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Nevada Nuclear Waste Storage Investigations Project

A Comparative Study of Radioactive Waste Emplacement Configurations

H. F. Gram, L. W. Scully, R. I. Brasier, M. L. Wheeler

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
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A COMPARATIVE STUDY OF RADIOACTIVE WASTE EMPLACEMENT CONFIGURATIONS

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ABSTRACT

This study is an evaluation of the self-shielded package and the vertical and horizontal waste emplacement methods. The study suggests a preferred emplacement configuration and identifies the configuration's engineering problems requiring resolution. This study was conducted before September 1983 and used data and assumptions appropriate to that time. Subsequent data may change some results and conclusions in the future. The selection of a preferred waste emplacement method is based on estimates of dependability, safety, and cost effectiveness. The factors evaluated according to these characteristics are the waste package design, analysis of thermal and structural conditions within the repository, emplacement and retrieval operations, repository mining and ventilation, and sealing of the repository. This study indicates that each waste emplacement method has strong points when compared to the others. The three methods differ primarily because of the length and volume of the drifts, heat flow from the waste into open ventilated drifts, the time required for waste emplacement or retrieval, and the extent to which available technology can be applied to the mining and repository operation. Based on this analysis, horizontal emplacement is the preferred method because it requires the least mining, has the lowest ventilation requirements during emplacement and retrieval, and requires the least time for waste emplacement. There are uncertainties associated with horizontal borehole drilling and with the emplacement and retrieval of canisters. Prototype equipment for horizontal drilling, for lining the borehole, and for emplacing and retrieving the waste packages should be developed and tested to resolve these uncertainties.

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EXECUTIVE SUMMARY

The Nevada Nuclear Waste Storage Investigations project is conducting detailed studies of the Nevada Test Site in southern Nevada to determine whether a technically acceptable site exists there for a commercial nuclear waste repository. A major factor affecting repository design is the method used for waste emplacement. This study evaluates three waste emplacement methods, suggests a preferred emplacement configuration, and identifies the associated engineering problems requiring resolution.

Three waste emplacement methods were evaluated:

- the self-shielded package (SSP),
- vertical emplacement in the drift floor, and
- horizontal emplacement in the drift walls.

Each emplacement method results in significantly different drift layouts and dimensions. The primary objective of this comparison is to identify a waste emplacement method that will be the most dependable, safest, and cost effective.

The study is a relative comparison based on the characteristics of consolidated spent fuel. The thermal output of consolidated spent fuel exceeds the thermal output of other types of waste and thus provides a conservative basis for selecting a waste emplacement method. The factors or aspects contributing to the selection of a waste emplacement method examined and evaluated in this report are

- the waste package design,
- analyses of thermal and structural conditions within the repository,
- emplacement and retrieval operations,
- repository mining and ventilation, and
- sealing of the repository.

The evaluation is based on a systematic assessment of these factors against seven criteria:

- reliability,
- flexibility,
- worker hazards,
- environmental impact,
- resource commitments,
- scheduling, and
- cost.

The evaluation indicated that each waste emplacement method has strong points as compared to the others. The three methods differ primarily because of four conditions: (1) the length and volume of the drift required; (2) heat flow from the waste into ventilated drifts; (3) the time required for waste emplacement or retrieval; and (4) the extent to which available technology can be applied to the mining and repository operation. These conditions directly or indirectly contribute to worker hazards, environmental impact, resource commitments, and the cost of construction and operation.

The evaluation of the SSP, vertical, and horizontal methods, indicates that the SSP concept is the least advantageous for emplacement of spent fuel and does not warrant further development. The potential for worker injuries and fatalities is highest for this

method, and the potential radiation exposure of workers exceeds that for the horizontal emplacement method. Costs of the SSP are the highest, primarily because of material requirements for the waste package. The mining requirements, ventilation requirements, and potential operational problems associated with the presence of the waste package in the emplacement drift also contribute significantly to this cost. The SSP concept may, however, prove to be adequate for wastes with low levels of radiation and thermal output.

Vertical emplacement offers no distinct advantages over horizontal emplacement other than the fact that it is a currently accepted technology; however, it appears to be superior to the SSP. Information regarding techniques and equipment appears to be sufficient for the purpose of evaluating the vertical emplacement method, and no significant additional design effort is warranted until comparable information regarding horizontal emplacement has been developed.

The placement of waste in horizontal boreholes appears to be the most attractive method. The advantages of horizontal emplacement result from the significantly smaller volume of mining required; better use of the rock to distribute waste heat, which results in lower ventilation requirements during waste emplacement and retrieval; and the shorter period of time (per waste package) required for waste emplacement. Horizontal emplacement has the lowest potential for worker injuries, fatalities, radiation exposure, and environmental impact, and would require the fewest resource commitments. It is the least expensive of the three emplacement methods evaluated.

However, there are significant unknowns that need to be addressed before horizontal emplacement can be shown to be the most reliable method for radioactive waste disposal. These uncertainties are associated with the drilling and lining of horizontal boreholes and with emplacement and retrieval of waste canisters. Initial evaluation of concepts suggests that equipment can be built to resolve these uncertainties, but final approval of horizontal emplacement as the preferred method requires the fabrication and demonstration of this equipment. Therefore, it is recommended that emphasis be placed on developing the necessary prototype equipment to demonstrate the viability of horizontal emplacement.

GLOSSARY

Access Drift	A drift in the repository that connects the parallel emplacement drifts. Access drifts serve as passageways for waste transporters and are used as haulageways for muck, materials, and equipment.
Backfill	Backfill is the loose material used to refill an excavation with no specific intent that a tight bond be formed with the perimeter of the excavation.
Barrier	A barrier is an isolated barricade that forms a tight bond with the perimeter of the drift; is intended to be resistant to penetration by water, air, or other gas movement; and could limit the quantity of waste that would be affected by inadvertent, unauthorized intrusion.
Canister	As used in this document, a steel container for solid radioactive waste. A canister provides physical containment but no shielding against penetrating gamma radiation. During transfer from work station to work station, shielding is provided by a cask in which the canister is placed.
Conceptual Design	Defined as that design which thoroughly establishes the scope of the project and provides a basis for a reliable budget estimate. The types of construction, utilities, power, services, equipment, shielding, processes, instrument requirements, and space allocations are all established.
Design Criteria	Rules, regulations, codes, standards, and design-dependent constraints that govern the design of the repository. These criteria have been developed to ensure that facility design, construction, and performance objectives will be met.
Drift	Horizontal, or nearly horizontal, mined passageway. In this document, the term "access drift" is used to describe the tunnels that provide access to the emplacement drifts.
Emplacement Drift	Drift in which radioactive waste packages are disposed in either horizontal or vertical boreholes.
Ground Support (or Control)	Methods by which underground openings are supported to provide long-term stability; e.g., rockbolts, steel sets, shotcrete.
Groundwater	Water that exists or flows within a zone of saturation beneath the land surface.
Horizon	A particular level, or subdivision, of a geologic medium.
Hot Cell	A heavily shielded containment structure, usually constructed of concrete and equipped to permit remote viewing and handling of highly radioactive material. It is used during the removal of waste from the shipping cask, repackaging, and transferring the waste to the waste transporter.
Muck	Ore or rock broken and removed during excavation operations.

Nevada Test Site (NTS)	An area of 3,367 km^2 in Clark and Nye counties in southern Nevada dedicated to DOE programs.
Plug	A combination of materials used to close off a shaft, drift, or borehole; these materials may include crushed tuff, sand, grout, or concrete.
Radiation	Particles and electromagnetic energy emitted by nuclear transformation that are capable of producing ions when interacting with matter; gamma rays and alpha and beta particles are primary examples.
Ramp	An inclined opening that leads from the surface to the underground facility. Ramp access is planned for waste emplacement activities.
Repository	Any system licensed by the NRC that is intended to be used for the permanent deep geologic disposal of high-level radioactive waste and spent nuclear fuel, whether or not the system is designed to permit the recovery, for a limited period during initial operation, of any materials placed in the system. This term includes both surface and subsurface areas in which waste-handling activities are conducted.
Rockbolting	A method for stabilizing underground openings by anchoring and tensioning steel bolts in holes drilled specifically for the purpose. Wire mesh anchored to the rock bolts may be used to prevent small pieces of rock from falling into the underground openings.
Sealing	Those activities associated with the permanent closure of the underground facility, shafts, ramps, and boreholes. Materials used in sealing may include crushed tuff, grout, and concrete.
Shaft	A vertical excavation, commonly made from the surface. Compared to its depth, it has a small cross-sectional area. A shaft may be used for lowering and hoisting men and materials, for draining water, or for ventilation.
Spent Fuel (Nuclear)	Fuel that has been withdrawn from a nuclear reactor following irradiation.
Tuff	Rock formed of compacted volcanic particles, usually no larger than 4 mm in diameter.
Ventilation Drift	A mined drift used exclusively as a conduit for ventilation air.
Waste	Radioactive material emplaced in the repository for disposal.
Waste Package	A waste package consisting of the waste canister and any packing, liners, or overpack material designed to enhance performance of the overall waste package.
Water Table	The upper surface of the zone of water saturation at which the pressure is equal to atmospheric pressure; the upper surface of an unconfined aquifer.

ABBREVIATIONS AND ACRONYMS

BWR	Boiling water reactor
CHLW	Commercial high-level waste
DHLW	Defense high-level waste
DOE	Department of Energy
MTHM	Metric tons of heavy metal
NNWSI	Nevada Nuclear Waste Storage Investigations
NRC	Nuclear Regulatory Commission
NTS	Nevada Test Site
PWR	Pressurized water reactor
SNL	Sandia National Laboratories
SSP	Self-shielded package
TRU	Transuranic
USGS	U.S. Geological Survey
WBGT	Wet bulb global temperature

1.0 INTRODUCTION

1.1 Purpose and Justification

The work described in this report was performed for Sandia National Laboratories (SNL) as a part of the Nevada Nuclear Waste Storage Investigations (NNWSI) project. SNL is one of the principal organizations participating in the project, which is managed by the U.S. Department of Energy's (DOE) Nevada Operations Office. The project is a part of the DOE's program to safely dispose of the radioactive waste from nuclear power plants.

The DOE has determined that the safest and most feasible method to dispose of such wastes is to emplace them in mined geologic repositories. The NNWSI project is conducting detailed studies of an area on and near the Nevada Test Site (NTS) in southern Nevada to determine the feasibility of developing a repository.

The target horizon for the prospective underground repository facilities at NTS is the Topopah Spring Member of the Paintbrush Tuff located at Yucca Mountain, Nevada. The repository will be located in a welded portion of the tuff unit approximately 200 to 400 m below the surface. The water table is more than 100 m below the potential repository level.

The Yucca Mountain waste disposal system is divided into three subsystems, as follows:

- waste package,
- repository, and
- site.

The selection of an emplacement configuration must consider the impact of the configuration on repository operations and pre- and postclosure waste containment and isolation. The evaluation of the impact on postclosure containment and isolation is beyond the scope of this report. No work has been done yet to assess the impact of configuration on preclosure waste package performance. Analytical studies performed to date indicate that the emplacement configuration will not affect preclosure site performance (Johnstone and Peters, 1984).

The engineering design of the repository will integrate the selected emplacement configuration with operational requirements, site characteristics, and the constraints imposed by the waste form and package to minimize adverse impacts on performance. However, the potential impact of any emplacement configuration on the postclosure performance of the three subsystems must be addressed before a final configuration is chosen. This study compares three emplacement configurations from the perspective of preclosure repository operations, suggests a preferred configuration, and identifies the configuration's engineering problems that require resolution.

The waste emplacement configurations being considered are

- the self-shielded package (SSP), which consists of cylindrical, self-shielded canisters, placed at uniform intervals on the floor of the drift;

- vertical emplacement of single canisters in unlined boreholes drilled in the drift floor; and

- horizontal emplacement of many canisters in long lined horizontal boreholes drilled in the drift walls.

The elements of repository design that differ, as a function of the emplacement configuration, are

- waste package characteristics;
- quantity and distribution of heat deposited by the waste in the host rock and the influence of this heat on the design and operation of the repository;
- repository excavation, construction, and stability; and
- characteristics of the waste handling, emplacement, and retrieval equipment.

This study systematically evaluates the repository design features associated with each emplacement configuration to establish its relative advantages and disadvantages. The repository design characteristics are subdivided into a set of evaluation factors by which repository subsystem performance may be evaluated. The criteria used to measure repository performance are reliability, flexibility, worker hazards, environmental impact, resource commitments, scheduling, and cost. The work reported here relies extensively on the results of other studies conducted by NNWSI project participants in support of repository development.

Conceptual design assessments indicate that the SSP could be more costly in meeting Nuclear Regulatory Commission (NRC) requirements (CFR, 1984b) than alternative waste packages (Rothman, 1982), and it has been recommended that the concept not be developed further (Scully, 1982). The reasons for discontinuing development of the SSP are presented in Appendix A.1. Because of the decision to discontinue development of the SSP, the data required to compare the technical differences and costs of the SSP with those of vertical and horizontal emplacement are not complete. The available data have been used to make specific comparisons among the three emplacement configurations.

Preliminary evaluations made prior to this study, based on an average thermal loading of 50 kW/acre, indicate that horizontal emplacement may have at least two advantages over the other configurations: (1) the temperature of unventilated emplacement drifts in the horizontal configuration remains below 50°C for the expected operational period (50 yr) of the repository, whereas the temperature of unventilated drifts for the SSP and vertical emplacement configurations exceeds 50°C within 2 or 6 yr, respectively; and (2) horizontal emplacement requires much less mining and drilling because the drifts for vertical emplacement holes are replaced, conceptually, by the smaller horizontal boreholes.

1.2 Basis for the Study

The recommendation of a waste emplacement configuration is based on a systems engineering assessment of factors and criteria that affect repository design and on conservative estimates of repository characteristics. The analyses and evaluations reported in this document were performed between October 1982 and September 1983. They are based on data and information available then and may not, therefore, accurately represent current knowledge and status of the NNWSI project. However, the study attempts to place upper and lower limits on the relative merits of the potential emplacement methods. Consequently, many of the conclusions will remain valid as new data are obtained.

The study focuses on major differences among the possible emplacement methods, including unknown effects that should be addressed in future studies. Therefore, not all combinations of factors and criteria affecting design have been analyzed. This approach provides a thorough yet concise investigation of potential consequences.

This is a relative study in which one configuration is compared to another and not one in which total repository costs, for example, are developed. Moreover, not all types of waste the repository would receive have been investigated. Instead, supporting data used are based on a canister of spent fuel that has a 3.4-kW thermal output at the time of emplacement. The thermal output of spent fuel exceeds the thermal output of other waste types and thus provides a conservative basis for selecting a waste emplacement configuration.

Using spent fuel as a basis for the selection of a waste emplacement configuration is considered applicable because it is similar to commercial high-level waste (CHLW) in thermal output. Together, these wastes represent the greater fraction of the remote-handled waste that the repository is being designed to accommodate The other waste types emit much less heat than either spent fuel or CHLW. Emplacement configurations for these cooler waste types will be determined independently and are not included in this study.

The average thermal loading for the repository area is assumed to be 50 kW/acre. Localized thermal loadings in the emplacement areas may exceed this value but are offset by underground areas where no waste is emplaced. Though the parametric study to fully justify this thermal loading has not yet been completed, initial studies have shown this figure to be reasonable (Johnstone and Peters, 1984), and no major deviations from it are expected.

Drift dimensions and emplacement configurations that are both typical and representative of a potential repository design were assumed in order to perform the required analyses. As the conceptual design has developed, there have been some modifications of initial assumptions. An engineering analysis was performed for each change to ensure that results based on the assumptions were not compromised. For example, the thermal/structural calculations were based on horizontal boreholes that extended between drifts, whereas current repository layouts are based on blind boreholes. An analysis indicated that the change in configuration should not affect the temperature field or the resulting thermal stress surrounding the boreholes and access drifts (Sisson, 1982; Peters, 1983).

The repository performance criteria for waste retrievability influence assumptions regarding drift ventilation requirements and the placement of drift backfill. Information available as of September 1983 does not suggest a viable method of removing emplaced backfill (should waste retrieval be required) at drift temperatures higher than 50 to 60°C. Thermal analyses indicate that these higher temperatures would be reached for the SSP and vertical emplacement configurations. Therefore, it is assumed that access and emplacement drifts will remain open and ventilated until repository decommissioning. This assumption dictates that if drift backfill is required, it will be emplaced at the time of repository closure.

2.0 DESCRIPTION OF ALTERNATIVES

The emplacement configurations considered in this study are the SSP, vertical emplacement, and horizontal emplacement. Preliminary emplacement configuration dimensions are given in Table 1. The canister spacing for each option was selected to limit the average thermal loading of the repository to 50 kw/acre. This results in a localized thermal loading of approximately 15 W/m^2. The thermal power output was assumed to decay in the manner of 10-yr-old spent fuel.

2.1 Self-Shielded Package

The SSP configuration, shown in Figure 1, consists of cylindrical, self-shielded canisters placed on the emplacement drift floor at 9-m intervals. This spacing accommodates 50 SSPs of spent fuel in a 465-m-long drift. A generic SSP is illustrated in Figure 2 and described in detail in a report by Westinghouse (1982). A summary description of the SSP is provided in Appendix A.1. A preliminary repository layout for emplacement of SSPs in tuff is shown in Figure 3.

2.2 Vertical Emplacement

The vertical emplacement of waste canisters in drilled boreholes is shown in Figure 4. In this configuration, cylindrical canisters are placed in 7.6-m-deep vertical boreholes evenly spaced along the emplacement drift floor at 9-m intervals. Each borehole contains a single canister and is capped with an isolation plug in the top 3 m. This plug, between the canister and the emplacement drift floor, acts as a thermal buffer and radiation shield. Fifty canisters of spent fuel can be emplaced in a 465-m-long drift. A preliminary repository configuration for vertical emplacement in tuff is shown in Figure 3.

2.3 Horizontal Emplacement

The horizontal emplacement of waste canisters is shown in Figure 5. In this configuration, cylindrical canisters are placed end to end in blind horizontal boreholes drilled into rock pillars from either side of the emplacement drift. The borehole is closed by a shield plug adjacent to the last canister of waste and sealed by a second plug at the drift wall. A 24-m space between the last waste package and the emplacement drift wall acts as a thermal buffer zone. Preliminary data indicate that 34 canisters with a heat generation rate of 3.4 kW/canister can be emplaced in each 200-m horizontal borehole. A preliminary repository configuration for horizontal emplacement in tuff is shown in Figure 6.

Conceptual design studies performed during the writing of this report indicate that the emplacement drifts will have to be wider at the site of each borehole to provide space for the waste transporter to maneuver into position to emplace the canisters. The dimensions of these alcoves are 6 m wide, 6 m deep and 3.7 m high.

TABLE 1

Emplacement Method	Access Drift (m)		Emplacement Drift (m)		Borehole Length (m)	Borehole Diameter (m)	Length of Emplacement Drift (m)	Center-to-Center Spacing of Emplacement Drifts (m)	Distance Between Boreholes (m)
	Height	Width	Height	Width					
SSP	3.7	6.0	3.7	6.0	NA[b]	NA	465	24.0	9[c]
Vertical	3.7	6.0	6.7	6.0	7.6	0.7	465	24.0	9
Horizontal	3.7	6.0	3.7	6.0	200	0.8	480	414	48

a Based on BWR spent fuel (3.4 kW/canister) (Lynch, 1983).

b NA = Not applicable.

c Distance between SSPs.

