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Volume 2

HIGH-LEVEL RADIOACTIVE WASTE MANAGEMENT ALTERNATIVES

SECTION 4: GEOLOGIC DISPOSAL

May 1974

Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

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NOTICE

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SECTION 4: GEOLOGIC DISPOSAL

May 1974

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FOREWORD

This report is a comprehensive overview study of potential alternative methods for long-term management of high-level radioactive waste. The study includes a compilation of information relevant to technical feasibility, safety, cost, environmental considerations, policy conflicts, public response and research and development needs for:

1. Disposal in terrestrial locations
    a. In geologic settings on land
    b. In the seabed
    c. In ice sheets
2. Disposal into space
3. Elimination by transmutation (nuclear transformation of certain waste constituents into nuclides having less long-term toxicity).

The study is limited to the management of high-level radioactive waste from nuclear power by variations of these alternatives. Consideration of alternative types of electrical power generation are not within the scope of the study. In addition, evaluation of interim storage of radioactive waste in retrievable surface storage facilities is not part of this study. Disposal of waste in bedded salt deposits was studied extensively in other AEC programs, and the concept is included here as part of the overall matrix of geologic disposal techniques.

To complement these studies, investigations were also conducted on waste partitioning (separation of radionuclides in radioactive waste into different elements or groups of elements according to their long-term toxicity or suitability for different disposal methods), and systems methodology was developed to assess the effects of radionuclides from waste introduced into man's ecological cycle, assuming some failure of the primary waste containment.

Information pertinent to evaluating the various potential waste disposal techniques was developed without promoting any single disposal concept. The study is concerned with management of the waste and does not consider the potential for recovery of resources within the waste, including the heat. Concepts are developed only to the detail necessary to describe them for the overall investigation and in general are studied on a systematic, generic basis. This information can be used in comparing and assessing the various disposal concepts as a basis for decisions regarding their further study.

The evaluations of feasibility are not restricted to currently available technology. Rather, the study attempts to take into account technology which can be developed or is expected to be available at least within the next four decades. Indeed, most of the concepts studied are estimated to require 15 to 30 years for full implementation.

The study includes most currently known waste management alternatives, but is not considered to be all-inclusive. As new data become available, and as new or varied concepts become evident (e.g., disposal in rocks in permafrost areas, isotopic dilution of selected materials, etc.,) comparable follow-on studies will be carried out.

This investigation has been performed largely by a multiple-discipline technical staff at the Pacific Northwest Laboratory of Battelle Memorial Institute with significant input from a large number of consultants and outside contributors. This wide involvement of persons was an attempt to assure up-to-date and accurate coverage of the broad scope of subject matter, including areas where there are diversities of opinions.

This report is issued as nine major sections in four volumes:

Volume 1	Section 1	Summary[a]
	Section 2	Background and Data Base
	Section 3	Evaluation Methodology
Volume 2	Section 4	Geologic Disposal
Volume 3	Section 5	Ice Sheet Disposal
	Section 6	Seabed Disposal
Volume 4	Section 7	Waste Partitioning
	Section 8	Extraterrestrial Disposal
	Section 9	Transmutation Processing

Appendix material is included with its own respective volume.

In general, metric system units are used in this report. Conversion factors to English units are given in Appendix 1.A.

---

a. This section is almost identical to WASH 1297, High-Level Radioactive Waste Management Alternatives, US AEC Division of Waste Management and Transportation, May 1974.

ACKNOWLEDGMENTS - TOTAL REPORT

This study, performed over a period of about 1.5 years, received significant support from many people who are not listed as key contributors. The contributions of these persons are gratefully acknowledged. Although the total of such participants is too numerous to mention, the following list shows many of the major contributors.

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CONTENTS - TOTAL REPORT

Abbreviated contents of the total 4-volume report are listed here. Detailed contents of each of the nine sections are listed at the front of each section.

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APPENDICES FOR VOLUME 3

VOLUME 4

APPENDICES FOR VOLUME 4

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4.0 GEOLOGIC DISPOSAL

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

Disposal in bedded salt,which is under study for the U.S. Atomic Energy Commission at the Oak Ridge National Laboratory, is not specifically covered in this study but it is included in the overall study matrix. The concepts presented in this report are typically suggested by others, sometimes with modifications which are outgrowths of the study itself.

The geologic disposal concepts were studied on a generic and systematic basis, with studies aimed at inherent characteristics. No attempts were made to define the concepts in detail or to optimize any of the concepts.

Section 4.0 discusses general considerations relevant to more than one concept. Sections 4.1 through 4.11 discuss the details of individual disposal concepts including a description of the concepts; waste management systems requirements beginning with discharge of high-level liquid waste from a plant reprocessing "spent" nuclear fuel and ending with final waste emplacement in a geologic formation; concept related geologic considerations; technical feasibility; concept safety; research and development needs, including estimated costs; time required to commission, and estimated capital and operating costs associated with a facility for disposal of commercially generated radioactive waste; and policy, environmental, and public response considerations.

