in Ref 13.

Direct exposures to waste management workers at the disposal site can be estimated based on the average nuclide content of the shipping packages, and by comparisons with present burial operations. Currently, waste management personnel at waste burial sites do not receive doses in excess of established guidelines. Doses are usually much less than the allowable 5 rem/yr to radiation workers. Because the operations personnel are trained radiation workers aware of the hazards involved, they will protect themselves and keep to ALARA levels.

Long-term hazards include potential reclamation attempts after institutional controls are relinquished, and migration of the nuclides through ground water to water systems used for human consumption. Future reclaimers could include construction workers building a structure on the former disposal site or archaeologists investigating an earlier civilization. This study, however, considers only the former.

Future construction workers erecting buildings at the former SLBF site could dig into the buried wastes while placing foundations and footings. Such activities could stir up contaminated dust from the wastes which are assumed to be, by then, largely decomposed. Workers could inhale some contaminated dust particles. If the reclamation workers are exposed to relatively high dust loadings[6,26] of 0.5 mg/m^3 of air for one-fourth of a work-year (500 hr), and the dust from the waste has been diluted by a factor of 2 with clean dirt from burial, the workers would receive doses of about 110 mrem, 150 years after the waste was buried. The results of the calculations are summarized in Table 3.3.

From ground water migration, two possible water consumption events have been considered. The first is consumption of drinking water from a well drilled adjacent to a disposal trench. The water is assumed to be contaminated by leaching and subsequent migration of contaminants from the disposed wastes. The second event involves consumption of drinking water from a nearby stream that receives the contaminated discharge from an aquifer underlying the disposal site.

A well drilled through or adjacent to a disposal trench into the underlying aquifer would tap water containing maximum contamination levels from leaching of the wastes. Contamination concentrations at farther distances from the trenches would be lower because of decay, dilution and adsorption. Using the ground water migration calculational methodology from Ref 6, if an individual were to consume 100% of his drinking water from the hypothetical on-site well adjacent to the disposal trenches, he would receive a maximum dose of about 80 mrem/yr 12 years after disposal. However, no drinking water wells will be allowed on site during the 150-year period of institutional control. Maximum doses from the on-site well after 150 years would be much lower. Table 3.4 contains a summary of the pertinent results of the calculations, including maximum doses that occur before 150 years, even though restrictions would preclude their occurrence. The doses that occur before 150 years are also representative of exposures that could occur from nearby off-site wells, and are therefore included in the comparisons.

When contaminated ground water moves through an underlying aquifer to a surface stream, movement of radionuclides will be inhibited by ion exchange and sorption along the path. Individuals obtaining 100% of their drinking water from the surface stream would receive much smaller maximum doses than those calculated for the on-site well water exposure event.[6] This results from the fact that the nuclides will arrive at the surface stream at different times because of differences in adsorption of the individual nuclides, and that the contamination travels further in the aquifer and is diluted more by the surface stream.

Another possible exposure event involves growing food, including vegetables, beef and dairy cows, on ground that has been contaminated with disposed waste that was brought to the surface by excavation activities during future reclamation of the site.

TABLE 3.3

DOSES TO FUTURE RECLAIMER EXPOSED FOR 500 HRS TO DUST FROM WASTES 150 YEARS AFTER DISPOSAL

Nuclide	Initial Concentration in Waste (Ci/m^3)	Dose to Reclaimer From Inhalation (mrem)
^{3}H	0.12	2.9×10^{-7}
^{14}C	3.8×10^{-3}	6.0×10^{-4}
^{51}Cr	6.5	0
^{54}Mn	4.0	0
^{55}Fe	4.3×10^{-1}	5.2×10^{18}
^{58}Co	6.5	0
^{59}Ni	1.3×10^{-3}	7.6×10^{-4}
^{60}Co	21	3.0×10^{-6}
^{63}Ni	2.4×10^{-1}	3.3×10^{-1}
^{90}Sr	4.8×10^{-3}	1.2×10^{-1}
^{99}Tc	3.2×10^{-5}	2.3×10^{-4}
^{125}Sb	5.3×10^{-3}	3.0×10^{-18}
^{129}I	6.4×10^{-6}	3.1×10^{-6}
^{134}Cs	7.0	6.4×10^{-21}
^{137}Cs	13	2.3
^{152}Eu	4.8×10^{-5}	3.9×10^{-7}
^{226}Ra	1.2×10^{-4}	1.0
^{230}Th	7.1×10^{-5}	12
^{232}Th	8.4×10^{-7}	1.2×10^{-1}
^{235}U	3.2×10^{-6}	1.1×10^{-2}
^{237}Np	4.6×10^{-8}	5.5×10^{-3}
^{238}U	7.1×10^{-5}	2.3×10^{-1}
^{238}Pu	3.2×10^{-4}	19
^{239}Pu	4.3×10^{-5}	9.3
^{240}Pu	6.7×10^{-5}	14
^{241}Pu	1.6×10^{-2}	6.7×10^{-2}
^{242}Pu	2.4×10^{-7}	4.9×10^{-2}
^{241}Am	3.0×10^{-5}	1.7
^{243}Am	2.1×10^{-6}	1.5×10^{-1}
^{243}Cm	6.0×10^{-7}	8.2×10^{-4}
^{244}Cm	1.9×10^{-4}	2.4×10^{-2}
	Total	60

TABLE 3.4

DOSE RATES TO PERSONS CONSUMING
100% OF DRINKING WATER FROM ON-SITE WELL

Nuclide	Leach Constant (yr^{-1})	Sorption Coefficient	Time of Peak Release (yr) Eastern Site	Time of Peak Release (yr) Western Site	Maximum Individual Dose Rate (mrem/yr) Eastern Site	Maximum Individual Dose Rate (mrem/yr) Western Site
^{3}H	10^{-1}	1	12	22	76	34
^{14}C	10^{-4}	10	120	220	$1.2x10^{-1}$	$1.2x6^{-6}$
^{51}Cr	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{54}Mn	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{55}Fe	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{58}Co	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{59}Ni	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	7.4	4.9
^{60}Co	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{63}Ni	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{90}Sr	10^{-2}	100	$1.2x10^{3}$	$2.2x10^{3}$	$4.8x10^{-8}$	$5.1x10^{-23}$
^{99}Tc	10^{-4}	1	12	22	$2.2x10^{-3}$	$2.2x10^{-3}$
^{125}Sb	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{129}I	10^{-1}	1	12	22	$6.7x10^{-1}$	$6.7x10^{-1}$
^{134}Cs	10^{-3}	1000	$1.2x10^{4}$	$2.2x10^{4}$	0	0
^{137}Cs	10^{-3}	1000	$1.2x10^{4}$	$2.2x11-^{4}$	0	0
^{152}Eu	10^{-1}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{226}Ra	10^{-5}	500	$5.8x10^{3}$	$1.1x10^{4}$	$3.4x10^{-1}$	$1.3x10^{-2}$
^{230}Th	10^{-5}	$5.0x10^{4}$	$5.8x10^{5}$	$1.1x10^{6}$	$9.5x10^{-4}$	$1.1x10^{-6}$
^{232}Th	10^{-5}	$5.0x10^{4}$	$5.8x10^{5}$	$1.1x10^{6}$	$1.7x10^{-3}$	$1.7x10^{-3}$
^{235}U	10^{-5}	$1.4x10^{4}$	$1.6x10^{5}$	$3.0x10^{5}$	$2.9x10^{-3}$	$2.9x10^{-3}$
^{237}Np	10^{-5}	100	$1.2x10^{3}$	$2.2x10^{3}$	$7.1x10^{-5}$	$7.1x10^{-5}$
^{238}U	10^{-5}	$1.4x10^{4}$	$1.6x10^{5}$	$3.0x10^{5}$	$6.2x10^{-2}$	$6.2x10^{-2}$
^{238}Pu	10^{-5}	10^{4}	$1.2x10^{5}$	$2.7x10^{5}$	0	
^{239}Pu	10^{-5}	10^{4}	$1.2x10^{5}$	$2.7x10^{5}$	$1.3x10^{-3}$	$2.0x10^{-2}$
^{240}Pu	10^{-5}	10^{4}	$1.2x10^{5}$	$2.2x10^{5}$	$2.7x10^{-7}$	$6.2x10^{-14}$
^{241}Pu	10^{-5}	10^{4}	$1.2x10^{5}$	$2.2x10^{5}$	0	0
^{242}Pu	10^{-5}	10^{4}	$1.2x10^{5}$	$2.2x10^{5}$	$1.7x10^{-4}$	$1.3x10^{-4}$
^{241}Am	10^{-5}	10^{4}	$1.2x10^{5}$	$2.2x10^{5}$	0	0
^{242}Am	10^{-5}	10^{4}	$1.2x10^{5}$	$2.2x10^{5}$	$4.0x10^{-8}$	$5.1x10^{-14}$
^{243}Cm	10^{-5}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
^{244}Cm	10^{-5}	3300	$3.8x10^{4}$	$7.1x10^{4}$	0	0
				Totals*	84	40

* Note that exposures occur at different times.

Based on an additional dilution of the wastes by a factor of 10 with clean surface soil by mixing and cultivating, and assuming that a person consumes 10% of his total dietary intake from produce, meat and milk grown on the site, dose rates of up to 625 mrem/yr could occur. The nuclide specific dose rates are summarized for this exposure pathway in Table 3.5 for food production after 150 years of institutional control, based on the methodology from Ref 27.

Dropping a waste container, with a subsequent release to the atmosphere of airborne contamination, is another possible event leading to public exposure. It is assumed that the accident occurs during atmospherically stable Class F conditions, and that the nearest member of the public is at the site boundary 160 m away from the accident. If 10^{-3} of the contents of the drum become airborne, a maximum dose to the nearest individual of 200 mrem would occur if he were to stay at that location during the entire time the plume of comtamination passes his position. An average wind speed of 1.6 m/sec was used in the calculations. The methodology described in Ref 6 was followed for estimating the consequences. The nuclide specific doses for this event are also tabulated in Table 3.5. Small continuous airborne releases from routine handling of the radioactive wastes will be a few orders of magnitude smaller than for the accident case,[6] and are not presented here. Further details are provided in Appendix C for support of values used.

Direct gamma radiation is another possible type of exposure which could occur to future reclaimers digging into the wastes. Reclaimers directly exposed to the wastes after institutional controls are relinquished could receive up to 340 mrem for 10 hr of direct contact with the higher radiation level containers. This dose was calculated using the methodology from Refs 6 and 28. The major contributor to the direct gamma radiation after 150 years is ^{137}Cs. Although reclamation workers may be around the waste for longer periods, they would not be continuously in direct contact (surface of drums) with the small (10%) fraction of the waste containers. Therefore, 10 hours of direct contact is assumed to represent a likely period of exposure.

A summary of the radiological impacts for the SLBF is presented in Table 3.6. The food pathway appears to be the most important contributor to individual exposures, followed by direct gamma radiation of future reclaimers exposed to the wastes. A single measure of potential dose, for use in the comparative analysis, is obtained by summing the annual dose rates. Not all events are likely to occur simultaneously just after control of the site is relinquished, nor would the same individuals necessarily receive the dose. Therefore, this relative indicator should not be interpreted as an anticipated dose to any individual. The population exposures along the transportation routes are arbitrarily assumed to be incurred by a reference population of 1000 persons to provide consistent units on the dose rates for the comparison. Although the reclaimer direct gamma and

TABLE 3.5

DOSE RATES TO MAXIMALLY EXPOSED INDIVIDUAL FROM SLBF EVENTS

Nuclide	Dose Rate from Food Pathway (mrem/yr)	Dose Rate from Airborne Accident (mrem/yr)
^{3}H	2.6×10^{-2}	4.9×10^{-5}
^{14}C	160	2.2×10^{-5}
^{51}Cr	0	1.8×10^{-2}
^{54}Mn	0	1.8
^{55}Fe	0	1.5
^{58}Co	0	1.9
^{59}Ni	3.4×10^{-2}	2.7×10^{-5}
^{60}Co	4.0×10^{-5}	4.0×10^{1}
^{63}Ni	430	5.1
^{90}Sr	28	1.4×10^{2}
^{99}Tc	3.3×10^{-2}	8.3×10^{-6}
^{125}Sb	0	3.8×10^{-3}
^{129}I	2.3×10^{-3}	1.1×10^{-7}
^{134}Cs	0	1.9
^{137}Cs	6.6	2.6
^{152}Eu	1.8×10^{-6}	4.2×10^{-5}
^{226}Ra	2.7	3.9×10^{-2}
^{230}Th	1.0	4.2×10^{-1}
^{232}Th	1.0×10^{-2}	4.3×10^{-3}
^{235}U	1.1×10^{-2}	4.0×10^{-4}
^{237}Np	1.6×10^{-4}	2.0×10^{-4}
^{238}U	2.3×10^{-1}	8.4×10^{-3}
^{238}Pu	3.2×10^{-2}	2.2
^{239}Pu	1.3×10^{-2}	3.4×10^{-1}
^{240}Pu	2.1×10^{-2}	5.3×10^{-1}
^{241}Pu	1.0×10^{-4}	2.5
^{242}Pu	7.1×10^{-5}	1.8×10^{-3}
^{241}Am	7.7×10^{-3}	7.7×10^{-2}
^{243}Am	7.0×10^{-4}	5.4×10^{-3}
^{243}Cm	4.6×10^{-6}	1.2×10^{-3}
^{244}Cm	1.1×10^{-4}	2.9×10^{-1}
Totals	620	200

TABLE 3.6

SUMMARY OF RADIOLOGICAL IMPACTS FOR SLBF

	Eastern Site	Western Site
Long-Term Effects (mrem/yr)		
Reclaimer Inhalation[a]	60	60
Food Pathway	620	620
Reclaimer Direct Gamma Exposure[a]	340	340
Short-Term Effects (mrem/yr)		
On-Site Well Water Consumption	80	40
Accidental Airborne Releases	200	200
Transportation Exposures[b]	10	30
Total Overall Effect for Comparison (mrem/yr)	1310	1290
Normalized Effect[c]	1.0	0.98

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison

(b) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison.

(c) Normalized to reference SLBF eastern site case.

inhalation events would probably occur only once, they are assumed to occur for 10 and 500 hours per year respectively, to obtain consistent units for the comparison.

To compute a single evaluation factor for environmental effects, the normalized nonradiological impacts and normalized radiological impacts are averaged (from Tables 3.2 and 3.6 for this case). For the SLBF eastern site (the base case for this study), the value for this factor is 1.0. For the western site, the value is 1.7.

3.1.2.5 Availability of Techniques

Shallow land burial has been practiced for disposal of low-level radioactive wastes in this country for the past 30 years. The techniques for trench design, capping and nuclide movement prediction have improved in that period. The technology for adequately designing and operating shallow land burial facilities has been demonstrated. This evaluation factor is assigned a value of unity for shallow land burial as the base case.

3.1.3 Sociopolitical Implications

The sociopolitical implications of continued use of shallow land burial for disposal of low-level radioactive waste are assumed to reflect current public trends and positions concerning ongoing waste disposal activities in this country. Both public acceptance and existing regulatory controls appear to be adequate for continuing current practices, with implementation of improvements that may become apparent in the future.

3.1.3.1 Public Acceptance

Even though shallow land burial has been practiced with no major impacts on workers, the public, or the environment, there appears to be some public resistance to new disposal sites. At least one commercial nuclear waste management company has withdrawn interest in establishing a new waste burial site, partially because of perceived public objections.[29] Such opposition comes primarily from nearby urban areas, not the rural areas in which disposal facilities would be located. This is similar to experience in siting other technological facilities such as power plants, where the local population feels the growth potential outweighs environmental concerns.

Public acceptance of nuclear waste disposal operations is influenced by public perception of risk. To date there has been little information which would allow the public to make rational assessments of the risks associated with radioactive wastes, relative to other activities arising from use of modern technology. Compounding this problem is the fact that the public, as well as large portions of the scientific community, appear inexperienced at assessing risks, in either relative or absolute terms, or in distinguishing between calculated consequences and risks. (The latter are the result of multiplying consequences by the probability of occurrence of the accidents leading to the consequences.) Recent events, such as the incident at Three Mile Island, tend to instill a suspicion of all risk calculations, since to the public the fact that the event occurred appears to make previous statements that it would be unlikely seem purposely misleading.

There is also public concern over the morality or ethics of leaving areas containing concentrated radioactive wastes as a "legacy" for future generations, although this does not seem to extend to other hazardous wastes presently disposed of in large quantities. For the low-level radioactive wastes considered in this study, however, there is less concern over long term hazards than for high-level wastes.

For the base case of shallow land burial, the evaluation factor for public acceptance is assigned a value of unity for the comparative analysis. For the other alternatives, an attempt will be made to identify, within the constraints associated with public understanding stated above, significant items influencing public acceptance. To the extent they can be identified, the public acceptance evaluation factor will be modified from the base case value to reflect the influence of these items.

3.1.3.2 Institutional Controls

Domestic governmental controls for regulating shallow land burial are already well defined and established.[29] There are some unresolved questions, however, such as ultimate state versus federal ownership, final site decommissioning and long-term monitoring and control responsibility.[3,30] Additional coordination and definition of responsbilities among government regulatory agencies is also required to provide effective utilization of funding and manpower resources available for waste management activities. No international concerns are relevant to shallow land burial operations within national territory. The evaluation factor relating to institutional controls is set at unity for the base case.

3.1.4 Cost Analysis

The cost estimates are based upon the conceptual design of the reference SLBF. Reasonable estimates have been incorporated for such factors as site surveillance, monitoring, security fencing, alarms, necessary support facilities, and final stabilization of the site. For many of the alternatives, the support activities will be essentially the same. The number of workers required for waste handling, monitoring and surveillance are assumed to be essentially the same for all concepts except the ocean disposal alternatives.

3.1.4.1 Cost Estimates

This section contains information used as the basis for the consumer costs. The cost estimates are based on the factors explained in Section 2.5 and the facility design described in Section 3.1.1. For the reference SLBF, the cost estimate is summarized in Table 3.7. The costs for implementing this alternative, including transportation, at an eastern site total $150 million, and at a western site, $310 million. These equate to $240 and $500 per cubic meter of waste, respectively. Excluding transportation costs, the estimated disposal costs would be about $\$130/\text{m}^3$. This estimate is comparable to current commercial burial rates for waste delivered to the site.

Transportation costs are based on actual charges for rail shipments of low radiation level wastes from Rocky Flats, Colorado, to the Idaho National Engineering Laboratory. Based on available data for truck shipping costs,[15] the rail costs used in this study are the same order of magnitude as those for trucking the wastes to the disposal facilities. In practice, it is expected that the waste generators would utilize the more economic of the available transportation methods in any given situation. Although there may be small differences in costs for the two transportation methods, use of rail shipments for this comparative analysis allows consistent and meaningful intercomparisons among the alternatives. The evaluation factor representing consumer costs is based on the total costs normalized to the SLBF eastern site case.

3.1.4.2 Economic Impact

The economic impact section presents the industrial costs used as an evaluation factor in this study. All of the waste at a typical disposal site would not be generated in nuclear power production facilities. However, to estimate the economic impact, it is assumed that all the waste arises from nuclear reactors producing about 800 GW(e)yr of electricity. Based on the total costs for the reference SLBF, it would cost the consumer of electricity about 0.021 mills/kwhr to pay the costs of waste disposal at an eastern reference SLBF. Compared to a base of 45 mills/kwhr,[31] this is only 0.05% of the base generation costs. Clearly, disposal costs are not prohibitive. For the western site, the cost would be about 0.044 mills/kwhr, or less than 0.1% of the total electricity production costs. Because non-fuel cycle wastes are usually generated in relatively small quantities, the costs of their disposal will not represent an inordinately large economic impact to the involved industries. The evaluation factor representing industrial costs is assumed to be the same as for the consumer costs.

TABLE 3.7 COST ESTIMATE SUMMARY FOR REFERENCE SHALLOW LAND BURIAL FACILITY

Item	Estimated Costs (Millions of Dollars)			
	Eastern Site		Western Site	
Capital Costs				
Land Acquisition	5.00 ($10k/acre)		2.50 ($5k/acre)	
Site Studies	.50		.40	
Licensing	.32		.32	
Environmental Reports	.25		.15	
Site Preparation	0.46		0.46	
Site Fencing & Security Alarms	0.25		0.25	
On-site Structures and Roads	1.04		1.04	
Excavation of Trenches	2.35		2.35	
Backfill and Compaction	1.24		1.24	
Capital Subtotal		11.41		8.71
Engineering (5% of Subtotal)	.57		.44	
Higher Radiation Waste Facilities	.28		.28	
Total Capital Costs		12		9
Operating Costs				
Emplacement Costs	2.02		2.02	
Facility Operating Personnel	19.75		19.75	
Supplies and Equipment	1.88		1.88	
Total Operating Costs		24		24
Contingency (30% of Total Capital & Operating Costs)		11		10
Profit, Financing, and Escalation		37		33
Total Facility Costs		84		76
Transportation Costs		68		237
Total Facility plus Transportation Costs		152		313
Total Unit Costs for Waste Disposal ($/m^3)	240		500	

3.2 Improvements to Shallow Land Burial

Shallow land burial is the major waste disposal method now in use in this country, and there is substantial impetus to improve the performance of shallow land burial rather than turn to more exotic alternatives to current practices. The improvements considered in this study represent changes to the reference SLBF described in Section 3.1.1, but may be in use at some specific shallow land burial sites at present.

3.2.1 Description of Improvements to Shallow Land Burial

Possible means of improving the performance of shallow land burial are described below. Improvements that could easily be applied to shallow land burial include better disposal trench capping, improved trench design, better operational and water management techniques, improved waste forms, and in-situ encapsulation of the buried wastes.

3.2.1.1 Impermeable Covers over Trenches

It has been stated that 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".[7] If this is true, one of the most effective improvements that could be made on a burial ground would be to place a permanent water resistant cover over the trenches to restrict percolation of surface water through the waste. Many materials could be used to form the protective cover. This study considers some of the more common materials, ranging in cost from some of the least expensive to the most exotic. They are: clay, soil additives, asphalt, plastic membranes, concrete and stainless steel.

Existing or new burial trenches can be protected from water penetration by a <u>cover (cap) of common clay</u>. Clay is widely distributed throughout the world and usually can be obtained locally. If not available locally, bentonite, which is available commercially, could be used at a slightly higher cost.

The clay covers would be designed to slope from the centers of the trenches outward and overlap ones from the adjacent trenches at the edges. The overlap creates a drainage channel. This can be coupled with a slight slope to one end of the disposal area, to facilitate drainage of the site and prevent lateral movement into the wastes of water percolating from between the trenches. An initial covering of several inches of clay could be applied for short-term moisture control as the trenches are being filled.

When the site is filled to capacity, additional cover could then be applied to make a final thickness of 1 m of clay, after correcting for subsidence. (If several years pass before the final cover is applied, no further subsidence from compaction and deterioration of the wastes would be expected.) On top of the clay, soil 1 m in depth could be placed and graded for drainage and protection of the clay. This depth of soil cover would probably be sufficient to prevent problems of cracking from dehydration or freeze-thaw cycles. On top of the soil, a final riprap cover of crushed rock would be applied for erosion and burrowing animal control. This type of final cover should be thick enough to maintain its effectiveness even if further subsidence or mild earthquakes were to occur. It is reported[32] that under saturated conditions, the hydraulic conductivity of inorganic clays ranges from 10^{-6} to 10^{-8} cm/sec or about an average of 1.2 in/yr.

In general, the application of a clay cap as a moisture barrier would be effective as long as it remains in place. Hawkins and Horton[33] have reported that in tests at Oak Ridge, a cap of dry bentonite as thin as 2 in. (5 cm) under 2 ft (0.61 m) of soil was 100% effective in preventing annual rainfall exceeding 50 in. (127 cm) from penetrating the test pits. The major threats to the integrity of the clay cap would be surface subsidence due to compaction and decomposition of biodegradable waste, erosion due to surface water, burrowing animals, and drying out and cracking. Much of the potential surface subsidence in a low-level waste burial pit can be eliminated by prior volume reduction of the buried waste followed by compaction of the cover. Volume reduction by compaction of 90% of routine low-level wastes prior to burial has been reported.[34] Incineration of combustible materials would achieve an even greater volume reduction, although this treatment may require some development work before it is put into general practice. Some form of prior compaction would aid in assuring the long-term integrity of the clay cap or cover by minimizing subsidence.

The most significant threat to the permanence of the cover is surface erosion. Control of surface erosion requires the proper construction of drainage ditches and diversion dams, to control the flow of flood waters and divert any possible flooding away from the trenches. Erosion from water falling directly upon the trench cover can be controlled with the use of rock riprap. This is the method used to control erosion on the face of earth-fill dams and is a well established engineering practice. The use of riprap would also inhibit the digging of most troublesome burrowing animals. Use of vegetation for erosion control over the trench covers would possibly cause a reduction in water shedding because of root penetration through the clay. A well designed riprap covering would be expected to last for hundreds of years.

The incremental impact on national resources from using clay as a moisture barrier and for exchange medium would be minimal. Clay is one of the most abundant and widespread mineral substances on the surface of the earth.[35] The annual amount of clay that would be used for the SLBF would be about 40,000 metric tons, based on covering 315 trenches (4×10^5 m^2 of disposal area) with 1 m of clay. The annual production of common clay in the United States is about 50 million metric tons.[36] Since the type of clay that would be used for a burial ground moisture barrier is so plentiful in this country, its use as recommended here would have no measureable economic effect upon the clay industry, nor would it appreciably reduce the resource reserves.

There are a number of chemical products on the market which are advertised to render soil moisture-proof, but the long-range effectiveness of these products needs to be proven. In view of the need for additional research on these products before they could be recommended for use with confidence, no further discussion of them will be presented here.

Various mixtures of asphalt materials could be used to cover waste trenches. These include asphalt concrete, hydraulic asphalt concrete, soil asphalt and hot liquid asphalt. Since they are all somewhat similar, only hydraulic asphalt concrete will be discussed here, with the understanding that the other materials vary slightly with regard to costs and permeability but are generically similar. The cover would be constructed similar to that described for clay.

Hydraulic asphalt concrete has a hydraulic permeability of 3.3×10^{-9} cm/sec or 4.1×10^{-2} in./yr.[32] This is approximately two orders of magnitude more water resistant than clay. However, when exposed to sunlight and oxygen, asphalt is subject to relatively rapid degradation; therefore, for long-range protection of burial trenches, it would be necessary to cover the asphalt with a layer (1 m) of soil. Thus covered, asphalt probably would be effective for at least 100 years. The soil covering would be protected against erosion with riprap. Subsidence problems would be similar to those discussed for the clay cover, except that the latter would be more self-healing than asphalt. Prior compaction of the wastes, however, would reduce the magnitude of this potential problem.

The use of hydraulic asphalt cement for a moisture barrier would require approximately one million gallons of oil to cover the disposal area, or about 1,200 barrels annually. This is a small fraction of our national oil utilization, and would have no appreciate impact on petroleum resources.

There are many plastic membranes, such as polyethylene, polyesters, polyvinyl chloride, butyl rubber, nylon, etc., that make excellent water barriers. Most of these materials can be heat sealed or cemented so that joints can be sealed to make a continuous cover. Water permeability is essentially zero unless the membrane is ruptured. Preventing holes and tears, however, would be difficult; the physical act of installing the membrane could cause some punctures or tears. All of the commonly used membrane materials degrade in sunlight, so they also would require a protective soil covering. How long these materials will last under covered conditions is unknown, but no manufacturer has been found who will guarantee his product for over 20 years. It is doubtful that any membrane material would be effective for 100 years.

Approximately 18,400 m^2 of plastic membrane would be needed annually to cover the SLBF. This amount would have an insignificant effect on national resources.

Concrete could be used but would not be especially advantageous. The need for expansion joints, to prevent the concrete from cracking due to temperature changes, creates zones which would be difficult to seal against moisture indefinitely. Also, concrete would be vulnerable to cracking as a result of an earthquake or settling.

Concrete is chemically basic, having a pH of about 13, and therefore is attacked by soil acids.[37] Much deterioration of concrete is caused by internal chemical reactions from the silica in the aggregate and the alkalies. This well known behavior called the alkali-silica reaction, may, under certain conditions, cause concrete to expand, crack, and generally deteriorate in periods of time ranging from one to several years.