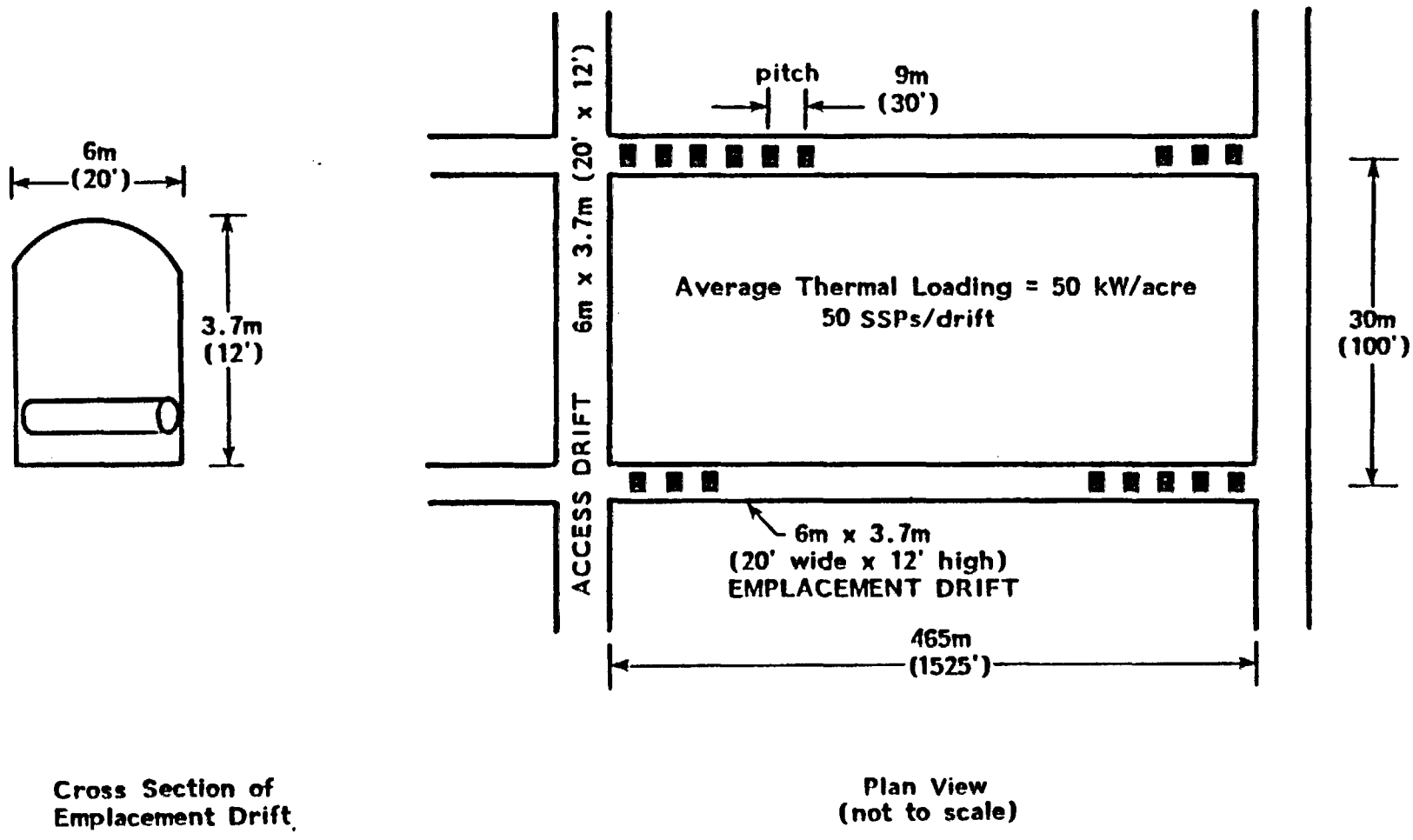


Figure 1. Typical Configuration for Self-Shielded Packages

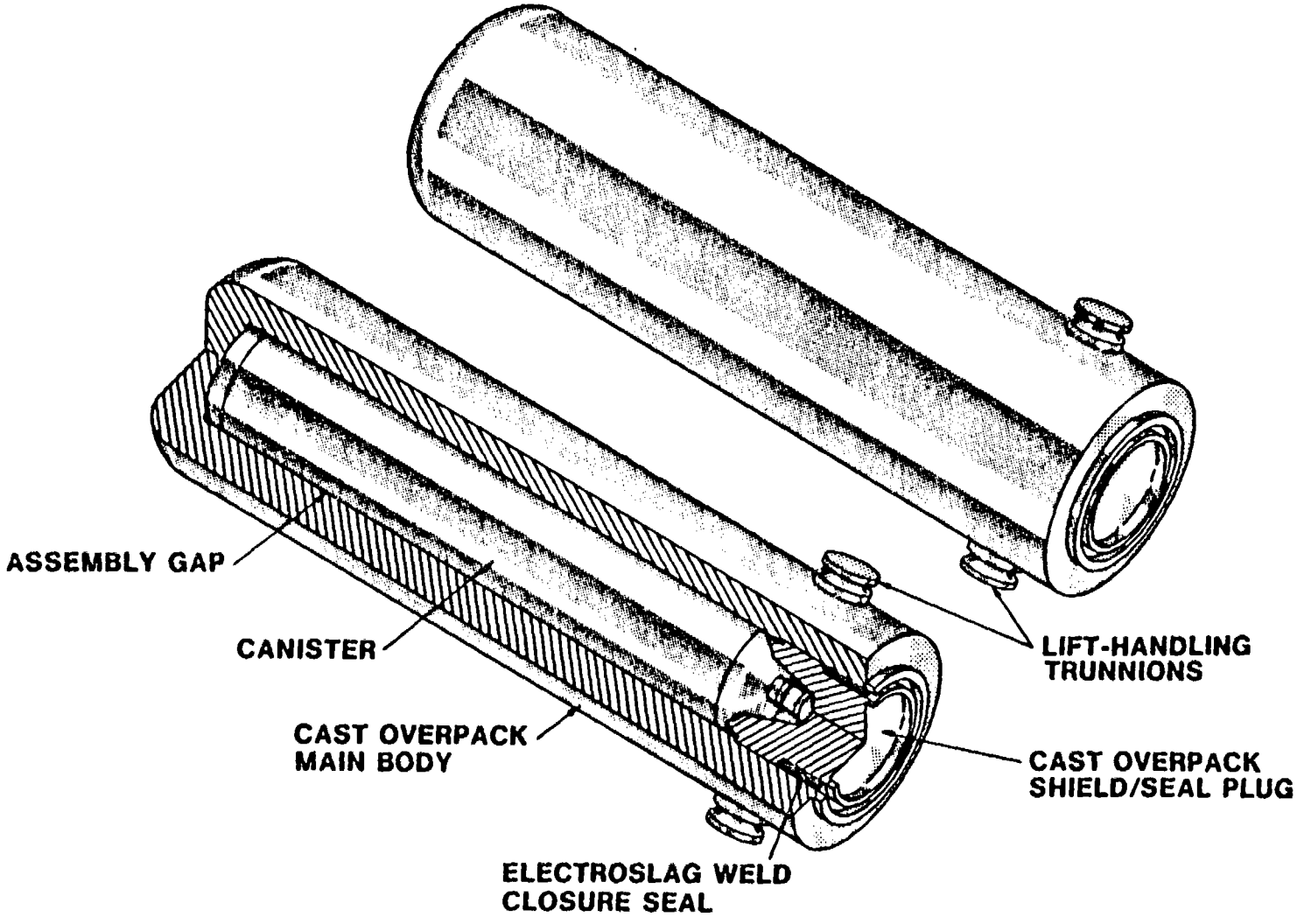
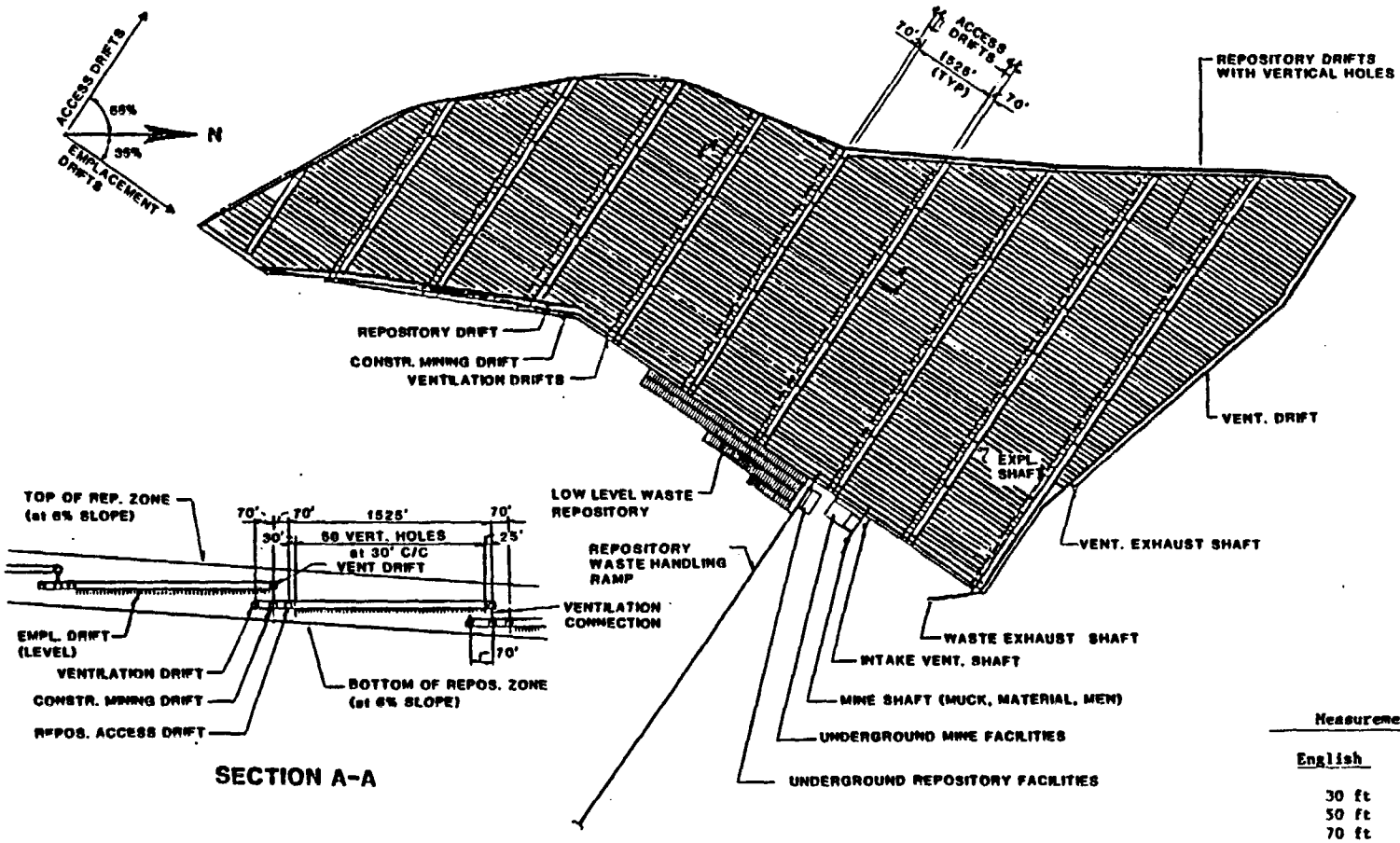


Figure 2. Generic Self-Shielded Package



Measurement Equivalents

English	Metric
30 ft	9.2 m
50 ft	15.2 m
70 ft	21.3 m
525 ft	160.0 m
1,525 ft	464.8 m

Figure 3. Preliminary Repository Layout for Self-Shielded Packages and Vertical Emplacement of 3.4-kW Canisters

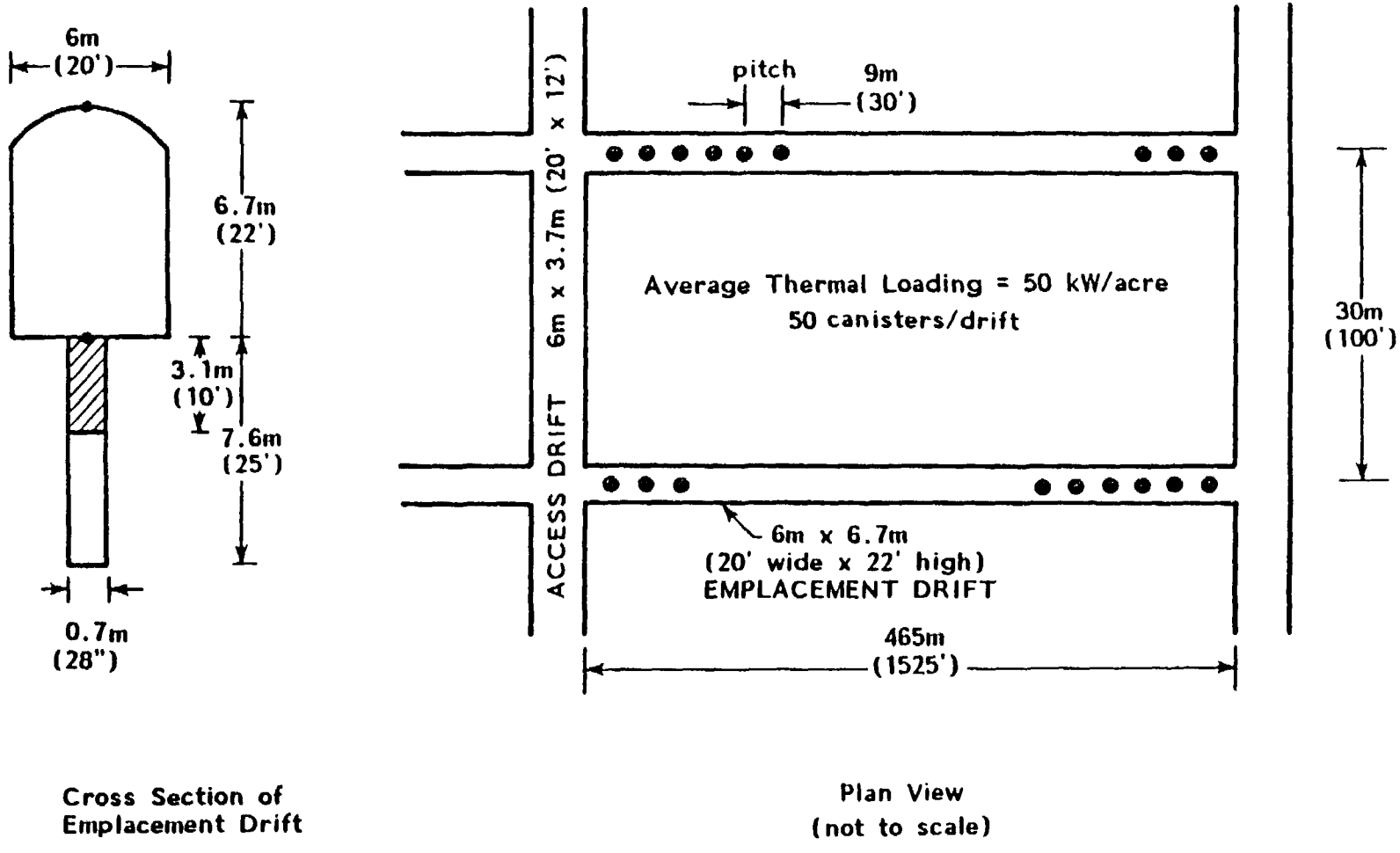


Figure 4. Typical Configuration for Vertical Emplacement of 3.4-kW Canisters

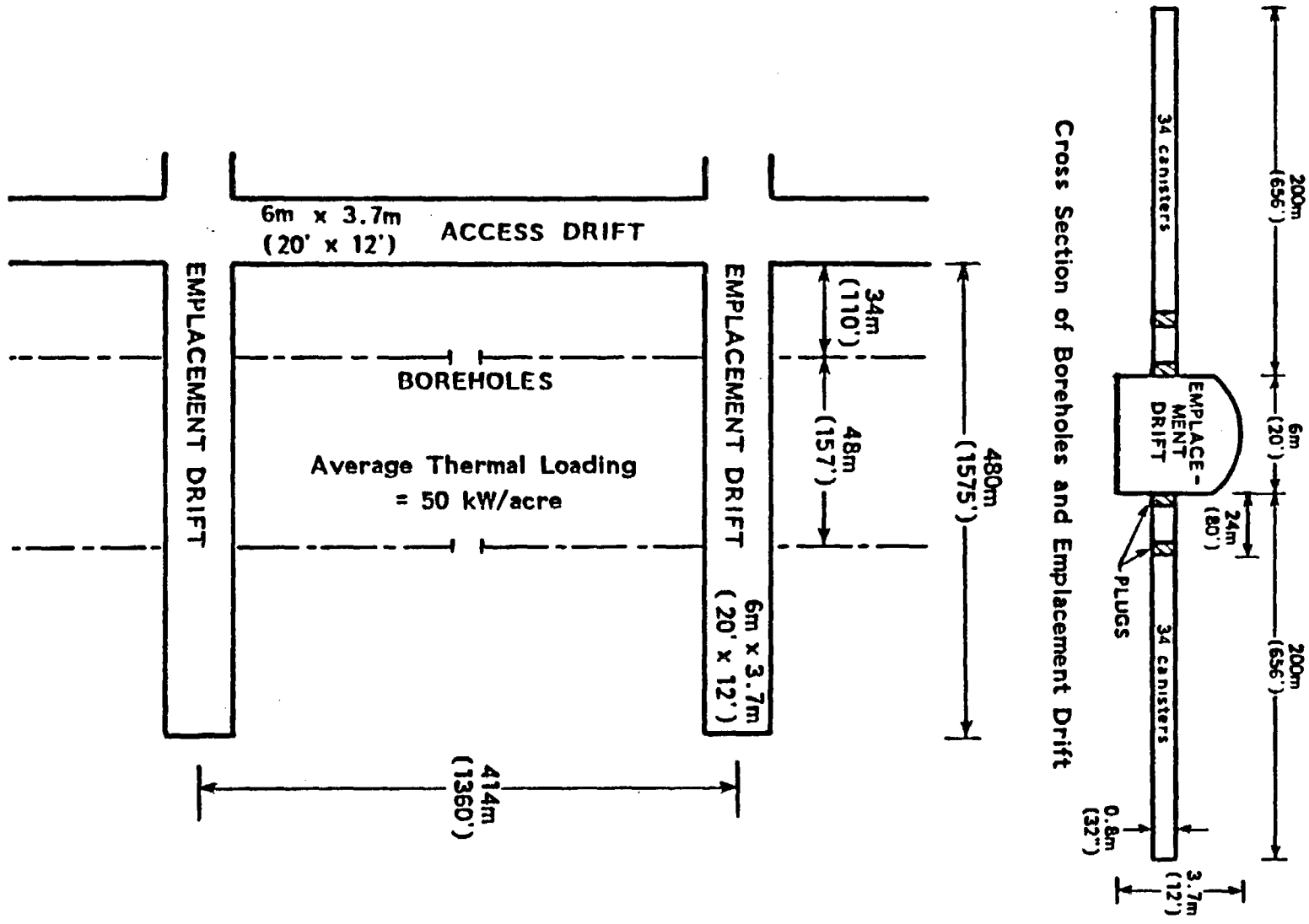
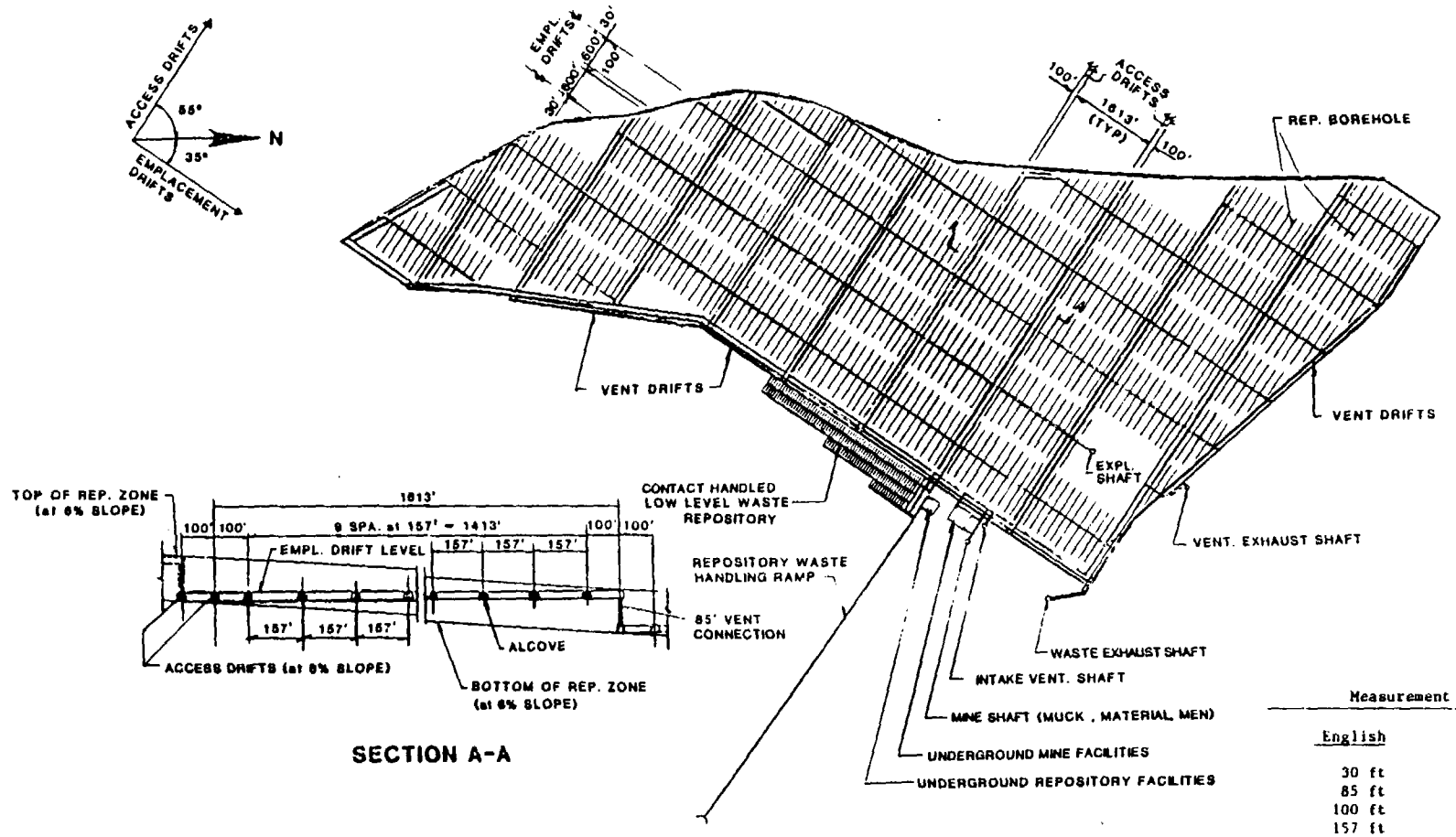


Figure 5. Typical Configuration for Horizontal Emplacement of 3.4-kW Canisters



Measurement Equivalents

English	Metric
30 ft	9.1 m
85 ft	25.9 m
100 ft	30.5 m
157 ft	47.9 m
600 ft	182.9 m
1,413 ft	430.7 m
1,613 ft	491.6 m

Figure 6. Preliminary Repository Layout for Horizontal Emplacement of 3.4-kW Canisters

3.0 FACTORS TO BE EVALUATED

Factors that must be considered in the evaluation of an emplacement configuration can be categorized as follows:

- waste package design,
- thermal/structural analyses,
- repository mining and ventilation,
- emplacement and retrieval operations, and
- sealing procedures and timing.

The categories have been further subdivided to compare the major differences between the emplacement alternatives. These evaluation factors, as used in this study, are discussed in the following subsections. Only the aspects of each evaluation factor which differ significantly among the three configurations were included in the analysis.

3.1 Waste Package Design

The primary function of a waste package is to provide containment and to contribute to the isolation of radionuclides from the accessible environment in conformance with federal regulations 10 CFR 60 (CFR, 1984b) and draft 40 CFR 191 (CFR, 1984a). The waste package formally consists of the waste canister and any packing, liners, or overpack material designed to enhance performance of the overall waste package (CFR, 1984b).