4.0.1 Background on Geologic Disposal Concepts

The basic requirement for any geologic environment to be suitable for disposal of radioactive waste is the capability to safely isolate the emplaced radioactive material until decay has reduced the radioactivity to nonhazardous levels. The geologic environment should a) be adequately far removed from man's environment, b) not permit waste transport readily, c) remain relatively stable over geologic time periods, and d) adequately contain a highly immobile waste form.

A geologic formation can be penetrated and altered in several ways to provide a repository for waste emplacement purposes. This study considers the use of drilling, mining (mechanical and dissolution), exploded cavity formation and hydraulic fracturing. All of these methods become more difficult with increasing depth. At depths up to nearly 3 kilometers any of the methods may be used. Drilling has the potential of going to great depths; the present record is around 9 kilometers (about 5.5 miles).

The general methods considered in this study for placement and disposal of radioactive waste in geologic formations include:

- Placing solidified waste directly in a geologic formation
- Placing solidified waste in man-made containment barriers within a geologic formation
- Placing solidified waste in a geologic formation in a configuration to allow the waste to melt and form a rock-waste matrix
- Converting liquid waste in-place within a geologic formation to form a solid waste or a rock-waste matrix.

Each of these basic concepts has a number of variations, depending upon the specific method of accomplishing this placement of waste. Furthermore, each of the variations will have specific requirements with respect to the host geologic environment. A total of ten concept variations was considered in this study, with at least two in each of the basic methods listed above.

4.0.2 General Systems Requirements for Geologic Concepts

The general management system flow diagram for potential geologic waste disposal concepts is shown in Figure 4.1. This figure shows the major possible steps required in managing waste using geologic disposal. The flow diagram starts with bulk high-level aqueous waste from the fuel reprocessing plant and carries it through final isolation and sealing from man's environment.

In general, geologic disposal options are not considered to require preconditioning or partitioning of the aqueous waste. Geologic disposal does not preclude the use of these steps, but if such steps are taken, they may be done for reasons not directly related to geologic disposal needs. It is assumed in this study that geologic disposal options will be aimed at managing the total high-level waste, including the long-lived radionuclides.

Most geologic disposal concepts will require similar waste management steps. The primary differences exist between the liquid and the solid waste emplacement concepts. For the solid waste emplacement concepts interim retrievable storage of the liquid waste may or may not be used; solidification of the waste must be done at the reprocessing plant; interim retrievable storage of solid waste is optional, but is considered to be likely;(a) the solid waste must be transported to the disposal site; following site preparation, the waste is emplaced in the disposal site; and the disposal site is sealed from man's environment and monitored for an indefinite time period.

For the liquid waste disposal concept interim retrievable storage of the liquid waste is generally not anticipated (with the probable

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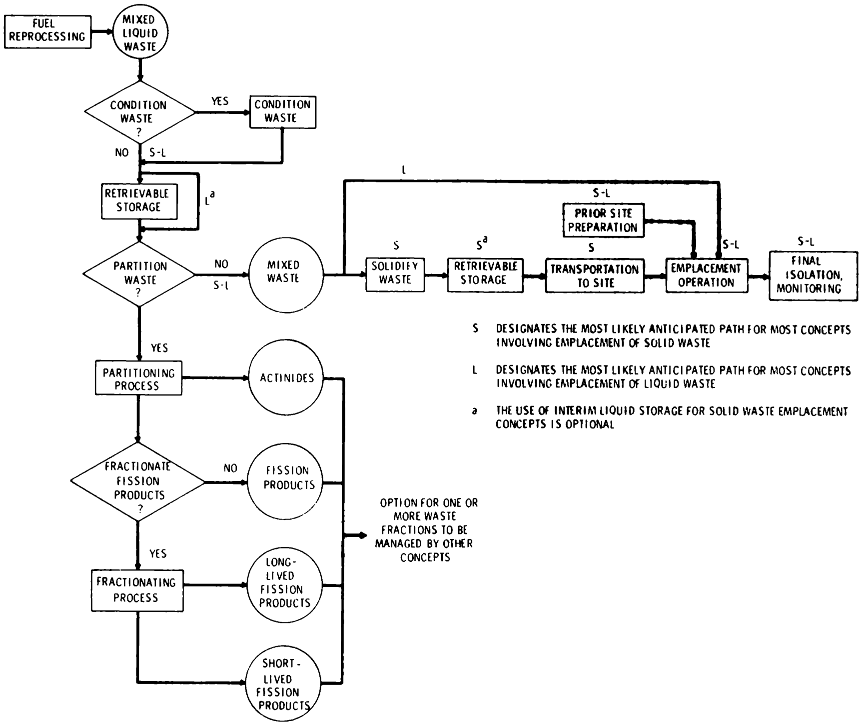
a. Interim retrievable storage of solidified waste is planned to be done at the proposed federal repository, the Retrievable Surface Storage Facility, for extended periods of time (until an ultimate disposal concept is ready for use).