A possible disadvantage in using concrete would be in removing it if it became necessary to retrieve the underlying waste and move it to another repository. If this should become necessary, the shear bulk and strength of the concrete would make the task much more difficult. It would take about 2,450 yd^3 (1,870 m^3) of concrete yearly to cap the area of the burial trenches with a 4-in. cover of concrete. This amount is negligible when compared with national annual usage and resources.

One material for a water barrier that could last for many years is stainless steel. Use of stainless steel would assure minimum water penetration for thousands of years, but the cost would be high. Stainless steel (i.e., 304) 0.32 cm thick would take approximately 250,000 years to corrode away in soil.[38] Capping the burial area with a stainless steel cover (0.32 cm thick) would require 9,200 metric tons of steel over a 20-year period. This is equivalent to 460 metric tons per year at a uniform annual rate. This amount would have no significant effect upon the steel industry in the United States, or upon national resources.

3.2.1.2 Operational Improvements

In areas having heavy rainfall, the use of a temporary weather shield to exclude water from the pit during the filling operation may be a useful device. Air support buildings have been used quite successfully at the INEL to protect radioactive waste storage and retrieval operations from the weather.[39,40] Such a building can be erected over a burial pit and moved to new locations as required. This protective cover would reduce water washing through the waste during the filling operation. Covering the waste with soil each day would then be required only to reduce direct radiation levels for personnel protection. This might increase the utilization factor for a given disposal site by improving the ratio of waste to soil in the disposal trenches.

The weather shield would have the additional benefits of permitting burial in any kind of weather, eliminating wind scattering of waste during dumping, and greatly reducing the need for pumping water out of pits and operating an evaporator.

Filling the interstitial spaces between waste containers with dry sand before covering the trenches is a method of reducing subsidence problems that could be used in conjunction with improved waste forms to minimize settling of trench covers. This method would help reduce long-term maintenance and site repair operations.

3.2.1.3 Improved Waste Forms

It is probable that, at some future date after institutional control of a burial ground has been relinquished, individuals may dig into the waste either intentionally or accidentally. Assuming that the reclaimer will not know to protect himself, it may be advantageous to make the waste residue as unattractive as possible so that he will not prolong his stay, and so that it represents a minimum hazard at the time of the reclamation activities.

One method of providing an improved waste form could be to incinerate all combustible waste materials before burial. Another way would be to compact all materials and destroy the usefulness of any artifact buried. The wastes could also be converted to a form not likely to be consumed or inhaled if reclamation activities were to disturb the disposal site. Even the waste containers, which would be contaminated from contact with the waste, might be considered useful utensils by a future reclaimer. It may therefore be advantageous to bury the waste in monolithic, leach-resistant blocks not easily removed from the containers. The solidification agent used for the encapsulation of the waste could be concrete, polymeric resins, or other suitable bonding materials.

3.2.1.4 Improved Trench Design

Besides improving trench covers, operational procedures and waste forms, certain improvements can be made in the trench design can be made to further isolate the buried wastes from the environment. Most of these features have been incorporated in one or more existing burial grounds but are not in universal use. The following features could be included in new burial trench designs:

- To avoid a bathtub effect, incline the trench bottom a minimum of one degree to facilitate drainage toward one end, and incorporate an appropriately sized sump or drain to allow eventual removal of water that may accumulate in the trench.

- Maintain a minimum of 1 m of compacted clayey or silty type soil between the trench bottom and underlying strata for enhanced ion exchange. If local soil is sandy, mix in a mimimum of 2 in. (5 cm) of clay over the bottom to provide increased ion-exchange capacity. This can be accomplished without increasing the tendency of the site to retain water in the waste region.

- Cover the trench bottoms with 2 ft (0.6 m) of coarse sand to assure that any water that accumulates in the trench will be able to flow to the drain without inundating the waste.

- Provide a drainage ditch at least 1 ft (0.3 m) square along the bottom of each wall of the burial trench. Fill the ditch with crushed rock.

- Provide the sump or drain at the lower end of trench with a means for sampling and pumping out any accumulated trench water.

- Process all water entering the sump or drain. This can be done by passing it through an ion exchange column to remove radionuclides before discharging the water to the environment or by evaporation to prevent its acting as a means of transporting radioactive materials.

Improvements in trench design could be extended to complete lining of the trench with concrete as is presently done for waste storage in Canada.[41] The construction of engineered concrete structures for waste disposal is addressed in Section 3.5. The improvements in trench design considered in this study are those that have been or can be easily implemented at typical shallow land burial facilities, and are consistent with plans for improvements being developed for government disposal sites.[42]

3.2.2 Technical Evaluation

The evaluation factors for improvements to the reference SLBF are discussed in the sections that follow. Changes from the base case are described, and their impacts discussed.

3.2.2.1 Compatibility with Waste

Implementing the improvements may make shallow land burial generally more compatible with a broader range of physical waste forms. However, for the wastes assumed in this study, no significant change is anticipated. The evaluation factor for compatibility with waste is therefore unchanged from unity.

3.2.2.2 Site Selection Factors

The improvements to the SLBF which involve overall weather protection could make heavy rainfall or other adverse climatic conditions less important. Use of a weather shield building to protect the waste from moisture during the pit filling operation and the use of moisture barriers over the pits could make avoidance of high precipitation areas unnecessary.

Because some of the improvements to the SLBF will allow a wider choice of burial sites in areas of moderate to high rainfall, the evaluation factors for site selection at both eastern and western sites are set at 0.9.

3.2.2.3 Safeguards

Addition of some capping materials over burial trenches could make the wastes slightly more difficult to retrieve for unauthorized uses than in the reference SLBF case. However, the anticipated change in vulnerability to unauthorized access is not of sufficient magnitude to justify a safeguards evaluation factor different from that of the reference SLBF.

3.2.2.4 Environmental Effects

The nonradiological impacts on construction and operational personnel would be very similar to those from the base SLBF case. These impacts are summarized in Table 3.8. There are no significant changes in the normalized values of the overall

TABLE 3.8

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR IMPROVED SLBF

Transportation	Eastern Site	Western Site
Average Transit Distance to Disposal Site	400	1,400
Total Train Car Miles	21,100,000	73,900,000
Total Projected Accidents[a]	3.0	10
Total Projected Injuries[b]	8.0	28
Total Projected Fatalities[c]	0.60	2.0
Construction Phase		
Average Crew Size (man-years)	22	20
Comparable Industry[d]	Construction/ Surface Mining	Construction/ Surface Mining
Total Projected Injuries	0.67	0.61
Total Projected Fatalities	0.01	0.01
Operational Phase		
Crew Size (man-years)	265	265
Comparable Industry[d]	Construction/ Storage and Warehousing	Construction/ Storage and Warehousing
Total Projected Injuries	8.1	8.1
Total Projected Fatalities	0.09	0.09
Total Overall Effect for Comparison[e]	23.8	57.7
Normalized Effect[f]	1.0	2.4

(a) Based on 1.4×10^{-7} accidents/car mile from Ref 13.
(b) Based on 2.7 injured/accident from Ref 13.
(c) Based on 0.2 fatalities/accident from Ref 13.
(d) From Table 2.2, for rates used for statistical injury and accident projection data. (Highest projected frequencies for given categories were used in the calculation.)
(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted more heavily than injuries to account for the more significant loss of life.)
(f) Normalized to reference SLBF eastern site case.

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impacts used in the comparative analysis. Approximately 1.7 injuries and 0.7 fatalities are projected over the operational life of the facility.

The area over each trench would be covered with rock riprap to control erosion. Deep-rooted plants will be discouraged from growing over the trenches at least through the period of institutional control.

The radiation level over the trenches would be maintained at or very near background levels, and the trench cover would be deep enough to protect the waste from intrusion by small burrowing animals.

Releases calculated for the improved SLBF with clay cover show the magnitude of protection to the general public that would result. (See Appendix C for details of the calculations performed.) For the accidental release and reclamation inhalation events, the improvements discussed in this section would not offer a large change over the reference SLBF. The differences are attributable only to a slight increase in the overall dilution factor due to the additional cover thickness. For the well water pathway, potential maximum individual doses would be reduced from 80 to 77 mrem/yr at eastern sites, and from 40 to 34 mrem/yr at western sites. The ground water model used does not account for further reduction in doses that would arise from the impermeability of the cover. The clay cover would also provide a small additional dilution factor for the food pathways. The potential radiological impacts are summarized in Table 3.9 for this case. The normalized overall effects are improved slightly over the base case for both the easter and western sites, as shown by the values less than unity.

The various materials used for moisture barriers were considered essentially equal in moisture resistance except for the stainless steel. Since materials such as concrete, asphalt and plastic are subject to degradation with time, any initial advantage they may have over clay would eventually be lost. In the absence of specific data on weathering and useful life for these materials, no credit in the calculations was taken for the initial greater impermeability from the moisture barrier cover (clay) analyzed. Covers alone also would not necessarily prevent submersion of the wastes from rising ground water underneath the trenches, although reducing percolation of water from the surface would generally tend to cause ground water levels in the area to sink.

Since stainless steel is impervious to water and could have a useful life of thousands of years, a stainless steel cover would be effective in eliminating percolation, and thus in reducing migration of nuclides via ground water. If the ground water does not rise to inundate the wastes from below, ground water doses from a stainless steel covered disposal area would be eliminated.

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TABLE 3.9

SUMMARY OF RADIOLOGICAL IMPACTS FOR IMPROVED SLBF

Long-Term Effects (mrem/yr)	Eastern Site	Western Site
Reclaimer Inhalation	51	51
Food Pathway	530	530
Reclaimer Direct Gamma Exposure[(a)]	290	290
Short-Term Effects (mrem/yr)		
On-Site Well Water Consumption	77	35
Accidental Airborne Releases	150	150
Transportation Exposures[(b)]	10	30
Total Overall Effect for Comparison (mrem/yr)	1108	1086
Normalized Effect[(c)]	0.84	0.83

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison.

(b) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison.

(c) Normalized to reference SLBF eastern site case.

3.2.2.5 Availability of Techniques

Basically, no new research is required to use the improved shallow land-based techniques described here. Because these improvements are all technologically proven and available, the evaluation factor for availability of techniques is unchanged from the value of unity for the base case.

3.2.3 Sociopolitical Implications

At the present time, shallow land burial is the only waste disposal alternative that is being practiced in the United States for low-level radioactive waste. Some groups oppose the continued burial of any radioactive wastes. However, general public acceptance and regulatory controls now in effect for shallow land burial disposal of low-level radioactive wastes will not be adversely affected by incorporating appropriate improvements.

3.2.3.1 Public Acceptance

Improvements to shallow land burial practices currently in use will likely be accepted by the public with few reservations. Making improvements implies a lessening of risks from waste disposal. An issue may be whether risks are being reduced to low enough levels. In any case, the public will recognize that improving shallow burial techniques will reduce the risks from waste disposal. The perceived hazards and risks will be less than the base case, since the improvements will be designed to reduce those risks that appear most important. The improvements contemplated will not change any of the long-term moral or ethical issues from waste disposal operations from those associated with the baseline SLBF. Improvements to current waste disposal practices will undoubtedly be received more readily by the general public than simple continuation of present methods, especially if the costs for improvements are not excessive. Based on the foregoing considerations, the public acceptance evaluation factor is assigned a value of 0.9 to reflect greater public acceptability than for the baseline case.

3.2.3.2 Institutional Controls

Improvements to shallow land burial practices will not change the institutional control implications from the base case. Existing domestic institutional regulatory controls and regulations governing waste disposal would require no modification to implement the improvements described above. No international controls are directly involved in shallow land burial within national territory. The evaluation factor for institutional controls is therefore assigned a value of unity.

3.2.4 Cost Analysis

The major costs associated with improvements to shallow land burial are described below. The costs for adding a 1-m thick clay cover, an air-supported weather protection building over the reference trenches, and additional site preparation and final grading have been added to those for the SLBF base case.

3.2.4.1 Cost Estimates

Total costs for improved site preparation, the different types of trench covers and the weather protection building have been estimated and are summarized in Table 3.10. The total cost increase over the reference SLBF case is about \$5 million These improvements would cost about \$8/m^3 of disposed waste. The cost of the clay cover alone would be about \$5/m^3, based on installed costs of roughly \$3/m^2 for the 1 m thick cover.

Costs for the plastic membrane type cover would amount to about twice those for clay, or \$10/m^3 of waste, based on an installed cost of \$6/m^2. The ashalt cap would cost about \$8/m^3, based on installed costs of \$5/m^2. A 4-in. thick concrete cover would cost about \$18/m^3 of waste disposed of, based on an installed cost of \$11/m^2. A 1/8-in. thick 304 stainless steel cover over the trenches would cost approximately \$117/m^3 based on installed cost of cover, including welding, of about \$72 /m^2. For the reasons given in the text, the clay cover is most feasible, durable and cost effective. Further explanation of the costs is given in Appendix D.

3.2.4.2 Economic Impact

The incremental costs for the improvements estimated in Table 3.10 (\$5 million) amount to about 3% of the total waste disposal cost for the reference SLBF eastern site. No significant incremental economic impact is expected from implementing these improvements.

3.3 Deeper Burial

An alternative to shallow land burial is burial at greater depth. The generic concept for deeper burial has been referred to as "intermediate depth" burial.[6] The concept is essentially the same as shallow land burial, except that an additional 10 to 15 m of clean soil cover are applied over the buried wastes. The extra cover would be provided for by appropriate site selection, perhaps excavating the site to the desired depth before digging the disposal trenches, or by reclaiming suitable sites, such as former strip mines.

TABLE 3.10 COST ESTIMATE SUMMARY FOR IMPROVED SHALLOW LAND BURIAL CONCEPTS

	Estimated Costs (Millions of Dollars)			
Item	Eastern Site		Western Site	
Capital Costs				
Land Acquisition	5.00		2.50	
Site Studies	.50		.40	
Licensing	.32		.32	
Environmental Reports	.25		.15	
Site Preparation	.66		.66	
Site Structures	1.04		1.04	
Site Fencing and Security Alarms	.25		.25	
Trench Excavation	2.35		2.35	
Backfill and Compaction	1.24		1.24	
Clay Cover (1 m thick)	.92		.92	
Air Support Weather Protection	.33		.33	
Capital Subtotal		12.86		10.16
Engineering (5% of Subtotal)	.64		.51	
Higher Radiation Waste Facilities	.31		.31	
Total Capital Costs		14		11
Operating Costs				
Emplacement Costs	2.02		2.02	
Facility and Surveillance Personnel	19.75		19.75	
Expenses	1.88		1.88	
Total Operating Costs		24		24
Contingency (30% of Total Capital and Operating Costs)		11		10
Profit, Financing and Escalation		40		36
Total Facility Costs		89		81
Transportation Costs		68		237
Total Facility Plus Transportation Costs		157		318
Total Unit Costs for Waste Disposal ($\$/m^3$)	250		500	

3.3.1 Description of Deeper Burial

The concept of deeper burial differs from the improved reference SLBF only in the depth at which the wastes are buried, or the subsequent depth of clean cover material placed over the disposed wastes. A schematic layout of the deeper burial facility is shown in Figure 3.2. The tops of the disposal trenches would be about 10 to 15 m below the planned final site grade. The improvements in cover, trench design and operations discussed in Section 3.2.1 are also assumed to be included in the deeper burial facility.

After the site is prepared, the waste disposal operations would be essentially the same as for the reference SLBF. After the trenches or group of trenches in a given area within the facility were filled, the final covering would be applied. Appropriate measures to control surface water to prevent accumulation of water in the waste disposal area would be incorporated. Appropriate site landscaping and contouring for erosion protection would follow.

3.3.2 Technical Evaluation

Most of the technical aspects of deeper burial are the same as those for shallow land burial. The anticipated differences will be described in this section.

3.3.2.1 Compatibility with Waste

Deeper burial facilities would exhibit the same compatibility with physical waste forms as the reference SLBF. This evaluation factor is therefore the same as for the reference SLBF case.

3.3.2.2 Site Selection Factors

A suitable reference deeper burial site would need to meet the same requirements as the reference SLBF described in Section 3.1.2.2. In addition, soil depths from 15 to 20 m would be required or the topography would have to accommodate the extra 10 to 15 m of clean cover. The site should be selected so that there is sufficient depth to underlying strata to accommodate the disposal trenches. The depth to regional ground water tables should also be sufficient to assure that the disposal trenches do not penetrate to that level.

Many areas of the country have more than adequate soil depths. For instance, surface soil thicknesses of more than 100 m are not uncommon near West Valley, New York,[43] and near Hanford, Washington the surface soils are about 80 m thick.[44] Many former strip mines are also available, where the recontouring could be environmentally advantageous. Because these sites are

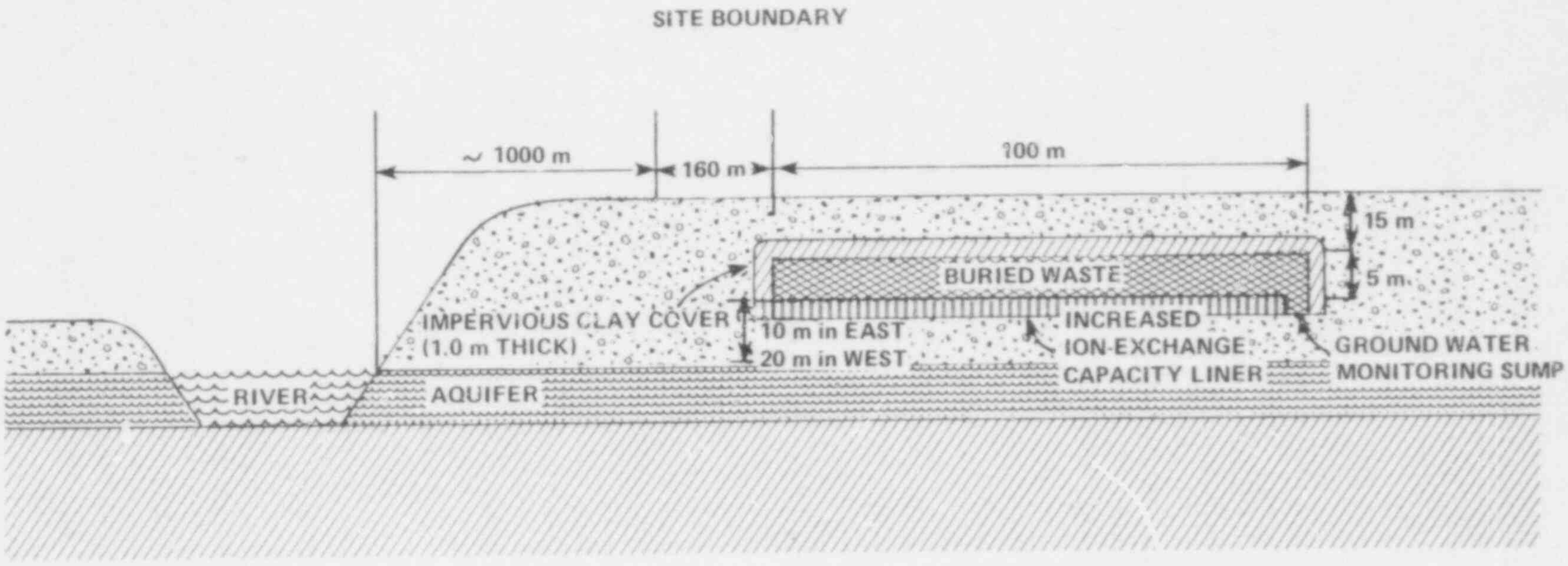


FIGURE 3.2 SCHEMATIC OF DEEPER BURIAL FACILITY

not as plentiful as those for the reference SLBF, however, this evaluation factor is assigned a value of 1.2 in the eastern U.S. and 1.1 in the west, where suitable sites are more available.

3.3.2.3 Safeguards

The deeper burial concept would provide a disposal method less vulnerable to unauthorized uses of the wastes after burial, because of the extra depths of clean fill that would need to be moved to gain access to the wastes. The evaluation factor representing the safeguards and physical security aspects of this deeper burial alternative is assigned a value of 0.9 to reflect the increased resistance to unauthorized dislocation of the buried wastes.

3.3.2.4 Environmental Effects

Deeper burial will generate non-radiological impacts that are similar to those arising from the reference SLBF case, although more workhours will be consumed. The non-radiological impacts for this case are summarized in Table 3.11. Over the operational life of the facility, about 17 injuries and 0.7 fatalities are projected.

The most obvious advantage of deeper burial is the additional degree of isolation from inadvertent intrusion into the wastes.[6] Future reclamation activities at the site would probably not excavate to depths necessary to contact the buried wastes. Some additional retardation of the downward percolation of surface moisture, such as rainfall, would also occur as a result of the additional depth of cover. Changes in anticipated exposures involve elimination of the postulated excavation direct contact, inhalation and food pathway exposure events. The radiological impacts for deeper burial are summarized in Table 3.12.

3.3.2.5 Availability of Techniques

Although the technique of deeper burial for disposal of low-level radioactive wastes has not been demonstrated, there are no technological problems foreseen in implementing this mode of waste disposal. This method has also been suggested for disposal of radioactive uranium mill tailings.[45] The relative value assigned for this evaluation factor is 1.1, to reflect less experience than is available for the reference SLBF case.

TABLE 3.11

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR DEEPER BURIAL

Transportation	Eastern Site	Western Site
Average Transit Distance to Disposal Site	400	1,400
Total Train Car Miles	21,120,000	73,920,000
Total Projected Accidents(a)	3.0	10
Total Projected Injuries(b)	8.0	28
Total Projected Fatalities(c)	0.60	2.0
Construction Phase		
Average Crew Size (man-years)	31	28
Comparable Industry(d)	Construction/ Surface Mining	Construction/ Surface Mining
Total Projected Injuries	0.95	0.85
Total Projected Fatalities	0.01	0.01
Operational Phase		
Crew Size (man-years)	265	265
Comparable Industry(d)	Construction/ Storage and Warehousing	Construction/ Storage and Warehousing
Total Projected Injuries	8.1	8.1
Total Projected Fatalities	0.09	0.09
Total Overall Effect for Comparison(e)	24.0	58.0
Normalized Effect(f)	1.0	2.4

(a) Based on 1.4x10^{-7} accidents/car mile from Ref 13.
(b) Based on 2.7 injuries/accident from Ref 13.
(c) Based on 0.2 fatalities/accident from Ref 13.
(d) From Table 2.2, for rates used for statistical injury and accident projecton data. (Highest projected frequencies for given categories were used in the calculations.)
(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted more heavily than injuries to account for the more significant loss of life.)
(f) Normalized to reference SLBF eastern site case.

TABLE 3.12

SUMMARY OF RADIOLOGICAL IMPACTS FOR DEEPER BURIAL

Long-Term Effects (mrem/yr)	Eastern Site	Western Site
Reclaimer Inhalation[a]	0	0
Food Pathway	0	0
Reclaimer Direct Gamma Exposure[a]	0	0
Short-Term Effects (mrem/yr)		
On-Site Well Water Consumption	77	35
Accidential Airborne Releases	150	150
Transportation Exposures[b]	10	30
Total Overall Effect for Comparison (mrem/yr)	237	215
Normalized Effect[c]	0.18	0.16

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison.

(b) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison.

(c) Normalized to reference SLBF eastern site case.

3.3.3 Sociopolitical Implications

The sociopolitical implications of implementing this disposal alternative would be similar to those for the reference SLBF. Some increase in public acceptance might be expected.

3.3.3.1 Public Acceptance

Because deeper burial provides a higher degree of isolation of the wastes from the human environment, and because of the possibility of using former strip mines or other land areas unsuitable for more productive use, this option may be perceived as being more acceptable by the general public than the reference SLBF case. The publicly perceived risks associated with deeper burial will be similar to those from the base case. The acceptability of the risks will be improved by deeper burial because of elimination of the likelihood of inadvertent intrusion into the buried wastes. The hazards associated directly with the wastes will not be changed, but the probabilities of exposure will be reduced. This should lead to enhanced public acceptance of waste disposal. Concern for the moral and ethical issues will also be reduced because the likelihood of future generations encountering the deeper buried wastes is less. Because of these considerations, the evaluation factor for public acceptance is assigned a value of 0.8 to reflect better public acceptability than for the base case.

3.3.3.2 Institutional Controls

Some relatively small changes in existing domestic institutional controls and requirements regulating shallow land burial may be necessary to implement this type of disposal alternative. The changes would involve redefinition of safety requirements to accommodate deeper burial, site selection criteria, and operational procedures. As for the other land-based disposal facilities, no international controls are directly involved in deeper burial. Although the anticipated changes in domestic controls are small, the evaluation factor for institutional controls is increased to 1.1 to reflect the difficulties inherent in implementing regulatory changes.

3.3.4 Cost Analysis

The cost for deeper burial is the same as for the reference SLBF, except for the added efforts for site excavation and final site covering.

TABLE 3.13 COST ESTIMATE SUMMARY FOR DEEPER BURIAL FACILITY

Item	Estimated Costs (Millions of Dollars)			
	Eastern Site		Western Site	
Capital Costs				
Land Acquisition	5.00		2.50	
Site Studies	.50		.40	
Licensing	.32		.32	
Environmental Reports	.50		.40	
Site Preparation	.66		.66	
Site Structures	1.04		1.04	
Site Fencing and Security Alarms	.25		.25	
Trench Excavation	5.49		5.49	
Backfill and Compaction	2.18		2.18	
Clay Cover (1 m thick)	.92		.92	
Air Support Weather Protection	.55		.55	
Capital Subtotal		17.41		14.71
Engineering (5% of Subtotal)	.87		.74	
Higher Radiation Waste Facilities	.42		.42	
Total Capital Costs		19		16
Operating Costs				
Emplacement Costs	2.12		2.12	
Facility and Surveillance Personnel	19.75		19.75	
Expenses	1.88		1.88	
Total Operating Costs		24		24
Contingency (30% of Total Capital and Operating Costs)		13		12
Profit, Financing, and Escalation		46		42
Total Facility Costs		102		94
Transportation Costs		68		237
Total Facility Plus Transportation Costs		170		331
Total Unit Costs for Waste Disposal ($/m^3)	270		520	

3.3.4.1 Cost Estimates

The costs for the additional excavation, earthmoving and hauling required for a 10 m thick final cover are estimated to be $16 million. This equates to $25/m^3$ of waste disposed, or about 10% of the total costs for disposal at the reference shallow-land burial eastern site. The cost estimate for deeper burial is summarized in Table 3.13.

3.3.4.2 Economic Impact

The incremental change in economic impact for implementing this alternative would be about a 10% increase in the total waste management cost, compared to the reference SLBF case. The total waste disposal cost at an eastern deeper burial site would represent only 0.05% of the total costs for electricity to the consumer, and at a western site, only 0.1%.

3.4 Disposal in Mined Cavities

Disposal in cavities in geologic formations has been categorized into natural caverns and mined chambers. Mined cavities have been selected as the reference example for this comparative analysis. Mines considered include both existing nonproductive mines and new excavations made explicitly for low-level waste disposal.

The mined cavity concept uses rooms or chambers in a geologic formation for disposal of wastes. It offers the potential advantage over shallow land burial of increased isolation of the wastes from the biosphere.

Disposal in geologic formations has been previously proposed and presented in great detail,[7,31,46] principally in relation to high-level wastes. All concepts appropriate for high-level waste disposal are considered in this study to also be technically viable for low-level waste disposal. The mined cavity repository in a geologic formation could be formed by either room and pillar excavation or solution mining.

3.4.1 Description of Mined Cavity Disposal Facility

A reference Mined Cavity Disposal Facility (MCDF) consists of a number of excavated rooms and connecting tunnels located below the surface of the ground, in a geologic formation which would be selected on the basis of its favorable characteristics to contain radioactive waste. The total excavation would cover several square kilometers on one or several levels, as required by the volume of solid waste to be disposed and by the emplacement methods used. The excavations would be appropriately ventilated during waste handling operations. Conventional drilling and mining operations to excavate new disposal rooms would be controlled to avoid compromise of previously completed sections of the MCDF.