The SSP design consists of a waste canister surrounded by sufficient shielding to reduce the radiation level at the surface to 100 mrem/hr or less. Reference designs for vertical and horizontal emplacement in tuff consist of waste canisters placed in holes without packing material. Horizontal emplacement would utilize a borehole liner to facilitate emplacement and retrieval, should retrieval be necessary. Both horizontal and vertical emplacement configurations utilize borehole plugs to limit radiation levels in the emplacement drifts. Thus, for this comparison, the "waste package" includes the waste canister, the shielded overpack for the SSP, and the plugs and/or borehole liner required for horizontal and vertical emplacement. The major differences among the three reference waste packages can be grouped under items pertaining to their fabrication and material requirements. Specific descriptions of the waste package designs are given in Appendix A.1.

3.2 Thermal/Structural Analyses

The generation of heat within the waste canister, through radioactive decay, imposes a significant thermal load on the repository horizon and adjacent rock systems. Engineering analyses of the thermal and structural effects of this thermal load on repository performance were performed for each emplacement configuration. They evaluate

- the temperature of the waste canister,
- temperature distributions in the host rock surrounding ventilated and unventilated drifts,
- temperatures of unventilated drifts,
- thermally driven moisture flow around and into open drifts,

- effects of elevated temperatures on the structural stability of open drifts, and

- heat flow into ventilated drifts.

Results of these analyses, as used in this evaluation, are presented in Appendix A.2.

3.3 Repository Mining and Ventilation

The most important factors associated with repository development that are influenced by the choice of a waste emplacement method are mining and ventilation requirements. These factors are detailed in Appendix A.3. Preliminary estimates of mining, drilling, and ventilation requirements are shown in Table 24. Mining requirements include excavation of access and emplacement drifts for all three configurations, the drilling of boreholes for vertical and horizontal emplacement, and placement of a liner in the horizontal borehole. The ventilation system for the active repository zone will be separate from the ventilation system for the active mine area. Additionally, the ventilation requirements within the repository differ between emplacement operations and potential retrieval operations, and are thus evaluated separately.

3.4 Waste Emplacement and Retrieval Operations

The operations and equipment required to emplace and retrieve canisters of waste are important factors in evaluating the suitability of waste emplacement methods. Dennis et al. (1984a) have described waste handling procedures for vertical and horizontal emplacement. SSPs were not included in the study because of the limitations stated in Subsection 1.1. Waste handling procedures were based on the assumption that no fuel consolidation would occur and that waste would only be repackaged following delivery at the repository. The retrievability requirement was addressed as a planned contingency, and repository design is proceeding on the assumption that at least retrievability of nonradioactive waste packages will be demonstrated before selecting an emplacement method. Emplacement and retrieval equipment and labor requirements for horizontal and vertical emplacement are detailed in Appendix A.4.

3.5 Sealing Procedures and Timing

The selection of a site and a specific geologic stratum for waste disposal is based primarily on their natural isolation capability. Repository sealing is intended to ensure permanent closure of the underground facility in an acceptable manner (Fernandez and Freshley, 1984). The requirements for and the extent of backfilling in the unsaturated zone have not been established. However, this report assumes a need for both repository sealing and backfilling in order to compare the potential effects of these activities for the three emplacement configurations.

The purposes and possible techniques for repository sealing and backfilling are detailed in Appendix A.5. In particular, the constraints that each emplacement configuration places on the methods for drift backfilling are described. In the comparison, it is assumed that drift backfill, if required, will be emplaced at the time of repository closure for reasons discussed in Subsections 1.2 and A.5.

4.0 EVALUATION OF ALTERNATIVES

The comparison of waste emplacement alternatives is based on a systematic assessment of a set of evaluation factors according to seven evaluation criteria. The evaluation factors are those aspects of repository design, construction, operation, and closure that are influenced by the selection of a particular waste emplacement configuration (see Section 3). The criteria, which are either qualitative or quantitative measures of preclosure repository performance, are reliability, flexibility, worker hazards environmental impact, resource commitments, scheduling, and cost. Postclosure repository performance is not evaluated because the repository will be designed to comply with all applicable standards in 10 CFR 60 (CFR, 1984b), and draft 40 CFR 191 (CFR, 1984a).

The matrix chart, Figure 7, shows the factors affected by the method of waste emplacement, arrayed against the evaluation criteria, and identifies the information required to evaluate and compare the configurations. Each block in the matrix is identified uniquely by a combination of the number corresponding to a criterion and a letter corresponding to an evaluation factor. This alphanumeric identifier is included in the title of the discussion of each matrix block. The entries in the blocks of the matrix are either designated as not applicable (NA) or by the standard of comparison.

Where applicable, comparisons are based on 1,000 canisters of waste. Worker hazards, environmental impact, resource commitments, and cost are evaluated quantitatively in appropriate units, and the emplacement methods are ranked accordingly. The remaining factors are evaluated qualitatively by assessing the relative performance of the emplacement method against the evaluation factor. The term "degree" appearing in the boxes in Figure 7 refers to a quality described as good (G), acceptable (A), acceptable with additional cost (A/AC), and unknown (U). The interpretation of these terms is different for each evaluation criterion, and the ratings are defined in each subsection prior to their use.

The blocks in the matrix (Figure 7) are designated as NA for any one of three reasons:

- There is no connection between the factor and the criterion.
- There is no difference between emplacement configurations, or the difference is judged to be small enough to be ignored for purposes of this study.
- The comparison duplicates one identified elsewhere in the matrix.

The remainder of this section is organized so that each of the evaluation criteria is discussed for each applicable factor displayed across the top of the matrix. When factors are not applicable, the reasons are stated. Evaluations are summarized at the end of each discussion. The discussion of reliability is presented in Subsection 4.1, and flexibility is discussed in Subsection 4.2. Worker hazards are described in Subsection 4.3, environmental impact is discussed in Subsection 4.4, and resource commitments are presented in Subsection 4.5. Scheduling is discussed in Subsection 4.6, and costs are described in Subsection 4.7.

LEGEND

DEG = DEGREE
I = INJURIES
ID = INJURIES AND DOSES
ΔT = CHANGE IN TEMP
NA = NOT APPLICABLE

CRITERIA \ EVALUATION FACTORS	WASTE PACKAGE			THERMAL/ STRUCTURAL ANALYSIS		REPOSITORY					OPERATIONS			SEAL-ING
						MINING		VENTILATION			EMPLACEMENT		RETRIEVAL	
	FABRICATION A	MATERIALS B	THERMAL HYDROLOGY C	THERMAL/STRUCTURAL STABILITY D	DRIFTS E	BOREHOLES F	MINING G	EMPLACEMENT H	RETRIEVAL I	LABOR J	EQUIPMENT K	LABOR L	EQUIPMENT M	BACKFILL AT CLOSURE N
RELIABILITY 1	NA	NA	DEG	ΔT STRESS	NA	DEG	NA	DEG	DEG	NA	DEG	NA	DEG	DEG
FLEXIBILITY 2	DEG	NA	NA	ΔT	NA	DEG	NA	DEG	DEG	NA	DEG	NA	DEG	DEG
WORKER HAZARD 3	I	NA	NA	NA	I	I	NA	NA	NA	ID	NA	ID	NA	ID
ENVIRONMENTAL IMPACT 4	NA	NA	NA	NA	VOL SPOIL	VOL SPOIL	NA	NA	NA	NA	NA	NA	NA	NA
RESOURCE COMMITMENT 5	NA	TONS OF STEEL	NA	NA	KW	KW	KW	KW	KW	NA	NA	NA	NA	NA
SCHEDULING 6	NA	NA	NA	NA	DEG	DEG	NA	NA	NA	NA	DEG	NA	NA	NA
COST 7	$	$	NA	NA	$	$	$	$	$	$	$	$	$	$

Figure 7. Identification of Information Requirements for Comparing Emplacement Configurations

4.1 Reliability

The construction and operation of the repository will rely on technology commonly used by the mining and nuclear industries. However, some equipment and techniques will be specially developed for handling and emplacing wastes in the repository. Because the reliability of equipment and techniques will affect repository operations and the cost of waste emplacement, differences in reliability associated with each waste emplacement method have been evaluated. Repository elements, such as waste repackaging facilities that are similar for all three emplacement methods, have not been considered. The following terms are used in the evaluation:

Good (G)

Equipment or operations are very similar to those in common use for comparable activities and have performed satisfactorily in those activities.

Acceptable (A)

Equipment or operations are unique to repository application but are sufficiently similar to those used in other applications that no major uncertainties exist regarding their performance.

Acceptable with Additional Cost (A/AC)

Equipment or operations are unique to this application and there is no comparable experience with similar activities. Design studies have identified areas of performance that require additional cost for improvement.

Unknown (U)

Planning and design studies have identified uncertainties that require resolution, or the studies that have been done are not adequate to evaluate reliability.

The reliability criterion was not evaluated against the waste package because it is expected to be similarly reliable for all three emplacement methods. Although ventilation requirements during mining will vary with emplacement method, system reliability should be similar for all three methods. Emplacement and retrieval operations will require specially trained personnel, but a reliable labor force is assumed to be available.

A summary of the rating of each evaluation factor to which the reliability criterion applies is presented in Table 2. The rating of unknown given to several factors for the SSP results from a lack of analyses or design studies. The unknown ratings for horizontal emplacement relate to the need for prototype equipment to evaluate various aspects of that emplacement method.

4.1.1 Thermal/Structural Analyses

4.1.1.1 Thermal Hydrology (1-C)

The impact of thermally induced moisture flux into emplacement drifts is discussed in Appendix A.2. Some dehydration of the drift walls will result from the drying effect of the ventilation system. However, any structural impacts of this dehydration will be those common to other underground operations.

TABLE 2

EVALUATION OF RELIABILITY CRITERION

Evaluation Factor*	Emplacement Method		
	SSP	Vertical	Horizontal
Thermal/Structural Analyses			
Thermal Hydrology (1-C)	U	A	G
Thermal/Structural Stability (1-D)	A/AC	A/AC	A/AC
Repository Mining			
Drifts (1-E)	G	G	G
Boreholes (1-F)	NA	G	U
Repository Ventilation			
Emplacement (1-H)	A/AC	A	G
Retrieval (1-I)	A/AC	A	G
Operations			
Emplacement Equipment (1-K)	G	A	U
Retrieval Equipment (1-M)	A	A	U
Sealing			
Backfill at Closure (1-N)	U	A	A

* Good (G), Acceptable (A), Acceptable with Additional Cost (A/AC), Unknown (U), Not Applicable (NA).

In the SSP configuration, drift temperatures would be similar to but higher than those in the vertical configuration. Additional stress could result from drying of the drift surfaces, but studies have not been done to determine the effects of dehydration; thus, the SSP configuration is rated unknown.

In the vertical configuration, canister temperature will cause moisture flux into the emplacement drifts but not at a rate that will lead to condensation. Thus, vertical emplacement is rated acceptable for this criterion.

In the horizontal configuration, the high canister temperatures produce a dry environment in the vicinity of the waste package for a longer period of time than in the other two emplacement methods. Moisture flux into drifts should be no greater than for vertical emplacement, but no moisture problems should occur; overall, the method is rated good.

4.1.1.2 Thermal/Structural Stability (1-D)

The results of the analyses of temperature distributions surrounding unventilated emplacement drifts for the three emplacement methods are discussed in Appendix A.2. Unventilated drift temperatures remain much lower in the horizontal method than in the other two emplacement methods (Table 22).

Unventilated emplacement drifts for both the SSP and vertical emplacement methods show calculated temperatures of 90°C within about 25 yr after emplacement. Temperatures after the same time period in the horizontal configuration are about 30°C.

Structural analyses were not performed for the SSP configuration. However, unventilated drift temperatures for the SSP are similar to those for the vertical configuration, and, therefore, the structural effects should be similar. Flanagan and Subia (1983a) evaluated the impact of elevated temperatures on rock structural stability for the vertical configuration. The elevated temperatures led to some potential movement along joints in the corners of the drift. However, the potential joint movement was sufficiently localized so that rockbolt and wire-mesh technology would prevent roof collapse. Consequently, the SSP and vertical configurations are rated acceptable with additional cost.

Thermal stress analysis of horizontal emplacement (Flanagan and Subia, 1983b) indicated a similar amount of potential joint movement that could be controlled by structural support with rockbolts and wire mesh. Some potential for horizontal tension crack development exists in the drift walls and will require consideration in the design of the borehole seals. Some tension cracks may also develop near the center of the borehole, demonstrating the need for a borehole liner. Thus, with regard to this criterion, horizontal emplacement is also rated acceptable with additional cost.

4.1.2 Repository Mining

4.1.2.1 Drifts (1-E)

As shown in Table 1, drift dimensions differ for the three emplacement methods, but there are no significant differences in requirements for rockbolting or other structural support. Assuming that drill-and-blast excavation is used, none of the emplacement methods present unusual mining or structural support problems. All three methods are thus rated good.

4.1.2.2 Borehole Drilling (1-F)

As discussed in Appendix A.3.1, the drilling and/or lining of boreholes for both the vertical and horizontal emplacement configurations requires equipment and techniques specially developed for this application. Vertical drilling will involve only modifications of commonly used methods; whereas, horizontal drilling and borehole lining will require design and development of unique equipment. In addition, problems experienced with drilling tend to increase with hole length, and the horizontal holes are considerably longer (200 m) than the vertical boreholes (7.6 m). Thus, more reliability problems can be anticipated with the horizontal emplacement configuration than with the vertical method. Therefore, the vertical method is rated good and the horizontal method is rated unknown.

4.1.3 Repository Ventilation

4.1.3.1 Emplacement (1-H)

The requirements for ventilation during emplacement depend upon the volume of air that must be processed and the heat flow into open drifts (Appendix A.3.3). Ventilation will be required to maintain an acceptable working environment for all three emplacement methods. The heat flow into ventilated drifts, and the volume of air in the

drifts to be ventilated, is much lower for horizontal emplacement than for the other two configurations.

Heat flux into drifts in the SSP emplacement method is high at the time of emplacement. In addition, the large volume of air in the drifts requires additional cost to ensure acceptable reliability of the ventilation system. The SSP method is therefore rated acceptable with additional cost. Ventilation requirements for the vertical configuration during the emplacement phase would be lower than those for the SSP but higher than those for the horizontal configuration. As shown in Figure 10, heat flux into drifts for the vertical method remains relatively low for a year or two after emplacement. Reliability of the ventilation system should be acceptable, especially if filled emplacement drifts are barricaded to restrict flow of heated air into connecting drifts. Therefore, vertical emplacement is rated acceptable.

Heat flux into emplacement drifts for the horizontal configuration does not increase significantly during the 50-yr retrieval period. Additionally, the significantly lower drift volume associated with horizontal emplacement reduces the ventilation requirements below that for the SSP or vertical emplacement, independent of heat flux. Thus, ventilation requirements may not exceed those common to underground mines, and reliability of the ventilation system is rated good.

4.1.3.2 Retrieval (1-I)

Ventilation requirements during retrieval operations depend on drift volume and heat flow into drifts. In order to allow for retrieval, maintenance of the drift structural support will be required throughout the operational period. Maintenance, in turn, will require varying amounts of ventilation to provide suitable working conditions. The ventilation requirements are related to drift volumes and heat flux (Appendix A.2). The reliability of the ventilation system during retrieval operations is thus rated the same as it is during waste emplacement: acceptable with additional cost for the SSP, acceptable for the vertical method, and good for the horizontal emplacement configuration.

4.1.4 Operations

4.1.4.1 Emplacement Equipment (1-K)

As a general rule, the more complex a piece of equipment, the greater the potential for failure. The complexity of emplacement equipment differs for the three emplacement methods. The equipment required to transport and to emplace SSPs is relatively simple, and the reliability is therefore rated good. The vertical emplacement equipment is moderately complex but involves elements commonly used by the nuclear industry. Therefore, although much of the equipment is unique to this application, reliability is rated acceptable. The horizontal emplacement equipment is relatively complex and involves elements unique to this application. Although planning and design studies are well advanced, prototype equipment has not been developed or tested. Reliability therefore cannot be evaluated and is rated unknown.

4.1.4.2 Retrieval Equipment (1-M)

As with emplacement operations, the potential for equipment failure during waste retrieval is related to its complexity. Should equipment fail, the waste emplacement methods pose different degrees of resistance to alternative retrieval methods.

For the SSP configuration, retrieval equipment is relatively simple. However, the presence of the SSPs in the drifts would prevent normal maintenance of the structural support system; thus, some unusual problems can be expected during waste retrieval. Equipment reliability during retrieval is thus rated acceptable for the SSP method; however, should extensive roof collapse occur, retrieval costs would increase.

For the vertical emplacement method, retrieval equipment is similar to emplacement equipment. The retrieval process is relatively straightforward, and equipment reliability should be acceptable. Equipment failure is unlikely, and alternative retrieval methods are well thought out. The proximity of the waste to the emplacement drift allows for some flexibility in the selection of alternative retrieval methods, and failure to retrieve the waste from a particular borehole would involve only one canister. Therefore, retrieval equipment is rated acceptable.

For horizontal emplacement, retrieval equipment is identical to emplacement equipment and would receive extensive testing during emplacement operations. However, until prototype evaluations are complete, equipment performance cannot be evaluated and is therefore rated unknown.

4.1.5 Sealing

4.1.5.1 Backfilling at Closure (1-N)

Backfilling the repository, if required, would involve placement of excavated muck or other material in the emplacement and access drifts. Although the equipment required is relatively standard, underground workings are not routinely backfilled. The equipment reliablity for the three emplacement methods would differ.

Backfilling of emplacement drifts containing SSPs at the time of repository closure would require special equipment designed to move backfill over or around the canisters of waste. Such equipment has not been developed; thus, the level of reliability is rated unknown.

If the open drifts in the vertical emplacement method are ventilated to maintain a low rock temperature, drifts can be backfilled at the time of closure using conventional equipment and techniques. However, while these techniques are reliable, they are not normally used underground. Thus, overall reliability is rated acceptable.

Backfilling of drifts required for horizontal emplacement would similarly present no unusual reliability problems, assuming drifts are ventilated to allow for inspection and maintenance. Therefore, as for vertical emplacement, the reliability of backfilling is rated acceptable.

4.2 Flexibility

The flexibility criterion assesses the type and degree of constraint that each emplacement method imposes on facilities, equipment, and operations at the repository. The most effective emplacement method should be flexible and have the fewest limitations for safely accommodating different types of radioactive waste with dissimilar thermal levels and scheduling requirements for rates of receipt. The following terms are used in the evaluation:

Good (G)

The equipment or operation can accommodate all potential requirements.

Acceptable (A)

The equipment or operation can accommodate all potential requirements with only minor modifications.

Acceptable with Additional Cost (A/AC)

The equipment or operation can be adapted to the potential requirements, but significant modifications are required.

Unknown (U)

Planning and design studies are not sufficient to evaluate flexibility.

There is no relationship between the flexibility criterion and the material requirements of the waste package. The flexibility criterion does not apply to thermal hydrology or ventilation of drifts during mining because these factors impose constraints that are similar and not significant for the three emplacement methods. The constraints imposed on labor during emplacement and retrieval would be similar for all three methods, and a flexible labor force is assumed to be available.

A summary of the evaluation of those factors to which the flexibility criterion applies is given in Table 3. The rating of unknown applied to backfilling for the SSP results from the lack of detailed design studies. The rating of unknown for factors under horizontal emplacement relate to the need for prototype equipment to fully evaluate that method. The flexibility of the repository layouts associated with each method to accommodate variations in geologic conditions was not evaluated. However, this concern is addressed in Appendix A.3.1.

4.2.1 Waste Package

4.2.1.1 Fabrication (2-A)

The additional shielding requirements of the SSP make it much less flexible in accommodating changes in waste types than vertical or horizontal emplacement and cause it to be relatively inflexible for responding to changing demand or waste types. The cost-effective disposal of several different wastes, with variable radiation levels, would necessitate different SSPs for each waste type. The SSP is therefore rated acceptable with additional cost. The borehole liner required for the horizontal configuration makes this method less flexible than the vertical configuration in accommodating changes in canister size. Thus, the vertical and horizontal configurations are rated good and acceptable, respectively.

4.2.2 Thermal/Structural Stability (2-D)

Temperatures in unventilated emplacement drifts are highest for the SSP method and lowest for the horizontal emplacement configuration. The structural impacts of these temperature differences are described in Appendix A.2.3. The analyses indicate that the SSP method should be rated acceptable with additional cost, the flexibility of the vertical configuration should be rated acceptable, and the flexibility of the horizontal configuration for accommodating increases in thermal loading should be rated good.

TABLE 3

EVALUATION OF FLEXIBILITY CRITERION

Evaluation Factor*	Emplacement Method		
	SSP	Vertical	Horizontal
Waste Package			
Fabrication (2-A)	A/AC	G	A
Materials (2-B)	A/AC	G	A
Thermal/Structural Analyses			
Thermal/Structural Stability (2-D)	A/AC	A	A
Repository Mining			
Boreholes (2-F)	NA	A/AC	A
Repository Ventilation			
Emplacement (2-H)	A/AC	A	G
Retrieval (2-I)	A/AC	A	G
Operations			
Emplacement Equipment (2-K)	G	A	U
Retrieval Equipment (2-M)	G	A	U
Sealing			
Backfill at Closure (2-N)	U	A	G

* Good (G), Acceptable (A), Acceptable with Additional Cost (A/AC), Unknown (U), Not Applicable (NA).

4.2.3 Repository Mining

4.2.3.1 Boreholes (2-F)

As shown in Table 25, drift and borehole spacings required to obtain the 50-kW/acre average thermal loading for all waste types satisfy the criterion of limiting the extraction ratio to 25%. However, in addition to the extraction ratio criterion, structural integrity of a drift is influenced by its height and width. The lowest thermal output, 0.5 kW/canister for defense high-level waste (DHLW), allows borehole spacing that may be difficult to achieve in both the vertical and horizontal method because of structural considerations.

For vertical emplacement, a center-to-center borehole spacing of 2.5 m can be obtained if two staggered rows of boreholes are used. However, the large number of boreholes in the drift floor has a similar effect, structurally, to increasing the drift height. Additional structural support may be required with this concept. Also, some operational problems may be encountered in constructing boreholes at such close spacings.

For horizontal emplacement, alcoves will be required for maneuvering the waste transporter with both 2.2-kW and 3.4-kW canisters. If the same alcoves, 6 m wide, were required for the DHLW (0.5 kW/canister), the alcoves would nearly overlap, reducing the

structural stability of the drift to an unacceptable level. However, complete or partial elimination of the alcoves may be possible for 0.5-kW waste by using emplacement equipment different from that currently being considered because DHLW canisters are shorter than the canisters for spent fuel.

In addition to structural constraints, the flexibility of the borehole must be evaluated for the different waste types. The borehole for vertical emplacement is unlined and could readily accommodate a variety of waste packages. For horizontal emplacement, variation in canister dimensions may be more difficult to accommodate.

In summary, for vertical emplacement, the close spacing of boreholes required to accommodate wastes cooler than spent fuel and CHLW may impose additional operational or structural cost, and the method is rated acceptable with additional cost. The horizontal emplacement configuration is the least flexible in accommodating different waste types. Structural considerations restrict borehole spacing for wastes cooler than spent fuel and CHLW, and additional cost would be required to accommodate the range of potential waste types. However, as stated in Section 1 of this report, the configuration for emplacing cooler wastes will be determined independently of the configuration for spent fuel and CHLW disposal. Overall, horizontal emplacement is therefore rated acceptable.

4.2.3.2 Ventilation

The ventilation requirements of the three emplacement methods vary for both emplacement and retrieval operations as a function of the drift volume and heat flow into open drifts.

Emplacement (2-H)

The heat removal rates required to maintain drift temperatures at 30°C are highest for the SSP method and lowest for the horizontal method (Figure 10). The additional ventilation factor, drift volume, results in ventilation requirements being lowest for horizontal emplacement and highest for the SSP. With regard to ventilation requirements, a change in thermal output or other waste characteristics will have relatively little impact on horizontal emplacement, and it is therefore rated good. Ventilation requirements are more sensitive to waste types for vertical emplacement, and flexibility for vertical emplacement is rated acceptable. Additional cost will be incurred in the SSP configuration to maintain a ventilated environment similar to that for vertical emplacement; thus, the SSP configuration is rated acceptable with additional cost.

Retrieval (2-I)

It may not be necessary to ventilate all of the drifts continuously in order to maintain an acceptable working environment during retrieval. In the horizontal method, temperatures in unventilated drifts remain below 40°C for 30 yr, and re-entry for inspection, monitoring, or retrieval would not require significant ventilation. In the SSP and vertical configurations, however, temperatures rise rapidly, exceeding 50°C within 10 yr. Retrieval would require much more ventilation than would be required in the horizontal emplacement method. Consequently, the SSP method is the least flexible, and the horizontal method is the most flexible in accommodating hotter wastes in terms of ventilation requirements. Thus, the SSP method is rated acceptable with additional cost, the vertical method is rated acceptable, and the horizontal method is rated good.

4.2.4 Operations

4.2.4.1 Emplacement Equipment (2-K)

For the SSP method, the emplacement equipment is relatively simple, involving only lifting, transport, and shielding elements. Variations in size, shape, thermal, and radiation characteristics of waste types would place relatively few demands on this equipment. Therefore, the SSP method is rated good.

The vertical and horizontal emplacement methods require remote handling of waste packages. Variations in package characteristics or waste types not included in original design specifications could be difficult to accommodate. However, a change in borehole spacing or dimensions to accommodate various waste types is easier for vertical than for horizontal emplacement, and vertical emplacement is therefore rated acceptable. The horizontal emplacement, method is the most complex, and the equipment appears to be the least flexible for handling a variety of waste packages. Until prototype equipment is developed and tested, evaluation of its flexibility is not possible, and it is rated unknown.

4.2.4.2 Retrieval Equipment (2-M)

Retrieval is expected to be a reversal of the emplacement process; thus, the flexibility of retrieval equipment for handling a variety of waste types is similar to that of the emplacement equipment. However, the higher canister temperatures (Table 21 and Figure 8) in the horizontal configuration may adversely impact retrievability compared to the vertical or SSP configurations. The emplacement methods are rated the same for retrieval as for emplacement: good for the SSP, acceptable for vertical emplacement, and unknown for horizontal emplacement.

4.2.5 Sealing

4.2.5.1 Backfilling at Closure (2-N)

Backfilling the emplacement drifts can be done at the time of waste emplacement, at some time after emplacement, or it can be delayed until repository closure or not done at all. As detailed in Appendix A.5, it is assumed here that backfill, if required, is placed at the time of closure.

The emplacement methods would produce different thermal and radiation fields at the time of repository closure. For the SSP method, delaying the emplacement of backfill until closure could cause significant problems because of high drift temperatures, radiation levels, and the physical obstruction presented by the SSPs. Design studies to develop the required equipment have not been done, and the SSP is therefore rated unknown.

For both vertical and horizontal emplacement, backfilling of the repository at the time of closure imposes no constraints on repository operations. The placement of backfill at the time of closure is similar to the requirement for waste retrievability in that structural support in the drifts must be maintained, and some ventilation will be required to maintain or create an acceptable working environment. Due to the low heat flux into drifts, the horizontal configuration places few additional constraints on repository operations and is rated good. The higher heat flux into drifts associated with vertical emplacement places more constraints on repository operation, and vertical emplacement is therefore rated acceptable.

4.3 Worker Hazards

The discussion in this subsection includes both nonradiological and radiological hazards to workers. The nonradiological hazards evaluated for each method include worker injuries and fatalities that could result from waste package fabrication, mining of the repository drifts and boreholes, waste emplacement and retrieval, and the backfilling of the drifts. Radiological hazards evaluated include worker radiation doses received during waste emplacement, waste retrieval, and backfilling the drifts.

The evaluation of worker hazards does not apply to the waste package materials, thermal/structural analyses, or emplacement and retrieval equipment. The ventilation system will be designed to maintain a healthy working environment, and the differences in ventilation requirements for the three emplacement methods are evaluated under other criteria.

The nonradiological operations involved in waste emplacement and retrieval are similar to other common industrial practices. Because of this similarity, occupational injury and fatality rates from comparable industries (Table 4) were used to quantify the expected impact on workers from waste management operations. Repository mining was assumed to be comparable to underground mining, operations were compared to surface mining, waste package fabrication was compared with that of the primary metal manufacturing industry, and backfilling was compared to the heavy construction industry.

TABLE 4

INJURY AND FATALITY RATES FOR COMPARABLE INDUSTRIES[a]

Industry	Standard Industrial Classification (SIC) Code	Incidence Rates[b]	
		Injury[c]	Fatality
Underground Mining[d] (metal and nonmetal, noncoal)	10, 14	5.93	0.09
Surface Mining[d] (metal and nonmetal, noncoal)	10, 14	4.75	0.10
Primary Metal Industries	33	7.80	0.05
Heavy Construction (except highway)	162	6.40	0.10

a DOL, 1978.

b Incidence rates per 200,000 employee hours, based on cases per 100 worker-years (40 hr/wk, 50 wk/yr).

c Lost workday cases (injury) are those days that the employee would have worked but could not because of occupational injury or illness.

d Johns, 1983.

The data from related industries provide perspective on the expected magnitude of the hazards. However, the differences in injury and fatality rates between nuclear waste management operations and similar industries may be substantial. For instance, many nuclear waste management operations can be performed remotely. Compared to similar hazards in comparable industries, remote handling would greatly reduce the risk to workers. Therefore, the values presented in this study are for comparative purposes, and caution should be exercised in applying the results of the injury and fatality projections to actual nuclear waste management activities.

Table 5 presents a summary of the projected nonradiological injuries and fatalities for waste management workers for each waste emplacement method. The total worker injuries and fatalities are highest for the SSP emplacement method and lowest for the horizontal emplacement method. The major difference is caused by fabrication of the SSP. Worker injuries for the SSP method are more than three times that of the worker injuries for the vertical method; the SSP results in 75% more worker injuries and 45% more fatalities than result in the horizontal emplacement method.

The radiation doses received by workers during waste emplacement and retrieval depend on the material-handling facilities and equipment. These are described by Dennis et al. (1984a). In order to meet current regulations for occupational exposure [design objective, 1 rem/yr; maximum exposure 5 rem/yr (DOE, 1981)] and to maintain the maximum occupational exposure rate below 0.5 mrem/hr, spent fuel and high-level waste canisters will require remote, shielded handling.

A summary of the projected worker exposure for each emplacement method is presented in Table 6. The operations and backfill manpower commitment is an estimate of the total exposure time for the workers involved in a particular operation. The exposure data presented in Table 6 were developed specifically for this study and are based on preliminary operations scenarios without the benefit of actual designs. The exposure values were determined using an assumed source term and are intended to be used for comparison purposes only. The total worker exposure is highest for the vertical emplacement method (4.73 man-rem) and lowest for the horizontal emplacement method (1.10 man-rem). The dose from vertical emplacement is 25% higher than the dose from the SSP method and 77% higher than the dose from horizontal emplacement. Maximum annual dose rates are well within design limits (1 rem/yr) for all emplacement configurations.

4.3.1 Waste Package Fabrication (3-A)

The hazard level for fabrication of waste packages was assumed to be comparable to that for the primary metal industry (Table 4). The manpower involved in waste package fabrication was estimated to be 50% of the total package cost, based on an average hourly wage of $40.

The injury and fatality rates per 1,000 canisters (Table 5) are highest for the SSP (43.68 and 0.280) and equal for the vertical and horizontal emplacement packages (7.41 and 0.048).

4.3.2 Repository Mining (3-E, 3-F)

The mining of access and emplacement drifts in preparation for waste emplacement was assumed to be analogous in hazard level to mining operations in the metal and nonmetal, noncoal, and underground mining industry (Table 4). This hazard level was also used for projecting injuries and fatalities in drilling boreholes for the

TABLE 5

MANPOWER COMMITMENTS AND
PROJECTED NONRADIOLOGICAL INJURIES AND FATALITIES
FOR WASTE MANAGEMENT WORKERS PER 1,000 CANISTERS

Activities	Emplacement Method		
	SSP	Vertical	Horizontal
	Manpower Commitment (10^4 man-hours)		
Waste Package Fabrication	112	19	19
Repository Mining			
Drifts	10.38	17.90	2.03
Boreholes	NA*	2.00	6.79
Operations			
Emplacement	0.10	1.07	0.22
Retrieval	0.20	1.08	0.32
Backfill	0.91	1.80	0.21
Total Estimated Hours	123.58	43.28	29.46
	Estimated Number of Injuries		
Waste Package Fabrication	43.68	7.41	7.41
Repository Mining			
Drifts	3.08	5.31	0.60
Boreholes	NA	0.59	2.57
Operations			
Emplacement	0.02	0.25	0.05
Retrieval	0.05	0.26	0.08
Backfill	0.29	0.57	0.07
Total Estimated Injuries	47.12	14.39	10.78
	Estimated Number of Fatalities		
Waste Package Fabrication	0.280	0.048	0.048
Repository Mining			
Drifts	0.047	0.080	0.009
Boreholes	NA	0.009	0.019
Operations			
Emplacement	0.001	0.005	0.001
Retrieval	0.001	0.005	0.002
Backfill	0.005	0.009	0.002
Total Estimated Fatalities	0.334	0.156	0.081

* Not applicable.

TABLE 6

MANPOWER COMMITMENTS AND PROJECTED RADIATION DOSES FOR WASTE MANAGEMENT WORKERS PER 1,000 CANISTERS

Activities	Emplacement Method		
	SSP	Vertical	Horizontal
	Manpower Commitment (10^4 man-hours)		
Emplacement	0.10	0.29	0.13
Retrieval	0.20	0.26	0.27
Backfill	1.10	2.23	0.09
Total Manpower (10^4 man-hours)	1.40	2.78	0.49
	Individual Exposure Rate (10^4 rem/hr)		
Emplacement	2.50	2.50	2.50
Retrieval	2.50	2.50	2.50
Backfill	2.50	1.50	1.00
	Exposure (man-rem)		
Emplacement	0.25	0.73	0.33
Retrieval	0.50	0.65	0.68
Backfill	2.75	3.35	0.09
Total Exposure[a] (man-rem)	3.50	4.73	1.10
Annual Exposure Rate[b] (man-rem/yr)	0.52	0.21	0.47

a Based on a maximum exposure rate of 0.25 mrem/hr.

b Assumes maximum of 2,080 working hours per man per year.

vertical and horizontal waste emplacement configurations and in lining the horizontal borehole (Westinghouse, 1982).

The injury and fatality rates for mining the access and emplacement drifts (Table 5) are 5.44 and 0.082, respectively, for the vertical method; and 3.08 and 0.047, respectively, for the SSP method. The rates for horizontal emplacement are considerably lower, with 0.87 for injuries and 0.013 for fatalities.

Borehole drilling is not applicable to the SSP method. Injuries and fatalities for drilling the vertical borehole are 0.59 and 0.009, respectively; and 2.57 and 0.019, respectively, for drilling and lining the horizontal borehole.

4.3.3 Emplacement and Retrieval Operations (3-J, 3-L)

Injuries and fatalities associated with waste emplacement and retrieval operations were assumed to be comparable in hazard level to the mining operations in the metal and nonmetal, noncoal, and surface mining industry (Table 4). The exposure of workers to radiation during emplacement and retrieval was estimated based on the amount of time a worker is involved in the handling or transporting of waste packages (Table 5).

The injury and fatality rates are highest for both vertical emplacement, 0.25 and 0.005, respectively; and vertical retrieval, 0.26 and 0.005. The injury and fatality rates are lowest for the SSP method, 0.02 and 0.001 for emplacement, respectively; and 0.05 and 0.001 for retrieval, respectively.

The estimated radiation doses to workers are highest during emplacement for the vertical method, 0.73 man-rem; and lowest for the SSP method, 0.25 man-rem. Retrieval doses are highest for the horizontal method, 0.68 man-rem; and lowest for the SSP method, 0.50 man-rem.

4.3.4 Backfilling (3-N)

The nonradiological and radiological hazard estimates for backfilling the waste emplacement drifts are based on the volume of fill material required in each emplacement method. The total drift volumes (Table 24) were reduced by 30% for the vertical and horizontal methods, and 40% for the SSP method in order to allow for fill expansion and void space. It is assumed that fill material would be placed in the drifts by a three-man crew operating a hopper-fed conveyor and bucket elevator at a rate of 46 m^3/hr with fill material delivered or available at each drift entrance.

The backfilling of the drifts was assumed to be comparable in worker hazard to that of the heavy construction industry (Table 4). The injury and fatality rates are the highest for the vertical emplacement method, 0.57 and 0.009, respectively; and lowest for the horizontal emplacement method, 0.07 and 0.002, respectively. Injury and fatality rates for the SSP are 0.29 and 0.005, respectively.

The estimated radiation doses to backfill workers is highest for vertical emplacement, 3.35 man-rem; and lowest for horizontal emplacement, 0.09 man-rem. As waste package emplacement is completed, the background radiation level will increase and then level off. With equipment shielding, this exposure level will not exceed 0.25 man-rem, the level assumed for the SSP emplacement method. Lower background radiation levels have been estimated for vertical and horizontal emplacement because of the hole closure covers and the waste package-to-surface distances (3 m for the vertical emplacement method and 24.4 m for the horizontal method).

4.4 Environmental Impact

Changes to the surface environment or to the near-field subsurface environment resulting from the emplacement method were considered in assessing environmental impact. The only significant impact identified to date is the need to dispose of excavated rock in an environmentally acceptable manner. Consequently, no evaluation factors are applicable to the environmental impact criterion except the mining of drifts and boreholes.

The three emplacement methods differ significantly in the volume of excavated rock as shown in Table 24 (Appendix A.3). The horizontal emplacement method would

produce the least muck (47,435 m^3), the vertical emplacement method the most (429,640 m^3), and the SSP configuration 42% (262,240 m^3) less than the vertical method. The cost of stabilizing the muck pile to control erosion and dust is not included in the cost estimates given in Subsection 4.7.

4.5 Resource Commitments

Only significant differences in resource commitments are considered in evaluating the three waste emplacement methods. Energy consumption is similar for fabrication of the waste package for all three configurations, and only the material requirements differ significantly among the three. Consequently, the resource commitment criterion is not applicable to waste package fabrication, and there is no relationship between this criterion and thermal/structural analyses, repository operations, or sealing factors.

Significant relative resource commitments associated with waste emplacement are given in Table 7 per 1,000 canisters. The cost of these resources is included in the cost estimates provided in Subsection 4.7. Resources consist of the steel used in shielding the SSPs; the carbon steel used for the horizontal borehole liners; diesel fuel consumed in mining drifts and boreholes; and electrical power requirements for ventilation and cooling during mining, waste emplacement, and retrieval operations.

The SSP method requires the largest commitment of resources. A significant quantity of steel is needed for shielding, in addition to the requirements for the waste canister. This method also requires more electrical power than either the vertical or horizontal emplacement methods. However, the power requirement for the SSP method would be less than that in the vertical method if retrieval costs are not considered. Based on the assumption that retrieval is a planned contingency in repository design, the horizontal emplacement method would require the fewest resources.

4.6 Scheduling

Throughout the construction and operating periods of the repository, many diverse operations will occur that depend on highly specialized equipment and techniques. The schedule for repository construction and operation could be significantly altered by delays in developing essential drilling, waste handling, and emplacement equipment. For example, schedule delays could result from unexpectedly lengthy research and development (R&D) requirements or from dependence on materials and equipment that require long periods of time for delivery. The scheduling criterion evaluates the potential for significant disruption in the construction or operations schedule associated with each waste emplacement method. The following terms are used in the evaluation:

Good (G)

Anticipated delays in implementing the method are similar to those for other large, comparable industrial construction and operations activities.

Acceptable (A)

Anticipated delays arise from the unique character of the operation or equipment, and though undesirable, they can be planned for.

TABLE 7

RELATIVE RESOURCE COMMITMENTS PER 1,000 CANISTERS

Resource	Emplacement Method		
	SSP	Vertical	Horizontal
Waste Package			
Steel (MT)	58,378	0[a]	0[a]
Mining			
Steel (MT)			243[c]
Diesel Fuel (L)			
Drifts	642,693	1,022,329	159,349
Boreholes	NA[b]	378,500	129,069
Total	642,693	1,400,829	288,418
Ventilation			
Electrical Power (million kWh)			
Mining	9.6	14	4
Emplacement	21.8	24	19
Retrieval			
Ventilation	21.8	24	19
Refrigeration[d]	155	94	2.9
Total 208.2	156	44.9	

a The waste package for vertical and horizontal emplacement consists of a canister that is common to all three emplacement methods; therefore, it is not included in the evaluation.

b NA = Not applicable.

c Borehole liner used in horizontal emplacement.

d The amount required for retrieving 1,000 canisters; the operating period is 0.71 yr.

Acceptable with Additional Cost (A/AC)

Present planning and design efforts indicate unavoidable delays of a significant nature. Solutions have been identified that, for additional cost, will reduce the expected delays to acceptable or good status.

Unknown (U)

Present planning and design efforts are not sufficient to evaluate possible schedule delays.

There is no relationship between scheduling impacts and thermal/structural analyses, repository ventilation, or backfilling at closure. The waste package is assumed to be equally available for all emplacement schemes. Labor for emplacement and retrieval is also assumed to be equally available. Since retrieval is not a scheduled part of repository operations, delays caused by unplanned waste retrieval operations are not considered in the evaluation.

The evaluation of the scheduling criterion for each applicable evaluation factor is summarized in Table 8. The rating of unknown applied to factors under horizontal emplacement relates to the need for prototype equipment to fully evaluate that method.

TABLE 8

EVALUATION OF SCHEDULING CRITERION

Evaluation Factor*	Emplacement Method		
	SSP	Vertical	Horizontal
Repository Mining			
Drifts (6-E)	G	G	G
Boreholes (6-F)	NA	G	U
Operations			
Emplacement Equipment (6-K)	G	A	U

* Good (G), Acceptable (A), Acceptable with Additional Cost (A/AC), Unknown (U), Not Applicable (NA).

4.6.1 Repository Mining

4.6.1.1 Access and Emplacement Drifts (6-E)

The difficulties and potential delays in mining of access and emplacement drifts are directly related to the total volume of excavation required. Thus, the potential for schedule delays is highest for the SSP and vertical configurations, which require the most drift excavation. The potential for these delays is lowest for the horizontal configuration, which requires the least drift excavation (see Table 24). However, no unusual delays should occur for any of the emplacement methods because standard techniques will be used. The three methods are rated good.

4.6.1.2 Borehole Construction (6-F)

Boreholes are not required for emplacement of SSPs. Standard equipment developed for similar applications would be used to drill vertical boreholes. While the total length of vertical boreholes is 1.4 times longer than the total length of the horizontal boreholes, the technology for drilling vertical boreholes is well established. Therefore, vertical emplacement is rated good with respect to scheduling.

The drilling and lining of horizontal boreholes of the required length and diameter is a new technology that must be developed for repository application. The amount of

research and development required is uncertain, and potential delays during drilling and lining operations cannot be predicted before testing prototype equipment. Therefore, the impact of horizontal emplacement on scheduling is rated unknown.

4.6.2 Operations

4.6.2.1 Emplacement Equipment (6-K)

The emplacement equipment will be specially designed and constructed for the three methods. Because the design of the required equipment differs for each method, potential schedule delays due to downtime will differ also.

The SSP configuration relies on emplacement equipment that is comparatively simple and relatively standard, requiring only lifting, transporting, and shielding of waste. Therefore, nonavailability of equipment should have minimal impact on the repository schedule. The SSP configuration is rated good.

The equipment for vertical emplacement is moderately complex, requiring remote operation within a borehole. Occasional moderate delays can be expected when equipment is down, but design errors should not cause significant difficulty. The vertical configuration is rated acceptable.

Emplacement equipment for the horizontal method has not been developed yet. While design concepts are based on proven technology, there has been no operational experience with such equipment. Thus, the extent of possible delays during emplacement cannot be predicted, and the horizontal configuration is rated unknown.