Sedimentary basins in the continental interior and coastal plain that contain salt are suitable for mined chambers at depths of about 910 m or less.[7] Salt appears suitable because of its low permeability, high thermal conductivity and natural plasticity. The Salina Formation, the interior province of the Gulf Coast dome region, and the Paradox Basin are all considered to be formations of high potential. Salt formations have received the most attention in the past for disposal of high-level radioactive wastes.

Clay and shale formations also appear suitable as disposal sites because of their low permeabilities and high ion-exchange capacities. The greatest potential for using shale is in arid and semi-arid parts of the United States, where chambers can be mined well above existing water tables. The basin and range province of the western U.S. (particularly the great basin exclusive of seismic risk zone 3) appears to have potential for mined cavities in tuff, shale or argillite that would be above deep water tables.

The stable continental interior where sedimentary cover is thin or absent, the shield area of the North Central states, and the metamorphic belt of the Eastern United States (primarily the Piedmont) are also possibly suitable for mined cavities. Rock formations with low permeability at depths from 305 m to 6,100 m within these areas may be suitable for mined chambers.[7] Some granitic deposits (for example, the Climax Stock at the Nevada Test Site) may also be suitable for mined cavities. Rocks originating from consolidation of materials ejected by volcanic eruptions (tuffs) are sometimes dense and compact enough to be appropriate for mined cavities.

Shafts or tunnels would connect the excavated rooms to surface receiving facilities for introducing packaged waste and operations personnel into the MCDF central control area. From this point, the waste would be transferred through tunnels to its point of disposal in excavated rooms. The shaft or tunnel supports and associated equipment would be fireproof to prevent fire problems in the mine.

Surface receiving and handling facilities would occupy a few acres and would be the only visible surface evidence of the MCDF. Packaged low-level radioactive wastes would be delivered to the facility by truck or rail. Temporary storage space and capacity for package repair would be provided within the facility. The receiving facility could be operated to permit use of the surrounding surface land even though the land would be above the underground repository.

For a reference MCDF formed by solution mining, the cavity would have dimensions consistent with the volume of waste to be disposed of. Waste packages could be lowered from the receiving facility into the cavity by a hoist and then dropped from the hoist. This concept has the possible advantage of not requiring human access to the disposal cavity.

A conceptual sketch of both the room and pillar mine concept and the solution-mine concept is shown in Figure 3.3. Entrance to a room and pillar mine is possible by two means: Vertical shafts when the excavated rooms are below the entrance, and horizontal tunnels when the mine is excavated into a hill.

Because of problems associated with removing all waste solutions after a waste disposal cavity is produced by the solution mining process and problems in finding geologic formations suitable for both solution mining and long-term isolation of the disposed wastes from ground water systems, this concept has not been pursued further.

Waste disposal operations in a reference MCDF would be similar to disposal operations on the surface, except that the wastes would be stacked and not necessarily buried or covered. When sections of the cavity are filled to capacity with waste, the entire completed portion of the room could be backfilled and sealed.

3.4.2 Technical Evaluation

The analysis of the reference MCDF is based on the conceptual room and pillar design presented schematically in Figure 3.3.

3.4.2.1 Compatibility With Waste

The MCDF could provide sufficient additional degrees of containment of the wastes to justify disposal of higher activity wastes or other less restrictive waste forms, if the site were appropriately chosen. In any case the MCDF concepts will be compatible with the low-level wastes analyzed in this study. Therefore, the evaluation factor representing compatibility with waste for the MCDF is the same as for for the SLBF.

3.4.2.2 Site Selection Factors

Potential sites exist in many areas of the United States in various geologic formations. Formations of interest include salt (either in thick beds or stable domes), shale, clay and crystalline rock. Suitable geologic disposal sites will not be as readily available as those for shallow land burial. The three variations of the MCDF concept considered in this study--abandoned mines and newly excavated horizontal tunnel and vertical shaft mines--have been assigned values for this evaluation factor of 1.5, 1.4 and 1.3, respectively for eastern sites, and 1.4, 1.3 and 1.2 for sites in the west. Care

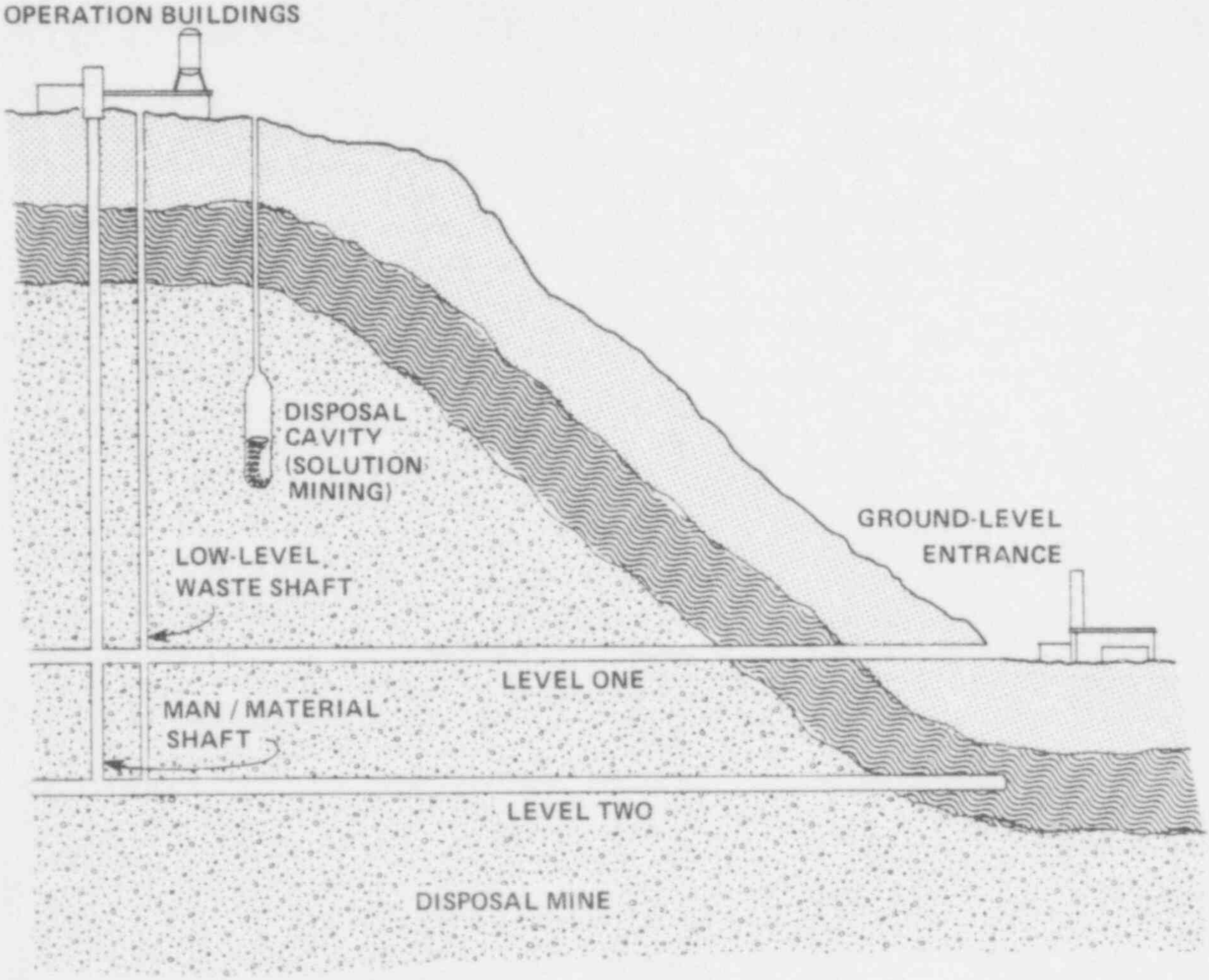


FIGURE 3.3 MINED CAVITY CONCEPT FOR THE DISPOSAL OF LOW-LEVEL RADIOACTIVE WASTE

must be taken to select sites where competing uses of nearby natural resources will not compromise the long-term suitability for waste disposal. Vertical shaft mine sites are more common than suitable horizontal shaft locations, and thus are assigned the lowest values. Abandoned sites that are also suitable for waste disposal will be the most difficult to locate, and are therefore assigned the highest values.

3.4.2.3 Safeguards

Disposal of wastes in the MCDF would provide a larger degree of assurance that unauthorized uses of the wastes would not occur than does the reference SLBF, because of the physical barriers between the wastes and the surface. The evaluation factor representing safeguards and physical security is therefore valued at 0.8 for the MCDF concept.

3.4.2.4 Environmental Effects

Nonradiological hazards to workers are assumed to be similar to those encountered in the non-coal subsurface mining and construction industries. Approximately one death and 23 injuries are projected, based on the estimated construction and operations crew sizes. The non-radiological impacts for the MCDF concepts are summarized in Table 3.14. Additional rail facilities may be required in many cases, although the implications of constructing additional track mileage have not been considered in this study.

The MCDF would provide greater degrees of isolation for the wastes than the reference SLBF. The inadvertent reclamation and on-site well water consumption exposure events would be eliminated by the assumed geologic features of the MCDF. Exposures to the general public from single container accidents would be approximately half that from the reference SLBF, because most accidents would occur inside the mine. Transportation distances to suitable MCDF sites could be longer than the SLBF. The radiological impacts from the MCDF concepts are summarized in Table 3.15.

3.4.2.5 Availability of Techniques

Waste disposal in mined cavities is presently taking place in West Germany.[2] Mining technology is well developed, but waste disposal techniques will require some additional development. Methods of emplacing wastes efficiently (especially the higher radiation level wastes) will require further design and evaluation, as will techniques for stockpiling mined rock that may be used as backfill. The three variations of the MCDF analyzed (abandoned mines, new horizontal tunnels and new vertical shafts) are given evaluation factors of 1.2, 1.3 and 1.3, respectively.

TABLE 3.14

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR MCDF CONCEPTS

	Eastern Site			Western Site		
Transportation	Abandon Mine	Horizontal Tunnel	Vertical Shaft	Abandon Mine	Horizontal Tunnel	Vertical Shaft
Average Transit Distance to Disposal Site	600	600	600	1,600	1,600	1,600
Total Train Car Miles	$3.17x10^{7}$	$3.17x10^{7}$	$3.17x10^{7}$	$8.45x10^{7}$	$8.45x10^{7}$	$8.45x10^{7}$
Total Projected Accidents(a)	4.4	4.4	4.4	12	12	12
Total Projected Injuries(b)	12	12	12	32	32	32
Total Projected Fatalities(c)	0.88	0.88	0.88	2.4	2.4	2.4
Construction Phase						
Average Crew Size (man-years)	12	54	62	12	54	62
Comparable Industry(d)	Non-Coal Mining/Construction					
Total Projected Injuries	0.63	2.8	3.3	0.63	2.8	3.3
Total Projected Fatalities	0.01	0.06	0.07	0.01	0.06	0.07
Operational Phase						
Crew Size (man-years)	265	265	265	265	265	265
Comparable Industry(d)	Construction/Storage and Warehousing					
Total Projected Injuries	8.1	8.1	8.1	8.1	8.1	8.1
Total Projected Fatalities	0.09	0.09	0.09	0.09	0.09	0.09
Total Overall Effect for Comparison(e)	30.5	33.2	33.8	65.7	68.4	69.0
Normalized Effect(f)	1.3	1.4	1.4	2.8	2.9	2.9

(a) Based on $1.4x10^{-7}$ accidents/car mile from Ref 13.

(b) Based on 2.7 injuries/accident from Ref 13.

(c) Based on 0.2 fatalities/accident from Ref 13.

(d) From Table 2.2, for rates used for statistical injury and accident projection data. (Highest projected frequencies for given categories were used in the calculations.)

(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted more heavily than injuries to account for the more signigicant loss of life.)

(f) Normalized to reference SLBF eastern site case.

TABLE 3.15
SUMMARY OF RADIOLOGICAL IMPACTS FOR MCDF CONCEPTS

	Eastern Site			Western Site		
Long-Term Effects (mrem/yr)	Abandon Mine	Horizontal Tunnel	Vertical Shaft	Abandon Mine	Horizontal Tunnel	Vertical Shaft
Reclaimer Inhalation[a]	0	0	0	0	0	0
Food Pathway	0	0	0	0	0	0
Reclaimer Direct Gamma Exposure[a]	0	0	0	0	0	0
Short-Term Effects (mrem/yr)						
On-Site Well Water Consumption	0	0	0	0	0	0
Accidental Airborne Releases	100	100	100	100	100	100
Transportation Exposures[b]	14	14	14	38	38	38
Total Overall Effect for Comparison (mrem/yr)	114	114	114	138	138	138
Normalized Effect[c]	0.09	0.09	0.09	0.10	0.10	0.10

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison.

(b) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison.

(c) Normalized to reference SLBF eastern site case.

3.4.3 Sociopolitical Implications

Because of the increased isolation provided by geologic disposal concepts, the MCDF for low-level waste should be more readily accepted by the public than the reference SLBF. Existing regulations and institutional controls could be modified to accommodate this alternative.

3.4.3.1 Public Acceptance

The MCDF will provide greater degrees of isolation and long-term control of the wastes with less adverse enviromental effects than the reference SLBF. The MCDF concept has been successfully demonstrated in Europe.[2] The MCDF concepts will allow disposal of many types of hazardous wastes, and should therefore provide a more publically acceptable image for low-level waste disposal compared to the reference SLBF case, although some resistance toward use of a similar concept for high-level waste has been encountered in New Mexico. If an SLBF presents an acceptable risk then the MCDF concepts should be more acceptable, particularly for the cases involving mining cavities specifically for waste disposal. The hazards from disposal of wastes in stable geologic formations should also be perceived as less than those from the base case. Because the wastes are more securely isolated from man's activities, the ethical and moral concern over leaving unsuspecting future generations problems from our waste disposal activities should also be reduced. Therefore, public acceptance of this alternative will be higher than for shallow land burial. The evaluation factor for public acceptance has been assigned a value of 0.8 for abandoned mines and 0.7 for new cavities mined expressly for waste disposal, to reflect the improvement over the base case, with some skepticism concerning use of existing mines.

3.4.3.2 Institutional Controls

Existing domestic regulations would require revision to accomodate this alternative. Coordination among regulatory agencies governing waste disposal and mining would be required. Controls on competing surface land uses and resource reclamation would be required to assure that the long-term integrity of the disposal mine is not compromised. These controls, such as prohibitions on well drilling and resource exploration, may have to cover more area to be effective than would be required for the SLBF. However, the controls on surface land use above the MCDF would be less restrictive than those necessary for the SLBF. Changes in current waste disposal operating practices and procedures would also be required to accommodate this alternative. No international control implications are associated with waste disposal using the MCDF alternative within national territorial boundaries. The evaluation factor for institutional constraints is set at 1.2 for this alternative to reflect these difficulties.

3.4.4 Cost Analysis

The cost analyses are based on revamping an existing non-productive mine and on constructing new mine facilities with either horizontal tunnel or vertical shaft access, as dictated by the geologic features of the site.

3.4.4.1 Cost Estimates

The estimated costs for the three variations of this alternative for both eastern and western sites are summarized in Table 3.16. Total facility costs range from \$72 to \$139 million for the variations. Transportation costs are about \$102 million for an eastern site and \$271 million for a site in the west. Unit costs range from \$280 to $\$650/m^3$ of waste disposed of in a MCDF.

3.4.4.2 Economic Impact

If the reference waste volume was generated in production of electricity, it would cost from about 0.025 mills/kwhr to dispose of it at an eastern abandoned mine to 0.058 mills/kwhr at a western shaft mine. These costs are equivalent to from 0.06% to 0.13% of the base cost for power production (45 mills/kwhr). These costs do not represent prohibitively adverse economic impacts for waste disposal using MCDF concepts.

3.5 Disposal in Structural Facilities

Enclosing the radioactive waste in engineered structures may offer advantages over the reference SLBF. The structure itself can provide an important added barrier to the escape of radioactivity if radioactive waste containers eventually fail. Monitoring for leaking radioactivity could be better accomplished with an engineered structure. Keeping the waste containers isolated from moisture and providing less difficult retrieval may be perceived as additional advantages. Some of these advantages have been exploited in certain structures used for storing radioactive wastes in Canada.[41]

3.5.1 Description of Structural Disposal

The structural disposal facility (SDF) would be built of reinforced concrete to obtain the best durability and fire resistance at a reasonable cost. Concrete has been estimated to last at least 1000 years in contact with moist soil.[47] Both covered and exposed structures are considered. Structures could be built at any appropriate location. Generic eastern and western sites are used in this comparative analysis.

TABLE 3.16 COST ESTIMATE SUMMARY FOR MCDF CONCEPTS

Item	Estimated Costs (Millions of Dollars) Abandoned Mine		Horizontal Tunnel		Vertical Shaft	
Capital Costs						
Site Purchase, Licensing and Reports	2.96		2.96		2.96	
On-Site Structures	0.56		0.56		0.56	
Site Fencing and Improvements	0.10		0.20		0.20	
Mine Construction or Revamp	2.38		23.72		27.68	
Capital Subtotal		6.00		27.44		31.40
Engineering (5% of Above Item)	0.30		1.37		1.57	
Extra Facilities for Higher Radiation Waste	0.76		0.76		0.76	
Total Capital Costs		7		30		34
Operating Costs						
Emplacement Costs	2.84		2.84		2.84	
Facility Operative Personnel	19.75		19.75		19.75	
Supplies and Equipment	1.88		1.88		1.88	
Total Operating Costs		24		24		24
Contingency (30% of Total Capital and Operating Costs)		9		16		17
Profit, Financing, and Escalation		31		59		64
Total Facility Costs		71		129		139
Transportation to:						
Eastern U.S. Site		102		102		102
Western U.S. Site		271		271		271
Total Unit Costs for Eastern U.S. Site ($/m^3)	280		370		380	
Total Unit Costs for Western U. S. Site ($/m^3)	540		630		650	

Figures 3.4 and 3.5 and Table 3.17 describe the structural concepts and their relationship with the hydrological surroundings. Parameters of interest include the surface grade, the cover thickness (if any), the distance to the underlying aquifer, and the distance to the river into which the ground water system drains.

The easiest and least expensive structure to build and to fill with waste would be an exposed structure with its foundation at grade. An alternative structure would be of similar construction with a 0.3- to 1-m covering of soil, gravel or rock. Capping the cover with asphalt would improve the facility's resistence to penetration by rainwater. Shallow-rooted vegetation might be planted on a soil cover. The structure's roof could be at or near grade so that the completed facility would present only a low mound or be even with the surface grade. This would be technically suitable where the water table is consistently low enough to be below the resulting level of the floor, and the adjoining soil has good drainage. Sites of this nature may be found most frequently in the west. This type of structure provides the best protection from tornadoes, high winds, lightning, crashing aircraft or motor vehicles, warfare, terrorism, etc.[48,49]

Existing structures could possibly be used for waste disposal after making appropriate modifications. For instance, the MAD buildings at the Nevada Test Site or unused REDOX cells at the Hanford Reservation might be adaptable. There could be advantages in using certain former missile sites although the capacity of each is somewhat limited.[2] This study will concentrate on structures designed and constructed expressly for waste disposal, however.

Inside the SDF, the 55-gal. waste drums are stacked upright, five high, with horizontal sheets of steel mesh between the drums for stability. Cells are arbitrarily assumed to be about 70 ft long. They would each contain 4,445 drums (close-packed), accommodating 920 m^3 of waste. Additional cells would be connected by sharing adjacent walls. Six hundred eighty-five cells would be required. The drums would be stacked in place with a forklift or by an internal traveling crane.

When a cell becomes filled, it would be closed with a wall of poured-in-place, reinforced concrete tied to the rest of the structure with reinforcing bar. For weather protection, a cell would be loaded under an air-support structure.

The SDF would be identified by markers that are designed to last for long periods. Markers could consist of metal plaques with warnings and radiation symbols, for example.

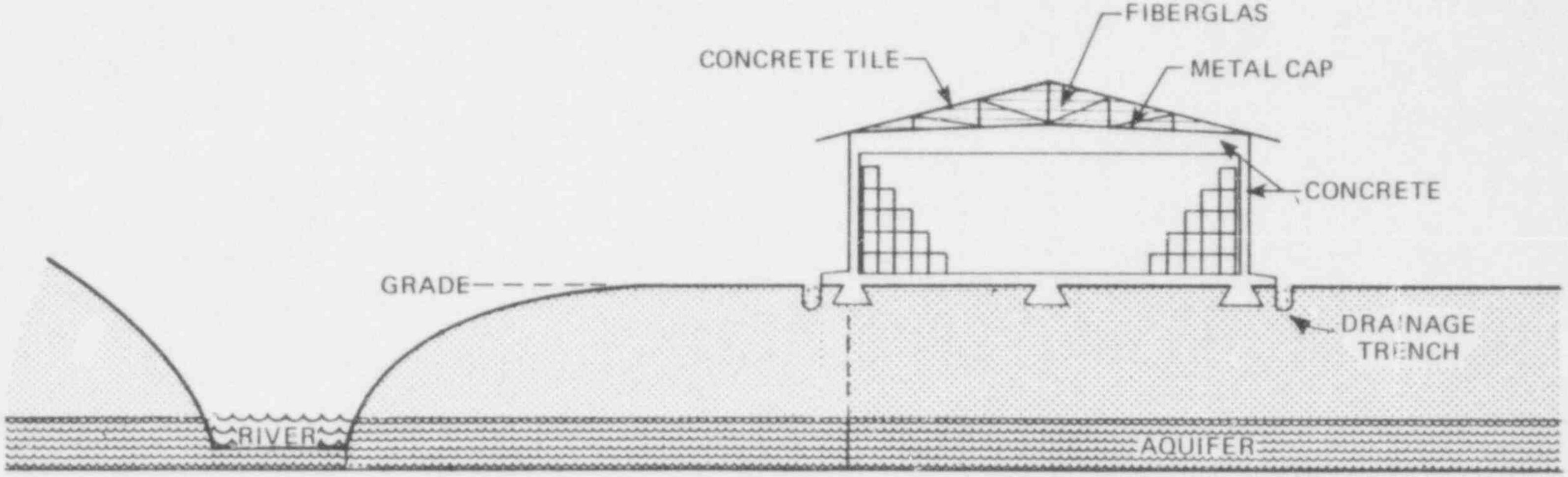


FIGURE 3.4 EXPOSED STRUCTURAL DISPOSAL FACILITY

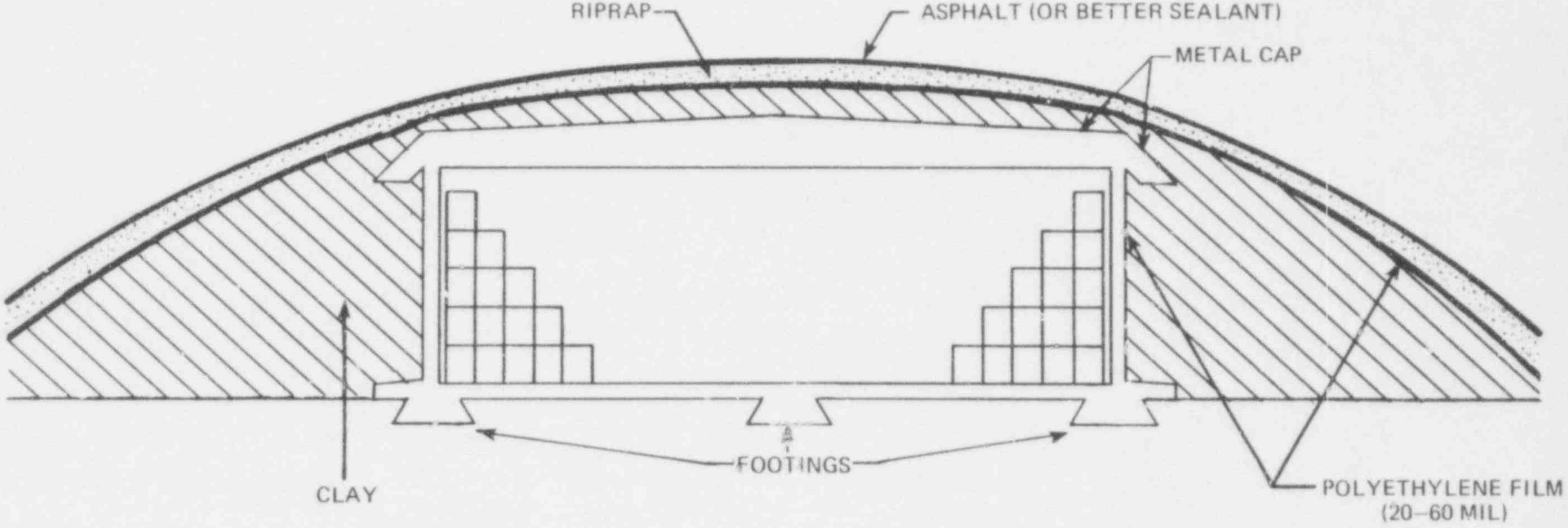


FIGURE 3.5 THE COVERED STRUCTURAL DISPOSAL FACILITY

TABLE 3.17

DETAILS OF THE COVERED STRUCTURAL DISPOSAL FACILITY

Internal storage dimensions:	47' w x 15' h x 70' l
All concrete:	Poured-in-place, reinforced, monolithic.*
Roof:	5% slope from crown to eave, supported by internal columns as necessary. Metal cap to be made of welded sheets of a stainless steel such as Type 304 (Extra Low Carbon). Cap to be grounded.
Covering:	A 1 foot section of riprap over roof underlain by a 1 foot section of clay. The riprap should be stabilized against slumping by toe walls, if necessary.
Walls and floor:	1 foot thick.**

---

* Imperviousness to moisture could be better attained with poured-in-place concrete rather than precast panels. The cost of transporting precast structural elements to remote building sites would also decrease their economic attractiveness.

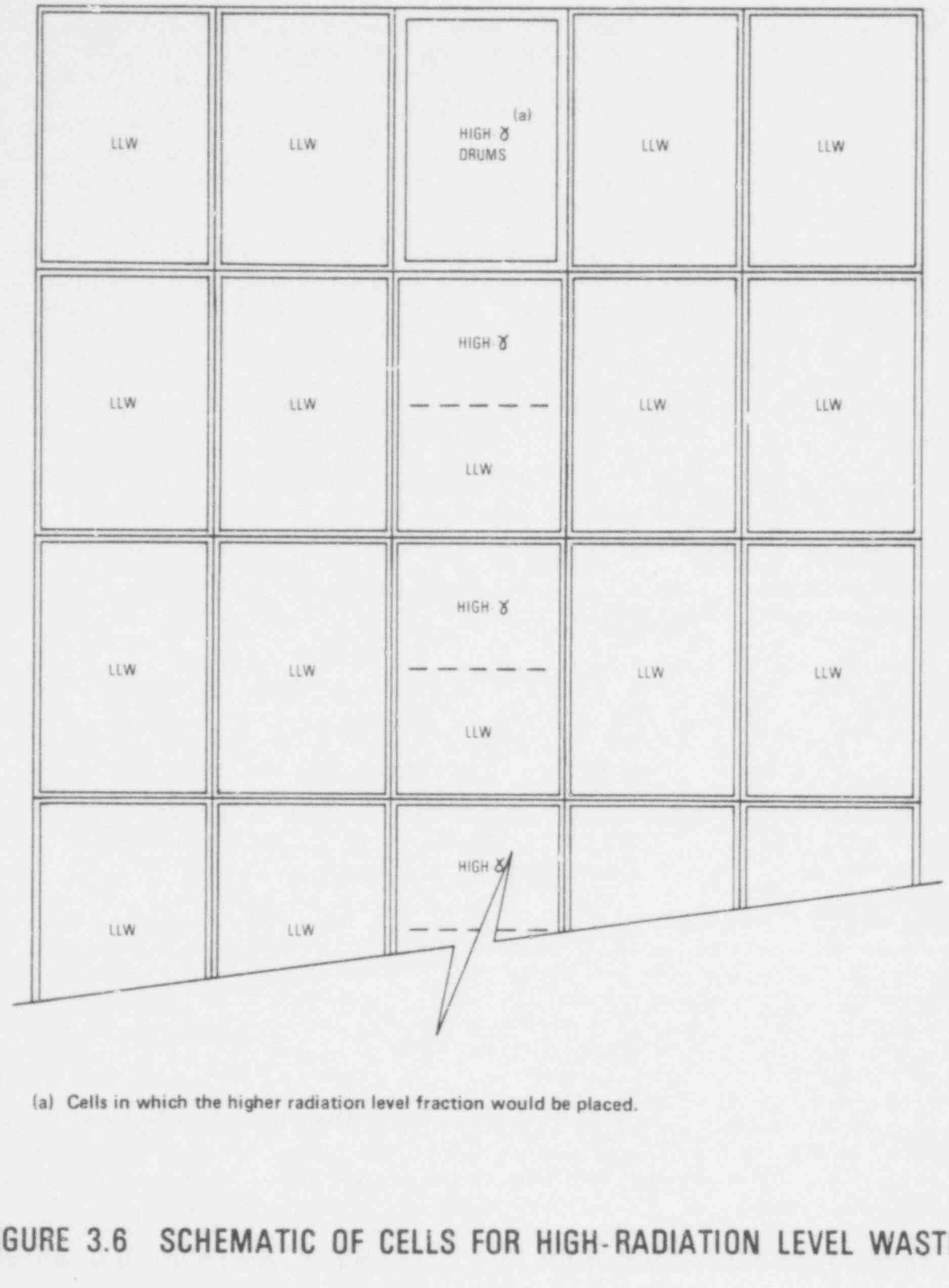
** Floor to rest on footings via seismic rollers.

The perimeter of the facility would also be fitted with security devices to alert authorities in case of an intrusion. In addition, it might be possible to automatically warn or repel an intruder or reclaimer who attempts to enter a cell after institutional control is relinquished. This could be accomplished by having a warning agent[50,51] within the cell (similar to the insertion of the foul-smelling mercaptan in natural gas that the public uses).

The ten percent of the radioactive waste containing higher radiation levels would necessitate different handling techniques than the lower radiation level wastes. Two different approaches for handling the higher radiation fraction of the waste are described below. One involves little basic change in the cell design beyond installing a remotely operated bridge crane and the other involves sunken storage vaults in the floors of the cells.

The first approach is based on a facility that is at least five cells wide, as illustrated schematically in Figure 3.6. Fourteen 5 x 10 cell buildings would be required for the SDF. The higher radiation level wastes would be restricted to the center cells to utilize shielding properties of the concrete walls and adjacent cells filled with the lower-level wastes. The first higher radiation level waste cell in the center building would have 2-ft thick walls of iron-loaded concrete to protect exterior personnel at that end of the building and personnel filling the adjacent cells. Waste loading in the higher radiation level waste cells would be remotely observed and controlled. The higher radiation level waste containers would be stacked only three or four high with a layer or two of lower radiation level waste on top for added vertical shielding. The radiation levels through the roof would then be essentially the same as from the lower radiation waste cells.

The second approach has been used for storage of intermediate-level solid transuranic wastes.[52] Shielding is provided by the floor and subsoil around the "floor safe" storage holes. These cylindrical holes would have inside diameters of slightly more than 2 ft to accommodate 55-gal. drums. The concrete lining and shield plug are described in Ref 52. However, the cap could be modified to present a surface flush with the floor of the cell. A truck, cask and vacuum lowering device could be adapted to lowering higher radiation level containers into the floor safes. The floor safes would be located above the water table to minimize rusting and deterioration of the drums. This approach would be more expensive and operationally difficult than the first one, and is not considered further in this study.



(a) Cells in which the higher radiation level fraction would be placed.

FIGURE 3.6 SCHEMATIC OF CELLS FOR HIGH-RADIATION LEVEL WASTE

3.5.2 Technical Evaluation

The technical evaluation of the structural disposal concept is based on the reference SDF's shown in Figures 3.4, 3.5 and 3.6, either built above the surface grade uncovered by soil, or designed for a final protective covering of soil.

3.5.2.1 Compatibility with Waste

Structural disposal facilities can be designed to accommodate whatever waste forms require disposal. The SDF, however, is designed to accommodate the standard waste forms used in this study. Therefore, the evaluation factor for compatibility with waste has a value of unity for the SDF.

3.5.2.2 Site Selection Factors

Suitable sites for structures for waste disposal are abundant. However, because the structures are more exposed than the other alternative facilities, care should be exercised to locate the SDF in an area where competing land use and desirability of reoccupying the structures is favorable to long-term waste isolation. The locations would be basically less restrictive than those for the reference SLBF, because of possibly less stringent requirements on site metrology, hydrology and geology. The evaluation factor for site selection is set to 0.9 for sites in the east and 0.8 for western sites, because there is more suitable land in the west.

3.5.2.3 Safeguards

Protection from unauthorized use of the disposed wastes would be more difficult for the SDF concepts than for the reference SLBF, because of the presence of the building and the confinement of the wastes with no diluting agents (such as soil in the burial case). The above-grade structures would be more vulnerable than the buried structures. The evaluation factors for the above- and below-grade SDF concepts are 1.2 and 1.1, respectively, to reflect the increased vulnerability to unauthorized access to the wastes.

3.5.2.4 Environmental Effects

Table 3.18 contains a summary of the non-radiological hazards for the SDF concepts. Considerably more construction effort is required for this alternative than the others. Non-radiological hazards to construction and operational workers are estimated to be 26 injuries and 0.8 fatalities for an eastern site, and 47 injuries with 2.2 fatalities for a western site. There are

TABLE 3.18

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR STRUCTURAL DISPOSAL CONCEPTS

	Eastern Site		Western Site	
	Above Grade	Buried	Above Grade	Buried
Transportation				
Average Transit Distance to Disposal Site	400	400	1,400	1,400
Total Train Car Miles	2.11×10^7	2.11×10^7	7.39×10^7	7.39×10^7
Total Projected Accidents(a)	3.0	3.0	10	10
Total Projected Injuries(b)	8.0	8.0	28	28
Total Projected Fatalities(c)	0.60	0.60	2.0	2.0
Construction Phase				
Average Crew Size (man/years)	330	363	326	352
Comparable Industry(d)		Construction		
Total Projected Injuries	10	11	9.9	11
Total Projected Fatalities	0.12	0.13	0.12	0.12
Operational Phase				
Crew Size (man/years)	265	265	265	265
Comparable Industry(d)		Construction/Storage and Warehousing		
Total Projected Injuries	8.1	8.1	8.1	8.1
Total Projected Fatalities	0.09	0.09	0.09	0.09
Total Overall Effect for Comparison(e)	34.2	35.3	68.1	69.2
Normalized Effect(f)	1.4	1.5	2.9	2.9

(a) Based on 1.4×10^{-7} accidents/car mile from Ref. 13.

(b) Based on 2.7 injuries/accident from Ref 13.

(c) Based on 0.2 fatalities/accident from Ref. 13.

(d) From Table 2.2, for rates used for statistical injury and accident projection data. (Highest projected Frequencies for given categories were used in the calculations.)

(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted more heavily than injuries to account for the more signigicant loss of life.)

(f) Normalized to Reference SLBF eastern site case.

many uncertainties in evaluating potential environmental effects at the SDF. Durability of containers, likelihood of reclamation efforts, and long-term structural integrity are some of the difficult areas to assess. In this study, it was assumed that a reclaimer will be exposed to the wastes immediately after institutional control is relinquished and that the waste characteristics will be the same as those for shallow land burial, except that the wastes would not be diluted with clean soil. The containers are assumed to have deteriorated at the time of reclamation. The effects of reclaimer inhalation and direct contact radiation exposure events will thus be twice as large as for the SLBF.

Airborne exposures to the public from single container accidents will be similar to those for the MCDF. The concrete floors of the structure are assumed to have ion-exchange and retardation properties greater than those for the clay liner used in calculations of ground water movement for the improved SLBF as long as they remain intact, which is assumed to be at least 150 years. As time passes, the concrete floors will ultimately fracture. As contamination is moved downward by moisture, it would be slightly attenuated by ion exchange as it passes through the cracks and fissures. However, no credit for this effect is taken in the calculations. For the food pathway, it is assumed that the waste is taken outside the building and scattered over the surface prior to mixing by cultivation. While this is less likely than for the SLBF, the consequences are taken to be the same as the base case. Transportation exposures will also be the same as for the SLBF. A summary of the radiological impacts calculated for this alternative is presented in Table 3.19.

3.5.2.5 Availability of Techniques

Although little experience concerning waste disposal in engineered structures is available, the technology exists to construct buildings that will last for centuries. However, effective means of guaranteeing that the buildings and contents will be left intact are not well developed. Therefore, the evaluation factor for status of technology is assigned a value of 1.1.

3.5.3 Sociopolitical Implications

The public may view disposal in engineered structures as potentially less hazardous than shallow land burial because of better understanding of the engineered barriers. Current disposal regulations would need to be modified to accommodate this alternative, however, to provide additional controls and long-term protection of the public.

TABLE 3.19

SUMMARY OF RADIOLOGICAL IMPACTS FOR STRUCTURAL DISPOSAL CONCEPTS

	Eastern Site		Western Site	
Long-Term Effects (mrem/yr)	Above Grade	Buried	Above Grade	Buried
Reclaimer Inhalation[a]	120	120	120	120
Food Pathway	620	620	620	620
Reclaimer Direct Gamma Exposure[a]	680	680	680	680
Short-Term Effects (mrem/yr)				
On-Site Well Water Consumption	9	9	6	6
Accidental Airborne Releases	100	100	100	100
Transportation Exposures[b]	10	10	30	30
Total Overall Effect for Comparison (mrem/yr)	1539	1539	1556	1556
Normalized Effect[c]	1.2	1.2	1.2	1.2

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison.

(b) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison.

(c) Normalized to reference SLBF eastern site case.

3.5.3.1 Public Acceptance

The acceptability of risks from low-level radioactive waste disposal in a reference SDF is an important issue because the wastes may be considered to be more securely contained and more easily monitored, but are also more readily available for future reclamation activities. The structures themselves may appear attractive for other uses after institutional controls are relinquished. The risks from the SDF can be larger than from the reference SLBF because the wastes will not be diluted with clean soil. While risks from wastes generated by other energy sources that are simply buried or otherwise disposed of may be as high as those associated with the SDF, the public perception of the relative magnitudes of the risks may differ. Adequate information and education of the public concerning the inherent risks and benefits of the SDF concept will be required. Concern about the moral and ethical issues revolving around leaving the wastes in structure at the earth's surface in perpetuity will also be heightened. The public will probably view disposal in the SDF as more safe and environmentally acceptable than the SLBF because they are familiar with massive structures, and may have more confidence in the SDF's performance. Disposal in a carefully engineered, massive structure could be readily defended against perceived defects in current shallow land burial practices. The public is familar with examples of buildings that have lasted thousands of years, such as the pyramids, and may accept this form of disposal more readily than a new SLBF. The public acceptance evaluation factor is assigned a value of 0.9 to reflect increased public acceptance.

3.5.3.2 Institutional Controls

Existing domestic institutional controls would have to be modified to accommodate the SDF. The wastes would be more readily available for exposure by workers and the public, so additional controls to ensure safety of the operations would be required. Longer periods of excluding the public from the site would be desirable. Ultimate ownership of the sites and the structures would need explicit resolution. No international controls are involved in waste disposal within a nation's territory. The evaluation factor for institutional control is assigned a value of 1.1 to reflect the additional difficulties in changing regulations and controls from present practices.

3.5.4 Cost Analysis

Costs were estimated for both buried and above-ground structures located at typical eastern or western waste disposal sites.

3.5.4.1 Cost Estimates

The cost estimates for this concept are summarized in Table 3.20. The estimated facility costs range from \$496 million to \$536 million. Transportation to an eastern site is estimated at \$68 million and to a site in the west at \$237 million. The resultant unit costs per cubic meter of waste disposed of at the SDF range from \$900/m^3 to \$1300/m^3.

3.5.4.2 Economic Impact

The cost estimates equate to from 0.081 to 0.111 mills/kwhr. Based on a basic power cost of 45 mills/kwhr, these represent 0.18% to 0.25% of the total cost of electricity production.

3.6 Ocean Disposal

Ocean dumping has been used nationally and internationally for the disposal of low-level solid radioactive wastes since 1946. With increasing competing demands for a decreasing amount of available land, more nations are looking towards the oceans to solve their low-level radioactive waste disposal problem. A history of ocean dumping of radioactive wastes is contained in Appendix E.

The Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) has developed a program for ocean disposal. This led to the first internationally organized (five-country) disposal operation in 1967. Subsequent operations have been carried out from 1969 through 1976. The International Atomic Energy Agency (IAEA) has prepared a number of regulations governing operational control of sea disposal of radioactive waste.[53] The regulations stipulate measures dealing with the choice of a suitable dumping site, the design and construction of waste containers, the choice of an appropriate ship, provisions for radiation protection of the crew, adequate record keeping, and an adequate supervision of the dumping operations by competent escorting officers.

Although this country suspended ocean disposal operations in 1971, two major research and developmental activities are continuing to contribute significantly to the technical data base pertaining to ocean dumping.[54,55] One of these efforts has been a series of environmental surveys of the principal ocean disposal sites that have been used by this country. These surveys provided documentary photography, current flow analysis, and radiochemical analysis of sediments near wastes disposed of over two decades ago. There was evidence from the photography of hydrostatic implosion of some of the containers. At the

TABLE 3.20 COST ESTIMATE SUMMARY FOR THE STRUCTURAL DISPOSAL FACILITY

	Estimated Costs (Millions of Dollars)			
	Above Grade Structure		Buried Structure	
Item	Eastern Site	Western Site	Eastern Site	Western Site
Capital Costs				
Site Purchase	5.00	2.50	5.00	2.50
Site Studies	.50	.50	.50	.50
Licensing	.32	.32	.32	.32
Environmental Reports	.75	.65	.50	.40
On-site Structures	158.24	158.24	171.34	171.34
Site Preparation	0.66	0.66	0.66	0.66
Site Fencing and Security Alarm	0.25	0.25	0.25	0.25
Air Support Building	0.30	0.30	0.30	0.30
Capital Subtotal	166	163	178	176
Engineering (5% of Capital Subtotal)	8.30	8.17	8.94	8.81
Higher Radiation Waste Facilities	4.01	4.01	4.32	4.32
Total Capital Costs	178	176	192	189
Operating Costs				
Facility Operating Personnel	19.75	19.75	19.75	19.75
Emplacement Costs	3.00	3.00	3.00	3.00
Supplies and Equipment	1.88	1.88	1.88	1.88
Total Operating Costs	25	25	25	25
Contingency (30% of Total Capital & Operating Costs)	61	60	65	64
Profit, Financing, and Escalation	237	234	254	250
Total Facility Costs	501	495	536	528
Transportation Costs	68	237	68	237
Total Facility Plus Transportation Costs	569	732	604	765
Total Unit Costs for Waste Disposal ($\$/m^3$)	900	1200	960	1200

Pacific site, levels of ^{239}Pu and ^{240}Pu were about one order of magnitude greater than the expected range of values due to fallout. Levels of ^{137}Cs at the Atlantic site were 3 to 70 times maximum concentrations expected at this site from fallout. This contamination was found in the local vicinity of the drums, and no widespread contamination was observed. In the past 2 years, two drums (one from the Pacific site and one from an Atlantic site) have been retrieved and are undergoing examination.

The other major effort undertaken in the last 6 years has been a study to determine the feasibility of disposal of high level solid radioactive waste in the seabed. The seabed disposal program has identified certain oceanic areas--the mid-plate/mid-gyre regions--that may offer practical and nonpunitive areas for the disposal of high-level radioactive wastes. The program is continuing to: gather the data necessary to an understanding of the features and processes of the mid-plate/mid-gyre regions; develop analytical models to support the overall systems analysis effort; evaluate the sorption properties of the sediments with respect to the individual nuclear ions; characterize the sediments; develop waste package emplacement techniques; conduct corrosion studies to evaluate package materials; perform biological investigations in support of assessment studies addressing environmental impact (planned and accident scenarios); and develop an international program of scientific investigations and information exchange. Many aspects of the seabed disposal program have been utilized in developing the following concept for ocean disposal of low-level radioactive wastes.

3.6.1 Description of Ocean Disposal Concept

There are two primary potential barriers between the waste and the environment--waste conditioning and waste packaging. Two additional barriers--the sediment and the ocean itself--provide additional protection to man. In developing the concept, the first two barriers must be sufficiently engineered to assure protection (containment) under normal conditions for a reasonable length of time. The protection afforded by the sediment and the ocean should be considered as backup for additional assurance that the quality of the environment will be protected.

Identification of generic characteristics of suitable ocean disposal sites was simplified because they had already been studied for the NEA ocean dumping program[56] and the sea bed disposal program.[54] The desirable characteristics delineated in these programs were reviewed and those determined to be generic to ocean disposal of low-level radioactive waste are presented in Table 3.21.

TABLE 3.21

GENERIC CHARACTERISTICS FOR OCEAN DISPOSAL SITE

SITE CHARACTERISTICS

Maximum geological stability.
Minimum ocean current.
Minimum bio-activity.
Minimum interference with recovery of sea resources.
Minimum depth of 4,000 meters.
Minimum unconsolidated sediment thickness of 20 meters.
Multiple sites - stratigically located.
Sites located in international waters.
Site as far removed as possible from all activities of mankind.
Recovery of waste is not a criterion.
Individual sites should be of sufficient size.

WASTE CONDITIONING AND PACKAGING

Waste shall be either solid, solidified, or absorbed in a solid substrate.
Waste in the liquid form shall be excluded.
Packages shall be designed to ensure adequate containment of waste.
Packages (and all internal containers) shall have an overall specific gravity of not less than 1.2.
Packages shall be sufficiently strong to withstand hydrostatic implosion or equipped with a pressure equalization device, and buoyant material shall be excluded or packaged to preclude such material from floating to the surface.

TRANSPORT SHIP

Capable of safely carrying its consignment to the dump site.
Provided with the appropriate navigational and communication equipment.
Contain provisions for adequately decontaminating holds and bilges.
Have adequate facilities to safely stow waste packages.

It is assumed that the single most important generic site characteristic deals with the geologic stability of a proposed site. Based upon information currently available, major portions of the ocean floor have been identified as being extremely stable. Fortunately, data exist which allow man to predict the geologic processes in the three major ocean provinces--the mid-oceanic ridge, the ocean basin floor, and the continential margin. These provinces comprise about 70% of the earth's surface that is covered by ocean.

Oceanographers have divided each province into four regions and have examined the geologic stability and predictability of processes for each region.[57] Two regions--the flank region of the Mid-Ocean Ridge province and the Abyssal Hills (mid-plate) region of the Ocean Basin Floor province--exhibit excellent geologic stability and predictability. These regions are quite large and can be considered to be large solid rock "plates." Plate (or region) boundaries are either areas of crustal destruction or areas of construction. Thus, the mid-region or mid-plate area exhibits the greatest geologic stability within a region.

Since the pathway from the waste to man involves the bio-activity at the disposal site, the second most important characteristic requires the identification of those areas of the ocean where the bio-activity is at a minimum. Nearly as important as identifying areas of low bio-activity is the need to identify areas of minimal current flow, for current is the main mechanism for distributing activity from the disposal site to areas that might have impact upon man. The oceans contain large gyres--great circulating currents. It has been determined by researchers that these gyres have the lowest biological activity of any of the ocean provinces. Furthermore, the current flow in these gyres is also quite low. Thus, a likely potential site (from the bio-activity and current flow characteristic standpoint) would be in the middle of a gyre.

The generic site characteristics for low-level waste disposal closely parallel those previously identified by the Seabed Disposal Program for high-level radioactive wastes. Table 3.22 summarizes characteristics of the most promising ocean regions--the flank region of the Mid-Ocean Ridge province and the Abyssal Hills (mid-plate) region of the Ocean Basin Floor province.

The requirement for unconsolidated sediment as a site characteristic is essential for the projectile disposal concept described. As noted in Table 3.22, both oceanic regions contain an adequate layer of sediment. At least four mid-plate gyre (MPG) regions have been identified (two in the Pacific Ocean and two in the Atlantic Ocean), one north and one south of the Equator. One of these areas (about 600 mi north of Hawaii) has been bathymetrically surveyed previously by the National

TABLE 3.22

CHARACTERISTICS OF MID-OCEAN RIDGE FLANKS AND OCEAN BASIN FLOOR ABYSSAL HILLS (MIDPLATE) REGIONS OF THE OCEAN (SOURCE: Ref 61)

	Mid-Oceanic Ridge Flanks	Ocean Basin Floor Abyssal Hills
ENVIRONMENT		
Water depth (km)	3-5	5-6
Local relief (m)	100's	10-100
Regional slope (deg)	2-5	<1
Bottom temperature (^{o}C)	2-4	<2
Testure of bottom sediment	sand, silt, clay	clay
Sediment thickness (m)	500-2000	250-500
DYNAMIC PROCESSES		
Rate of sediment accumulation (cm/1000 yr)	2-4	<1
Non-tidal currents (cm/sec)	3-5	2-10
Earthquake frequency	very low	very low
Biological activity	moderate	very low
Frequency of sediment failure	low	very low
Volcanic activity	low	very low
GENERIC CHARACTERISTICS		
Geologic stability (predictability)	moderate	high
Areal extent (km^2 x 10^6)	<120	130
Accessibility by man	low	very low

Oceanic and Atmospheric Administration (NOAA). As a result, the Seabed Disposal Program concentrated upon this region of the ocean as an area warranting additional research.

In 1974 a current flow measurement program was initiated to obtain records for a period of 18 months in the MPG area north of Hawaii. Data were collected from three specific locations. Measured speeds were low with 20-30% of the data recording zero speeds. The magnitude of the current flows was approximately 2 to 4 cm/sec.

The research efforts of the Seabed Disposal Program have identified an area covering 40,000 km^2 in the north Pacific MPG that is more or less evenly covered with about 20 to 40 m of unconsolidated sediment. The Abyssal Hills in this region have about three-quarters as much sediment cover as the valleys, suggesting at least some downslope concentration of sediment.

Both direct dumping of waste containers onto the ocean floor and sediment penetration concepts have been considered in this study. The free-fall projectile containing drums of waste is designed to penetrate into the unconsolidated sediments on the ocean floor. This concept was developed to provide additional assurance that the wastes will not migrate into environmental exposure pathways. There are large uncertainties in biologic information at candidate waste disposal sites. The ion-exchange capacity of the sediments covering the projectiles provides another isolation mechanism, which further reduces radiological impacts from ocean disposal.

Preliminary analysis of a single long core (24.4 m) taken from the Pacific MPG area indicates a continuous sequence of mostly brown oxidized clays (mean grain size 2 micrometers). It is estimated that the sediments at the bottom of the core were deposited more than 65 million years ago. A few ash layers from volcanic eruptions were interspersed in the clay. Future deposition of such ash would provide additional cover over the disposed wastes. Data taken from shorter (10-20 m) cores suggests that the Pleistocene glacial stages that have occurred every 100,000 years in the recent geologic past increased the rate of sediment supply, but otherwise had no effect on the North Pacific MPG. This suggests that future major glaciation would not be expected to disturb a disposal site located in this region.

The behavior of the sediment during and subsequent to penetration has been the subject of laboratory simulation studies, in-situ experiments, and theoretical analyses.[54] These suggest that closure of a completely penetrating projectile would be immediate and total. The clays that make up the sediment layer have a number of properties that make them especially attractive as a barrier to the release of radionuclides. They are very finely grained, hence, they have low permeabilities. The very large surface area per unit volume of sediment contributes to the ability to absorb contaminants from solutions.

The migration of elements through sediments has been the subject of a number of experiments.[58] Specifically, the experiments have attempted to determine the distribution coefficient of each element (the ratio of the element that is sorbed to the sediment and that which remains dissolved in the pore waters). The distribution coefficient for each radionuclide is a function of temperature, concentration, pressure, exposure time, and the presence of other competing ions. Experiments performed to date indicate that in one million years, the following elements would diffuse over the indicated distances: ^{90}Sr, 0.4 to 3.2 m; ^{137}Cs, 0.8 m; ^{65}Zn, 0.2 to 0.6 m; ^{144}Ce, 0.1 m; and ^{228}Th, less than 0.03 m. Recent work suggests that the actual barrier effect of the sediment may be even more impressive than the earlier experiments indicate.

If some portion of the biosphere were exposed to the waste, it is desirable that the biological pathways leading back to man be as few and weak as possible. Research to date, as limited as it is, indicates that mid-gyre waters have very low bioactivity, even near the ocean surface. The circulatory nature of the gyres, coupled with their remoteness from land, reduce any significant terrestrial contribution. These factors, combined with great water depth, result in a lower nutrient supply to the ocean bottom than found at other places in the ocean.

In summary, experience from dumping operations conducted since 1946, coupled with the technical data collected thus far, has not presented any information which might discourage use of this concept for disposal of solid low-level radioactive waste. Conversely, current information is insufficient to declare this concept acceptable at this time. It has some advantages over other disposal concepts. In the absence of any identified disadvantages, additional research and development is warranted.

Currently available data indicate that the mid-plate/mid-gyre regions are the most promising of all ocean areas. The MPG areas appear to meet all of the generic site characteristics established for this concept. In addition, certain definite advantages afforded by the sedimentary layer warrant consideration of a concept differing from that having been practiced in the past or the present. The past and present methods are adequately described by the phrase <u>ocean dumping</u>, which is the dropping of individual packages into the ocean. An additional concept described within this study employs an engineering improvement: placement of individual packages within a projectile designed to be free-falling and self-burying in the sediment. For the purpose of differentiating between the two methods, the latter method will be termed <u>ocean projectile disposal</u>. Ocean projectile disposal has been investigated because of uncertainties in biological pathways from the ocean floor.

Ion exchange processes in the sediments will retard migration of contamination from covered wastes and reduce the consequences of any eventual biological exchange that may take place.

Figure 3.7 depicts the free-fall projectile for the ocean projectile disposal concept and provides the dimensions of a projectile sized to accommodate 10 55-gallon drums. The minimum length of the projectile is dictated by requirements of hydrodynamic stability. Its maximum length is controlled by the amount of sediment available for burial, as well as handling problems during disposal. A projectile sufficiently long to contain six drums is considered to be of minimum length, while one containing 10 drums is maximum. Table 3.23 contains the free-fall projectile characteristics and performance, based on a 10-drum projectile. The nose of this size projectile is calculated to penetrate the sediment surface to a depth of nearly 25 m. This would produce a minimum depth of sediment from waste to ocean/sediment surface of 14 m. Based upon presently available distribution coefficients, a minimum burial depth of 2 m should provide well over 1,000 years of confinement.[59]

It is assumed for this study that two ocean disposal sites are available in the northern hemisphere--one in the Pacific Ocean and one in the Atlantic Ocean. These sites will be in international waters. All countries desiring to utilize these disposal sites shall be bound to the same governing regulations.

For the purpose of this discussion, it is assumed that the United States operations would be conducted by private corporations. It is assumed that a set of regulations based on international guidelines would govern the operation and that federal (and perhaps international) inspectors would monitor all phases of the operation.

To minimize surface transportation, it is assumed that five ports are developed--two on the west coast (Seattle and San Diego), two on the east coast (Boston and Savannah), and one on the Gulf Coast (Houston). It would not be necessary to identify a ship for each port. Prudent scheduling could reduce the number of ships to two, with perhaps a third as the volume of waste increases.

The waste generators will be required to condition and package the wastes in accordance with regulations developed to meet the applicable generic characteristics identified in Table 3.21. The generator would be required to ship the wastes in cargo container lots to the port where the containers would be immediately loaded aboard ship. The cargo containers would be individually equipped with air sampling ports, and otherwise meet all applicable International Standards Organization (ISO) specifications. The ship's cargo holds would be opened only during actual loading.