4.7 Cost

Current (1983) relative costs per 1,000 canisters have been estimated for all waste emplacement and retrieval activities. Equipment, labor, material, and maintenance costs are included in the estimates. Costs common to all emplacement methods were not considered because the study is based on a relative comparison.

The total relative costs of the vertical and horizontal emplacement configurations are shown in Table 9. Because of an unfavorable preliminary evaluation of the SSP, cost data for this method are not complete. Preliminary studies indicated that the SSP concept would be considerably more expensive than the other two emplacement configurations. As shown in Table 9, the SSP method would cost at least 2.4 times more than the vertical emplacement method. Vertical emplacement is 3.3 times more costly than the horizontal method if backfilling is done at the time of closure. The details of these costs are developed in the following subsections.

4.7.1 Waste Package (7-A, 7-B)

The waste container will be the same for all three emplacement methods; therefore, canister cost is not a factor in the comparison. The waste package for the three methods differs only with regard to the shielding for the SSP.

The massive shield for the SSP would be purchased and delivered as a unit. The price of material at $1,100/MT (Means, 1982) includes fabrication and delivery. Total costs of materials and fabrication for all three emplacement methods are shown in Table 10.

TABLE 9

TOTAL RELATIVE COST PER 1,000 CANISTERS

Cost Element	Emplacement Method ($k)		
	SSP	Vertical	Horizontal
Waste Package	$64,350	$ 0[a]	$ 0[a]
Drift Mining	5,810	8,971	1,698
Borehole Construction	0	3,173	1,287
Muck Handling	2,041	2,653	987
Ventilation			
Mine Development	432	606	211
Emplacement	1,103	1,217	858
Retrieval	8,631	5,817	1,096
Equipment and Labor			
Emplacement	NA[b]	7,797	2,084
Retrieval	NA	1,758	1,360
Backfill			
At Closure	NA	3,083	1,034
Total	$82,367	$35,075	$10,615

a The cost of the waste canister is common to all three emplacement methods, and is not included in the relative cost.

b NA - Not available.

TABLE 10

WASTE PACKAGE COSTS[a]

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Materials	$64,350,000	$0	$0
Fabrication	0	0	0
Total	$64,350,000	$0	$0

a Exclusive of canister, which is common to all emplacement methods.

b Fabrication cost is included in the cost of materials.

4.7.2 Repository Mining

4.7.2.1 Mining Costs

Mining costs include only the costs for the access and emplacement drifts, boreholes, and muck handling for the three emplacement methods. Main haulageways and mine entrances, common to all methods, are not considered. Repository design is based on the waste from 70,000 metric tons of heavy metal (MTHM) and on a 24-yr operating period. This equals an average of 1,388 canisters annually; 1,000 canisters represent 0.71 yr of operation.

4.7.2.1.1 Access and Emplacement Drifts (7-E)

The dimensions and configurations of the access and emplacement drifts for the three emplacement methods are shown in Figures 1, 4, and 5. In addition to other direct costs for mining activities, additional surface facilities are required to support the greater numbers of employees and equipment required for mining the SSP and vertical emplacement configurations. Dravo (1984a) estimates a one-time cost differential that equals $38,863 per 1,000 canisters for these methods. Associated mining cost estimates for the three waste emplacement methods are shown in Table 11.

TABLE 11

DRIFT MINING COSTS PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Capital (equipment)	$ 899,663	$1,258,963	$ 402,300
Equipment Maintenance (fuel, repairs, etc.)	625,500	993,000	156,600
Labor	2,183,900	3,456,900	559,800
Materials and Supplies	2,101,200	3,261,900	579,400
Total	$5,810,263	$8,970,763	$1,698,100

4.7.2.1.2 Borehole Construction Costs (7-F)

Waste canisters are inserted into boreholes in the vertical and horizontal emplacement methods. To emplace 1,000 canisters, 1,000 boreholes are required for the vertical configuration, and 29.4 boreholes are required for the horizontal configuration. The steel liner for the horizontal borehole, purchased in 20-ft lengths to allow transfer from the surface to the emplacement location, would require 860 welds per 1,000 canisters. A total fabrication cost is estimated conservatively at $48,000 and includes one full-time welder. The cost of welding materials would be minimal. Boreholes are not required for the SSP configuration. The cost of borehole drilling is given in Table 12.

4.7.2.1.3 Muck Handling

The muck must be transported to the surface and stored for later use as backfill or disposed in an environmentally acceptable manner. It is assumed that the density of intact rock is 2,290 kg/m^3 and that muck is transferred out of the repository by shaft. The costs of these operations are given in Table 13.

TABLE 12

BOREHOLE CONSTRUCTION COSTS PER 1,000 CANISTERS[a]

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Capital (equipment)	$0	$1,374,000	$ 335,750
Cutters and Maintenance	0	990,000	111,500
Overhaul	0	296,000	73,000
Labor	0	383,400	195,700[b]
Power	0	130,000	57,800
Material	—	—	513,000[b]
Total	$0	$3,173,400	$1,286,750

a After Robbins, 1983. Costs are based on conceptual designs and do not include the cost of prototype development.

b Includes cost of horizontal borehole liner.

TABLE 13

MUCK HANDLING COSTS PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Capital (equipment)	$ 238,000	$ 270,800	$195,800
Repair and Maintenance	1,142,000	1,300,000	671,400
Operating Costs*	660,600	1,082,300	119,500
Total	$2,040,600	$2,653,100	$986,700

* Operating costs are based on $1/ton of rock handled.

4.7.2.2 Ventilation Costs (7-G, 7-H, 7-I)

Ventilation costs consist of the capital and operating costs of the equipment, and costs for any cooling required during mining and waste emplacement. Operational and cooling costs will vary during development of the underground facility, during and after emplacement, and during retrieval, should retrieval be required. Depending on the desired drift temperature, refrigeration may or may not be required. In this report, it is assumed that some refrigeration is required. For purposes of this study, capital equipment costs are arbitrarily assigned to the repository development phase, and refrigeration costs are assigned to the retrieval phase.

Two independent systems provide repository ventilation, one for mine development and one for air circulation in the repository after waste has been emplaced. The greater number of drifts in the SSP and vertical emplacement configurations requires a larger volume of ventilation air for both the mining and repository circuits.

Table 14 shows ventilation costs during mine development (Dravo, 1984a). The ventilation costs during waste emplacement are shown in Table 15.

TABLE 14

VENTILATION COSTS DURING MINE DEVELOPMENT PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Capital (equipment)	$131,100	$169,260	$ 82,400
Maintenance	13,100	16,930	8,240
Operating Costs	288,000	420,000	120,000
Total	$432,200	$606,190	$210,640

TABLE 15

VENTILATION COSTS DURING WASTE EMPLACEMENT PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Maintenance	$ 13,000	$ 16,930	$ 8,240
Operating Costs	1,090,000	1,200,000	950,000
Total	$1,103,000	$1,216,930	$958,240

Two types of ventilation are required for retrieval: cooling required to maintain the drifts at an acceptable temperature and ventilation to support workers during retrieval operations. Based on the assumption that retrieval is accomplished at the same rate as emplacement, operating costs for the ventilation system during retrieval operations would be the same as during emplacement (Table 15).

Hickox (1983) calculated cooling requirements for maintaining an acceptable working environment in the drift using refrigeration. Assuming 50% efficiency to allow for air leakage, fan efficiency, and cooling efficiency and assuming an energy cost of $0.05/kWh, the cost to operate the system during the period required to retrieve 1,000 waste packages is shown in Table 16.

4.7.3 Operations

Salary and equipment costs associated with waste emplacement and waste retrieval have been estimated for the three emplacement configurations. The equipment for emplacement and retrieval is listed in Appendix A.4.

TABLE 16

VENTILATION COSTS DURING RETRIEVAL PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Maintenance	$ 13,000	$ 16,930	$ 8,240
Operating Costs			
Drift Cooling	7,527,920	4,600,520	138,130
Ventilation	1,090,000	1,200,000	950,000
Total	$8,630,920	$5,817,450	$1,096,370

4.7.3.1 Emplacement (7-J, 7-K)

Table 17 shows equipment and labor costs for the vertical and horizontal waste emplacement methods. For reasons stated in Subsection 1.1 and Appendix A.1, emplacement costs for the SSP were not estimated. Cost estimates are based on an equipment lifetime of 5 yr and maintenance at 10%/yr (Fisk et al., 1983). Labor costs have been estimated by Dennis et al. (1984a). Fuel costs are estimated at $0.29/L ($1.10/gal). The installed cost of borehole plugs is estimated at $1,000/borehole for vertical emplacement and $2,000/borehole for horizontal emplacement.

TABLE 17

EQUIPMENT AND LABOR COSTS FOR EMPLACEMENT OPERATIONS PER 1,000 CANISTERS

Cost Element	Emplacement Method	
	Vertical	Horizontal
Labor	$ 426,000	$ 83,200
Capital (equipment and materials)	7,212,000*	1,879,600*
Maintenance (equipment)	121,200	104,200
Fuel	38,170	17,050
Total	$7,797,370	$2,084,050

* Includes installed cost of borehole plugs.

4.7.3.2 Retrieval (7-L, 7-M)

In estimating the costs of retrieval, it has been assumed that retrieval occurs at the same rate as emplacement and that backfilling occurs at closure. Costs are based on the assumptions stated for estimating the emplacement cost. Estimated costs for equipment, maintenance, fuel, and labor for retrieval operations are shown in Table 18.

TABLE 18

EQUIPMENT AND LABOR COSTS FOR RETRIEVAL OPERATIONS PER 1,000 CANISTERS

Cost Element	Emplacement Method	
	Vertical	Horizontal
Labor	$ 386,667	$ 196,986
Capital	1,212,000	1,041,600
Maintenance	121,200	104,160
Fuel	38,170	17,050
Total	$1,758,037	$1,359,796

4.7.4 Sealing (7-N)

Backfilling costs can be derived from Table 13 (Muck Handling Costs), with the following changes. It is assumed that drifts are backfilled using crushed tuff previously removed from the drifts. Equipment, repair, and maintenance costs are assumed to be the same as for muck removal (Table 13). Emplacement and compaction of backfill material will proceed at a slower rate than muck removal, which is assumed to add $\$1/m^3$ to those operating costs listed in Table 13. Based on these assumptions and on the data in Tables 13 and 24, backfilling costs are given in Table 19.

TABLE 19

BACKFILLING COSTS PER 1,000 CANISTERS

Cost Element	Emplacement Method	
	Vertical	Horizontal
Capital (equipment)	$ 270,800	$ 195,800
Repair and Maintenance	1,300,000	671,400
Operating Costs	1,511,900	167,000
Total	$3,082,700	$1,034,200

5.0 COMPARISON OF ALTERNATIVES

5.1 Basis of the Comparison

The evaluation of waste emplacement methods, given in Section 4 of this study, includes quantitative data and qualitative performance ratings. In this section, each method is compared on the basis of this information for the seven evaluation criteria.

Each of the emplacement methods is apparently superior, equal, or inferior to the others in some respect. Each has some merit. In addition, several factors affected by the emplacement method cannot be evaluated without the benefit of further studies. The extremes in potential preclosure performance offer the best basis for contrasting the three emplacement methods. Consequently, the comparison focuses on those factors that are rated good or unknown and on the relative cost of each emplacement method. The other criteria (worker hazards, environmental impact, and resource commitments) have the potential for increasing costs or for introducing uncertainty. The impact of these considerations is reflected in the cost analysis.

A summary of the evaluations, presented in Section 4, is shown in Table 20. The implications of this information for each waste emplacement method are discussed in the remainder of this section.

5.2 Self-Shielded Package

5.2.1 Factors Rated Good

The primary qualitative advantage of the SSP method results from the simplicity of repository mining and waste emplacement or retrieval equipment. However, because of the much lower (73%) drift mining costs for the horizontal emplacement method and the high heat flux into the drifts, the SSP may only have an advantage over the vertical emplacement method.

5.2.2 Factors Rated Unknown

The presence of the SSP on the drift floor introduces significant uncertainties regarding procedures for drift maintenance or backfilling after the waste is in place. Although no specific studies have been done, preliminary evaluations suggest that these complicating factors alone could cause the SSP method to be unacceptable.

5.2.3 Worker Hazards, Environmental Impact, and Resource Commitments

The potential injuries and fatalities associated with the SSP are significantly higher than for the other two emplacement methods. Fabrication of the SSP waste package is primarily responsible for the high level of hazard. Radiation doses do not vary significantly among the three methods. The worker exposure that results from handling the SSP is less than the worker dose for the vertical emplacement method, but it is three times higher than the dose for the horizontal emplacement method. This relationship is also similar for environmental impact; the volume of muck produced by the SSP method is less than in the vertical method but substantially more than that produced by the horizontal method. Resource commitments are highest for the SSP method because of the large quantity of steel required to shield the waste canister and the amount of power required to cool the drifts, should retrieval be necessary.

TABLE 20

COMPARISON OF ALTERNATIVES PER 1,000 CANISTERS

Cost Element	Emplacement Method		
	SSP	Vertical	Horizontal
Reliability	a		
Thermal Hydrology	U	A	G
Thermal/Structural Stability	A/AC	A/AC	A/AC
Mining Drifts	G	G	G
Boreholes	NA	G	U
Ventilation (Emplacement)	A/AC	A	G
Ventilation (Retrieval)	A/AC	A	G
Emplacement Equipment	G	A	U
Retrieval Equipment	A	A	U
Backfill at Closure	U	A	A
Flexibility			
Waste Package Fabrication	A/AC	G	A
Waste Package Materials	A/AC	G	A
Thermal/Structural Stability	A/AC	A	A
Boreholes	NA	A	A
Ventilation (Emplacement)	A/AC	A	G
Ventilation (Retrieval)	A/AC	A	G
Emplacement Equipment	G	A	U
Retrieval Equipment	G	A	U
Backfill at Closure	U	A	G
Worker Hazards			
Injuries	47.18	14.66	11.01
Fatalities	0.33	0.14	0.08
Radiation Doses (man-rem)	3.50	4.73	1.10
Environmental Impact			
(m^3 of muck)	262,240	429,640	47,435
Resource Commitments			
Steel (MT)	58,378	0	243
Diesel Fuel (L)	642,693	1,400,829	288,418
Power (million kWh)	208.2	156	44.9
Scheduling			
Mining Drifts	G	G	G
Boreholes	NA	G	U
Emplacement Equipment	G	A	U
Retrieval Equipment	G	A	U
Relative Cost ($k)	82,367[b]	35,075	10,615

a Good (G), Acceptable (A), Acceptable with Additional Cost (A/AC), Unknown (U), Not Applicable (NA).

b Costs do not include backfilling of access drifts.

5.2.4 Cost Analysis

The estimated cost of the SSP would exceed $82 million/1,000 canisters, 2.5 times that of vertical emplacement and more than 7.8 times the cost of horizontal emplacement. The primary cost element for the SSP method is the SSP itself ($64.3 million). In addition to the undetermined equipment and labor costs for waste emplacement, retrieval, and backfilling, other unknown factors, such as backfilling techniques, would increase the total cost of the SSP method. Drift cooling costs would be a major factor, should an extended period (50 yr) of maintenance be required before retrieval or closure.

5.3 Vertical Emplacement

5.3.1 Factors Rated Good or Acceptable

The primary advantages of vertical emplacement result from the flexibility of the waste package and borehole to accommodate a broad range of waste types. In addition, borehole drilling uses available technology. Even though most of the operations and equipment required for vertical emplacement would be adapted for use in a repository, they are expected for the most part to perform acceptably without additional cost.

5.3.2 Factors Rated Unknown

As shown in Table 20, sufficient information is available to adequately evaluate the vertical emplacement method.

5.3.3 Worker Hazards, Environmental Impact, and Resource Commitments

The potential nonradiological injuries and fatalities associated with vertical emplacement are significantly lower than for the SSP but only slightly greater than those for horizontal emplacement. The additional labor required for drift excavation and backfilling contributes to the proportionally higher hazard level than that for horizontal emplacement. In addition, emplacement and retrieval operations require more time per canister for vertical emplacement than for the other two methods.

Although radiation doses do not vary significantly among the emplacement methods, vertical emplacement has the highest potential dose. Exposure during backfilling operations contributes significantly to the increase over the other two methods.

The environmental impact caused by the excavated rock is the highest for vertical emplacement because of the large drift volume that must be mined to emplace waste vertically. Vertical emplacement also uses the most diesel fuel. The electrical power requirement for ventilation, particularly if waste retrieval is necessary, is lower than for the SSP method but three times greater than the power required for the horizontal method.

5.3.4 Cost Analysis

The relative cost of vertical emplacement is $33.6 million per 1,000 canisters, assuming that backfilling is done at the time the repository is decommissioned. The cost of vertical emplacement is at least 40% less than the cost of the SSP method and about three times the cost of horizontal emplacement. The primary cost factors are mining and waste emplacement activities. Ventilation during retrieval and borehole drilling also

contributes signficantly to the total cost of vertical emplacement. Of the three methods, cost estimates for vertical emplacement are the most reliable since there are relatively few unknown factors that could increase the cost.

5.4 Horizontal Emplacement

5.4.1 Factors Rated Good or Acceptable

The primary advantages of horizontal emplacement are the significantly smaller volume of drifts required and the signficantly lower heat flux into these drifts during the operational and retrieval periods. The low heat flux results from locating the waste within the rock mass at a significant distance from the emplacement drifts. The lower drift temperatures in the horizontal configuration result in lower ventilation requirements and insignificant impacts on thermal hydrology and thermal/structural stability of the repository.

5.4.2 Factors Rated Unknown

All uncertainties related to horizontal emplacement result from the construction and use of the long horizontal borehole. The technology for drilling long horizontal holes is not in use, and prototype equipment must be developed and tested before the horizontal emplacement method can be fully evaluated.

5.4.3 Worker Hazards, Environmental Impact, and Resource Commitments

The smaller volume that needs to be excavated and the reduced time per canister required for emplacement or retrieval result in lower potential nonradiological injuries and fatalities for horizontal emplacement than for the other two methods. In addition, radiation doses to workers are significantly lower during backfilling operations for horizontal emplacement than for the other two methods.

The environmental impact of the excavated rock is lowest for the horizontal emplacement method because of the significantly smaller volume of drifts required. Consequently, resource commitments are minimal. The amount of carbon steel used in the borehole liner is relatively small, the diesel fuel requirement is about 20% of that required for vertical emplacement, and the electrical power requirement is the lowest by a factor of four. The method has the added advantage of a minimal refrigeration requirement, should retrieval be necessary.

5.4.4 Cost Analysis

The total relative cost of horizontal emplacement is $10.6 million per 1,000 canisters, assuming that backfilling is done at the time the repository is decommissioned. The relative cost of horizontal emplacement is less than one-third that of vertical emplacement primarily because of the smaller drift volume and reduced equipment and labor costs for waste emplacement. However, there are signficant uncertainties associated with drilling and emplacing waste in horizontal boreholes. Borehole drilling and waste handling equipment have not been developed and tested. Consequently, there is greater potential for change in the relative cost estimates for horizontal emplacement than for the SSP and vertical methods.

5.5 Unresolved Issues

Development of information required for this comparison has identified several issues related to all three emplacement options that require further analyses. None of these issues appear to have a significant impact on the selection of a preferred emplacement configuration, but they may influence the extent to which a given alternative is superior or inferior to others.

The need for and extent of ventilation will be influenced by the results of radon emanation studies, a decision on the possible need for and design of drift backfill, and analysis of heat flow into access drifts. Further thermomechanical analyses are required to establish minimum spacings for boreholes for both horizontal and vertical emplacement and to determine the possible need for liners in vertical emplacement. The long-term performance of each concept will need to be evaluated with regard to the interactions of the slow vertical water flux with the zone of dehydration surrounding the emplacement boreholes. Finally, the extent to which repository designs for each emplacement method are constrained by variations in geologic conditions will need to be determined. This information will contribute to the eventual analysis of alternative respository designs associated with licensing actions.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this study is to identify the waste emplacement configuration that will be the safest, most dependable, and the least costly. Each of the emplacement configurations, as described in this report, is expected to satisfy preclosure repository performance requirements. Comparison of postclosure performance of the emplacement configurations is beyond the scope of this report.

6.1 Conclusions

The three emplacement methods differ primarily with respect to four factors: the length and volume of drifts required, heat flow from the waste into open ventilated drifts, the time required for waste emplacement or retrieval, and the extent to which available technology can be applied to the mining and repository operations. Safety, measured in terms of worker hazards, is most strongly influenced by the first three factors. Dependability, evaluated in terms of reliability, flexibility, and scheduling criteria, is controlled by all four factors. The relative cost of each configuration, including construction and operations, resource commitments, and environmental impact, is most strongly influenced by the first factor, length and volume of drifts required. The principal uncertainties in this comparison relate to the extent to which current technology is applicable to the equipment and operations required for each emplacement configuration.

6.1.1 Self-Shielded Package

The evaluation of the SSP concept indicates that it is the least desirable emplacement method and does not warrant further development. Costs are the highest, primarily because of material requirements for the waste package. The volume of mining needed, ventilation requirements, and potential operational problems associated with the presence of the waste package in the emplacement drift also contribute significantly to the cost. Potential worker injuries and fatalities are highest for this method, and potential radiation doses exceed those associated with horizontal emplacement.

As shown in Table 20, the only inherent advantage of the SSP over other emplacement methods is that the emplacement and retrieval equipment is relatively standard. It should be noted, however, that because of the great weight of the SSP, the equipment is exceptionally large and heavy and would necessitate additional shielding to minimize the exposure of workers to radiation. Furthermore, the obstruction presented by the waste package in the emplacement drift during backfilling and retrieval operations has not yet been addressed in design studies.

However, the placement of waste on the drift floor may be practical for those types of waste with lower thermal output than that of spent fuel or CHLW. Low thermal output is associated with lower radiation. A significant reduction in thermal and radiation fields around the waste package would eliminate many of the disadvantages of the SSP.