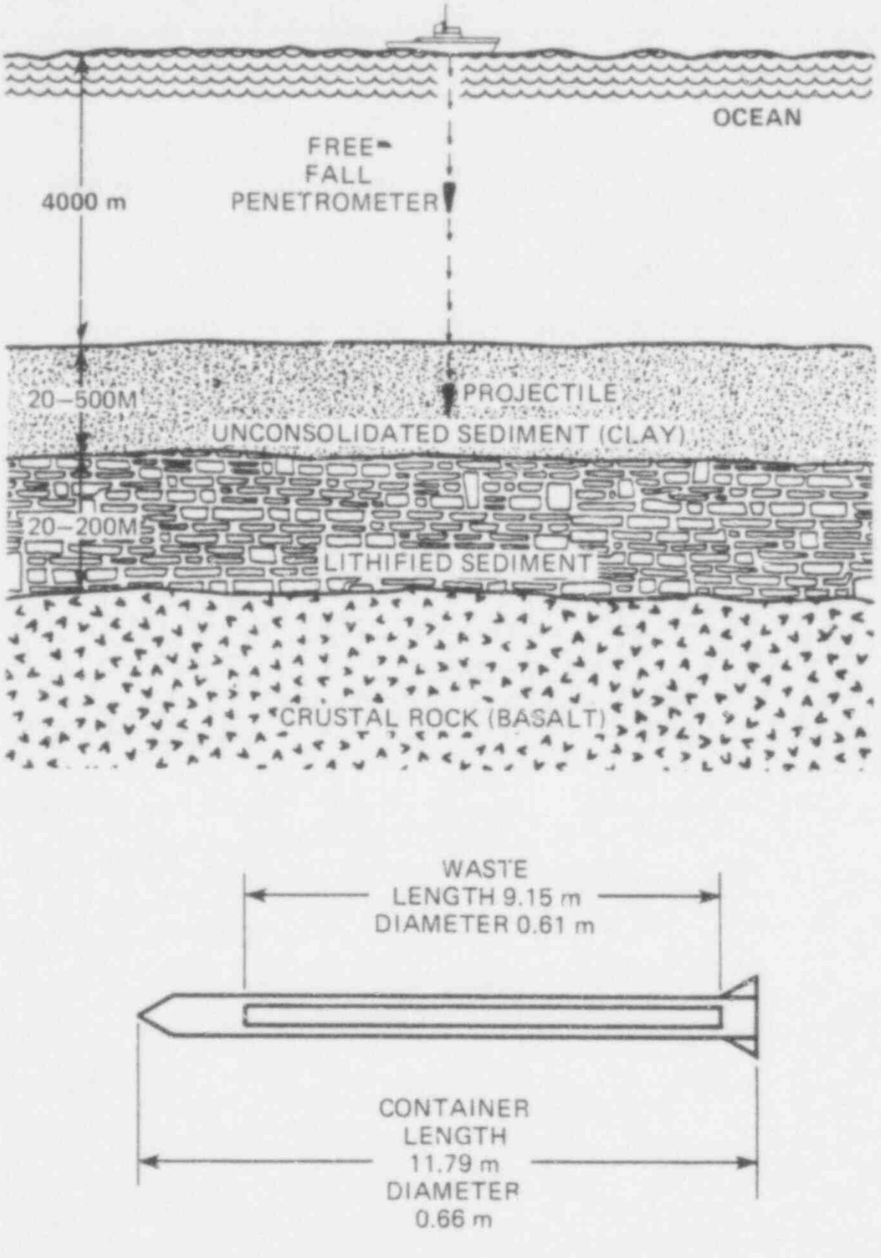


FIGURE 3.7 ENGINEERING CONCEPT OF PROJECTILE EMPLACEMENT IN UNCONSOLIDATED SEDIMENT

TABLE 3.23

FREE-FALL PROJECTILE CHARACTERISTICS AND PERFORMANCE

(Source: Ref 62)

Payload (Waste Packages)		
Length (10 55 gal drums)	9.0	m
Diameter	0.61	m
Volume	2.7	m^3
Weight (Air weight)	78.5	kN
Projectile		
Length	12.0	m
Diameter	0.66	m
Weight, submerged (water-filled) kN	78.5	kN
Penetration depth: nose to ocean/sediment interface	25	m

It is assumed that the projectiles would be loaded with drums while the ship is enroute to the disposal site. The ship's arrival at the disposal site would be confirmed by two independent locating techniques--such as sonar and satellite navigation. Each projectile will be lifted by its tail and lowered over the side and into the water. The projectile will contain a valve to allow the void space to be filled with water. This is an essential requirement if the desired penetration into the sediment is to be achieved and hydrostatic implosion avoided. Once the void space had been filled with water, the projectile would be released.

3.6.2 Technical Evaluation

Ocean disposal is analyzed for two variants in this study--direct dumping of waste containers, and multidrum projectile free-fall with penetration into the sea floor sediments.

3.6.2.1 Compatibility with Waste

The ability of the oceans to accommodate waste disposal depends on the waste physical form, the disposal site, and restrictions imposed on transport of the waste to the disposal site. Because variations and uncertainties in the suitability of the ocean for waste disposal exist today, extensive additional research needed to assure adequate containment of many possible waste types. However, the ocean disposal concepts and locations considered in this study should be able to accommodate the standard reference low-level waste. The evaluation factor for compatibility with wastes for the ocean disposal concepts investigated is therefore set at unity, the value for the base case.

3.6.2.2 Site Selection Factors

The midcontinent gyre regions described above are suitable locations for ocean disposal. The need for relatively thick unconsolidated sediments for the projectile method make site selection within the MPG regions somewhat more restrictive. Identification of appropriate sites will still be more difficult than for shallow land burial. Therefore, the evaluation factors for the ocean dumping and ocean projectile disposal options are assigned values of 1.2 and 1.4, respectively.

3.6.2.3 Safeguards

The wastes disposed of under either of the ocean disposal concepts evaluated in this study would be very difficult to retrieve accidentally or for unauthorized uses. The depth of the ocean would make it difficult to reach the wastes. For the projectile disposal case, the penetration into the sediments would further complicate access. Therefore, the safeguards and physical security evaluation factor for the ocean disposal concepts is given a value of 0.5 to reflect the improved invulnerability to unauthorized access.

3.6.2.4 Environmental Effects

The nonradiological effects of ocean disposal are calculated from estimated crew sizes and accident data for construction workers. (Similar information for ship crews was not available.) Approximately 57 injuries and 2.5 fatalities are projected for these alternatives. The non-radiological impacts for this alternative are summarized in Table 3.24.

The radiological impacts for the ocean disposal concepts are summarized in Table 3.25. For direct dumping, the methodologies described and summarized in Refs. 59 and 60 yield annual dose rates from contaminated food pathways from the ocean of less than 1 mrem/yr, using conservative order of magnitude estimates for important pathway and biological transfer parameters. There are no reclamation events likely for ocean disposal. Single container accidents will cause exposures similar to those for the SLBF. Transportation doses to the public will occur only during transit to the seaport, and will be about 38 manrem/yr based on an average distance from waste generator to port of 1,600 mi.

For the projectile concept, the projectile itself and the sediments into which the wastes penetrate provide additional barriers to movement of the contained wastes, which would reduce even further any radiological consequences. The movement of water within sediment beds has been measured to be very low. Therefore, if the projectile corrodes and the wastes dissolve, only physical dispersion because of concentration gradients will cause contaminants to reach the ocean floor interface. For these reasons, the resultant doses for this option would be much lower than those for direct dumping.

3.6.2.5 Availability of Techniques

Direct dumping into the ocean has been practiced for over 30 years. Projectile penetration into sediments will require some additional testing and demonstration before it is a proven technique. The evaluation factor concerning availability of techniques is given values of 1.0 and 1.3, respectively, for dumping and projectile disposal.

TABLE 3.24

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR OCEAN DISPOSAL CONCEPTS

	Ocean Dumping	Projectile Disposal
Transportation		
Average Transit Distance to Port (miles)	1,600	1,600
Total Train Car Miles	84,500,000	84,500,000
Total Projected Accidents(a)	12	12
Total Projected Fatalities(b)	32	32
Total Projected Fatalities(c)	2.4	2.4
Construction Phase		
Average Crew Size (man-years)	NA	NA
Comparable Industry(d)	NA	NA
Total Projected Injuries	NA	NA
Total Projected Fatalities	NA	NA
Operational Phase		
Crew Size (man-years)	300	300
Comparable Industry(d)	Construction/ Transit	Construction/ Transit
Total Projected Injuries	25	25
Total Projected Fatalities	0.11	0.11
Total Overall Effect for Comparison(e)	82	82
Normalized Effect(f)	3.5	3.5

(a) Based on 1.4×10^{-7} accidents/car mile from Ref 13.
(b) Based on 2.7 injuries/accident from Ref 13.
(c) Based on 0.2 fatalities/accident from Ref 13.
(d) From Table 2.2, for rates used for statistical injury and accident projection data. (Highest projected frequencies for given categories were used in the calculation.)
(e) Sum of all injuries plus 10 times all fatalities. (Fatalities are weighted none heavily than injuries to account for the more significant loss of life.)
(f) Normalized to reference SLBF eastern site case.

TABLE 3.25

SUMMARY OF RADIOLOGICAL IMPACTS FOR OCEAN DISPOSAL CONCEPTS

	Ocean Dumping	Projectile
Long-Term Effects (mrem/yr)		
Reclaimer Inhalation (a)	0	0
Food Pathway (b)	1	0
Reclaimer Direct Gamma Exposure (a)	0	0
Short-Term Effects (mrem/yr)		
On-Site Well Water Consumption	0	0
Accidental Airborne Releases	200	200
Transportation Exposure (c)	38	38
Total Overall Effect for Comparison (mrem/yr)	239	238
Normalized Effect (d)	0.18	0.18

(a) Based on the stated number of hours of exposure per year to obtain consistent exposure units for comparison. (No inadvertant reclaimation is assumed for ocean disposal concepts).

(b) Based on Refs. 59 and 60.

(c) Based on arbitrarily assuming total dose is borne by 1000 persons to obtain consistent exposure units for comparison. (Considers only exposures to public along transportation routes from waste generators to port facilities.)

(d) Normalized to reference SLBF eastern site case.

3.6.3 Sociopolitical Implications

Ocean disposal is an emotionally charged issue. Environmental groups strongly oppose potential contamination of the oceans. In some areas, lack of available land for burial makes the oceans appear attractive for waste disposal. Complicating the situation is the philosophy that the oceans are international resources, and their use by a few countries for waste disposal may be objectionable to the balance to the international community.

3.6.3.1 Public Acceptance

Public acceptance of the risks from using the oceans for disposal of low-level radioactive wastes will be low. The possibility of "contaminating" the ocean is not popular. The public will need substantial information to allow better understanding of the risks and the benefits to be obtained. A definition of acceptable levels of contamination and other risks will be required for this alternative, as well as a comparison with other wastes that presently end up in the ocean. Although contamination of the ocean is a potential hazard, because of the tremendous volumes of water involved, the risk is reasonably small from the reference ocean disposal alternative concepts. The ethical and moral issues of contaminating the ocean for other countries, as well as for future generations, will require investigation. There is not yet sufficient data on the ocean's response to waste disposal to allow quantitative prediction of the full range of risks, although based on information now available, the risks will be low.

Public acceptance of direct ocean dumping is likely to be much less favorable than for shallow land burial. The evaluation factor for public acceptance is therefore assigned a value of 1.4. Resistance to projectile penetration into the sediments may be less than for direct dumping but, because of its unproven nature, may still be greater than shallow land burial. Therefore, the evaluation factor for public acceptance is set at 1.2 for ocean projectile disposal.

3.6.3.2 Institutional Controls

International agreements and domestic governmental controls already exist for regulating waste disposal in the oceans. However, implementation of this alternative may be more difficult than for a new reference shallow land burial facility. Controls on shipping ports and vessel routing will also be required. The evaluation factor describing institutional controls is set to of 1.2 for both disposal options, to reflect the additional complexity.

3.6.4 Cost Analysis

The costs for ocean disposal depend on prices for ships and crews that are usually quoted on a job-by-job basis. The estimate reported here is based on judgement of what reasonable costs may be.

3.6.4.1 Cost Estimates

The costs for direct ocean dumping and projectile penetration of the sediments are presented in Table 3.26. Total costs for sophisticated navigation equipment, port charges, ship and crew rental and miscellaneous supplies and equipment amount to \$176 million for direct dumping and \$1,101 million for projectile disposal. Ground transportation costs to the shipping port amount to \$271 million, giving total unit costs for the two options of \$710/m^3 to \$7,200/m^3 of waste, respectively.

3.6.4.2 Economic Impact

The estimated costs amount to 0.064 mills/kwhr for direct dumping and 0.20 mills/kwhr for projectile disposal. These costs are equivalent to 0.1% and 0.4% of the total cost of nuclear power production, respectively.

3.7 Summary

This chapter has described the baseline method for disposal of low-level radioactive wastes--shallow land burial--and all the alternatives considered. It has provided information concerning the evaluation factors used to compare the alternatives and has stated what these factors were chosen to be. At this point it remains to gather the evaluation factors together, properly weight them, and determine the outcome of the comparative analysis. Chapter 4 performs that function.

TABLE 3.26 COST ESTIMATE SUMMARY FOR OCEAN DISPOSAL CONCEPTS

Item	Estimated Costs (Millions of Dollars) Direct Dumping	Estimated Costs (Millions of Dollars) Projectile Penetration
Refit Ship with Navigation Equipment	3.65	3.65
Projectiles for Drums	—	410.73
Operational Personnel, Port Charges, Ship Rental and Useage, Licensing, Studies and Reports	73.00	73.00
Supplies and Equipment	0.94	0.94
Subtotal	78	488
Contingency (30% of Total Capital and Operating Costs)	23	146
Financing, Escalation and Profit	75	467
Total Facility Costs	176	1101
Transportation to Port	271	271
Total Facility Plus Transportation Costs	447	1372
Total Unit Costs for Waste Disposal ($/$m^3$)	710	2200

4. SUMMARY OF RESULTS AND COMPARATIVE ANALYSIS

The major results of analyzing the various waste disposal alternatives are summarized in this chapter; the evaluation actors are weighed, and the alternatives are compared.

4.1 Environmental Effects

The environmental effects evaluation parameter is composed of a large number of individual effects which were calculated by the methods outlined in Chapter 3 and Appendix C. These effects are summarized and combined in this section. It should be noted that these effects are for the purpose of comparisons among alternatives, and are not intended to be predictive of the performance of a specific disposal site or method. Site- and facility-specific factors would need to be supplied, as well as waste uses and types, before the methodology used would yield more predictive results.

4.1.1 Non-radiological Effects

The non-radiological effects calculated for the various waste disposal alternatives, based on accident statistics from comparable industrial activities, are summarized in Table 4.1. They include projected injuries and fatalities, based on transportation distances and estimated construction and operational crew sizes.

From the information given in the table, it can be seen that transportation generally dominates both the number of projected injuries and fatalities in all cases. The differences in environmental effects resulting from different shipping distances to eastern and western sites tend to mask any differences between the various disposal alternatives.

The construction risks are based on the estimated construction effort and comparable industrial accident statistics. The projected risks for the various alternatives vary because of differences in crew sizes and types of activities. For instance, mining for the Mined Cavity Disposal Facility (MCDF) concepts could produce more injuries than construction of the open trenches for the Shallow Land Burial Facility (SLBF). Construction of ships and port facilities used for the ocean disposal concepts is not included in this analysis.

The operational crew for all concepts except ocean disposal was assumed to be the same size, because the same volume of waste would be handled at each facility. Hence, the accidental injuries and fatalities are the same for all but ocean disposal. For ocean disposal, the ship and loading crew was estimated to be somewhat larger than for the other alternatives. Also, the

TABLE 4.1

SUMMARY OF NON-RADIOLOGICAL IMPACTS FOR VARIOUS ALTERNATIVES[a]

Alternatives	Transportation		Construction		Operation		Cummulative Effect[b]	Normalized Effect[c]
	Total Injuries	Total Fatalities	Total Injuries	Total Fatalities	Total Injuries	Total Fatalities		
Shallow-Land Burial-Eastern Site	8	0.60	0.61	0.01	8.1	0.09	23.7	1.0
Shallow-Land Burial-Western Site	28	2.0	0.52	0.01	8.1	0.09	57.6	2.4
Improved Burial-Eastern Site	8	0.60	0.67	0.01	8.1	0.09	23.8	1.0
Improved Burial-Western Site	28	2.0	0.61	0.01	8.1	0.09	57.7	2.4
Deeper Burial-Eastern Site	8	0.60	0.95	0.01	8.1	0.09	24.0	1.0
Deeper Burial-Western Site	28	2.0	0.85	0.01	8.1	0.09	58.0	2.4
Abandoned Mine-Eastern Site	12	0.88	0.63	0.01	8.1	0.09	30.5	1.3
Abandoned Mine-Western Site	32	2.4	0.63	0.01	8.1	0.09	65.7	2.8
New Horizontal Shaft Mine-Eastern Site	12	0.88	2.8	0.06	8.1	0.09	33.2	1.4
New Horizontal Shaft Mine-Western Site	32	2.4	2.8	0.06	8.1	0.09	68.4	2.9
New Vertical Shaft Mine-Eastern Site	12	0.88	3.3	0.07	8.1	0.09	33.8	1.4
New Vertical Shaft Mine-Western Site	32	2.4	3.3	0.07	8.1	0.09	69.0	2.9
Above Grade Structure-Eastern Site	8	0.60	10	0.12	8.1	0.09	34.2	1.4
Above Grade Structure-Western Site	28	2.0	9.9	0.12	8.1	0.09	68.1	2.9
Buried Structure-Eastern Site	8	0.60	11	0.13	8.1	0.09	35.3	1.5
Buried Structure-Western Site	28	2.0	11	0.12	8.1	0.09	69.2	2.9
Direct Ocean Dumping	32	2.4	NA[d]	NA	25	0.11	82.1	3.5
Ocean Projectile Disposal	32	2.4	NA	NA	25	0.11	82.1	3.5

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[a] Based on disposal of 630,000 m^3 of waste over 20 years with 150 years of continued institutional control.

[b] Total injuries plus 10 times total fatalities.

[c] Normalized to SLBF eastern site case.

[d] NA - Not applicable. Construction of ships and ports not included.

accident statistics for comparable industries indicated higher injury rates. As a consequence, ocean disposal results in higher non-radiological environmental effects.

The cumulative non-radiological effect was obtained by adding the total projected injuries to a factor of ten times the total projected fatalities. The factor of ten was chosen to reflect the greater significance of loss of life. The cumulative effects were then normalized to the SLBF eastern site and averaged with the normalized radiological effects to determine the overall environmental effect evaluation factor used in the comparative analysis. It should be noted that in all cases except ocean disposal the effects of the longer transportation distance to the western sites are greater than the differences between alternatives.

4.1.2 Radiological Effects

The radiological effects calculated for the various alternatives are summarized in Table 4.2. As described in Section 3, the potential exposure estimates are presented in consistent annual dose rate units for the comparison. The long-term effects, those that occur after institutional control is relinquished, include inhalation of contaminated dust by a future reclaimer, direct gamma radiation to a future reclaimer, and exposures from consumption of food grown on the disposal site after it is contaminated by carrying the wastes to the surface. It can be seen that, for the reference inventory used in this study, the long-term effects dominate for the SLBF, improved SLBF and SDF concepts. No significant long-term effects attributable to reclamation activities are postulated for the deeper burial, MCDF and ocean disposal concepts. The estimate of the consequences of the food pathway for ocean dumping is less than 1 mrem/yr.

The short-term effects include exposures to the public along transportation routes, consumption of contaminated water from an on-site or nearby well, and a person at the site boundary inhaling airborne contamination from single containers accidentally ruptured during handling. Transportation exposures for ocean disposal and the western sites are about three times larger than for the eastern sites because of the longer transportation distances.

No well water exposures are postulated for the MCDF or ocean disposal cases. The well water exposures for the SDF concepts are lower than for the land burial cases because no leaching and subsequent groundwater movement is postulated until after institutional control is relinquished. The addition of increased ion-exchange capacity beneath the wastes, assumed to have no effect on the nuclides that are not sorbed (e.g., move at the same rate as the groundwater) reduces potential exposure rates

TABLE 4.2

SUMMARY OF RADIOLOGICAL IMPACTS FOR ALTERNATIVES (mrem/yr)[a]

Alternative	Long Term Effects: Inhalation	Long Term Effects: Direct Gamma	Long Term Effects: Food	Short Term Effects: Transportation	Short Term Effects: Well Water Consumption	Short Term Effects: Single Container Accidents	Cummulative Effect[b]	Normalized Effect[c]
Shallow-Land Burial-Eastern Site	60	340	620	10	80	200	1310	1.0
Shallow-Land Burial-Western Site	60	340	620	30	40	200	1290	1.0
Improved Burial-Eastern Site	51	290	530	10	77	150	1108	0.8
Improved Burial-Western Site	51	290	530	30	35	150	1086	0.8
Deeper Burial-Eastern Site	0	0	0	10	77	150	237	0.2
Deeper Burial-Western Site	0	0	0	30	35	150	215	0.2
Abandoned Mine-Eastern Site	0	0	0	14	0	100	114	0.1
Abandoned Mine-Western Site	0	0	0	38	0	100	138	0.1
New Horizontal Shaft Mine-Eastern Site	0	0	0	14	0	100	114	0.1
New Horizontal Shaft Mine-Western Site	0	0	0	38	0	100	138	0.1
New Vertical Shaft Mine-Eastern Site	0	0	0	14	0	100	114	0.1
New Vertical Shaft Mine-Western Site	0	0	0	38	0	100	138	0.1
Above Grade Structure-Eastern Site	120	680	620	10	9	100	1539	1.2
Above Grade Structure-Western Site	120	680	620	30	6	100	1556	1.2
Buried Structure-Eastern Site	120	680	620	10	9	100	1539	1.2
Buried Structure-Western Site	120	680	620	30	6	100	1556	1.2
Direct Ocean Dumping	0	0	1	38	0	200	239	0.2
Ocean Projectile Disposal	0	0	0	38	0	200	238	0.2

(a) Dose rates are calculated on consident basiter alternatives, but are not predictive of exposures to any single individual at actual sites.

(b) Sum of long and short term effects, even though times of occurance may be different. No Individual will receive a dose of this size. The cumulative effect is presented only for comparisons among the alternatives.

(c) Normalized to SLBF eastern case.

only slightly for the reference waste inventory. The effectiveness of that improvement is apparent only on the more slowly moving nuclides.

The single container accident dose rates for the improved SLBF and deeper burial cases are assumed to be 25% less than the base case because of the mitigating effect of the air supported weather protection building in which many of the waste handling operations take place. Dose rates are reduced by one half for the MCDF and SDF concepts because at least half of the waste handling will occur inside the mine or building, which are designed to mitigate the consequences of accidents.

The cumulative radiological effect is the sum of the dose rates from the pathways analyzed, even though the times of occurrence of the potential exposures are different. No individual would receive the cumulative dose listed. These doses are not predictions of actual exposures, but are used only for comparing alternatives. The cumulative effects are normalized to the reference SLBF eastern site to obtain the normalized effects listed in the table.

Note that there is little difference between the radiological effects for eastern and weatern sites for the same alternative. If different parameters were used to differentiate eastern and western sites, the radiological impacts would be altered somewhat, although the food and well water pathways are the only ones that are strongly site-dependent. Differences in the food pathways could arise from differences in productivity. Changing the parameters related to the ground water and aquifer velocities and distances will impact the projected well water dose rates. However, as can be seen from the table, well water is not one of the major contributors to the cumulative effect in any case.

4.2 Economic Evaluations

The economic evaluations are based on the cost estimates prepared for the alternative disposal facilities and detailed in Chapter 3 and Appendix D. Table 4.3 summarizes the cost estimates for the alternatives. Total capital, operating, contingency, financing, escalation, and profit costs are summed to give total facility costs. Transportation costs are added and total unit costs are calculated. Total costs are normalized to the reference SLBF eastern site for comparison. Cost differences between eastern and western sites are dominated by the extra transportation costs attributed to western sites.

4.3 Comparative Analysis

The evaluation factors for each of the various disposal alternatives are the basis for the comparative analysis.

TABLE 4.3

COST ESTIMATE SUMMARY FOR BASE CASE ALTERNATIVE FACILITIES ($MILLIONS)

Alternative	Capital Costs	Operating Costs	Contingency	Financing, Escalation & Profit	Total Facility Costs	Transportation Costs	Total Costs	Total Unit Costs ($/m^3)	Normalized Costs *
Shallow-Land Burial-Eastern Site	12	24	11	37	84	68	152	240	1.0
Shallow-Land Burial-Western Site	9	24	10	33	76	237	313	500	2.1
Improved Buiral-Eastern Site	14	24	11	40	89	68	157	250	1.0
Improved Burial-Western Site	11	24	10	36	81	237	318	500	2.1
Deeper Burial-Eastern Site	19	24	13	46	102	68	170	270	1.1
Deeper Burial-Western Site	16	24	12	42	94	237	331	520	2.2
Abandoned Mine-Eastern Site	7	24	9	31	71	102	173	280	1.1
Abandoned Mine-Western Site	7	24	9	31	71	271	342	540	2.3
New Horizontal Shaft Mine-Eastern Site	30	24	16	59	129	102	231	370	1.5
New Horizontal Shaft Mine-Western Site	30	24	16	59	129	271	400	630	2.7
New Vertical Shaft Mine-Eastern Site	34	24	17	64	139	102	241	380	1.6
New Vertical Shate Mine-Western Site	34	24	17	64	139	271	410	650	2.7
Above Grade Structure-Eastern Site	178	25	61	237	501	68	569	900	3.8
Above Grade Structure-Western Site	176	25	60	234	495	237	732	1200	4.8
Buried Structure-Eastern Site	192	25	65	254	536	68	604	960	4.0
Buried Structure-Western Site	189	25	64	250	528	237	765	1200	5.1
Direct Ocean Dumping	4	74	23	75	176	271	447	710	3.0
Ocean Projectile Disposal	4	484	146	467	1101	271	1372	2200	9.1

* Normalized to SLBF eastern site costs.

4.3.1 Summary of Evaluation Factors

The overall comparison based on the normalized evaluation factors used in this study is presented in matrix format in Table 4.4. The evaluation factor for compatibility with waste, as described in Chapter 3, is the same for all cases because the reference waste can be accomodated by all of the alternative disposal facilities. It is included in the comparison, however, because a weight or importance has been assigned to it.

Site selection evaluation factors differ from case to case to reflect the availability of suitable sites for the alternatives. Suitable western sites are assumed to be more readily available than analogous sites in the east. Finding suitable abandoned mines is the most difficult.

As reflected in the safeguards evaluation factors, only small differences in ability to keep the disposed wastes secure between alternatives is expected. The ocean disposal concepts are most secure, followed by the MCDF concepts.

The environmental effects evaluation factor is obtained by averaging the normalized non-radiological and radiological effects from Tables 4.1 and 4.2.

The factor representing availability of techniques shows the MCDF and ocean projectile concepts to be those for which the least direct experience and technology is available.

The difficulties inherent in making necessary changes in current regulatory and institutional controls, both international and domestic, to accommodate the various alternatives, are reflected in the institutional controls evaluation factor. The largest revisions in controls would be required for the MCDF and ocean disposal concepts.

The evaluation factors for public acceptance indicate that resistance to ocean disposal concepts would be the greatest, and that the MCDF concepts would be most readily accepted. The other alternatives would also be perceived as improvements to current practices, and therefore show better acceptability.

The individual cost and industry cost evaluation factors are based on the normalized total costs given in Table 4.3.

4.3.2 Weighted Comparison

Table 4.5 contains the overall weighted comparison of all alternatives. The evaluation factors have been modified by multiplying by the weights given in Table 2.6. The weighted comparison is the sum of the weighted evaluation factors for

TABLE 4.4

SUMMARY OF UNWEIGHTED RESULTS OF EVALUATIONS FOR THE ALTERNATIVES

	Evaluation Factors								
Alternatives	Compatibility with Waste	Site Selection	Safeguards	Environmental Effects	Availability of Techniques	Institutional Control	Public Acceptance	Consumer Costs	Industrial Costs
Shallow-Land Burial-Eastern Site	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Shallow-Land Burial-Western Site	1.0	0.9	1.0	1.7	1.0	1.0	1.0	2.1	2.1
Improved Burial-Eastern Site	1.0	0.9	1.0	0.9	1.0	1.0	0.9	1.0	1.0
Improved Burial-Western Site	1.0	0.9	1.0	1.6	1.0	1.0	0.9	2.1	2.1
Deeper Burial-Eastern Site	1.0	1.2	0.9	0.6	1.1	1.1	0.8	1.1	1.1
Deeper Burial-Western Site	1.0	1.1	0.9	1.3	1.1	1.1	0.8	2.2	2.2
Abandoned Mine-Eastern Site	1.0	1.5	0.8	0.7	1.2	1.2	0.8	1.1	1.1
Abandoned Mine-Western Site	1.0	1.4	0.8	1.4	1.2	1.2	0.8	2.3	2.3
New Horizontal Shaft Mine-Eastern Site	1.0	1.4	0.8	0.8	1.3	1.2	0.7	1.5	1.5
New Horizontal Shaft Mine-Western Site	1.0	1.3	0.8	1.5	1.3	1.2	0.7	2.7	2.7
New Vertical Shaft Mine-Eastern Site	1.0	1.3	0.8	0.8	1.3	1.2	0.7	1.6	1.6
New Vertical Shaft Mine-Western Site	1.0	1.2	0.8	1.5	1.3	1.2	0.7	2.7	2.7
Above Grade Structure - Eastern Site	1.0	0.9	1.2	1.3	1.1	1.1	0.9	3.8	3.8
Above Grade Structure - Western Site	1.0	0.8	1.2	2.0	1.1	1.1	0.9	4.8	4.8
Buried Structure - Eastern Site	1.0	0.9	1.1	1.4	1.1	1.1	0.9	4.0	4.0
Buried Structure - Western Site	1.0	0.8	1.1	2.0	1.1	1.1	0.9	5.1	5.1
Direct Ocean Dumping	1.0	1.2	0.5	1.8	1.0	1.2	1.4	3.0	3.0
Ocean Projectile Disposal	1.0	1.4	0.5	1.8	1.3	1.2	1.2	9.1	9.1

TABLE 4.5

WEIGHTED COMPARATIVE ANALYSIS FOR ALTERNATIVES

	Evaluation Factors									
	Compatibility with Waste	Site Selection	Safeguards	Environmental Effects	Availability of Techniques	Institutional Control	Public Acceptance	Consumer Costs	Industrial Costs	Weighted Comparison*
Weight	0.08	0.12	0.06	0.11	0.10	0.11	0.16	0.14	0.12	
Alternatives										
Shallow-Land Burial-Eastern Site	0.08	0.12	0.06	0.11	0.10	0.11	0.16	0.14	0.12	1.0
Shallow-Land Burial-Western Site	0.08	0.11	0.06	0.19	0.10	0.11	0.16	0.29	0.25	1.4
Improved Burial-Eastern Site	0.08	0.11	0.06	0.10	0.10	0.11	0.14	0.14	0.12	0.96
Improved Burial-Western Site	0.08	0.11	0.06	0.18	0.10	0.11	0.14	0.29	0.25	1.3
Deeper Burial-Eastern Site	0.08	0.14	0.05	0.07	0.11	0.12	0.13	0.15	0.13	0.98
Deeper Burial-Western Site	0.08	0.13	0.05	0.14	0.11	0.12	0.13	0.31	0.26	1.3
Abandoned Mine-Eastern Site	0.08	0.18	0.05	0.08	0.12	0.13	0.13	0.15	0.13	1.1
Abandoned Mine-Western Site	0.08	0.17	0.05	0.15	0.12	0.13	0.13	0.32	0.28	1.4
New Horizontal Shaft Mine-Eastern Site	0.08	0.17	0.05	0.09	0.13	0.13	0.11	0.21	0.18	1.2
New Horizontal Shaft Mine-Western Site	0.08	0.16	0.05	0.17	0.13	0.13	0.11	0.38	0.32	1.5
New Vertical Shaft Mine-Eastern Site	0.08	0.16	0.05	0.09	0.13	0.13	0.11	0.22	0.19	1.2
New Vertical Shaft Mine-Western Site	0.08	0.14	0.05	0.17	0.13	0.13	0.11	0.38	0.32	1.5
Above Grade Structure-Eastern Site	0.08	0.11	0.07	0.14	0.11	0.12	0.14	0.53	0.46	1.8
Above Grade Structure-Western Site	0.08	0.10	0.07	0.22	0.11	0.12	0.14	0.67	0.58	2.1
Buried Structure-Eastern Site	0.08	0.11	0.07	0.15	0.11	0.12	0.14	0.56	0.48	1.8
Buried Structure-Western Site	0.08	0.10	0.07	0.22	0.11	0.12	0.14	0.71	0.61	2.2
Direct Ocean Dumping	0.08	0.14	0.03	0.20	0.10	0.13	0.22	0.42	0.36	1.7
Ocean Projectile Disposal	0.08	0.17	0.03	0.20	0.13	0.13	0.19	1.27	1.09	3.3

* Weighted Comparison is the sum of the weighted evaluation factors for each alternative. Higher values indicated less desirability.

each alternative. Selection of other weightings could change some of the conclusions of this analysis; Table 4.4 can be used with other weights, if desired.

It can be seen from Table 4.5 that the differences among the alternatives are generally smaller than the differences between eastern and western sites. Political realities may dictate that both eastern and western sites be used, even though eastern sites appear to be more favorable. The real significance of the consistently large difference between eastern and western sites is that transportation dominates the comparisons because of higher non-radiological environmental effects and cost. This suggests that regional disposal sites are desireable to minimize transportation distances.

It is apparent that shallow land burial as now practiced is a viable disposal alternative. Improvements to present practices and deeper burial also compare favorably with the base case. Structural disposal and ocean disposal concepts appear to be least viable. The MCDF concepts would require further justification before they were selected for waste disposal. However, changing the weights used and the methods of combining impacts could result in different relative ranking among the alternatives.

5. CONCLUSIONS

Using the weighting factors described in Chapter 2 various alternatives for disposal of low-level radioactive wastes were compared. The following conclusions have emerged from this analysis:

- Several viable alternatives exist for disposing of low-level radioactive wastes.
- The analysis indicates that the alternatives to shallow land burial that were studied in this report can be ranked in descending order of preference as follows: improving current shallow land burial practices, deeper burial, use of mined cavities, ocean dumping, disposal in specially designed structures, and sea bed disposal via penetrating projectiles, based on the generic facilities and locations presented in this report.
- Transportation of the wastes dominates the comparison among alternatives, through both cost and safety considerations. This indicates that regional disposal sites near the sources of low-level wastes are highly desirable.

The above conclusions are strongly influenced by the weights assigned to each of the evaluation factors used. This report contains sufficient information to allow other weightings to be applied as desired.

It is recommended that an analysis be performed to determine the sensitivity of the ranking of alternatives to key factors such as duration of institutional control, cost estimation techniques and relative weights placed on evaluation factors. It is also recommended that the methodology be applied to specific potential waste disposal sites to demonstrate its use in selecting the best alternaives for particular locations. The methodology developed here can be applied to specific as well as generic situations. Further development of models and methods to evaluate the effects on waste migration from site specific differences should be considered, along with more detailed studies of the most viable alternatives to determine optimum waste management strategies.

APPENDIX A

TECHNICAL ADVISORY PANEL FOR WASTE DISPOSAL ALTERNATIVES STUDY

APPENDIX A

TECHNICAL ADVISORY PANEL FOR WASTE DISPOSAL ALTERNATIVES STUDY

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APPENDIX B

REVIEW OF EXISTING LOW-LEVEL WASTE DISPOSAL FACILITIES

APPENDIX B

REVIEW OF EXISTING LOW-LEVEL WASTE DISPOSAL FACILITIES

Current practice in this country for disposal of solid Low-Level Waste (LLW) is primarily shallow land burial. The reference Shallow Land Burial Facility (SLBF) used in this study is based on present shallow land burial practices. The numbers selected to mathematically describe the SLBF and other reference facility designs were obtained from measured values of those parameters at existing facilities, and from reasonably conservative estimates of the values that will be allowed at future waste disposal sites.

For perspective on current LLW handling and to provide a basis for describing the alternative facilities analyzed, a review of existing low-level waste burial facilities was performed. There are presently six commercial low-level radioactive waste burial facilities and five major active sites for burial of defense and research-related radioactive wastes at Department of Energy (DOE) facilities in the United States. Although the sources of the wastes differ from site to site, the general operational characteristics of the disposal facilities and the generic composition of the wastes are similar.

Basically, low-level wastes received at a disposal facility are placed directly in pits or trenches excavated into the native soil or till at the site. The overburden removed during excavation is then used to cover the wastes. The pits and trenches are usually sloped toward one end and a cover is applied for control of surface runoff from precipitation. Characteristics of the existing sites are summarized in the following tables. The information presented in the tables was collected and summarized from Refs 7, 24, 30, and 63 to 66.

Table B.1 lists the capacity or volume of waste than can be readily accomodated at the existing sites, the sizes of trenches or pits employed, covered types and procedures, and quantities of waste buried.

Climatological and hydrogeological information available for each site is tabulated in Table B.2. This includes data concerning precipitation and evapotranspiration, geomorphology, seismicity, surface soils and water, subsurface stratigraphy, and aquifers.

Characterization of the radioactivity in wastes at the commercial sites has been accomplished in the past by use of broad categories designated as special nuclear materials, source materials, and by-product materials for fissile, fertile, and fission and activation products, respectively. Table B.3 summarizes the data for existing sites using this method of categorization.

TABLE 8.1

CAPACITIES AND WASTE QUANTITIES HANDLED AT EXISTING SITES

SITE	YEAR LICENSED	COMMERCIAL SITE CAPACITY ($10^5 m^3$)	BURIAL TRENCH SIZE (m) (LENGTH x WIDTH x DEPTH)	COVER		FILL PROCEDURE	COVERING FREQUENCY	PROVISIONS FOR WATER COLLECTION AND CONTAINMENT	ACTIVITY (10^3 Ci AT TIME OF BURIAL)	VOLUME BURIED (10^4 m^3)	CUMULA-TIVE THROUGH
				TYPE	DEPTH						
HANFORD, WA*	-	-	Variable x 1.5-5 x 4-8	Mounded Earthfill	Min 2.5m, or To Reduce To <1 mr/hr at Surface	Filled from End	Daily	None	810	20	7/75
RICHLAND, WA	1965	9	90 x 8 x 6	Earthfill	Min. 2m Total; Mounded to 1m Above Grade	Trench Filled To 0.6m of Surface	As Trench Is Filled	None	434	1.6	12/77
BEATTY, NV	1962	7	260 x 12-15 x 8	Earthfill	Min. 2m Total; Mounded to 0.6m Above Grade	Trench Filled To 1m of Surface	As Trench Is Filled	None	156	6.1	12/77
INEL, ID*	-	-	275 x 2-3 x 4	Resended Earthfill	Min. 1m To Surface	Pits and Trenches Filled To 1m of Surface	As Trench Or Pit Is Filled	None	-	14	7/75
LOS ALAMOS, NM*	-	-	120-180 x 8-30 x 8	Excavated Tuff Compacted	Min. 1.5m Mounding To 0.5 To 1m Above Grade	Layered Filling To 1m of Surface	Combustibles On Day of Delivery Other As Required	None	-	23	7/75
SHEFFIELD, IL	1967	2	150 x 15-18 x 6-8	Compacted Clay Reseeded	Min. 1m Final Cover	Trench Filled To 0.6m of Surface	Daily	Trenches Sloped; Sump and Standpipe	58	8.5	12/77
MOREHEAD, KY	1962	31	60 - 150 x 24 x 6-8	1m Compacted Clay; Mounded; Reseeded	1m Cover; Mounded 0.6m Above Grade	Trench Filled To 0.6m of Surface	Daily	Trenches Sloped; Stanpipe; Clay Berm Around Trench	2400	14	12/77
OAK RIDGE, TN*	-	-	15 x 3 x 3-5	Reseeded Earthfill	Min. 1m To Surface	Trench Filled To 1m of Surface	As Trench Is Filled	Trenches Sloped; Monitoring Wells	-	18	7/75
SAVANNAH RIVER, SC*	-	-	Variable x 6 x 6	Mounded Earthfill	Min. 1.2m, Or To Reduce To <6 mr/hr at Surface	Random Placement in Trenches	After Disposal	Monitoring Wells	-	28	7/75
BARNWELL, SC	1971	25	140 x 15 x 5-7	0.6m Clay Additional Mounded Cover	3m at Centerline; 1.5m at Trench Edge	Trench Filled To 1m of Surface	Daily	Trenches Sloped 1° Sand at Trench Bottom	558	14	12/77
WEST VALLEY, NY	1963	2	180-210 x 10 x 6	Earthfill Compacted Topsoil Added	Min. 3m; Mounded 1.5m Above Grade	Trench Filled To Grade Level	Daily	Trenches Sloped 2° Sump With Riser Pipe	700	6.7	12/77

* DOE Site

TABLE B.2

CLIMATOLOGICAL AND HYDROGEOLOGICAL PARAMETERS AT EXISTING SITES

SITE	CLIMATE	PRECIPITATION Mean Annual (mm)	PRECIPITATION Net (mm)	GEOMORPHOLOGY	CLASSIFICATION	TOTAL THICKNESS (m)	INTERSTITIAL PERMEABILITY TO WATER (cm/day)	BEDROCK CLASSIFICATION	BEDROCK STRUCTURE
HANFORD, WA*	Semi-arid	200	-840	Columbia Plateau Semi-desert	Clay, Sand and Gravel	>150	Variable	Volcanic Basalt	Massive/flat-lying
RICHLAND, WA	Semi-arid	200	-840	Columbia Plateau Semi-desert	Clay, Sand and Gravel	>150	Variable	Volcanic Basalt	Massive/flat-lying
BEATTY, NV	Arid	100	1,575	Basin & Range Desert	Alluvial Sand and Gravel	>200	0.02-0.1	Metamorphic and Sedimentary	Folded
INEL, ID*	Semi-arid	200	-600	Volcanic Semi-desert	Alluvial Sand and Gravel	6	Moderate	Volcanic Basalt	Massive/flat-lying
LOS ALAMOS, NM*	Semi-arid	400	-870	Mountainous Semi-desert	Weathered Tuff	2	Moderate	Volcanic Tuff	Massive/flat-lying
SHEFFIELD, IL	Humid	900	90	Glacial	Glacial drift; Sand, Silt and Gravel	20-30	0.04-40	Shale, Sandstone and Coal	Flat-lying
MOREHEAD, KY	Humid	1,200	300	Ridge & Valley Appalachian	Weathered Shale Clay and Sand	3-5	0.02	Shale	Flat-lying
OAK RIDGE, TN*	Humid	1,300	460	Ridge & Valley Appalachian	Weathered Shale and Fill	10	Very low	Shale	Folded
SAVANNAH RIVER, SC*	Humid	1,100	0	Coastal Plain	Sand and Clay	10	Very low	Clay, Sand, and Sandstone	Flat-lying
BARNWELL, SC	Humid	1,100	0	Coastal Plain	Sand and Clay	10	0.2	Clay, Sand, and Sandstone	Flat-lying
WEST VALLEY, NY	Humid	1,000	300	Glacial	Glacial drift; Clay, Silt and Sand	20-30	0.5	Shale	Flat-lying

* DOE Site

TABLE B.2 (Con't)

CLIMATOLOGICAL AND HYDROGEOLOGICAL PARAMETERS AT EXISTING SITES

SITE	DEPTH TO AQUIFER ZONES (m)	TYPE	NEAREST SURFACE WATER	WATER FLOW PATHS FROM BURIAL AREAS	DOWNSTREAM RIVER FLOW RATE NORMAL ANNUAL MEAN (m^3/SEC)	SEISMIC HAZARD ZONE
HANFORD, WA*	100	Gradient	10km Perennial (Columbia River)	Pores in Sand and Gravel	Columbia River McNary Dam (5320)	2
RICHLAND, WA	100	Gradient	10km Perennial (Columbia River)	Unsaturated Flow in Sand and Gravel Pores	Columbia River McNary Dam (5320)	2
BEATTY, NV	80	Gradient	3km Ephemeral (Amargosa River)	Unsaturated Flow in Sand and Gravel Pores	None	3
INEL, ID*	60-300	Gradient	3km Ephemeral (Big Lost River)	Pores in Sand and Gravel	Snake River Hagerman, Idaho (260)	3
LOS ALAMOS, NM*	200	Gradient	1km Ephemeral	Bedrock Fractures and Sand and Gravel Pores	Rio Grande Albuquerque, NM (28)	2
SHEFFIELD, IL	5-20 100	Vadose Gradient	Site Boundary Perennial	Pore Spaces in Fill	Mississippi River St. Louis, Missouri (4935)	1
MOREHEAD, KY	1-2	Vadose	500m Perennial	Shale Fractures	Licking River Covington, KY (100) Ohio River, Louisville, KY (3215)	1
OAK RIDGE, TN*	5	Vadose	On Site Perennial	Shale Fractures and Pores in Fill	Clinch River, Oak Ridge, TN Tennessee River, Chattanooga (1045) Mississippi, Memphis, TN (13,365)	2
SAVANNAH RIVER, SC*	10 200	Vadose Gradient	On Site Perennial	Pore Spaces in Sand	Savannah River Clyo, Georgia (335)	2
BARNWELL, SC	10 200	Vadose Gradient	2km Perennial (Lower Three Run)	Pore Spaces in Sand	Savannah River Clyo, Georgia (335)	2
WEST VALLEY, NY	1-20	Vadose Gradient Not Observed	On Site Perennial	Shale Fractures	St. Lawrence River Lake Ontario Outlet (7080)	2

*DOE site

TABLE B-3

COMMERCIAL LOW-LEVEL WASTE BURIAL HISTORY
BY-PRODUCT MATERIAL* BURIED

COMMERCIAL SITES YEAR	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	TOTAL
Barnwell, SC																
Volume (m^3)										1,171	3,757	15,839	18,244	18,072	28,829	85,912
Curries										4,118	997	42,500	329,043	17,420	27,890	421,968
Beatty, NV																
Volume (m^3)	1,860	3,510	2,840	1,990	3,530	3,210	3,580	2,480	4,130	3,580	4,300	4,080	4,100	4,179	3,864	53,042
Curries		5,690	6,477	6,377	11,974	10,894	6,808	9,761	12,304	4,316	5,228	5,704	23,904	18,389	4,493	123,119
Morehead, KY																
Volume (m^3)		2,210	3,870	5,750	5,560	7,820	8,180	10,400	12,500	13,200	15,600	10,100	8,520	17,098	13,783	134,591
Curries		22,716	147,322	63,828	52,729	42,280	45,578	31,027	46,968	720,146	217,350	118,274	143,656	289,581	211,356	2,153,802
Sheffield, IL																
Volume (m^3)						2,530	2,710	2,010	2,830	4,430	5,960	8,530	12,400	14,112	13,480	68,992
Curries						3,850	2,381	2,192	5,427	7,895	4,857	2,834	3,229	6,104	7,744	46,513
Richland, WA																
Volume (m^3)				670	2,400	870	670	440	420	580	680	1,033	1,410	1,500	2,867	13,520
Curries				144	1,006	5,378	10,330	55,964	52,820	23,916	31,809	57,037	12,173	113,341	104,306	468,224
West Valley, NY																
Volume (m^3)		520	6,390	4,720	4,700	4,950	4,500	4,270	5,100	6,360	7,060	7,500	8,580	2,049		66,726
Curries		1,372	11,344	21,515	41,056	51,230	51,675	23,264	36,241	42,458	61,208	170,552	55,505	10,273		577,754
Total																
Volume (m^3)	1,860	6,240	13,100	13,100	16,200	19,400	19,600	21,400	25,000	29,301	37,285	47,046	53,242	57,010	62,823	422,607
Curries		29,778	166,154	91,874	106,765	113,632	116,722	122,209	153,810	802,849	321,449	396,901	567,510	455,098	355,789	3,800,590

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*Radioactivity produced by irradiation with neutrons, including fission and activation products.

TABLE B-3 (Con't)

LOW-LEVEL WASTE CHARACTERIZATION
SPECIAL NUCLEAR MATERIALS* BURIED AT COMMERCIAL SITES

COMMERCIAL SITES YEAR	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	TOTAL
Barnwell, SC																
gm										13,220	46,718	99,800	110,444	64,425	92,800	427,407
gm/m^3										11.3	12.4	6.30	6.05	3.56	3.22	4.97
Beatty, NV																
gm	319	41,304	172,030	334,762	5,872	22,644	8,602	5,005	7,708	757	21,177	15,164	16,954	29,276	2,096	683,670
gm/m^3	0.17	11.8	60.6	168	1.66	7.05	2.40	1.17	1.87	0.21	4.92	3.72	4.14	7.01	0.54	12.89
Morehead, KY																
gm		959	11,889	4,261	7,462	14,842	17,771	31,506	47,562	72,770	71,443	46,244	23,832	25,690	27,474	403,705
gm/m^3		0.43	3.07	0.74	1.34	1.90	2.17	3.03	3.80	5.51	4.58	4.58	2.80	1.50	1.99	3.00
Richland, WA																
gm				3	1,418	0.16	0.27	32	200	15	832	6,558	4,884	18,978	24,378	57,298
gm/m^3				4.0 -3	0.59	2.0 -4	4.0 -4	0.07	0.47	0.03	1.27	6.35	3.46	12.65	8.50	4.24
Sheffield, IL																
gm						1,238	1,754	3,843	5,649	9,934	5,898	6,126	6,198	5,285	1,738	47,663
gm/m^3						0.49	0.65	1.91	2.0	2.24	0.99	0.72	0.50	0.37	0.13	0.69
West Valley, NY																
gm		952	3,273	2,433	4,999	3,446	2,045	7,301	8,273	4,816	7,321	7,710	2,984			56,003
gm/m^3		1.82	0.51	0.52	1.06	0.70	0.45	1.71	1.62	0.76	1.04	1.03	0.35			0.84
Total																
gm	319	43,215	187,192	341,459	19,751	42,170	30,172	47,687	69,392	101,512	153,389	181,107	166,296	143,654	148,486	1,675,801
gm/m^3	0.17	6.93	14.29	26.06	1.22	2.17	1.54	2.23	2.78	3.46	4.11	3.85	3.12	2.52	2.36	3.97

*Fissile materials

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TABLE B-3 (Con't)

LOW-LEVEL WASTE CHARACTERIZATION
SOURCE MATERIAL* BURIED AT COMMERCIAL SITES

COMMERCIAL SITES YEAR	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	TOTAL
Barnwell, SC																
Kg										12,546	1,606	45,305	26,961	46,005	16,259	148,682
Kg/m^3										10.7	0.43	2.86	1.48	2.55	0.56	1.73
Beatty, NV																
Kg	296	472	331	236	91	346	1,040	290	322		9,340	11,500	9,710	1,438	5,000	40,412
Kg/m^3	0.16	0.13	0.12	0.12	0.03	0.11	0.29	0.07	0.08		2.17	2.82	2.37	0.34	1.29	0.76
Morehead, KY																
Kg		5,210	5,590	568	690	5,680	6,250	2,550	7,220	5,730	8,260	9,340	13,100	82,416	75,944	228,548
Kg/m^3		2.36	1.44	0.10	0.12	0.73	0.76	0.25	0.58	0.43	0.53	0.43	1.54	4.82	5.51	1.70
Richland, WA																
Kg				0.9	253.0	0.9	2.7	88.4	31.3	606	3,113	2,250	20.3	215	5,011	11,592
Kg/m^3				1.0 -3	0.11	1.0 -3	4.0 -3	0.20	0.07	1.04	4.76	2.18	0.014	0.14	1.75	0.86
Sheffield, IL																
Kg						3,930	8,703	6,330	2,000	212	3,600	2,410	13,900	35,950	3,854	80,889
Kg/m^3						1.55	3.21	3.15	0.71	0.05	0.68	0.28	1.12	2.25	0.29	1.17
West Valley, NY																
Kg		7,580	10,100	22,200	38,300	20,300	6,460	80,000	31,700	51,400	72,500	44,200	61,700			446,440
Kg/m^3		14.52	1.58	4.70	4.15	4.10	1.43	18.69	6.22	8.07	10.27	5.89	7.19			6.69
Total																
Kg	296	13,300	16,000	23,020	39,400	30,224	22,500	89,300	41,300	70,546	98,373	115,195	125,161	166,204	106,068	956,707
Kg/m^3	0.16	2.13	1.22	1.75	2.43	1.65	1.15	4.18	1.65	2.41	2.64	2.45	2.35	2.36	1.69	2.26

*Non-fissile uranium and thorium.

APPENDIX C

ENVIRONMENTAL TRANSPORT, RELEASES AND PATHWAYS TO HUMAN EXPOSURE

APPENDIX C

ENVIRONMENTAL TRANSPORT, RELEASES AND PATHWAYS TO HUMAN EXPOSURE

In assessing the radiological impacts from low-level waste disposal, potential doses to humans resulting from disposal operations were estimated. Hypothetical exposure events that could occur on both short- and long-term bases were analyzed for the various disposal alternatives. Dose rates to critial organs for the various radionuclides in the waste are used as the basis for comparison.

The short-term events are those that could occur during the operational phases of the disposal activities, and include airborne releases to the atmosphere from waste container handling accidents, exposures along transportation routes, and for the land-based disposal concepts, possible consumption of contaminated groundwater from a well on or near to the disposal site. The well water event is classified as short-term because some radionuclides could leak from the disposal wastes and be transported through the groundwater in only a few years.

Potential long-term exposure events would generally occur after institutional controls over the disposal site are relinquished, and include direct gamma radiation exposure to future individuals who may inadvertently contact the wastes, inhalation of contaminated dust during disposal site reclamation activities that may involve digging into buried wastes, and consumption of contaminated food that may be produced at or near the disposal site. The period of institutional control is assumed to be 150 years for the land-based disposal concepts. No institutional control over ocean disposal sites after their use is assumed, although the ocean itself provides a barrier to human contact with wastes.

The six pathways listed above are not the only possible exposure mechanisms from waste disposal operations, but they are among those shown by previous studies to be most important.[6] They are used in this study to represent potential radiological impacts from waste disposal activities, and are consistently applied to the various disposal alternatives to provide a basis for comparison.

C.1 Short-Term Events

Transportation exposures, contaminated well water consumption, and waste container handling accidents are included in the short-term events analyzed in this study. Each will be discussed separately in this section.

C.1.1 Transportation Doses

Exposures to the public along possible transportation routes from nuclear fuel cycle operations have been studied extensively in the past.[11-16] The cited references provide the basis for the approach taken in this study to estimate the relative impacts from transportating waste to various generic disposal site locations.

It is assumed that radiation levels from waste shipments will conform to the regulatory limit from 49 CFR 170 of 10 mrem/hr at 6 feet from the surface of the transport vehicle, and that the average gamma ray energy from the wastes is 1 MeV. The transport vehicle represents a point source to individuals along the route, who are assumed to be uniformly distributed in the area between 100 and 2600 feet along each side of the route. The exposure to this population is obtained by integrating the dose rates over the distances and time required for the vehicle to pass a given point. The vehicle is assumed to travel 200 miles per day. (Under these assumptions, the cumulative radiation dose to the population is the same regardless of how much time each day the vehicle takes to cover 200 miles.) Attenuation from gamma interactions with the air and distance from the source, as well as buildup from scattered gamma rays returning to the exposure point, have been included in the dose rate estimates. Assuming 300 people per square mile are uniformly distributed along the transportation route gives 1.8×10^{-5} man-rem per car mile of transportation.[13] The 300 people per square mile population distribution is consistent with an analysis of routes and population densities in this country for shipments from existing reactor facilities.[14]

To ship 6[illegible]0,000 m^3 of waste in 55 gallon drums by rail over a twenty year period would require about 220 six-car trains per year, with 64 drums in each of two International Standards Organization (ISO) cargo carriers per car. The resultant population doses for the transportation distances assumed for the various alternatives are summarized in Table C.1. These distances were based on locations of likely generic disposal sites or shipping ports and major nuclear waste sources. It was felt that sites for mined cavity concepts would probably be more remote than those for the other land-based alternatives, so 200 miles was added to the average distances to both the eastern and western mined cavity disposal sites.