6.1.2 Vertical Emplacement

Emplacement of waste canisters in vertical boreholes is an acceptable method that satisfies the requirements of being safe and dependable. However, the relative cost is significantly higher than for horizontal emplacement as a result of the larger volume of

mining necessary, additional ventilation requirements in response to higher drift temperatures, and the significantly longer period of time required for waste emplacement and retrieval. Potential worker hazards and radiation exposure are slightly greater than for horizontal emplacement. Environmental impact and the amount of diesel fuel used exceed that of the other two methods.

The inherent advantage of vertical emplacement, as shown in Table 20, is that the operations and equipment required to emplace waste are based on available technology. No unknown factors were identified in the evaluation, and the cost estimate is based on the most reliable information. Nevertheless, the vertical emplacement method appears to be less desirable than horizontal emplacement, based on current information.

6.1.3 Horizontal Emplacement

The emplacement of waste in long horizontal boreholes is the least costly of the three emplacement methods and has the lowest number of potential injuries, fatalities, and radiation exposure of the three methods evaluated. As shown in Table 20, the inherent advantages of horizontal emplacement result from the significantly lower volume of mining needed, lower ventilation requirements during emplacement and retrieval, and the reduced time for waste emplacement. Environmental impact and resource commitments would be lowest due to the relatively small amount of mining required and better use of the rock medium to distribute heat.

However, there are significant unknowns that need to be addressed in future studies before it can be determined whether horizontal emplacement is a dependable method for waste emplacement. The uncertainties are associated with horizontal borehole drilling and with emplacement and retrieval of waste canisters. Developmental programs, conducted to date, suggest that equipment and operations can achieve design goals, but selection of horizontal emplacement as the waste emplacement method requires the demonstration of the necessary equipment and procedures.

6.2 Recommendations

The following recommendations are made based on the conclusions reached regarding the emplacement configurations compared in this study.

- The SSP should be given no further consideration for disposal of spent fuel.
- No significant additional design effort should be expended on vertical emplacement equipment until comparably detailed information regarding horizontal emplacement has been developed.
- Additional data and information should be developed regarding the feasibility of horizontal emplacement. Prototype equipment for drilling and lining the horizontal borehole should be developed and tested, as well as prototype equipment for emplacement and retrieval of the waste packages.

APPENDIX

SUPPORTING DATA AND ANALYSES

APPENDIX

SUPPORTING DATA AND ANALYSES

A.1 Waste Package Design

The aspects of waste package design that differ significantly among the three emplacement configurations are the fabrication and material requirements, as detailed below.

A.1.1 Self-Shielded Package

The spent fuel package is designed to hold fuel rods from 8 pressurized water reactor (PWR) fuel assemblies or 18 boiling water reactor (BWR) assemblies. The dimensions of the SSP for PWR spent fuel are 142 cm x 142 cm x 5.2 m. The SSP concept involves placing high-level nuclear waste in cast-iron or steel canisters. The principal component of the package is the overpack, which consists of the cast main body and the cast shield/seal plug. The wall thickness of the main body (typically 30 to 47 cm) is sized to reduce the radiation level at the outer surface to 100 mrem/hr or less. The waste form is inserted in the overpack in a hot cell, and the shield/seal plug is installed. The assembly is moved out of the hot cell to a welding facility where local shielding protects personnel until the final closure. The SSP has an internal cage to aid in loading the fuel rods and to promote heat transfer from the fuel rods to the overpack. An exterior cast-iron plate facilitates transfer of heat to the surrounding rock and emplacement drift. The SSP is described in a report by Westinghouse (1982).

Potential advantages of the SSP include simplification of emplacement operations and elimination of drilled emplacement holes and the need for shielded transfer casks. However, conceptual design studies made by Lawrence Livermore National Laboratory indicate that the SSP could be more costly in meeting 10 CFR 60 (CFR, 1984b) requirements than would alternative waste packages (Rothman, 1982). SNL has recommended that the concept not be developed further (Scully, 1982) for the following reasons.

1. In part, Westinghouse bases its conclusion that the SSP is economically competitive on the assumption that no hot cell would be required in the repository. That assumption is not valid as a [redacted]. The recently imposed ground rule that the three Civilian Radioactive Waste Management Program repositories must be designed to accept "intact" fuel assemblies removes any possibility of operation with a simple, low-cost hot cell.

2. Handling equipment for the SSP would be inordinately large and heavy. The proposed SSP for PWR fuel rods (8 fuel assemblies, 4,400 W thermal power) weighs 77 metric tons. Even at that weight, a surface dose rate of 100 mrem/hr is predicted. (To add perspective to the issue of size, a ball of solid steel weighing 77 metric tons would be nearly 9 ft in diameter.)

3. Westinghouse implies that the SSP is a "hands-on" package. Surface dose rates for the various SSP configurations described by Westinghouse (1982) range from 50 to 100 mrem/hr. While this is within the 200-mrem/hr limit generally accepted as the limit for contact-handled TRU waste, the radiation hazard is different for the two waste types: every SSP will exhibit a relatively high surface dose rate, whereas the average for contact-handled

TRU waste is likely to be much lower. (The average surface dose rate for 55-gal drums of defense TRU waste at the Idaho National Engineering Laboratory is about 3 mrem/hr.)

4. Radiation dose rates notwithstanding, direct hands-on contact with SSPs would be impossible because of the high surface temperature. Westinghouse estimates that, for CHLW, the SSP surface temperature is in excess of 50°C even with blast cooling. In still air, the temperature would be much higher.

5. The retrieval of SSPs is considered to be much more complicated than a simple reversal of the emplacement process. The working environment, specifically temperature and radiation levels, would be more severe than for retrieval from either horizontal or vertical boreholes.

6. Delayed backfilling of the disposal drifts in the SSP method would be more difficult than in either of the other two emplacement methods. If backfilling proceeds as the waste is emplaced, remining the drifts for waste retrieval might well be impossible in the SSP disposal scenario, and, at best, it would be more difficult than for either horizontal or vertical borehole emplacement.

Based on these and other reasons, such as the large quantity of iron required for fabrication of the shielding, it has been decided that the SSP offers too few advantages to warrant further development.

A.1.2 Vertical Emplacement

The waste package for vertical emplacement consists of a waste canister and plug emplaced at the top of the borehole (see Figure 4). The reference canister for spent fuel (Westinghouse, 1982) consists of a 304-L stainless steel canister divided into six sections. The canister wall is 1 cm thick, which provides sufficient strength for handling and emplacement. The canister for spent fuel has an outside diameter of 50 cm, is 390 cm long, and will hold the fuel rods from 6 PWR assemblies. The canister has a thermal output of 3.4 kW for 10-yr-old fuel. The canister for BWR fuel is 60 cm in diameter, 410 cm long, and will hold the fuel rods from 18 BWR assemblies (3 assemblies per section). It has a thermal output of 3.42 kW for 10-yr-old fuel (O'Brien, 1984).

A.1.3 Horizontal Emplacement

The waste package for horizontal emplacement consists of several waste canisters, two plugs (see Figure 5), and a borehole liner to facilitate canister emplacement and retrieval. The waste canister is the same for both vertical and horizontal emplacement. Because the liner must remain intact only for the retrieval period (50 yr), it can be made of relatively inexpensive carbon steel.

A.2 Thermal/Structural Analyses

As described in the following sections, analyses were performed to calculate the effects of thermal loading on hydrologic and structural conditions in the underground facility and on ventilation requirements for the repository following waste emplacement.

A.2.1 Temperature Distributions and Heat Flow

To evaluate the effects of thermal loading, temperature distributions around the waste canisters and emplacement drifts and the heat flux into ventilated drifts must be calculated. The calculations are based on the following assumptions:

- The canisters of spent fuel have a thermal output of 3.4 kW/canister.
- The average thermal loading is 50 kW/acre.
- Drifts are not backfilled.
- Average properties of the potential emplacement horizon (Peters, 1982) are those of the Topopah Spring Member of the Paintbrush Tuff given in Appendix A.6.
- The concrete material used for the isolation plugs has the same properties as those of the host rock.
- The standard working temperature for miners and workers in the repository is 26°C, the wet bulb global temperature (WBGT) (Johnstone and Gnirk, 1982).

For each emplacement configuration, analytical and/or numerical calculations were made of the spatial and temporal temperature distributions around the waste canisters. From these calculations, three critical parameters were identified as having the greatest impact on repository design. These parameters are

- Temperature of the waste canister (or exterior of the SSP). Canister temperature is of concern with regard to both emplacement and retrieval operations and influences the performance of the steel liner for horizontal emplacement. The time-history of the canister temperature is one set of results in the calculation of moisture conditions around the emplacement location.

- Temperature of unventilated access or emplacement drifts. The time-history of drift temperatures influences structural stability of the drifts, as well as the need for ventilation during emplacement or retrieval operations.

- Heat flux into ventilated drifts. The ventilation required to maintain acceptable working conditions in the drifts is controlled by this parameter.

A.2.1.1 Methods of Analyses

The analysis of these parameters was done with different techniques for the three emplacement schemes. For example, both two-dimensional and three-dimensional models were used for calculation of temperature distributions. Attention was given to ensuring maximum consistency among the methods, and the differences in the computational methods do not invalidate the comparisons.

For the thermal analysis of the SSP (Bixler, in preparation), it was assumed that the heat source was distributed uniformly along the axis of the emplacement drift rather than being concentrated in a series of point sources. A dispersed heat source assumption will result in calculated canister temperatures that are significantly lower than those resulting from the actual, concentrated heat source. To compensate for this effect, a proportional reduction was made in the thermal capacity of the SSP material in the two-dimensional calculation. No adjustments were made in the thermal properties of the tuff.

For the analysis of vertical emplacement, the temperature distributions around and heat flow into the emplacement drift were evaluated using a two-dimensional model (Flanagan and Subia, 1983a).

For the analysis of horizontal emplacement, both two-dimensional and three-dimensional analyses were performed for temperature distributions around, and heat flow into, the emplacement drift. In the two-dimensional analysis (Wilson, 1983), the heat source was uniformly distributed parallel to the axis of the emplacement drift. This representation is adequate for calculation of temperatures and heat flow into the emplacement drifts but does not accurately portray temperature and heat-flow conditions in the vicinity of the boreholes. In the three-dimensional analyses (Sisson, 1982; Peters, 1983), the heat source was localized in the borehole. This localization is appropriate for calculating canister and borehole conditions. In both analyses, it was assumed that boreholes were open-ended, extending between adjacent emplacement drifts, with a computational line of symmetry midway between the drifts. Emplacement drift separation was taken as 200 m (Sisson, 1982; Peters, 1983).

A.2.1.2 Discussion of Analytical Results

The calculated temperatures of the waste package surface or the borehole surface are summarized in Table 21 and Figure 8.

Average drift temperature, as a function of time for unventilated emplacement drifts, is presented in Table 22 and Figure 9. Because the gross thermal loading is the same for all three configurations, it is reasonable that the access drifts for the SSP and vertical emplacement configurations exhibit thermal responses similar to those of the horizontal emplacement drifts (see Figures 1, 4, and 5).

The calculated heat flow into ventilated emplacement drifts varies with time and emplacement method, as shown in Table 23 and in Figure 10. For this analysis, all emplacement drifts were assumed to be open and ventilated to maintain a constant air temperature.

In the SSP configuration, most of the heat generated is transferred to the air in the drift space; the remaining heat is conducted into the rock beneath the SSP. Thus, to cool the emplacement drift, nearly all the generated heat would be removed by ventilating the drift.

The access drifts would be included in the ventilation airflow pathway and thus would be approximately the same temperature as that of the ventilated emplacement drifts. In the absence of ventilation and if the emplacement drifts are not sealed off from the access drifts, convective heat flow will raise access drift temperatures to temperatures approaching those of the emplacement drifts. If emplacement drifts are sealed off, access drift temperatures can be expected to be lower than in the unsealed case.

In the vertical emplacement configuration, the initial temperatures and heat flow into the emplacement drift are lower than those in the SSP configuration because the rock surrounding the drift can absorb more of the heat that is generated. As in the SSP concept, air temperatures in open access drifts will be similar to those in the emplacement drifts unless the access drifts are sealed off.

TABLE 21

WASTE PACKAGE TEMPERATURES[a]

Time (Years)	Emplacement Method Temperature of Borehole or Package Surface (°C) SSP[b]	Vertical[c]	Horizontal[d]
2	NC[e]	190	280
5	NC	190	NC
10	87	184	275
20	95	170	250
30	98	157	225
40	99	146	210
50	99	137	200
60	98.5	NC	190
70	98	123	180
80	98	NC	175
90	97.5	112	170

a Temperatures were not tabulated for all time periods in the analyses.
b Two-dimensional analysis of package surface temperature (Bixler, in preparation).
c Three-dimensional analysis (Mansure, 1983).
d Three-dimensional analysis (Peters, 1983).
e NC means not calculated.

TABLE 22

TEMPERATURE OF UNVENTILATED EMPLACEMENT DRIFTS[a]

Time (Years)	Emplacement Method Temperature of Borehole or Package Surface (°C) SSP[b]	Vertical[c]	Horizontal[d]
0	25	25	25
10	79	66	28
20	88	84	33
30	92	NC	38
40	94	NC	45
50	95	NC	NC
60	NC[e]	NC	56
70	NC	NC	NC
80	NC	95	63
90	94	NC	NC
100	NC	NC	68

a Elapsed times were not identical in all analyses.
b Bixler, in preparation.
c Flanagan and Subia, 1983a.
d Sisson, 1982.
e NC means not calculated.

TABLE 23

HEAT FLUX INTO ACCESS DRIFTS VENTILATED AT 30°C[a,b]

	Emplacement Method					
	SSP[c]		Vertical[d]		Horizontal[e]	
Time (Years)	kW/Canister	kW/1,000 Canisters	W/m	kW/1,000 Canisters 11,000-m Drift	W/m	kW/1,000 Canisters 1,360-m Drift
1	2.5	2,500	NC	NC	NC	NC
10	2.0	2,000	162	1,782	11	14.6
20	NC[a]	NC	156	1,716	NC	NC
30	1.7	1,700	NC	NC	42	55.6
40	1.6	1,600	128	1,408	NC	NC
50	1.4	1,400	113	1,243	56	74.1
60	NC	NC	NC	NC	NC	NC
70	NC	NC	NC	NC	NC	NC
80	NC	NC	85	935	NC	NC
90	0.8	800	NC	NC	66	87
100	NC	NC	74	814	66	87

a Heat flow values were not reported for the same time intervals in all analyses. NC means not calculated.
b Drift length reflects repository design concepts used for thermomechanical analyses at the time the analyses were performed.
c Bixler, in preparation.
d Flanagan and Subia, 1983a.
e Wilson, 1983.

In the horizontal emplacement configuration, the temperature curves in Figure 9 clearly show that unventilated drift temperatures remain much lower than those in the other two configurations. The lower temperatures associated with horizontal emplacement result primarily from the waste being significantly farther from the drift than in the SSP and vertical emplacement configurations. The intervening rock mass absorbs heat and dissipates the heat in the surrounding rock. This produces both lower drift temperatures and lower heat flow per unit length of drift. The magnitude of this effect is directly related to the standoff distance between the drift face and the waste canisters.

In the horizontal configuration, a portion of the heat flow away from the canisters occurs in a radial direction towards the access drifts that are parallel to the emplacement hole (see Figure 5). In particular, a significant portion of the heat generated in the emplacement holes closest to the access drifts will flow toward the access drifts. The magnitude of this effect can be controlled by the distance that separates the access drift from the emplacement holes on either side of the drift.

Subsequent to the analyses cited in this report, a decision was made to use blind horizontal boreholes in the repository design and to double the separation distance between adjacent emplacement drifts. However, the temperature distributions