C.1.2 Contaminated Well Water Consumption

For the consumption of contaminated well water, it is assumed that contaminants leach from the disposal wastes into groundwater and subsequently move into an underlying aquifer that may be tapped by a well. This is modeled by an exponential leaching

TABLE C.1

PROJECTED TRANSPORTATION EXPOSURES

Transportation Distance (mi)	Applicable Alternative Disposal Concepts	Total Car Mile (mi/yr)	Population Exposures* (manrem/yr)
400	SLBF, Improved SLBF Deeper Burial and SDF eastern sites	528,000	9.5
600	MCDF eastern sites	792,000	14
1400	SLBF , Improved SLBF, Deeper Burial and SDF western sites	1,850,000	33
1600	MCDF western sites and ocean disposal ports	2,110,000	38

* Based on 1.8×10^{-5} manrem/car mile

process, implying that the amount of material that leaches is proportional to the amount remaining from the initial source or inventory. The effects of radioactive decay are also incorporated into the model. Leaching and decay of the source are included as boundary conditions for the solution of the mass transport equation describing the movement of contaminants through a saturated porous medium.

A reasonable model for radionuclide migration in groundwater systems is given by the following second-order partial differential mass balance equation 6:

$$D \frac{\partial^2 C}{\partial X^2} - V \frac{\partial C}{\partial X} - K \lambda_d C = K \frac{\partial C}{\partial t} \tag{C.1}$$

where

C = nuclide concentration, pCi/l
X = longitudinal distance, m
t = time, yrs
D = longitudinal dispersion coefficient, m^2/yr
V = groundwater velocity, m/yr
K = sorption coefficient, unitless
λ_d = radioactive decay constant, yr^{-1}

The equation accounts for the major processes which influence nuclide migration in a porous saturated medium. The first term represents dispersion and is analogous to dispersion in many types of systems where the second derivative determines the importance of the process. The second term represents transport by advection, or by bulk fluid movement. The third term accounts for the radioactive decay of the nuclide in transit and shows the rate of destruction of the nuclide to be proportional to the concentration at any point in time and space. The final term represents the accumulation at any point in time and space.

In this equation, for conservatism and simplicity, the effects of lateral dispersion are ignored. It is also assumed that the sorption processes can be represented by the sorption coefficient, K, which indicates the relative speed with which a nuclide migrates with respect to groundwater migration rates. The values of sorption coefficients are nuclide-specific and are presumably also dependent upon soil characteristics. However, because the data base on soils is so limited,[68] the dependence on soil characteristics is ignored and a single set of values employed.

The sorption processes are characterized by the equilibrium sorption coefficient, or time transformation factor[69], K, which is also expressed as a relative velocity, i.e.:

$$K = \frac{V_{water}}{V_{nuclide}} \tag{C.2}$$

Alternatively, K is related to the distribution coefficient (the ratio of the concentration of the nuclide in the soil to the concentration of the nuclide in the water) by the equation

$$K = 1 + \frac{\rho}{\varepsilon} K_d \tag{C.3}$$

where K_d is the distribution coefficient, ρ is the soil density, and ε is soil porosity.

The time of arrival of the contamination front, t_a (yrs), is given approximately by:

$$t_a = \frac{KL}{V_{water}} \tag{C.4}$$

where L is the distance the nuclide travels.

The exponentially decaying boundary condition solution to Equation C.1 is of particular interest since it is believed to represent actual conditions well. First, the source is known to decay exponentially by radioactive decay. Secondly, it is assumed that the source is leached at a rate which is proportional to the amount of the source present at any time. The source inventory is given by:

$$I(t) = I_0 \exp[(\lambda_1 + \lambda_d)t] \tag{C.5}$$

where

I = the activity of the source inventory, pCi
I_0 = the initial activity of the source inventory, pCi
λ_1 = the leach constant, yr^{-1}
λ_d = the radioactive decay constant, yr^{-1}
t_d = time, yr.

With this description of the source inventory, the rate at which activity for a given nuclide is released to the groundwater system is given by

$$\frac{dI}{dt}_{\text{leached}} = \lambda_1 I(t) = \lambda_1 I_0 \exp[-(\lambda_1+\lambda_d)t] \qquad (C.6)$$

This release rate may be divided by an appropriate diluting water flow rate $\dot{m}$ to give the boundary condition, i.e.,

$$C(L=0,t) = \frac{\lambda_1 I_0}{\dot{m}} \exp[-(\lambda_1+\lambda_d)t] = \frac{\lambda_1 I_0}{\dot{m}} \exp[-\lambda_E t] \qquad (C.7)$$

An equivalent decay constant, λ_E, is defined to equal the sum of the leach constant and the radioactive decay constant, both nuclide-specific parameters.

With this boundary condition, the solution to the equations is found to be

$$C(L,T) = \frac{\lambda_1 I_o}{2\dot{m}} \exp\left(\frac{V_1 L_1}{2D} - \lambda_E t - ab\right) \operatorname{erfc}\left(\frac{a-2bt}{2\ t^{1/2}}\right) \qquad (C.8)$$

where

$$a = \sqrt{\frac{K}{D} L_1}, \qquad (C.9)$$

and

$$b = \sqrt{\frac{V_1{}^2}{4DK} - 1} \qquad (C.10)$$

where

L_1 = the length of migration
V_1 = the water velocity

and the other parameters are as defined earlier.

It should be observed that a real solution exists only when

$$\frac{V^2}{4DK} > \lambda_1 \qquad \text{(C.11)}$$

Occasionally, conditions may be specified which violate this requirement. Variations in V, D, or K would remove the difficulty, but only by reducing the magnitude of D is the solution assured to be a realistically conservative one.

Frequently, physical conditions are such that there are two distinct regions in the groundwater path. The first is represented by a vertical migration from the burial site through the foundation material to the aquifer below. Water velocities in this first region are generally considerably lower than in typical aquifers. The second region is the horizontal migration through the relatively long aquifer to the release point. The release may be either to a well or to surface water.

There must be two distinct solutions to the equation, one for each region. Migration through the first region is described by Equation C.8.

It is found from experience that the output from the first region can reasonably be approximated by an equation of the form

$$C_2(x_2=0,t) = A\exp[-a(t-\tau)]-B\exp[-b(t-\tau)] \qquad \text{(C.12)}$$

where,

$t > \tau$
τ = arrival time at the outlet from region 1, yr
A,B,a,b = constants determined by the form of the transient at the outlet from region 1.

Using this as a boundary condition for migration in the second region, the output from the second region is expressed by the equation:

$$C_2(x_2,t_2) = \frac{1}{2}\left\{ A \exp\left[\frac{V_2 x_2}{2D} - a_1(t_2-\tau) - G_2 x_2\right] \operatorname{erfc}\left[\frac{\sqrt{\frac{K}{D}}\, x_2 - 2\sqrt{\frac{D}{K}}\, G_2 t_2}{2 \quad t_2}\right]\right. \qquad \text{(C.13)}$$

$$-B \exp\left[\frac{V_2 x_2}{2D} - b_1(t_2-\tau) - G_3 x_2\right] \operatorname{erfc}\left[\frac{\sqrt{\frac{K}{D}}\, x_2 - 2\sqrt{\frac{D}{K}}\, G_3 t_2}{2 \quad t_2}\right]$$

$$+A \exp\left[\frac{V_2 x_2}{2D} - a_1(t_2-\tau) + G_2 x_2\right] \operatorname{erfc}\left[\frac{\sqrt{\frac{K}{D}}\, x_2 + 2\sqrt{\frac{D}{K}}\, G_2 t_2}{2 \quad t_2}\right]$$

$$\left.-B \exp\left[\frac{V_2 x_2}{} - b_1(t_2-\tau) + G_3 x_2\right] \operatorname{erfc}\left[\frac{\sqrt{\frac{K}{D}}\, x_2 + 2\sqrt{\frac{D}{K}}\, G_3 t_2}{2 \quad t_2}\right]\right\}$$

where

$$a_1 = \sqrt{\frac{K}{D}}\, X_1 \qquad \text{(C.14)}$$

$$b_1 = \sqrt{\frac{{V_1}^2}{4KD} - \lambda_1} \qquad \text{(C.15)}$$

V_2 = water velocity in region 2, m/yr
X_2 = distance in region 2, m
t_2 = time after arrival at inlet to region 2, yr

$$G_2 = \sqrt{\frac{{V_2}^2}{4D^2} - \frac{K(\lambda_1 - a_1)}{D}} \qquad \text{(C.16)}$$

$$G_2 = \sqrt{\frac{{V_2}^2}{4D^2} - \frac{K(\lambda_1 - b_1)}{D}} \qquad \text{(C.17)}$$

It is noted that G_2 and G_3 can be imaginary under certain conditions, as previously noted.

With the radionuclide concentration in the well water determined by Eq C.8 or C.13, the doses that an individual would receive from consuming that water may be estimated using Eq C.18 for each nuclide of interest:

$$R = CUF \qquad \text{(C.18)}$$

where

R = Dose commitment rate (mrem/yr)
C = Radionuclide concentration in well water from Equation C.8 or C.13 (pCi/l)
U = Water consumption factor[27] (l/yr)
F = Dose conversion factors[27] (mrem/pCi)

To estimate the dose rates from consumption of contaminated well water for the various alternatives, the values of the parameters in Eq C.8, C.13 and C.18 must be specified. Table C.2 summarizes the well water parameters and calculations performed for analysis of the disposal alternatives. No well water doses were calculated for the MCDF concepts, because it was assumed that the cavities would not be located near productive aquifers, and that the geologic formations would provide substantial barriers to movement of the radionuclides in the waste. No well water events were postulated for the ocean disposal concepts because of the salinity of the ocean.

For the rest of the alternatives, the following values of parameters were used in the calculations. The diluting volumetric flow rate of water, $\dot{m}$, was taken to be that annually passing underneath a disposal site in a 50 m deep aquifer with 25% porosity at a flow rate of 100 m/yr. Taking the width of a disposal site to be 2800 m gives an annual flow rate of water in the aquifer of $3.6x10^{9}$l/yr. Although aquifers will vary with specific site locations, this value was used for all calculations to provide a consistent basis for intercomparisons of alternatives. As seen in Eqs C.8 and C.13, the effect of variations in the diluting volumetric flow rate is inversely proportional to the resultant concentrations and dose rates.

The velocity of the ground water that leaches the wastes, V_1 is assumed to be 1 m/yr as it travels down to the underlying aquifer for all alternatives. The distance between the wastes and the aquifer, L_1, is assumed to be 10 m for eastern sites, and 20 m for western locations. The aquifer velocity V_2 is 100 m/yr. For the on-site well, the lateral distance from the wastes to the well, L_2, is assumed to be 150 m. (The model described is essentially one-dimensional, with the entire inventory of waste taken to be a point source. Note that the modeling of this pathway depends on the total inventory of the waste, not the average concentration of activity in the waste.) The longitudinal dispersion coefficient D is taken to be 1 m^2/yr. An earlier sensitivity study has shown the effect of variations of D to be small on the magnitude of peak release over the range of properties assumed in this study.[6]

POOR ORIGINAL

TABLE C.2

SUMMARY OF WELL WATER CALCULATIONS (EASTERN SITES)

Nuclide	Initial Inventory (pCi)	Leach Constant (yr^{-1})	Initial Sorption Coefficient	Ingestion Dose Conversion Factors(a) (mrem/pCi)	Base Case SLBF		Improved SLBF and Deeper Burial	SDF
					Time of Peak Release (yr)	Maximum Individual Dose Rate (mrem/yr)	Maximum Individual Dose Rate(c) (mrem/yr)	Maximum Individual Dose Rate(d) (mrem/yr)
^{3}H	6.8×10^{16}	10^{-1}	1	1.05×10^{-7}TB	12	76	76	1.6×10^{-2}
^{14}C	2.3×10^{15}	10^{-4}	10	2.84×10^{-6} B	120	1.2×10^{-1}	1.1×10^{-1}	1.2×10^{-1}
^{51}Cr	4.1×10^{18}	10^{-1}	3300	6.69×10^{-7}GI	3.8×10^{4}	0	0	0
^{54}Mn	2.5×10^{18}	10^{-1}	3300	1.40×10^{-5}GI	3.8×10^{4}	0	0	0
^{55}Fe	2.7×10^{16}	10^{-1}	3300	2.75×10^{-6} B	3.8×10^{4}	0	0	0
^{58}Co	4.1×10^{18}	10^{-1}	3300	1.51×10^{-5}GI	3.8×10^{4}	0	0	0
^{59}Ni	7.4×10^{14}	10^{-1}	3300	6.90×10^{-7}GI*	3.8×10^{4}	7.4	3.9×10^{-1}	7.4
^{60}Co	1.3×10^{19}	10^{-1}	3300	4.02×10^{-5}GI	3.8×10^{4}	0	0	0
^{63}Ni	1.5×10^{17}	10^{-1}	3300	1.30×10^{-4} B	3.8×10^{4}	0	0	0
^{90}Sr	2.7×10^{15}	10^{-2}	100	7.58×10^{-3} B	1.2×10^{3}	4.8×10^{-8}	0	1.3×10^{-9}
^{99}Tc	1.8×10^{13}	10^{-4}	1	6.08×10^{-6}GI*	12	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}
^{125}Sb	3.0×10^{15}	10^{-1}	3200	2.33×10^{-4} L*	3.8×10^{4}	0	0	0
^{129}I	3.6×10^{12}	10^{-1}	1	9.22×10^{-6}TB*	12	6.7×10^{-1}	6.7×10^{-1}	6.7×10^{-1}
^{134}Cs	4.4×10^{18}	10^{-3}	1000	1.48×10^{-4}Li	1.2×10^{4}	0	0	0
^{137}Cs	8.[illegible]$\times10^{18}$	10^{-3}	1000	1.09×10^{-4}Li	1.2×10^{4}	0	0	
^{152}Eu	2.7×10^{13}	10^{-1}	3300	2.56×10^{-5}GI*	3.8×10^{4}	0	0	
^{226}Ra	6.8×10^{13}	10^{-5}	500	3.00×10^{-2} B**	5.8×10^{3}	3.4×10^{-1}	6.3×10^{-11}	3.2×10^{-1}
^{230}Th	4.0×10^{13}	10^{-5}	5.0×10^{4}	2.08×10^{-3} B*	5.8×10^{5}	9.5×10^{-4}	5.6×10^{-24}	9.5×10^{-4}
^{232}Th	4.8×10^{11}	10^{-5}	5.0×10^{4}	1.80×10^{-3} B*	5.8×10^{5}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}
^{235}U	1.8×10^{12}	10^{-5}	1.4×10^{4}	8.02×10^{-4} B*	1.6×10^{5}	2.9×10^{-3}	2.9×10^{-3}	2.9×10^{-3}
^{237}Np	2.6×10^{10}	10^{-5}	100	1.38×10^{-3} B*	1.2×10^{3}	7.1×10^{-5}	2.8×10^{-5}	7.1×10^{-5}
^{238}U	4.0×10^{13}	10^{-5}	1.4×10^{4}	7.67×10^{-4} B*	1.6×10^{5}	6.2×10^{-2}	6.2×10^{-2}	6.2×10^{-2}
^{238}Pu	1.8×10^{14}	10^{-5}	10^{4}	6.73×10^{-4} B*	1.2×10^{5}	0	0	0
^{239}Pu	2.4×10^{13}	10^{-5}	10^{4}	7.60×10^{-4} B*	1.2×10^{5}	1.3×10^{-3}	1.4×10^{-16}	1.3×10^{-3}
^{240}Pu	3.4×10^{13}	10^{-5}	10^{4}	7.58×10^{-4} B*	1.2×10^{5}	2.7×10^{-7}	0	2.7×10^{-7}
^{241}Pu	9.1×10^{15}	10^{-5}	10^{4}	1.56×10^{-5} B*	1.2×10^{5}	0	0	0
^{242}Pu	1.4×10^{11}	10^{-5}	10^{4}	7.22×10^{-4} B*	1.2×10^{5}	1.7×10^{-4}	2.6×10^{-5}	1.7×10^{-4}
^{241}Am	1.7×10^{13}	10^{-5}	10^{4}	8.10×10^{-4} B*	1.2×10^{5}	0	0	0
^{242}Am	1.2×10^{12}	10^{-5}	10^{4}	8.12×10^{-4} B*	1.2×10^{5}	4.0×10^{-8}	0	3.9×10^{-8}
^{243}Cm	3.4×10^{11}	10^{-5}	3300	7.92×10^{-5}GI*	3.8×10^{4}	0	0	0
^{244}Cm	1.1×10^{14}	10^{-5}	3300	4.85×10^{-4} B*	3.8×10^{4}	0	0	0
					Totals(b)	84	77	8.5

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* Indicates Revision.0 of Ref 27. ** Ref 45.

(a) From Ref 27. B=Base, TB=Total Body, GI=Gastrointestinal Tract, L=Lung, Li=Liver

(b) Note that exposures occur at different times.

(c) Based on enhancing sorption coefficients by factor of 10 for all but those which were unity to begin with.

(d) Based on same parameters as base case with 150 years of decay before migration begins.

623299

The value for the water utilization factor U used in the calculations, 370 l/yr, was taken from Ref 27, as were the nuclide specific dose conversion factors F. This utilization factor is the value recommended for 100% of an adult's annual water intake. The nuclide specific leach constants and sorption coefficients used for the base case SLBF concepts were the same as used in a previous study for the NRC.[6] Although changes in these nuclide specific values were made for some alternatives, with consequent changes in the magnitudes of the calculated dose rates, use of values different from those specified would not change the relative order of the effects from disposal at the various alternatives as long as the changes were consistently applied to all cases. The values used represent an estimate of the magnitudes felt to be reasonable, but are not meant to be predictions of values for future applications. As noted, the actual values are extremely site and waste form dependent and should be determined on a case by case basis if a predictive application of this methodology is desired.

For the improved SLBF and deeper burial cases where an enhanced ion-exchange capacity soil layer is assumed at the bottom of each trench, the values of the sorption coefficient were multiplied by 10 to reflect the enhanced effectiveness, except for those nuclides with sorption coefficiencies of unity, whose values would not be affected. For the SDF concepts, it is assumed that the structure will remain intact for the period of institutional control 150 years, at which time migration into groundwater is assumed to begin with the same values for the other parameters as used in the base case.

C.1.3 Waste Container Handling Accidents

In the course of handling the containers of radioactive waste, some may be dropped, their contents become airborne, and subsequently transported off-site by the wind to places where the public may be exposed. It is estimated that one drum in each 10,000 handled may be ruptured and 10^{-3} of its contents become airborne. These estimates are based on experience in stacking drums of waste for interim storage,[52,65] and provide a reasonably conservative release estimation.

It is assumed that a member of the public is located at the site boundary, 160 m from the point of rupture of the container, directly downwind in a 1.6 m/sec wind. For a Pascal F stability class, σ_y = 7m and σ_z = 3.5m. It is assumed that the transport of the airborne materials can be modeled using the standard Gaussian Plume method.

The concentration at the plume centerline for an instantaneous point source is given by:[70]

$$d\chi_t = \frac{Q_t\ (2\pi)^{-3/2}}{\sigma_x \sigma_y \sigma_z} \exp\left[-\frac{(x-\bar{u}t)^2}{2\sigma_x\ 2}\right] \tag{C.19}$$

where

$d\chi_t$ = concentration at time t, Ci/m^3

Q_t = source strength, Ci

σ_i = dispersion coefficients, m

$\bar{u}$ = average wind speed, m/s

x = direction of plume axis (wind)

This equation is integrated and normalized to get the integrated concentration-time exposure:

$$\frac{\chi_t}{Q_t} = \frac{1}{\pi \sigma_y \sigma_z \bar{u}} \tag{C.20}$$

where

χ_t / Q_t = normalized concentration time (sec/m^3)

In order to correct for deposition of dust particles before they arrive at the site boundary, an effective source is calculated:

$$\frac{Q'}{Q} = \left[\exp \int_0^x \frac{dx}{\sigma_z \exp(h^2/2\sigma_z{}^2)}\right] = \sqrt{\frac{2}{\pi}\ \frac{v_d}{u}} \tag{C.21}$$

where

x = distance from source to observation point in wind direction. The ratio Q_{eff}/Q_t at 160 m from the source for the condition given above is 0.3 at 4 cm/sec deposition velocity.[6]

The normalized integrated concentration exposure becomes,

$$\frac{\chi_t}{Q_t} = 2.5 \times 10^{-3}\ \text{sec/m}^3 \tag{C.22}$$

The dose rate to the person at the site boundary can be calculated for each nuclide of interest using Eq C.23:

$$R = C\ V_c\ f_r\ (\chi_t/Q_t)\ U_a\ F_a\ P \tag{C.23}$$

where

R = dose rate to downwind individual, mrem/yr

C = nuclide concentration in waste, pCi/m^3

V_c = volume of vaste container (0.208 m^3)

f_r = fraction of container contents that become airborne (10^{-3})

χ_t/Q_t = normalized integrated concentration exposure from Equation C.22 (2.5×10^{-3} sec/m^3)

U_a = Breathing rate from Ref 27 (3.3×10^{-4} m^3/sec)

F_a = Dose conversion factors for inhalation from Ref 27 (mrem/pCi)

P = Annual frequency of accidents (1.5×10^5 drums/yr $\times 10^{-4}$ accidents/drum = 15 accidents/yr)

These values have been used in analyzing the accidents for all alternatives. For the improved SLBF and deeper burial cases, it was asumed that the air supported weather protection building would be only 25% effective in reducing the downwind exposures, as an outward positive air pressure is maintained to support the building. For the MCDF and SDF concepts, it was assumed that one-half of the handling accidents would occur inside the disposal facility and be contained there. The handling accidents for ocean disposal were assumed to occur at the waste loading port under similar circumstances. The releases are based on handling the lower radiation level fraction of the waste, because the higher level fraction will be handled with more care and control to preclude accidents.

C.2 Long-Term Events

Long-term potential exposure events involve future reclamation activities at the waste disposal site. In all cases, it is assumed that reclamation events occur immediately after institutional control is relinquished. The events considered include inhalation of dust during construction excavations that inadvertently encounter the waste, direct gamma radiation exposure from close contact to the higher radiation level wastes, and consumption of food grown on soil contaminated with the wastes.

C.2.1 Reclaimer Inhalation Event

At some time in the future, people may inadvertently dig into the disposed wastes that are near the surface, perhaps for construction of basements and footings for buildings, or in the case of the SDF, to reuse the structures. It is assumed that an individual may spend up to one-fourth of the work year (500 hours/yr) in close proximity to the wastes. The dust that becomes airborne will be contaminated by the wastes, with appropriate dilution factors to account for the clean materials that may be used to cover and fill in around the waste. The dose rates to an exposed individual can be calculated for each nuclide using Eq C.24:

$$R = \frac{CK}{\rho} U_a \; T \; F \; F_a \; \exp\,(-150\,\lambda\,)$$

where

R = dose rate to individual, mrem/yr

C = nuclide concentration in waste, pCi/m^3

K = dust loading factor in air $(5 \times 10^{-4}\ g/m^3)$[17]

ρ = density of waste material $(1.5 \times 10^6\ g/m^3)$

U_a = breathing rate of exposed individuals from Ref 27 $(0.91\ m^3/hr)$

λ = radioactive decay constant (yr^{-1})

For the reference SLBF base case, the dilution factor f is 0.42 to account for a 50% trench volume utilization during operations plus a 1 m covering. For the improved SLBF case, the factor f is 0.36 because of the additional cover thickness required to accomodate the 1 m thick clay cover. For deeper burial, the MCDF and ocean disposal concepts, no reclamation is postulated. For the SDF, the dilution factor is assumed to be 0.84 because the wastes would not be covered inside the structures. The doses calculated using Eq C.24 for the SLBF case are given in Table C.3. For the improved SLBF and SDF concepts, the total dose rate of 60 mrem/yr is adjusted using the stated dilution factors to arrive at 51 and 120 mrem/yr respectively.

C.2.2 Direct Gamma Radiation

After 150 years the only nuclide of significance for direct gamma radiation is ^{137}Cs. The dose rate from direct contact with the water is about 80 mrem/hr based on the methodology in Refs 56 and 28. For the SLBF case, a dilution factor of 0.42 is

TABLE C.3

DOSES TO RECLAIMER FROM DUST INHALATION

Nuclide	Initial Concentration in Waste (Ci/m^3)	Inhalation Dose Conversion Factors* (mrem/pCi)	SLBF Case Dose to Reclaimer From Inhalation (mrem/yr)
^{3}H	0.12	1.58×10^{-7}TB	2.9×10^{-7}
^{14}C	3.8×10^{-3}	2.27×10^{-6}B	6.0×10^{-4}
^{51}Cr	6.5	1.08×10^{-6}L	0
^{54}Mn	4.0	1.75×10^{-4}L	0
^{55}Fe	4.3×10^{-1}	9.01×10^{-6}L	5.2×10^{-18}
^{58}Co	6.5	1.16×10^{-4}L	0
^{59}Ni	1.3×10^{-3}	8.20×10^{-6}L**	7.6×10^{-4}
^{60}Co	21	7.46×10^{-4}L	3.0×10^{-6}
^{63}Ni	2.4×10^{-1}	5.40×10^{-5}B	3.3×10^{-1}
^{90}Sr	4.8×10^{-3}	1.20×10^{-2} B	1.2×10^{-1}
^{99}Tc	3.2×10^{-5}	1.01×10^{-4}L**	2.3×10^{-4}
^{125}Sb	5.3×10^{-3}	2.75×10^{-4}L**	3.0×10^{-18}
^{129}I	6.4×10^{-6}	6.91×10^{-6}TB**	3.1×10^{-6}
^{134}Cs	7.0	1.06×10^{-4}Li**	6.4×10^{-21}
^{137}Cs	13	7.76×10^{-5}Li	2.3
^{152}Eu	4.8×10^{-5}	3.43×10^{-4}L**	3.9×10^{-7}
^{226}Ra	1.2×10^{-4}	1.25×10^{-1}B**	1.0
^{230}Th	7.1×10^{-5}	2.29 B**	12
^{232}Th	8.4×10^{-7}	1.99 B**	1.2×10^{-1}
^{235}U	3.2×10^{-6}	4.90×10^{-2}L**	1.1×10^{-2}
^{237}Np	4.6×10^{-8}	1.69 B**	5.5×10^{-3}
^{238}U	7.1×10^{-5}	4.58×10^{-2}L**	2.3×10^{-1}
^{238}Pu	3.2×10^{-4}	2.69 B**	19
^{239}Pu	4.3×10^{-5}	3.05 B**	9.3
^{240}Pu	6.7×10^{-5}	3.04 B**	14
^{241}Pu	1.6×10^{-2}	6.05×10^{-2}B**	6.7×10^{-2}
^{242}Pu	2.4×10^{-7}	2.89 B**	4.9×10^{-2}
^{241}Am	3.0×10^{-5}	9.93×10^{-1}B**	1.7
^{243}Am	2.1×10^{-6}	9.94×10^{-1}B**	1.5×10^{-1}
^{243}Cm	6.0×10^{-7}	7.85×10^{-1}B**	8.2×10^{-4}
^{244}Cm	1.9×10^{-4}	5.90×10^{-1}B**	2.4×10^{-2}
		Total	60

* From Ref 27, TB=total body, B=bone, L=lung, Li=Liver,
** From Revision 0 of Ref 27.

used to obtain 34 mrem/hr, and for the improved SLBF case, the dose rate is 29 mrem/hr based on a dilution factor of 0.36. The dilution factor for the SDF, 0.25, gives a dose rate of 68 mrem/yr. It is assumed that a person could spend up to 10 hrs/yr in direct contact with the waste.

C.2.3 Food Pathway

The waste could eventually be carried to the ground surface by reclamation activities. Food products could then be grown on the site, take up contamination, and become a source of exposure to humans who consume the food. Eq C.25 is used to calculate dose rates from the food pathway:

$$R = \frac{CF\ B}{\rho} \left(U_{meat}\ F_f\ Q\ +\ U_{milk}\ F_m\ Q\ +\ U_{veg}\right) f \exp(-150\ \lambda)$$

where

R = dose rate to individual consuming food, mrem/yr

C = nuclide concentration in waste, pCi/m^3

F = ingestion dose conversion factor from Ref 27 (mrem/pCi)

B = nuclide biological uptake factor from Ref 27

ρ = density of waste, kg/m^3

U_{meat} = meat consumption factor from Ref 27 (220 kg/yr)

F_f = transfer fraction for meat from Ref 27 (d/kg)

U_{milk} = milk consumption factor from Ref 27 (310 l/yr)

F_m = nuclide transfer fraction for milk from Ref 27 (d/l)

Q = animal food consumption rate from Ref 27 (50 kg/day)

U_{veg} = vegetable consumption factor from Ref 27 (520 kg/yr)

f = fraction to account for dilution with clean soil, surface plowing, and portion of total diet obtained from site.