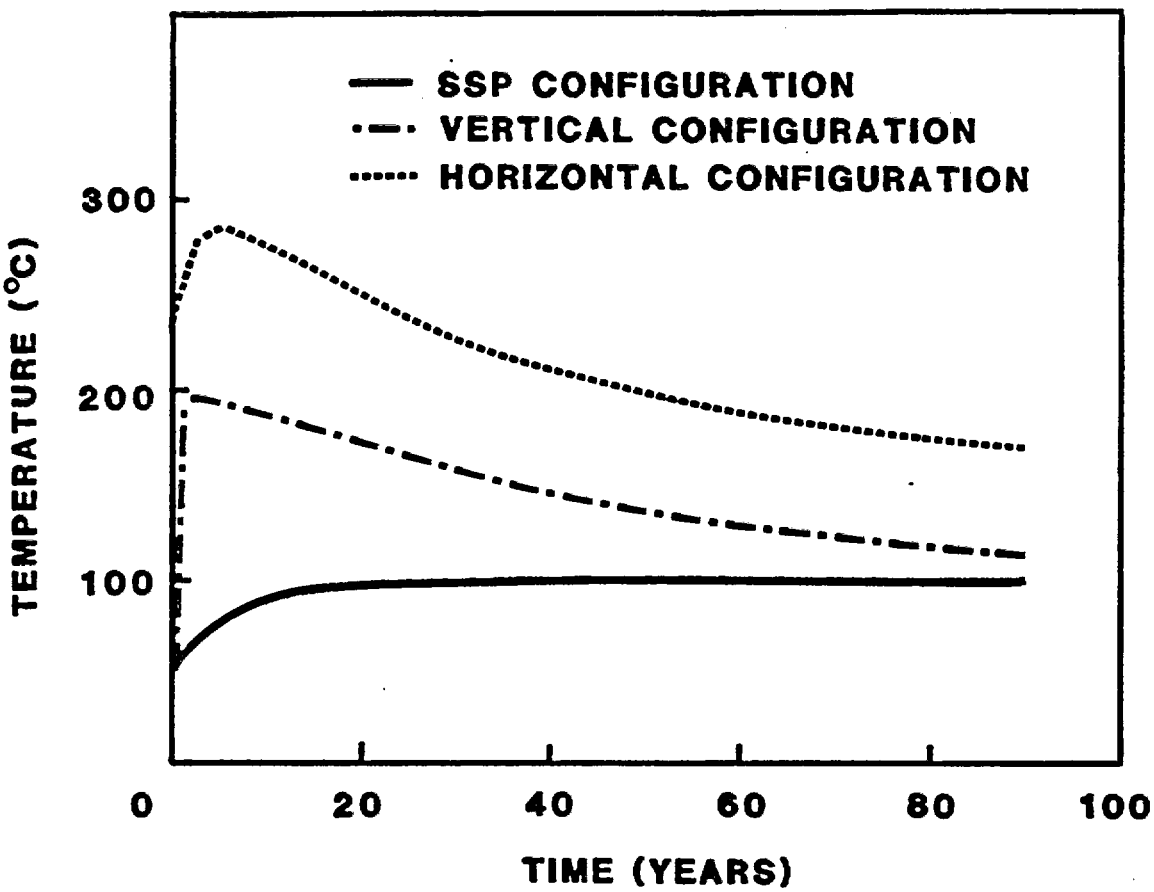


Figure 8. Temperature of Borehole or Package Surface Versus Time

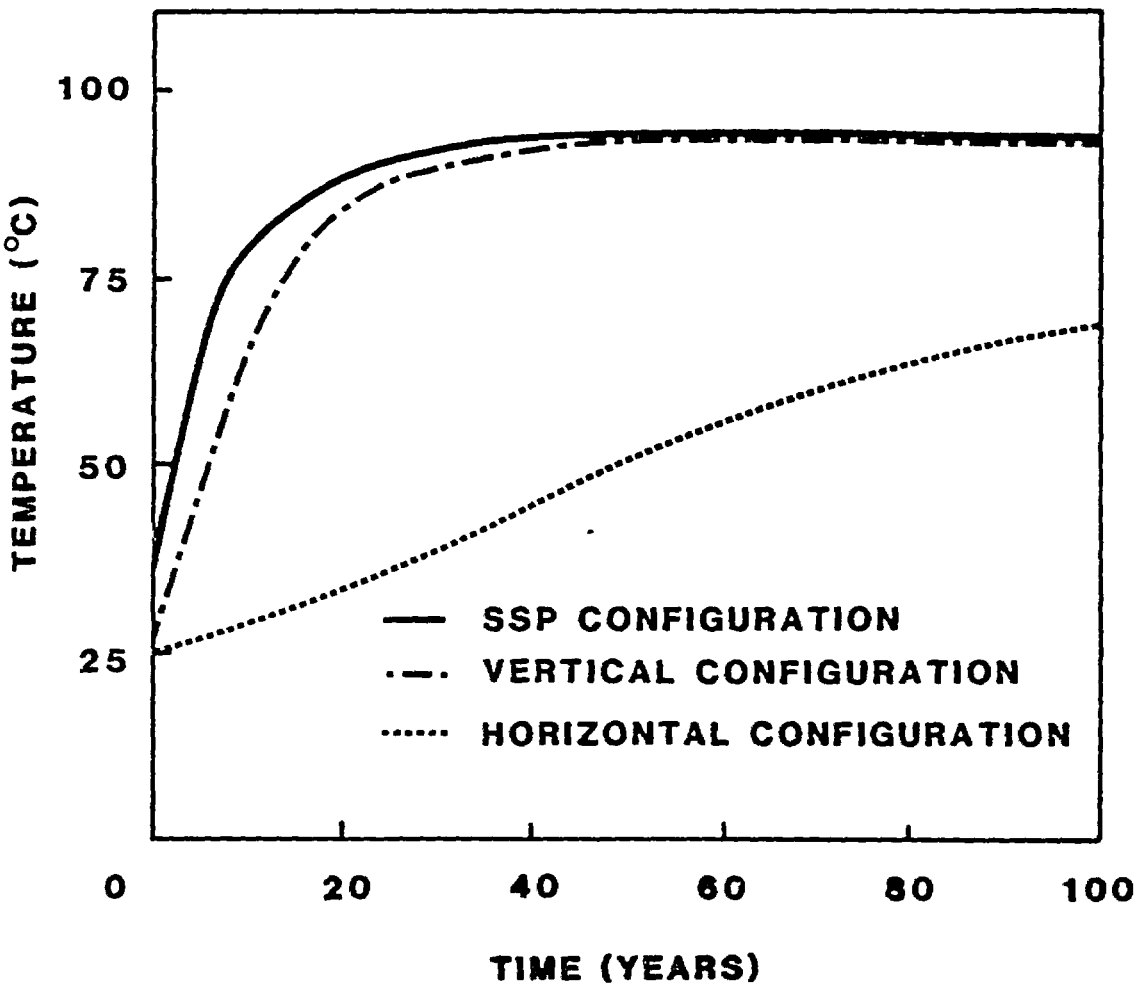


Figure 9. Temperature of Unventilated Emplacement Drifts

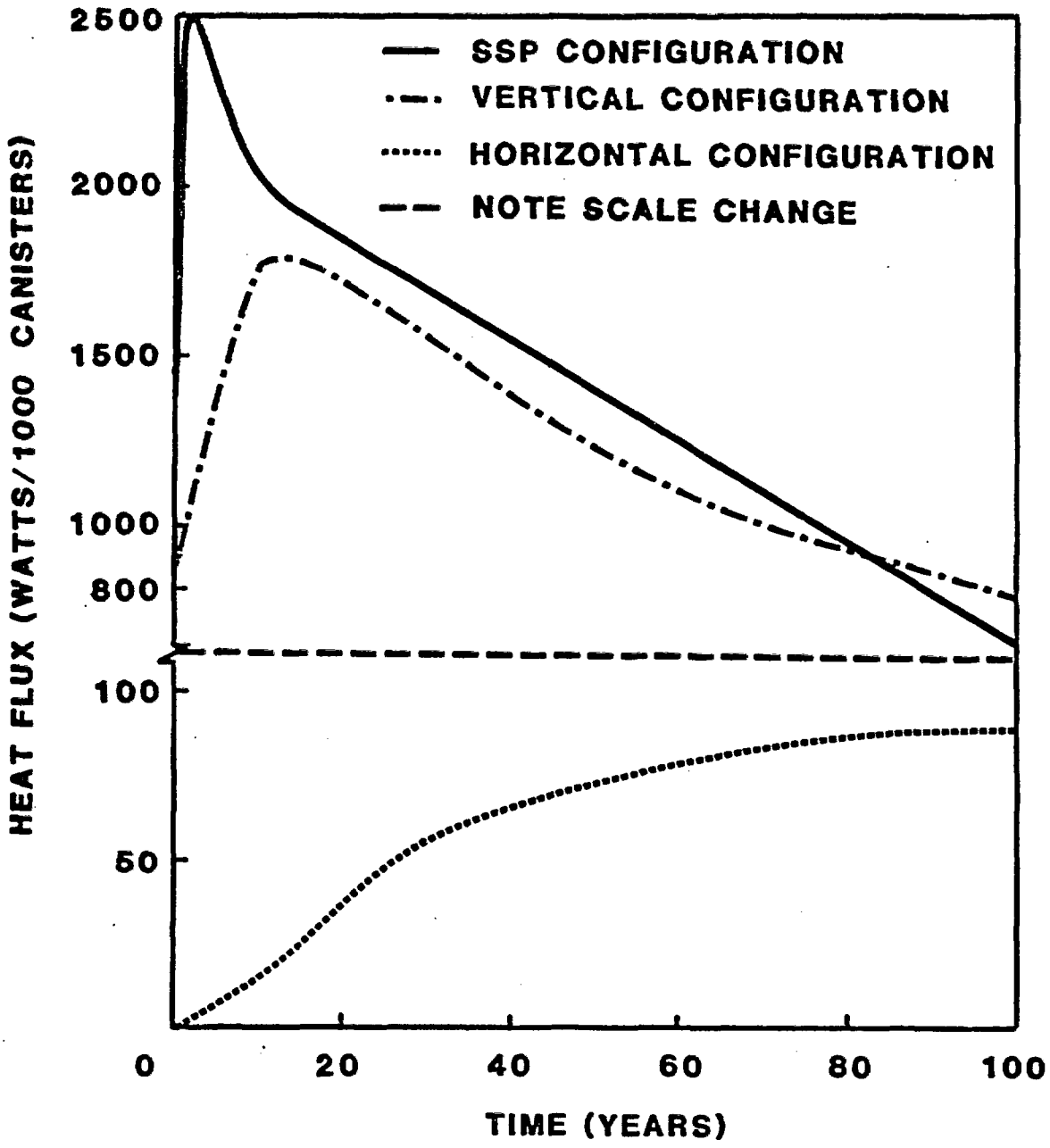


Figure 10. Heat Flux into Ventilated Drifts

calculated in the three-dimensional analysis of horizontal emplacement indicate that, with a 24-m standoff distance, nearly all the heat flowing towards the emplacement drift is generated within about 80 m of the drift. Beyond that distance, most of the heat flows radially outward from the borehole, suggesting that the length of the borehole beyond 80 m has little effect on emplacement drift temperatures based on a 24-m standoff distance. Thus, the change from the borehole configuration used in these analyses to the blind boreholes shown in Figure 5 will not significantly change the results for the purpose of comparing emplacement methods.

A.2.2 Thermal Hydrology

The presence of heat sources in partially saturated rock has two sequential effects on moisture distribution. First, at temperatures in the 110° to 120°C range, liquid water is vaporized and the tuff is dehydrated. This water vapor moves toward locations of lower temperatures. Second, after long periods of time have elapsed and the canister has cooled, water in the liquid state moves back toward the zone of dehydration that surrounds the decaying heat source.

In the vertical emplacement method, the dehydrated region extends about 3 m from the canister (Mansure, 1983). In the horizontal emplacement method, the dehydrated region extends about 16 m from the canister (Sisson, 1982). The consequences of dehydration are still being investigated. A dry environment for the waste package could be an advantage in protecting the canister from corrosion. Results to date indicate that there will be a significantly larger dehydration zone in the horizontal emplacement configuration, and the dehydration zone will last for a longer period of time.

The temperature rise around the emplaced waste canister can influence the repository hydrology in two significant ways. The first is due to forced convection resulting from expansion of water as it changes from liquid to vapor; the second is from free convection due to bouyancy forces. Free convection effects for partially saturated conditions are extremely difficult to calculate. However, free convection is less likely to occur in the event of partial saturation than in the case of 100% saturation because of the lower relative permeability conditions. Two-dimensional calculations were performed for the saturated case for the vertical emplacement method to determine whether conditions were sufficient to induce free convection (Mondy, 1983), and none was observed. Because thermal gradients are slightly higher in the horizontal emplacement method, the occurrence of free convection should be investigated; however, at this time it does not appear that the occurrence of free convection should be an issue in selecting a waste emplacement configuration.

The forced convective water movement away from the canisters has little or no impact on radionuclide transport because the flow away from the waste is in the vapor phase and does not dissolve and transport radionuclides. Condensation on the walls of open drifts during the operating phase of the repository is a potential concern. However, the superficial water velocity into the drift that results from ventilation of the drift is 10 to 100 times greater than the superficial water velocity towards the drift wall caused by the expansion of the dehydration zone (Mondy, 1983). This phenomenon suggests that it is unlikely that forced convection can move water to the drift walls faster than ventilation will cause it to evaporate. Because of the larger standoff distance used in the horizontal emplacement method, condensation problems are less likely to occur than in the SSP and vertical methods.

Ventilating the drifts will dry the drift walls and, as a result, water will migrate to the drifts from areas of higher saturation. Two-dimensional calculations of this effect have been performed for both the vertical and horizontal emplacement methods (Mondy, 1983). Horizontal emplacement showed slightly higher velocities (by a factor of 3), but the difference was not large compared to uncertainties in the model. Thus, there is no significant difference in the hydrologic effects induced by ventilation between the vertical and horizontal configurations.

A.2.3 Thermal/Structural Stability

Excavation of drifts and boreholes produces load stresses in the surrounding rock. Heating of the rock changes its mechanical properties and imposes additional stress through differential thermal expansion. Additional structural support in drifts may be required to prevent movement along joints that could lead to excessive rock fall into the drifts. Thermal and mechanical analyses of the near and far fields confirm that the waste emplacement configuration has no effect on the far-field repository unit (Johnstone and Peters, 1984).

No thermomechanical analysis of the SSP configuration was performed. However, calculated temperature distributions around the emplacement drift are similar to those for the vertical emplacement configuration. By inference, the thermal/mechanical effects would also be similar.

The thermomechanical effects on the emplacement drift for the vertical concept were analyzed using the two-dimensional thermal analysis described in Subsection A.2.1 (Flanagan and Subia, 1983a). The potential for joint motion and development of tension cracks was analyzed for both unventilated and ventilated conditions.

The unventilated case results indicate a potential for localized joint movement near the corners of the drift wall but not in the roof. The region of potential joint movement was sufficiently close to the drift that rockbolt and wire-mesh technology should be more than adequate to prevent significant rock fall. A potential may exist for development of tension cracks in the walls of the access drifts, but thermostructural analyses of access drifts have not yet been performed.

Evaluation of horizontal emplacement for both ventilated and unventilated conditions (Flanagan and Subia, 1983b) indicates that the same degree of potential joint movement exists as for vertical emplacement. The bulk of the potential movement is associated with excavation. There is a slight increase in potential joint movement in the unventilated case. Conventional rockbolt technology is adequate to provide any required structural support.

The evaluation also indicated a potential for development of tension cracks in the walls of the horizontal emplacement drifts. The predicted horizontal tension cracks do not pose a drift stability concern but will need to be considered in the design of the borehole covers.

Some potential for tension crack development was predicted near the midpoint of the horizontal borehole, where temperatures are greatest. However, the presence of the steel borehole liner will obviate any concerns from this issue. Thus, the result of induced stress from heating by the waste will require some additional design effort for horizontal emplacement but will not be of significance in repository development.

A.3 Mining and Ventilation

The most important factors associated with repository construction are mining and ventilation requirements. Preliminary estimates of mining, drilling, and ventilation requirements for the repository are shown in Table 24. Several excavation methods are now being considered. Cost estimate data presented in this report are based on the drill-and-blast technique (Dravo, 1984a). Structural support requirements for the drifts appear to be nominal (Johnstone and Peters, 1984). Conceptual descriptions of the mining of access and emplacement drifts, borehole drilling, and ventilation of the mine and repository during emplacement and retrieval are presented in the following subsections.

A.3.1 Mining and Drilling

As shown in Table 24, the waste emplacement configurations differ substantially in the amount of rock that must be excavated for emplacing the waste. About 5 and 9 times more rock, respectively, must be mined for the SSP and vertical emplacement methods than for the horizontal method. Drilling requirements for the three emplacement configurations also differ markedly. The SSP concept does not require drilling of boreholes. Vertical emplacement requires 1.4 times the borehole length than that required for horizontal emplacement. Horizontal emplacement requires larger diameter boreholes to accommodate the borehole liner.

The layout and dimensions of access and emplacement drifts are controlled in part by requirements for structural integrity of the underground facility. The spacing and dimensions of drifts (Table 1) assume placement of spent fuel (3.4 kW/canister) for a total areal power density of 50 kW/ acre. For wastes with lower thermal output, a larger number of canisters can be accommodated per acre while maintaining the same areal power density. An increase in the number of canisters would require modifications in the interval spacings of canisters, drifts, and/or boreholes. Table 25 summarizes the interval spacing of drifts and boreholes required for vertical and horizontal emplacement for waste types of three different power levels.

As shown in Tables 24 and 25, the two emplacement methods differ in two respects regarding structural stability: (1) the structural integrity of the drifts as influenced by their height, width, and borehole spacing, and (2) the total areal fraction of the repository zone penetrated by drifts or boreholes (extraction ratio). These factors also vary as a function of waste type.

The stability of drifts decreases some with increasing drift height and decreases more significantly with increasing drift width. As previously described, the drifts required for placement of spent fuel in all three configurations are of comparable stability. However, as shown in Table 25, closer spacing of horizontal boreholes is possible for waste with lower thermal output. This closer spacing would reduce the distance between adjacent alcoves, reducing the overall drift stability. This phenomenon will restrict the spacing of the boreholes where alcoves are required to some minimum value greater than that allowed by the areal power density value. Closer spacing of boreholes in the vertical configuration to efficiently accommodate waste with lower thermal output is also limited by the drift stability factor.

The extraction ratio, expressed as a percentage, is defined as the ratio between the excavated area in a horizontal plane through the repository and the total plan-view area of the repository zone. To ensure overall structural stability of the repository, it is desirable that the extraction ratio be less than 25%.

TABLE 24

PRELIMINARY MINING, DRILLING, AND VENTILATION CHARACTERISTICS PER 1,000 CANISTERS[a]

Characteristic	Emplacement Method		
	SSP	Vertical	Horizontal
Mining			
Drift Cross Section (Area)	3.7 x 6 m ($22\ m^2$)	Access 3.7 x 6 m ($22\ m^2$) Emplacement 6.7 x 6 m ($40\ m^2$)	3.7 x 6 m ($22\ m^2$)
Length of Mined Drift[b]			
Access	2,620	2,620 m	1,275 m
Emplacement	9,300	9,300 m	705 m
Total	11,920	11,920 m	1,980 m
Mined Material	262,240 m^3	429,640 m^3	47,435 m^3[c]
Drilling			
Total Drilling Length	0	7,620 m	5,555 m
Drilling Length per Canister	0	7.6 m	5.5 m
Canisters Emplaced	1,000	1,000	1,000
Drill Set-Ups per Canister	0	1	0.029
Ventilation			
Tons of Refrigeration	3,114	1,903	57

a 3.4 kW/canister.

b The central sections for both vertical and horizontal configurations are considered common and therefore are not included.

c Current concepts include alcoves for horizontal emplacement, which results in additional mining of 3,875 m^3 of tuff.

d Total mine area is assumed to be ventilated in the horizontal configuration; one-half of the mine is assumed to be ventilated in the SSP and vertical configurations.

TABLE 25

INFLUENCE OF WASTE TYPE ON EXTRACTION RATIO

kW per Canister	Canisters per Panel	Canisters per Borehole	No. of Boreholes	No. of Emplacement Drifts	Boreholes per Drift	Spacing Between Boreholes (m)	Mined Area (m^2)	Extraction Ratio (%)
Vertical[a]								
0.5	4,200	1	4,200	14	300	2.5[e]	50,052	24.1
2.2	1,054	1	1,050	14	75	6	50,052	24.1
3.4	700	1	700	14	50	9	50,052	24.1
Horizontal[b]								
0.5	4,800	50[c]	96	1	96	9[f]	22,248[f,g]	10.8
2.2	1,078	49[d]	22	1	22	43	12,310[f]	5.9
3.4	700	35	20	1	20	48	11,948[f]	5.7

a A panel is assumed to be 427 m (access drift length) by 486 m with a total area of 207,500 m^2 and a maximum thermal loading of 2,400 kW.

b A panel is assumed to be 414 m (access drift length) by 500 m with a total area of 207,000 m^2 and a maximum thermal loading of 2,400 kW.

c Assumes each canister occupies 3.4 m, with a 15.2-m standoff distance.

d Assumes each canister occupies 3.2 m, with a 23-m standoff distance.

e Boreholes may be alternately offset from drift centerline.

f Assumes no alcoves are required; includes area of borehole.

g Includes area of borehole.

The preliminary repository layouts depicted in Figures 3 and 6 are based on the present understanding of the thickness and configuration of the candidate horizon, and on location and orientation of major fault zones. The density and orientation of joints will also impact repository design (Dravo, 1984a). These designs will be modified as additional geologic data are collected from boreholes and the exploratory shaft. These data, along with additional information collected during construction of the underground facility will impact the repository layout in several ways (Dravo, 1984b). Fault zones with high fracture density may need to be avoided as emplacement zones. The orientation of drifts may be influenced by joint orientations. Vertical displacement of the emplacement horizon across fault zones may restrict the boundaries of repository panels. The dip and thickness of the repository horizon may also limit panel boundaries. The extent of these constraints is conjectural, and many of these concerns may be overcome by additional ground support in critical areas.

The ability of the repository layout for each emplacement method to accommodate geologic constraints may be an important consideration in selection of a method. This flexibility has not been evaluated to date, but some key elements can be identified.

The repository design associated with the SSP and vertical emplacement, Figure 3, is presented as a series of panels approximately 50 acres each in area. However, the spacing and orientation of drifts could be varied continuously within constraints imposed by structural considerations, as local geologic conditions dictate. Similary, the location of emplacement holes could be varied to avoid less desirable locations. The repository design associated with vertical emplacement thus appears to accommodate variations in geologic conditions with relative ease.

The advantages of horizontal emplacement stem, in part, from the large number of canisters that can be placed in a given borehole, and the heat distribution effects associated with the 24-m standoff distance. However, maintaining the limiting areal power density requires substantially greater separation between boreholes than that dictated by structural considerations alone (see Table 25). Restrictions on borehole length or orientation on emplacement drift location and orientation directly impact adjacent boreholes and panels. Some as yet undetermined minimum panel size exists below which the use of a given area is inefficient. Limitations on the allowable slope of emplacement boreholes have not been established, but the configuration of the potential horizon may influence the optimum slope.

Thus, limitations on the size and layout of a typical panel, imposed by geologic constraints, might limit the advantages of horizontal emplacement. Further design studies will be required to resolve this issue.

A.3.2 Drilling Equipment

One of the major reasons that preliminary conceptual designs have focused on the shallower vertical borehole instead of on the long horizontal borehole concept is the availability of equipment. The equipment required for drilling horizontal boreholes and emplacing and retrieving the waste must be developed. Innovative concepts that can be used have been described (Young et al., 1983). However, it is significantly more difficult to drill a 200-m horizontal hole 0.8 m in diameter and place a canister of waste at the end of it than it is to drill a 7.6-m vertical hole and lower the canister to the bottom.

A conceptual drawing of the equipment required to drill holes for vertical emplacement is shown in Figure 11 (Robbins, 1984). Vertical boreholes are only 7.6 m deep with a 3.1-m standoff distance between the waste canister and the plug emplaced in the drift end of the borehole.

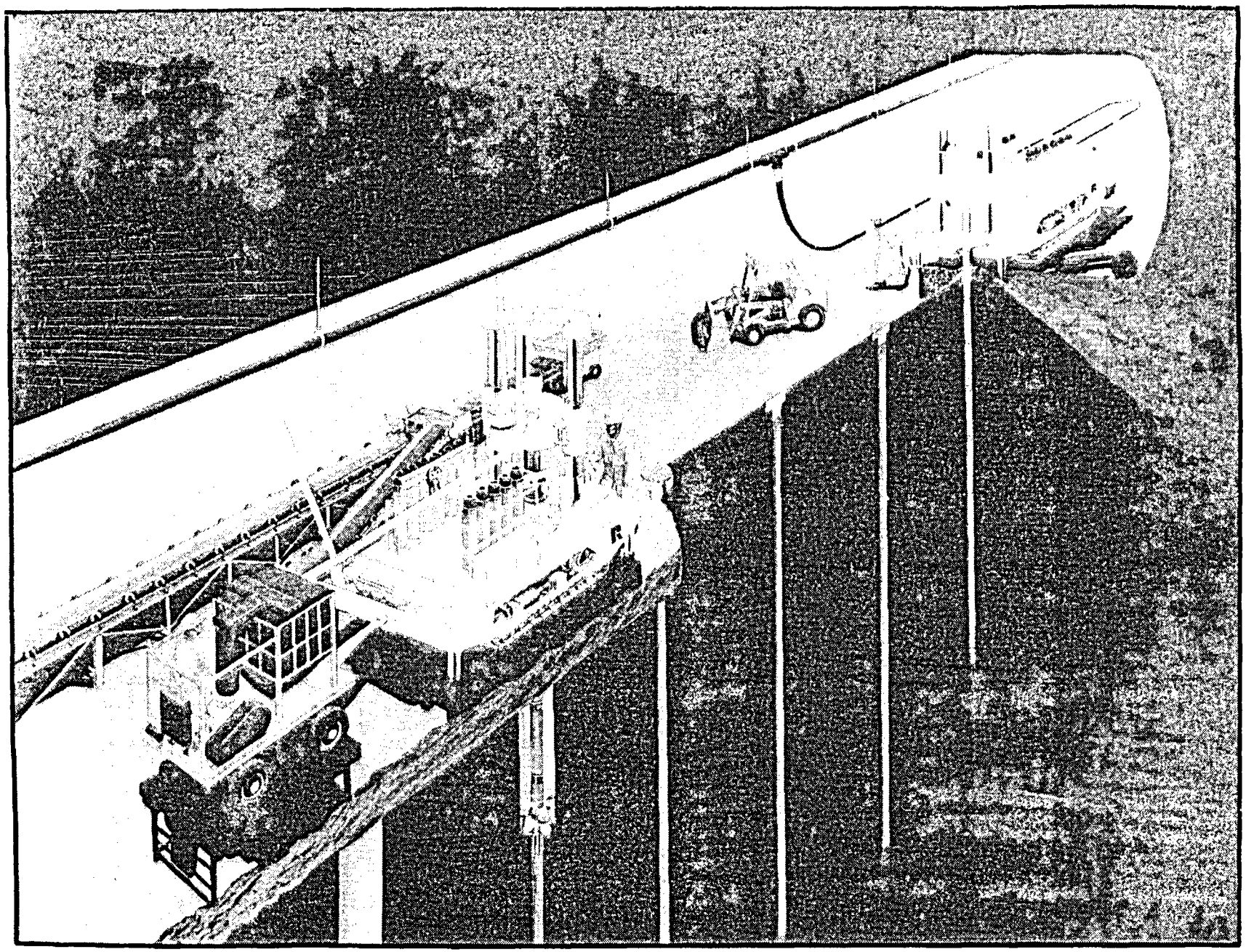


Figure 11. Vertical Boring Machine

Although the mining industry routinely drills horizontal holes, the boreholes are not drilled with precision. A conceptual horizontal boring machine that addresses the precision drilling problem and a guidance system for controlling the direction of the hole is shown in Figure 12 (Robbins, 1984). Stabilizing the long horizontal hole against rock fall appears to be feasible if existing technology is adapted to installing a steel liner (Young et al., 1983).

A.3.3 Ventilation

Health and safety considerations require that the repository be ventilated during mining, waste emplacement, and retrieval (Johnstone and Gnirk, 1982). The thermal analyses described in Subsection A.2.1 were used to evaluate ventilation requirements for each emplacement method, assuming all drifts were open and ventilated (Hickox, 1983). The air flow required for ventilation is directly related to the heat flow rate into the drift and to the volume of drift to be ventilated. Thus, as shown in Tables 23 and 24, the SSP configuration has the greatest ventilation requirement, and the horizontal emplacement configuration has the lowest.

Estimates were made of the refrigeration required to cool air from an ambient temperature of 27°C to an assumed drift inlet temperature in the range of 5° to 20°C for each of the three emplacement configurations. The SSP concept requires 55 times (3,114 MT), and the vertical configuration requires 33 times (1,903 MT), the refrigeration required by the horizontal emplacement method (57 MT) per 1,000 canisters of waste to maintain the same drift temperature. The power required to move air through the drifts depends upon the total drift volume, as well as the air velocity necessary to remove heat from the drift walls. Drift volumes are greatest for vertical emplacement and lowest for horizontal emplacement. To cool the drifts to 25°C, the horizontal emplacement concept requires the lowest air velocity (0.02 m/sec) compared to the SSP concept, which has the highest requirement ($\geq$1 m/sec).

A.4 Waste Emplacement and Retrieval Operations

The evaluation factors for the operations category are the labor and equipment required for waste emplacement and for waste retrieval, if retrieval should be required. Only those elements that differ between the configurations are included in the analysis.

As noted in Subsection 1.1 and detailed in Appendix A.1, development of the SSP concept has not proceeded beyond the preliminary design stage. A detailed evaluation of labor and equipment requirements has not been made, and evaluation of the SSP is therefore not included in this section.

A.4.1 Labor Requirements

The operations that must be considered in determining the difference in labor requirements between vertical and horizontal emplacement configurations include only the procedures required after canisters have been transported to the point of emplacement. These procedures are categorized as follows (Dennis et al., 1984a):

- preparations for waste emplacement and retrieval,
- waste emplacement and retrieval, and
- hole closure after emplacement and retrieval.

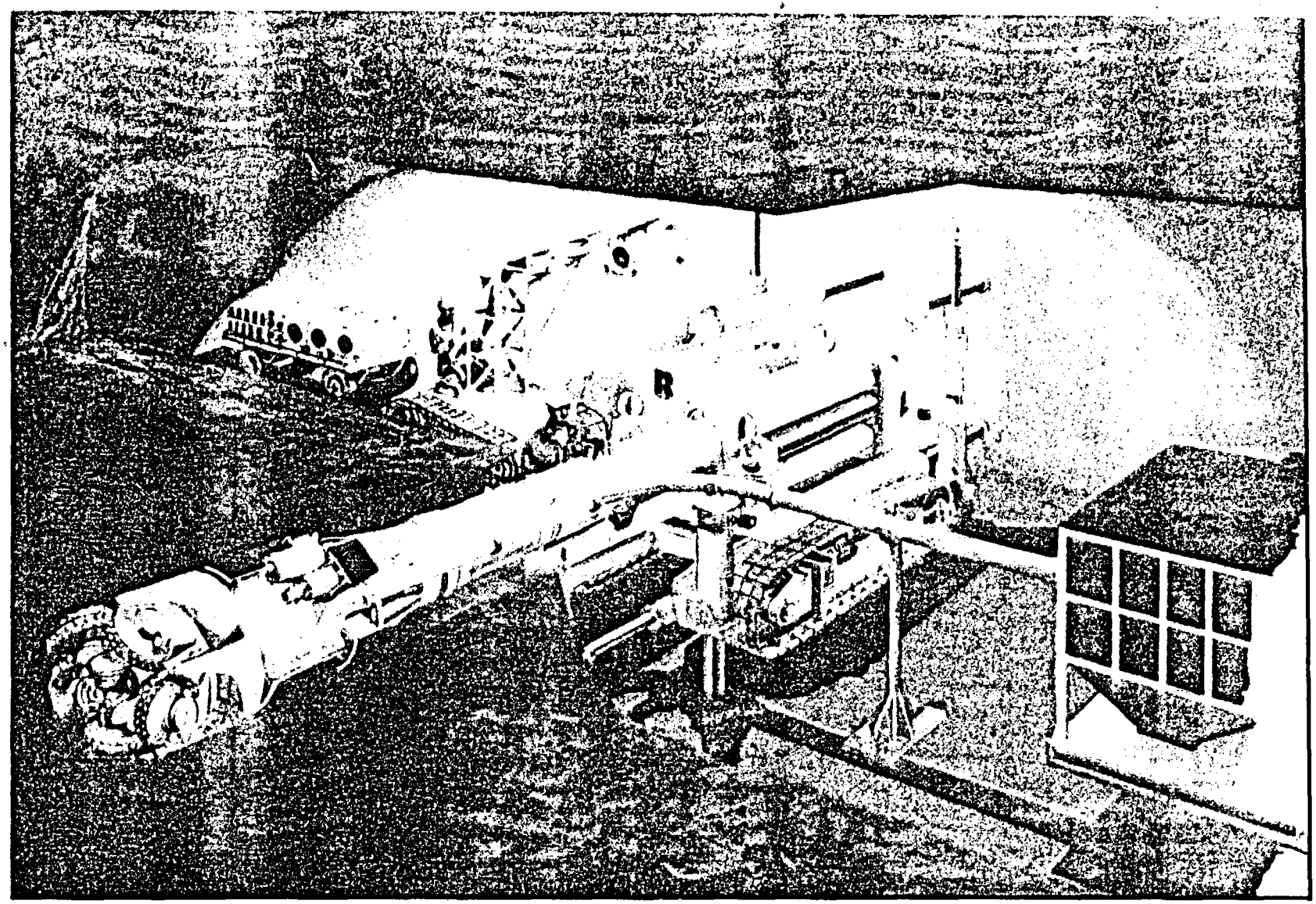


Figure 12. Horizontal Boring Machine

Table 26 shows the time and personnel required to perform the waste handling operations for emplacement and retrieval of 1,000 canisters of spent fuel. Operator radiation doses and number of worker injuries is proportional to the number of man-hours and personnel required to perform the job (Dennis et al., 1984b).

TABLE 26

TIME AND LABOR REQUIREMENTS
PER 1,000 CANISTERS OF SPENT FUEL

Emplacement Method and Operation	Labor Requirements	
	Man-Hours	Crew Size
Vertical		
Emplacement	11,495	12
Retrieval	11,670	12
Horizontal		
Emplacement	2,055	5
Retrieval	3,035	7

A.4.2 Equipment Requirements

Waste emplacement in both configurations is based on a specially designed eight-wheel, skid-steer vehicle illustrated in Figure 13 (Fisk et al., 1985). A detailed description of the transporter/emplacer and the transport/emplacement cycle is provided in a report on equipment for horizontal waste emplacement (Young et al., 1983).

The major pieces of equipment required to emplace and retrieve waste, consistent with the operational requirements shown in Table 26, have been identified for the vertical and horizontal emplacement configurations (Dennis, 1983a and 1983b). In developing this equipment list, it was assumed that all critical items have one backup for every four units.

Vertical Emplacement Configuration

- Radiation shield-door assembly.
- Dedicated transporter for the radiation shield-door assembly.
- Radiation detection equipment to certify acceptability of the shield-door installation.
- Alignment system to mate the waste cask with the shield door.
- Dedicated transporter for the alignment system.
- Eight-wheel, skid-steer vehicle for transporting the waste emplacement cask.
- Waste emplacement cask for in-facility waste handling and emplacement.
- Shielded equipment to implant the concrete closure plug.
- Shop equipment necessary for the decontamination, cleaning, maintenance, and repair of the above items; i.e., bridge cranes, hoists, and machine tools.
- Miscellaneous trucks and other transport vehicles that will be used to move small equipment and supplies to and from the boreholes.

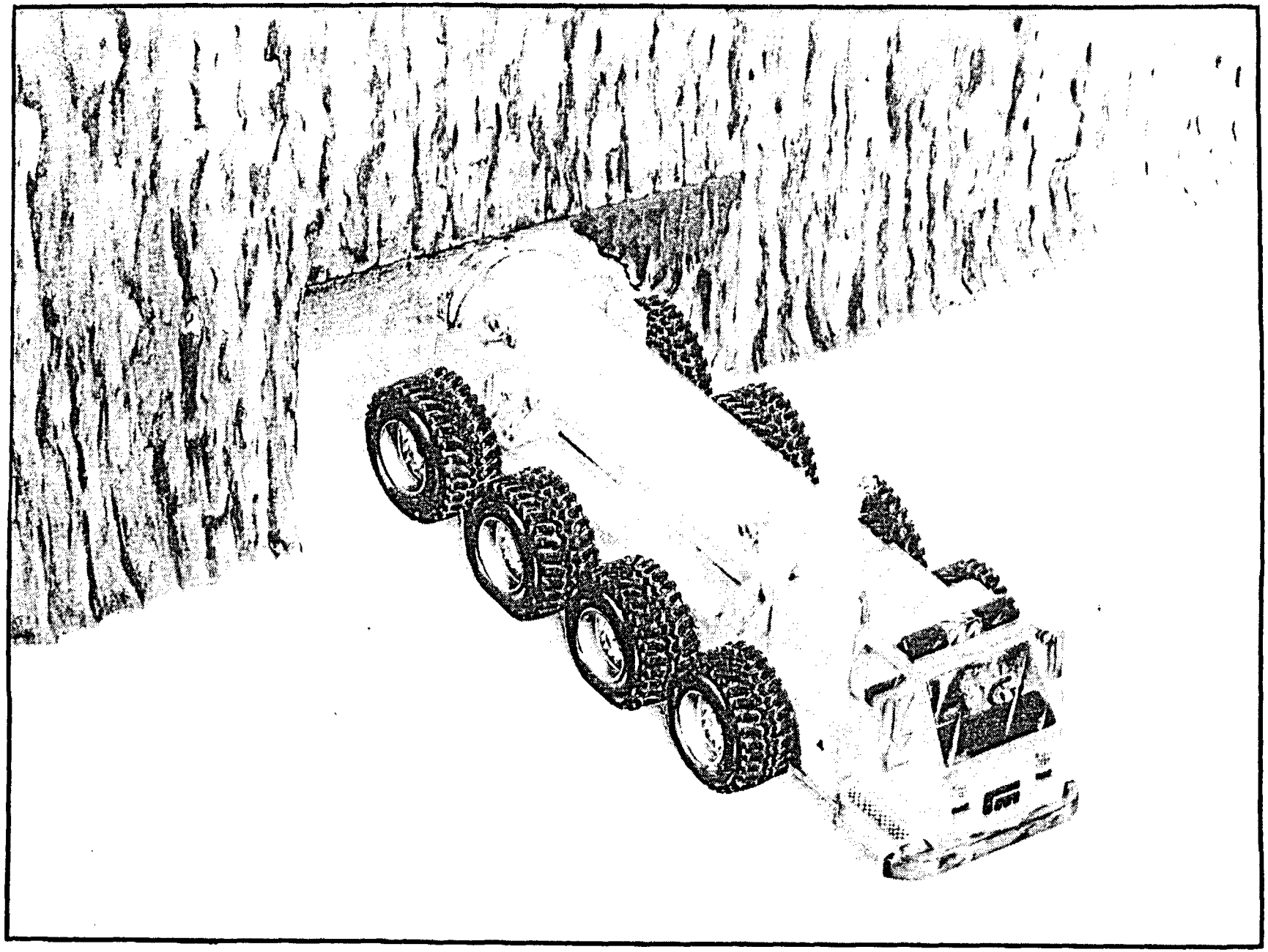


Figure 13. Transporter/Emplacer

Horizontal Emplacement Configuration

- Remote-controlled TV inspection unit and optical measurement system used to inspect boreholes before waste emplacement.
- Radiation shield-door assembly.
- Dedicated transporter for the radiation shield-door assembly.
- Radiation source and detection equipment to certify acceptability of the shield-door installation.
- Docking/automatic alignment system to mate the waste cask with the shield door.
- Dedicated transporter for the docking/automatic alignment system.
- In-hole powered conveyor system to move individual waste canisters from point of emplacement at the borehole opening to disposal location in the borehole.
- Dedicated transporter for in-hole powered conveyor system.
- Eight-wheel, skid-steer vehicle for transporting the waste emplacement cask.
- Waste emplacement cask for in-facility waste handling and emplacement.
- Automatic canister positioning used to determine the disposal location of each waste canister.
- Shielded removal equipment for the in-hole powered conveyor system.
- Shielded equipment to place the concrete closure plug in the borehole entry.
- Shop equipment necessary for the decontamination, cleaning, maintenance, and repair of the above items; i.e., bridge cranes, hoists, and machine tools.
- Miscellaneous trucks and other transport vehicles used to move small equipment and supplies to and from boreholes.

A.5 Sealing Procedures and Timing

A definition of the ways in which repository sealing differs among the three configurations is required when comparing the emplacement alternatives. Repository sealing is intended to ensure permanent closure of the underground facility, including shafts, ramps, drifts, and boreholes, in an acceptable manner (Fernandez and Freshley, 1984).

Sealing techniques for shafts, ramps, and exploratory boreholes would be common to all three emplacement alternatives. Backfilling of the boreholes associated with either horizontal or vertical emplacement is not anticipated. If a discrete water-producing zone is encountered in a horizontal borehole, seals may be emplaced to isolate that zone from the borehole. However, because of the uncertainity associated with the occurrence of discrete water-producing fault or fracture zones, the need for such seals will not be incorporated in the comparison of emplacement options. Thus, the sealing components of concern in this comparison are those that may be applied to the access and emplacement drifts required for each configuration. These components can be categorized as either seals or backfill.

Seals form a tight bond with the perimeter of the drift; are intended to be resistant to penetration by water; and could limit the quantity of waste that would be affected by inadvertant, unauthorized penetration of the repository. Backfill is loose material placed in the excavated drift with no specific intent that it form a tight bond with the perimeter of the drift (Fernandez and Freshley, 1984). In a partially saturated environment, such as that which exists at the potential NTS repository, the flow of free water within the repository zone is greatly restricted. Water flows through the partially saturated rock matrix at much slower rates than it does under saturated conditions, and large voids, such as open drifts, serve as obstacles to partially saturated flow. The

presence of backfill in drifts associated with horizontal emplacement was shown to have essentially no effect on water flow near the waste packages (Fernandez and Freshley, 1984). Backfill in drifts for vertical emplacement had a small effect on flow near the waste packages.

In addition to contributing to the repository sealing objectives, drift backfill may also contribute to the long-term structural and thermal response of the repository, as well as provide one alternative method for disposal of a portion of the excavated rock.

Backfill may be emplaced immediately before repository closure or at some other time after waste emplacement. The determination of when backfill is emplaced will depend on the specific functions that backfill will fulfill at the Yucca Mountain site.

Design studies to date have not been sufficiently detailed to support a decision on when or if backfill should be emplaced. However, a number of considerations suggest that the backfill should not be emplaced until the time of repository closure:

- Operational concerns with transfer of excavated rock (muck) from the active mine area to a filled repository zone suggest that interim surface storage of muck is desirable.

- For some emplacement schemes, emplaced backfill may reach temperatures approaching 100°C within the period required for possible waste retrieval. Removal of high-temperature backfill presents many operational problems.

- Proper maintenance of access and emplacement drifts, to allow for monitoring and waste retrieval, may require that drifts be open and ventilated during the required retrieval period.

- Ventilation, independent of cooling requirements, may be required to remove radon gas from both open drifts and the working face if backfill removal should be required. Radon emanation studies are currently in progress to address this concern.

The decision whether to backfill at emplacement or at repository decommissioning may also depend upon the waste type. A decision to retrieve spent fuel, with potential resource recovery value, could be made without regard to repository performance evaluations. Thus, sections of the repository containing spent fuel could be left open until the repository is decommissioned to allow for possible retrieval.

For these reasons, it is assumed that backfill is emplaced at the time of repository closure to evaluate the relative effects on the three emplacement configurations. The difficulty and expense of emplacing repository backfill for a particular emplacement configuration will depend on the size and number of drifts excavated for access and waste emplacement.

A.5.1 Seals

Because of the limited knowledge on the extent of discrete water-producing zones in the prospective repository horizon, reliable comparisons of seal requirements among the three emplacement configurations cannot be made, nor can cost estimates be developed. Nevertheless, the additional length and volume of drift mining associated with the SSP and vertical methods may result in a significantly greater number of seals for these methods than for the horizontal method.

A.5.2 Backfill

As explained in Subsection A.5, the following discussion of backfill requirements for each emplacement configuration assumes that drift backfill will be emplaced at the time of repository closure. Any evaluation of the removal of backfill to allow for resource recovery in some future time after repository closure is outside the scope of this comparison.

Interim surface storage of excavated rock and some form of conditioning, e.g., crushing, homogenization, additives, etc., are assumed before use of excavated material as backfill. However, no specific requirements for such conditioning have currently been defined. It is assumed that the primary impact of such conditioning would be on the overall cost of backfilling and would be proportional to the volume of backfill material required. Thus, while not specifically addressed in this comparison, these conditioning costs will vary in the same fashion as the relative costs of handling and emplacing the backfill.

Emplacement of backfill at time of closure will require that drift temperatures be within the same range as that necessary for drift inspection and maintenance during the operational period of the repository. Thus, no incremental impacts on ventilation requirements are anticipated from the backfilling process.

In the following subsections, the dominant concerns regarding backfill at time of closure are discussed for each emplacement configuration. Additionally, any significant differences between backfilling at closure and backfilling at some earlier time after waste emplacement are identified. These differences are not incorporated in the comparisons but are included here for completeness.

A.5.2.1 Self-Shielded Package

The presence of the waste packages in the emplacement drifts will significantly encumber the emplacement of backfill. Potential radiation levels are highest for the SSP, as compared with the other configurations, although within occupational exposure limits. The exposed surface of the waste package, as detailed in Table 21, will approach 100°C and may impose constraints on the equipment used for backfill emplacement. Some form of conveyor or pneumatic transfer unit could be used to move the backfill to the interior of the emplacement drift, and vehicle movement in the drift will be constrained by the presence of the waste package. Design studies of this equipment have not been completed. The total volume of backfill required is between the volumes required for the vertical and horizontal configurations.

Placement of backfill would be more easily accomplished at the time of waste emplacement for the SSP method. Direct access by vehicles to the backfill face would be possible, and package temperatures would not have reached maximum values. However, removal of the backfill in the event waste retrieval became necessary would be complicated by higher temperatures and radiation levels, compared with the other emplacement configurations.

A.5.2.2 Vertical Emplacement

Radiation levels in vertical emplacement drifts would be between those for the SSP and horizontal emplacement configurations but within occupational exposure limits. Assuming that drift ventilation is required for inspection and maintenance, there would be no unusual difficulties due to thermal conditions. The total volume of required backfill is greatest for vertical emplacement.

If backfill were emplaced soon after waste emplacement, the backfill would experience a temperature rise comparable to that calculated for the unventilated drift (Table 22). Although lower than for the SSP configuration, these elevated temperatures would necessitate additional cooling or ventilation if waste retrieval were required after backfilling was completed.

A.5.2.3 Horizontal Emplacement

Radiation levels in the drifts would be lowest for this configuration. No temperature-related problems would be experienced in drifts that were ventilated to allow inspection and maintenance. As detailed in Table 22, even unventilated drifts would remain within a temperature range experienced in conventional mines (see Subsection A.2.1.2). The total volume of backfill required is significantly less than that required for the other two configurations.

If backfill were placed at the time of waste emplacement, the backfill would experience a temperature rise similar to that calculated for unventilated drifts (Table 22). However, temperatures are considerably lower than those calculated for the SSP or vertical emplacement configurations and would impose fewer operational constraints if backfill removal for waste retrieval were required.

A.6 Average Properties for the Topopah Spring Member

This section provides the average properties (Peters, 1982) of the Topopah Spring Member that were used for the average-value, near-field thermal/mechanical calculation.

Variable			Value
Φ_m	-	matrix porosity	0.12
Φ_ℓ	-	lithophysal porosity	0.05
ρ_g	-	grain density	2.55 g/cm^3
s	-	matrix saturation	0.80
S_{OJ}	-	joint cohesion	1.0 MPa
σ_v	-	vertical stress	8.6 MPa
$\sigma_h\sigma_v$	-	horizontal to vertical stress ratio	0.96
$\sigma_{he}\sigma_{hn}$	-	orthogonal horizontal stress ratio	1.0

Thermal Rock Properties

$\rho_{db}C_p$	-	dehydrated heat capacity	0.42 cal/cm^3·°C
$\rho_{sb}C_p$	-	partially saturated heat capacity	0.55 cal/cm^3°C
ΔH	-	pore water vaporization energy	50 cal/cm^3
K_d	-	dehydrated thermal conductivity	1.6 W/m°C
K_s	-	partially saturated thermal conductivity	1.8 W/m°C

Dehydration is assumed to occur between 100° and 125°C with a change in properties, linearly, from the partially saturated to the dehydrated state. The pore water vaporization energy is spread over this interval.

Mechanical Rock Properties

E	-	Young's Modulus	28 GPa
ν	-	Poisson's Ratio	0.28
α_{ml}	-	low range expansion (?200°C)	11×10^{-6}°C^{-1}
α_{mm}	-	intermediate range expansion (200-350°C)	32×10^{-6}°C^{-1}
α_{mh}	-	high-range expansion (350-400°C)	15.5×10^{-6}°C^{-1}
S_{OM}	-	cohesion	12 MPa
θ	-	angle of internal friction	25°
S_{OJ}	-	joint cohesion	1 MPa
S_{1J}	-	joint coefficient of stable sliding friction	0.8
S_{TM}	-	matrix tensile strength	3.5 MPa
β_J	-	joint orientation from horizontal	90°
STJ	-	joint tensile strength	0.1 MPa

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