λ = radioactive decay constant, yr^{-1}

For the reference SLBF case, the factor f is made up of the dilution of 0.42 times an assumed additional dilution effect from plowing the surface soil of 0.1, and an assumed portion of food consumed from that grown on the site of 0.1. The overall factor is therefore 4.2×10^{-3}. For the improved SLBF the factor is 3.6×10^{-3}. Because of uncertainties in how the wastes from the SDF would be distributed, the factor for this case is assumed to be the same as the base case. The results of the calculations using Eq C.25 for the reference SLBF and SDF cases are summarized in Table C.4. The total dose rate of 620 mrem/yr is adjusted by the appropriate f factor to obtain 530 mrem/yr for the improved SLBF case.

TABLE C.4

DOSE RATES FROM FOOD PATHWAY (REFERENCE SLBF AND SDF)

Nuclide	Dose Rate from Food Pathway (mrem/yr)
^{3}H	2.6×10^{-2}
^{14}C	160
^{51}Cr	0
^{54}Mn	0
^{55}Fe	0
^{58}Co	0
^{59}Ni	3.4×10^{-2}
^{60}Co	4.0×10^{-5}
^{63}Ni	430
^{90}Sr	28
^{99}Tc	3.3×10^{-2}
^{125}Sb	0
^{129}I	2.3×10^{-3}
^{134}Cs	0
^{137}Cs	6.6
^{152}Eu	1.8×10^{-6}
^{226}Ra	2.7
^{230}Th	1.0
^{232}Th	1.0×10^{-2}
^{235}U	1.1×10^{-2}
^{237}Np	1.6×10^{-4}
^{238}U	2.3×10^{-1}
^{238}Pu	3.2×10^{-2}
^{239}Pu	1.3×10^{-2}
^{240}Pu	2.1×10^{-2}
^{241}Pu	1.0×10^{-4}
^{242}Pu	7.1×10^{-5}
^{241}Am	7.7×10^{-3}
^{243}Am	7.0×10^{-4}
^{243}Cm	4.6×10^{-6}
^{244}Cm	1.1×10^{-4}
Totals	620

APPENDIX D

COST ESTIMATE DETAILS

APPENDIX D

COST ESTIMATE DETAILS

The cost estimates generated for this study are based upon unit costs felt to be applicable to low-level waste disposal facilities. These costs are collected and modified by appropriate factors to arrive at total estimated costs. Basically, capital costs for constructing and providing final stabilization for the waste disposal facilities are first estimated. The required engineering effort for the construction is determined by taking 5% of the total capital costs. Additional costs to modify the facilities to accomodate the higher radiation level waste (10% of the waste volume) are estimated to add 23% to the average capital and engineering costs for the 10% volume. The additional costs will provide the extra shielding materials and remote handling equipment needed to accomodate the higher radiation level wastes. Operating costs are estimated by determining the necessary crew size to handle the wastes, and the miscellaneous supplies and material needed. The capital, engineering, higher-radiation level facility and operating costs are subtotaled, and a 30% contingency factor is added to account for uncertainties in the conceptual estimate. A figure representing profit, escalation and financing is then applied to arrive at the total estimated facility costs. Transportation costs are based on shipment of wastes to the generic eastern or western sites, or ocean ports. Transportation and total facility costs are added, and the sum used to determine unit costs for disposal of the 630,000 m^3 of low-level radioactive waste.

D.1 Unit Costs

The unit costs used in the estimates are summarized in Table D.1. These costs are based on quotes and standard engineering references.

D.2 Operating Costs

The operating cost estimate for all alternatives except ocean disposal is based on a work force, including health physics and management personnel, of 10 persons working for 20 years, plus 6 security personnel rotating to give 24-hour coverage for 20 years, plus ongoing surveillance and maintenance for 150 years at $25,000/yr. For the purposes of this study, an average annual direct labor cost including benefits and overhead was taken to be $50,000/person. These figures total $19,750,000 for the life of the facility plus 150 years of surveillance and monitoring. Miscellaneous supplies and materials, including anticontamination clothing, computerized inventory services, and office equipment are estimated to cost an additional $1,880,000

TABLE D.1

UNIT COSTS USED IN ESTIMATES

ITEM	ESTIMATED COSTS	
3" Asphaltic Concrete	$\$ 12.50/\mathrm{ton}$	$\$ 0.23/\mathrm{ft}^2$
Seal Oil	85.00/ton	0.0059/ft^2
Stainless Steel Cover	$1.30/\mathrm{lb} + \$.58$ lin ft field welding	
4" Concrete	9.20/yd^3	0.11.ft^2
Polymeric Cover	5.00/yd^2 installed	
4" Asphaltic Hydraulic Cement	4.20/yd^2 installed	
24" diameter 3/8" wall Standard CS Pipe	33.00/lin ft	
Fabricated Steel	1600/ton	
Excavation with 800' haul	1.52/yd^3 (includes cat, can & crew)	
Excavation with 1 mile haul	2.50/yd^3	
Land for Eastern Burial Site(a)	10k/acre	
Land for Western Burial Site(a)	5k/acre	
Navigation Equipment & Ship Refit(b)	3.65 million for 2 ships	
Site Studies in East(a)	500k	
Site Studies in West(a)	400k	
Site Lisencing(a)	320k	
Environmental Reports on Eastern Burial Site(a)	250k	
Environmental Reports on Wester Burial Site(a)	150k	
Environmental Reports on Eastern SDF Site(a)	750k	
Environmental Reports on Western SDF Site(a)	650k	
Surface Land for MCDF(a)	20k/acre	
Environmental Report on MCDF Site(a)	390k	
Rail Shipping Costs(c)	0.076/ton mile	
Air Supported Building for Improved SLBF(d)	330k	
Air Supported Building for Deeper Burial(d)	550k	
Air Supported Building for SDF(d)	300k	

(Estimates from Richardson Engineering Services, Inc. Handbook and International Construction Analysis except as noted.)

(a) Engineering estimate

(b) Quote from Interstate Electronics Corp., Environmental Engineering Div.

(c) Based on Actual Costs for Transport of Wastes from Rocky Flats, Colorado to INEL (D&RG Western Railroad)

(d) Quote from Irwin Industries

over the facility life. An additional item in the estimate is the emplacement cost, which includes costs for required equipment and materials for handling the waste, such as forklifts, cranes, caterpillers and graders. These costs are the same for all land based concepts except the SDR, where extra materials for stability in stacking the wastes are required.

For the ocean disposal concepts, a price quote of $3,650,000 per year for ships and crew, port charges, maintenance, dock loading and leases was obtained. The ship's capacity would be sufficient to handle the 31,500 m^3 of waste to be disposed of annually. About $940,000 of miscellaneous supplies and materials would also be required.

D.3 Financing, Escalation and Profit

Several factors make estimating financing, escalation and profit requirements difficult. It is recognized that possible government (Federal or State) control of the disposal sites may be established. For that reason, the financial arrangements necessary to pay for the waste disposal costs and long-term monitoring and surveillance are not as straightforward as normal business investments from which an eventual real property value can be recovered. The disposal site may already by owned by the government before disposal operations are implemented, and leased to an operator of the disposal facility. Construction activities obviously could be phased over the 20 year life of the facility to lead disposal operations only by sufficient capacity to prevent backlogs of waste requiring handling from being established. A perpetual care fund could be established to pay for monitoring and surveillance activities, perhaps by a surcharge on each unit volume of waste, or by a tax on disposed wastes.

To provide a consistent cost analysis, the foregoing considerations were accomodated by assuming that all construction would be performed in the first year, and that financing to pay for the total capital costs would be required to be paid back over a ten year period. All operating costs would be escalated at a uniform rate for ten years, and then hold steady. Profit is based on a percentage return on the total capital, operating, financing, and escalation costs. Use of this approach will make the estimate a realistic indicator of potential future costs in view of the uncertainties in financial arrangements and requirements. The costs for monitoring and surveillance for 150 years have been included in the operating cost category for this estimate.

Financing charges on capital expenditures were estimated to be approximately 7% per year for 10 years, or a multiplier of 0.97 times the total capital costs. Escalation on the operating costs was estimated to occur at an average annual inflation rate of 6% for ten years, then hold steady. This generates a multiplier of 0.75 on the total operating costs. Profit was based on a 10% return on the total investment, or a multiplier of 0.1 on the subtotal of all other facility costs. The financing and inflation escalation rate are based on data averaged over the 1967-1976 period from Ref 71. Predictions of inflation are uncertain, and going beyond 10 years does not seem constructive because of the unknowns in the methods of funding. In any case, the effects of additional escalation factors on the total cost comparison for the alternatives will generally be effectively masked by normalizing to the base case SLBF, although the ratio of operating to capital costs is important.

D.4 Transportation

Rail transportation costs are based on shipments of low-level wastes in 55-gallon drums to the INEL from Rocky Flats, a distance of 720 miles. Charges are $0.076/ton mile. This value was used as the basis for transportation costs. For the higher-radiation level wastes, it was assumed that a 4" thick lead shipping cask weighing 78,000 pounds holding 15 drums was used at the given shipping cost. Therefore, 90% of the waste is shipped at an effective rate of $0.076/ton mile and 10% is shipped at an effective rate of $0.62/ton of waste mile, for an overall average shipping rate of $0.13/ton mile. A 20% contingency was added to this value to account for uncertainties in future prices. The cost factor used was therefore $0.153/ton mile. The average transportation distances and charges are summarized in Table D.2.

Cost for shipment by truck was estimated for comparison purposes using Tables 2 and 3 of Ref 15. Based on the rates presented, escalated by the same 20% rate, the truck shipping costs appear to be somewhat less than those used for trains. It is assumed, however, that waste generators will perform analyses based on real disposal sites and available shipping routes. The use of rail shipments for this study provides a consistent means of comparing the alternatives, and is not meant to imply any future requirements or incentives for a specific transportation mode. The estimated truck shipment costs are also given in Table D.2.

The truck shipping estimates take into account the economies of shipping over longer distances. Similar data for rail shipment of low-level waste was not readily available, as train rates are negotiated on a case-by-case basis, and several states are becoming reluctant to allow shipments of radioactive waste in anything except unit trains, which would raise costs.

TABLE D.2

TRANSPORTATION COST ESTIMATES

Miles to Disposal Site (mi)	Ton-Miles of Waste(a)	Estimated Rail Shipping Costs(b) ($Millions)	Estimated Truck Shipping Costs(c) ($Millions)
400	$4.4x10^8$	68	55
600	$6.7x10^8$	102	82
1400	$1.6x10^9$	237	154
1600	$1.8x10^9$	271	140

(a) Based on 630,000 m^3 of waste with average density of 1.6 g/cm^3
(b) Based on $0.153/ton mile as developed in text
(c) Based on Tables 2 and 3 of Ref 15.

APPENDIX E

HISTORY OF OCEAN DUMPING OF RADIOACTIVE WASTES

APPENDIX E

HISTORY OF OCEAN DUMPING OF RADIOACTIVE WASTES

Ocean dumping has been used for the disposal of low-level solid radioactive wastes for over three decades. In 1946, the United States started ocean dumping of low-level radioactive wastes under licensing authority of the Automic Energy Commission. Most of the wastes were dumped between 1946 and 1962. From 1962 to 1970 ocean dumping of radioactive wastes was phased out. The practice was completely stopped in 1971. Ocean dumping of radioactive wastes was conducted at 5 different locations in the Pacific Ocean, 1 location in the Gulf of Mexico and 11 locations in the Atlantic Ocean.[57] However, 3 sites received more than 90% of the 200-liter packages and 95% of the estimated activity dumped. Two of the sites are located in the Atlantic Ocean off the Maryland-Delaware coast, while the other site is located in the Pacific Ocean off San Francisco, near the Farallon Islands. The Farallon Islands site contains two subsites at 900-m and 1700-m depths. A summary of the three principal U.S. dump sites is contained in Table E.1.

Ocean dumping operations were carried out in the Atlantic Ocean by the United Kingdom from 1951 through 1966, representing disposal of approximately 40,000 curies at the time of disposal.[72] In the mid-1960's the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD) began a special study to develop on an international level a safe and economic method for ocean disposal and to demonstrate this by joint disposal operations involving several member countries. This led in the summer of 1967 to the first internationally organized sea disposal operation for solid low-level radioactive wastes.[73] Subsequent to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, the International Atomic Energy Agency (IAEA) prepared a number of requirements governing operational control of sea disposal of radioactive waste, including requirements for the conditioning and packaging of the waste in order to ensure safe transport and handling, and minimization of the risk of accidental recovery of containers after disposal. This is covered by operational measures dealing with the choice of a suitable dumping site, the design and construction of waste containers, the choice of an appropriate ship able to dispose of the waste at a given dumping site, provisions for radiation protection of the crew, adequate record keeping, and adequate supervision of the dumping operations by competent escorting officers.

Factors to be considered in the selection of a site for the dumping of wastes include:

TABLE E.1

PRIMARY U.S. OCEAN DUMP SITES FOR RADIOACTIVE WASTES

Site	Coordinates	Depth (m)	Distance from Land (km)	Years Dumpsite Used	Estimated Number of 55-Gallon Drums Dumped	Estimated Activity in Drums at Time of Packaging (Ci)
Atlantic	38°30'N 72°06'W	2800	190	1951-56 1959-62	14,300	41,400*
Atlantic	37°50'N 70°35'W	3800	320	1957-59	14,500	2,100
Pacific						
Farallon Island (Subsite A)	37°38'N 123°08'W	900	60	1951-53	3,500	1,100
Farallon Island (Subsite B)**	37°37'N	1700	77	1946-50 1954-56	44,000	13,400

* This does not include the pressure vessel of the N/S Seawolf reactor with an estimated induced activity of 33,000 Ci.

** No longitude was listed for Subsite B in Ref 55.

- The chance of recovering the waste by processes such as trawling shall be minimized.

- The area shall have an average depth of at least 4,000 m and be well clear of the continental shelf.

- The area must be free from known undersea cables currently in use.

- Areas where it is known that sea-bed resources will be developed shall be avoided.

- The number of dumping sites shall be strictly limited.

- The area must be suitable for convenient conduct of the dumping operation and, so far as possible, shall be chosen to avoid the risk of collision with other traffic. The area chosen should preferably be one covered by electronic navigational aids.

- The dump site shall be defined by precise coordinates, but to ensure a reasonable degree of operational flexibility it should have an area about 10^4 square kilometers.

The locations of the NEA sea disposal sites for operations conducted from 1967 to 1976 are provided in Table E.2.

Special requirements for the conditioning and packaging of the wastes include:

- The waste in the package shall be either solid, solidified or absorbed in a solid substrate.

- Waste in the liquid form shall be excluded: Small quantities of liquids such as tritiated water may be absorbed on a material of good absorption capacity; containers of such absorbed liquids shall be mounted within a second enclosure of an appropriate design.

- The relevant provisions of the IAEA Transport Regulations shall be complied with, together with any applicable national and international transport regulations. In particular, the packages shall be designed to ensure adequate containment of waste during handling and transport until the end of the dumping operations.

TABLE E.2

LOCATION OF NEA SEA DISPOSAL SITES

Year	Position
1967	A square of 50 km, centered on 42° 30'N, 14° 30'W
1969	A square of 50 nautical miles, centered on 49° 05'N, 17° 05'W
1971-76	A circle of radius 35 nautical miles, centered on 46° 15'N, 17° 25'W (except for 1974, when circle radius was 15 nautical miles)

- The waste packages shall be designed to ensure that their contents are retained during descent to the sea floor. To achieve this, the following requirements shall be met:
  - -- The package shall have an overall specific gravity of not not less than 1.2 to ensure sinking to the sea floor to a depth greater than 4,000 m.
  - -- The design shall be such that any inner container would remain on the sea floor.
  - -- The container shall be made sufficiently strong or pliable to remain intact and retain its contents under the pressure encountered during descent to the sea floor or shall be equipped with a pressure equalization system which relieves the stress on the container.
  - -- Buoyant material shall be excluded unless it is treated or packaged either to preclude the return of such material to surface waters or to ensure that, on its return, it will not constitute a radiation hazard nor interfere materially with fishing, navigation or other legitimate uses of the sea.

Certain special requirements are necessary for ships engaged in the dumping of packaged radioactive wastes. These requirements include:

- The ship shall be capable of safely carrying its consignment to the dumping site.
- The ship shall be provided with the appropriate navigational and communication equipment.
- An adequate supply of dunnage and equipment shall be provided to ensure that containers can be suitably stowed.
- Provisions for hosing and pumping out the holds and bilges shall be available.
- The ship shall be available for inspection by the appropriate national authorities before an approved dumping operation is carried out and thereafter as necessary.

- The dumping operation shall be supervised by approved escorting officers having specific duties, responsibilities, powers, and qualifications. Approved records of the nature and quantities of all wastes permitted to be dumped shall be kept and reported under the rules of the London Convention.

Table E.3 summarizes NEA-supervised operations from 1969 through 1976.

The cost of the international (ship operations) phase of the 1967 operation varied between 6 and 10 pounds sterling ($12 to $20) per ton of waste. The cost of the national phase varied appreciably due to the method chosen for internal transport, the distance involved, the type of container used, etc. Given the experimental nature of the operation, it must be assumed that the costs of the international phase were higher than would apply to future similar operations. The experience gained, plus the fact that the operation was carried out without incident, makes it reasonable to assume that costs would reflect a lower margin for contingencies in any similar operation carried out in the future. Another factor contributing to the increased costs was the fact that the first voyage was loaded at five ports in five different countries. This seriously limited the ship's effective working time.

In 1975 the average cost of the international phase of NEA-supervised sea disposal was about 15 pounds (~$30) per ton of packaged waste. This covered:

- Shipping costs (vessel and port charges)
- Insurance premium
- Unloading operation at sea
- Cost of special navigational equipment

Handling and loading costs at port are not included and may be of the same magnitude as the shipping cost.

Although sea disposal of solid low-level radioactive waste by the United States was terminated in 1971, two major research efforts have continued. One of these deals with environmental surveys of the deep sea disposal sites utilized by the U.S. in the 1940's through 1971. The second major effort in the U.S. has been the research conducted to determine the suitability for the disposal of high-level radioactive wastes beneath the sea-floor, or sea bed disposal as it is commonly referred to.

TABLE E.3

QUANTITIES OF RADIOACTIVE WASTE DUMPED DURING NEA-SUPERVISED SEA DISPOSAL OPERATIONS

Year	Dumped weight (metric tons)	Approximate activity (Ci)	
		Alpha[a]	Beta-gamma[b]
1969	9,180	500	22,000
1971	3,970	630	11,200
1972	4,130	680	21,600
1973	4,350	740	12,600
1974	2,270	420	100,000[c]
1975	4,460	780	60,500[d]
1976	6,770	880	53,500[e]
1977	5,600	950	68,200[f]
Total	40,730	5,580	349,600

[a] Actinides
[b] Including tritium
[c] Almost exclusively tritium
[d] Including about 30,000 Ci of tritium
[e] Including about 21,000 Ci of tritium
[f] Including about 31,900 Ci of tritium

Attempts to survey the Pacific-Farallon sites were made in 1957 and 1960, while the Atlantic site was the subject of a search in 1960.[55] Although over 11,000 underwater photographs were taken during these surveys, no packaged radioactive wastes were identified. In 1974 the U.S. Environmental Protection Agency initiated surveys in both the Atlantic and Pacific Oceans that were successful in locating packages of radioactive wastes.

An unmanned, tethered, surface-controlled vehicle was selected for the 1974 survey at the Farallon Island 900-m subsite and the 1975 Farallon Island 1700-m subsite. This vehicle was called CURV III (Cable-Controlled Underwater Recovery Vehicle). The 2800-m Atlantic dumpsite was surveyed using the manned untethered submersible vehicle named ALVIN.

On all three surveys extensive use of colored photography was made to record the condition of the waste packages.[74] A detailed review of these photos revealed, for example, that many drums exhibited evidence of hydrostatic crushing generally occurring at the mid-section of the barrel. The photos clearly identify the penetration (or lack thereof) of barrels into the sediment. In some instances, the sedimentation rate can be determined from the photographs. The use of photography provides an excellent method of recording the biological abundance and diversity existing at a disposal site. The habits of benthic and demersal fish were readily observable in photographs. One barrel was lifted by the manipulator arm of CURV III to show the limited extent of barrel penetration. The sediment under this barrel exhibited black bands that may indicate anoxic corrosion of that part of the barrel in direct contact with the sediment.

Sampling of the sediment was performed at both Farallon Island sites and the Atlantic site.[75] Radiochemical analysis of sediment samples at the 900-m Farallon site indicate levels of ^{239,240}Pu about one order of magnitude greater than the expected range of values due to fallout. These results may not be totally unexpected considering a report that an estimated 30 curies or long-lived alpha activity was dumped off San Francisco between 1946 and 1953.[76] In one instance the higher ^{239}Pu and ^{239,240}Pu concentrations occurred in the 5 to 10 cm section of the core. This might suggest the possibility that the plutonium release may have occurred many years before, perhaps the result of pressure deformation of the package. Some sediment samples at the 900-m Farallon site showed ^{137}Cs concentrations exceeding average fallout values, but this was not a general situation.

A total of 27 sediment samples were taken at the 2800-m Atlantic site. Three sediment cores indicated the presence of ^{137}Cs contamination varying between 3 to 70 times maximum concentrations expected at this site from fallout. Although there was no evidence of hydrostatic implosion in any packages at this site there was evidence that some containers were breached. Since it was a common practice in the 1950's to occasionally slurry concrete packaging material with low-level radioactive waste liquids, many of which contained ^{137}Cs, it is possible that the higher ^{137}Cs concentrations could have resulted from the continuous leaching from the cement.

Measurements of the ocean current made at the 900-m Farallon site over a 27-day period in 1975 determined a mean velocity of 1.33 cm/sec. Maximum speed recorded for a one-half hour period was 16.5 cm/sec. During tidal periods, flows were east-west at 4 to 8 cm/sec. No direct flow measurements were made at the 2800-m Atlantic site; most packages that were examined were deeply buried in the sediment. The sediment was scoured out along the sides of the package and piled at the ends. Since these packages were in location 15 years, sediment build-up cannot be attributed to direct deposition. A strong current capable of horizontal sediment transport is suggested. Deep currents north and east of this dump site measured 10 to 22 cm/sec, sufficient to erode and transport sediment.

As expected, biological activity at the surveyed sites varies with depth. A wide variety of biological activity was noted at the 900-m Farallon Island site. A demersal food fish, the sable fish, was observed at this disposal, as were deep sea sole. Vase sponge, anemones, flat fish and thorny fish are a few of the species observed in the photographs taken at the 900-m site.

An interesting observation was made my the crew of the ALVIN during the 2800-m Atlantic site. One species of fish, the Nematonurus Armatus was often seen rooting in the seidments adjacent to the waste packages. The continual rooting and feeding action in potentially contaminated sediments could redistribute the radionuclides.

Environmental surveys of these disposal sites are continuing. In 1977, a package was retrieved from the Atlantic site and one was retrieved from the 900-m Farralon Island site in 1978. Both packages are undergoing examination at Brookhaven National Laboratory, Upton, New York.

Although the 1972 London Convention declared that high-level radioactive wastes or other high-level radioactive matter were unsuitable for dumping at sea, a major effort has been undertaken by the United States to expolore the subsea floor as a disposal site for these wastes.[77] This effort, now commonly referred to as the Seabed Disposal Program, must of necessity investigate may of the same scientific and engineering parameters needed to define low-level radioactive disposal sites. Is is logical to assume that sites suitable for sea floor disposal of high-level radioactive wastes will also be suitable for dumping low-level wastes. There also may be other locations suited for dumping low-level wastes; however, it is sufficient to examine the efforts to date in identifying and reviewing those parts of the ocean suited for disposal of high-level radioactive waste.

Basic criteria established at the onset of the Seabed Disposal Program were:[61]

- The area must be geologically stable.
- The disposal site should not seriously interfere with the recovery of resources from the ocean.
- The size of the disposal area should be sufficient to handle all of the wastes of the world for the foreseeable future.
- The area should be as far removed as possible from all activities of mankind.
- Recovery of the waste is not a criterion.
- The area should be outside the direct jurisdiction of any individual nation, i.e., a truly international disposal site.

The oceans were divided into three principal physiographic provinces, each occupying about a third of the planet's ocean area.[58] These are:

- Continental margins (continental shelf, inland seas, marginal plateaus, continental slopes and rises).
- Ocean basin floor (abyssal plains and hills, oceanic rises, deep sea trenches).
- Mid-oceanic ridge (ridge flank and crest, rift valleys and mountains, fracture zones).

Comparing these major provinces using the above criteria, two provinces were found best suited for disposal. In the order of suitability, these are the abyssal hills and the flanks of the mid-oceanic ridges. The provinces that also occur in the midst of the great oceanic gyres (great circular currents) are especially attractive because of their low biological productivity. Thus, the areas in the middle of the tektonic plates and in the middle of the gyres (mid-plates/mid-gyre) are the most promising sites for waste disposal.

The mid-plate/mid-gyre (MPG) regions of the major ocean basins are mong the most stable and unproductive regions of the planet. Four MPG regions have been identified: two in the Pacific Ocean and two in the Atlantic Ocean.

The Seabed Disposal Program chose as its study area the largest MPG region on the planet--located in the central North Pacific about 600 mi north of Hawaii. Program leaders point out that their selection of this region was purely to establish research efforts and does not represent official siting decision.

An 18-month current measurement program in the North Pacific recorded a significant number of zero flow speeds.[58] Typically, tidal currents dominated the records. The magnitudes of the current flows were approximately 2 to 4 cm/sec--values compatible to near bottom measurements at 5300 m in the western North Atlantic.

The existence and characteristics of seidments in the 40,000-km^2 area centered at 31° 30'N and 158°W were determined by the Seabed Disposal Program. The area is more or less evely covered with about 20 to 40 m of unconsolidated sediment. (This condition is ideal for ocean dumping of waste packages.) The rolling abyssal hills (roughly a hundred meters high) have about three-fourths as much sediment cover as the valleys, suggesting some downslope concentration of sediment.

Results of core sampling suggests that the Pleistocene glacial stages increased the rate of sediment supply but did not otherwise affect the abyssal environment in this region. The sediments at the bottom of an 24.4-m core taken in 1976 indicate age-dating of 65 million years.[78]

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NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION
BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-0680

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Evaluation of Alternative Methods for the Disposal of Low-Level Radioactive Wastes

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
Paul Macbeth and others

5. DATE REPORT COMPLETED

MONTH	YEAR
May	1979

DATE REPORT ISSUED

MONTH	YEAR
July	1979

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Ford, Bacon & Davis, Utah, Inc.
375 Chipeta Way
P.O. Box 8009
Salt Lake City, Utah 84108

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Waste Management
Office of Nuclear Material Safety and Safeguards
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
NRC-02-77-168

13. TYPE OF REPORT

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

A comparative analysis of the most viable alternatives for disposal of solid low-level radioactive wastes is presented to aid in evaluating national waste management options. Four basic alternative methods are analyzed and compared to the present practice of shallow land burial. These include deeper burial, disposal in mined cavities, disposal in engineered structures, and disposal in the oceans. Some variations in the basic methods are also presented. Technical, socio-political, and economic factors are assigned relative importances (weights) and evaluated for the various alternatives. Based on disposal of a constant volume of waste with given nuclear characteristics, the most desirable alternatives to shallow land burial in descending order of desirability appear to be: improving present practices, deeper burial, use of acceptable abandoned mines, new mines, ocean dumping, and structural disposal concepts. It must be emphasized that the evaluations reported here are generic, and use of otherweights or different values for specific sites could change the conclusions and ordering of alternatives determined in this study. Impacts and costs associated with transportation over long distances predominate over differences among alternatives, indicating the desirability of establishing regional waste disposal locations. The impacts presented are for generic comparisons among alternatives, and are not intended to be predictive of the performance of any actual waste disposal facility.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

623333

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
Unlimited

19. SECURITY CLASS *(This report)*

20. SECURITY CLASS *(This page)*

21. NO. OF PAGES

22. PRICE
$

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

POSTAGE AND FEES PAID
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