S DESIGNATES THE MOST LIKELY ANTICIPATED PATH FOR MOST CONCEPTS INVOLVING EMPLACEMENT OF SOLID WASTE

L DESIGNATES THE MOST LIKELY ANTICIPATED PATH FOR MOST CONCEPTS INVOLVING EMPLACEMENT OF LIQUID WASTE

a THE USE OF INTERIM LIQUID STORAGE FOR SOLID WASTE EMPLACEMENT CONCEPTS IS OPTIONAL

FIGURE 4.1 System Requirements for High-Level Radioactive Waste Management in Geologic Locations

exception of the hydrofracture concept); the bulk liquid waste would be emplaced directly into the geologic formation; and the disposal site is sealed from man's environment and monitored for an indefinite time period.

4.0.3 General Geologic Consideraations Relevant to Disposal Concepts

This section presents the basis for and, to the extent possible, establishes general geohydrologic considerations that can be used in evaluation of geologic disposal concepts exclusive of disposal in bedded salt. Except for the discussions of "Rock-Waste Interactions in the Presence of Water," "Molten Rock-Waste Interactions," "Resource Potential," and items identified by footnotes as materials prepared by the staff of the Pacific Northwest Laboratories, the text that follows in this section (4.0.3) is predominantly taken from an extensive review completed by the Special Projects Branch, U.S. Geological Survey at the request of the Atomic Energy Commission specifically for this study.(1)

This review, "Geologic and Hydrologic Considerations for Various Concepts of High-Level Radioactive Waste Disposal in Conterminous United States," by E. B. Ekren, G. A. Dinwiddie, J. W. Mytton, W. Thordarson, J. E. Weir, Jr., E. N. Hinrichs and L. J. Schroder is available as an open file report in the Denver, Colorado office, U.S. Geological Survey. In addition to the general geohydrologic considerations summarized here, the USGS review briefly evaluates and identifies the geohydrologic environments in the conterminous United States that they consider as possibly suitable for the various geologic disposal concepts.

Because the following section on waste disposal has been oriented to an audience not necessarily familiar with geohydrologic terminology, a short glossary of terms has been included in Appendix 4.A.(1) A reference geologic time scale has been included as Appendix 4.B.(1)

Of the various geohydrologic factors considered in evaluating potential sites for geologic disposal, the most important is hydrologic isolation to assure that the waste will be safely confined within an acceptable radius of the emplacement zone. To achieve this degree of hydrologic isolation the host rock for the waste should exhibit very low permeability and the site should be virtually free of geologic faults.

Areas considered generally unsuitable for waste disposal are those where seismic risk is high (seismic risk zone 3), where possible sea-level rise or changes in drainage patterns could inundate potential sites, where high topographic relief coincides with high fault densities and (or) unfavorable hydrologic conditions, where no suitable rock media are known to be present to reasonable depths, where a possible return of glacial or high rainfall climate will cause undesirable changes in the geology, where there is danger of exhumation by erosion, and where these strata either contain usable volumes of groundwater or have high oil and gas or other mineral potential.

Potentially suitable media for the deep drill-hole method appear to be crystalline rocks, either intrusive igneous (e.g., granite) or metamorphic (e.g., quartzite) because of their potentially low permeabilities and high mechanical strengths. These same crystalline rocks, in addition to salt and suitable shale formations below about 2100 meters in depth, are candidates for matrix hole sites. Salt (either in thick beds or stable domes), tuff, intrusive igneous and crystalline metamorphic rocks, and possibly shale appear to be suitable for mined chambers, cavities with separate manmade structures, and, exploded cavity methods. Salt appears to be suitable because of its very low permeability, high thermal conductivity, and natural plasticity. Tuff and shale appear suitable because of their very low permeabilities and high ion-exchange capacities. Sedimentary rocks other than shale and volcanic rocks, exclusive of tuff, are considered to be generally unsuitable for waste emplacement because of their potentially high permeabilities.

The physiography of a potential disposal site should have gentle relief to minimize any accelerated erosion or denudation that might occur because of natural climatic changes or changes brought about by the preparation for disposal operations. The most suitable geographic location for a disposal site is also one that is as far removed from major drainages, lakes, and oceans as possible and where the intrusion of man in a manner that will change the condition is minimal.

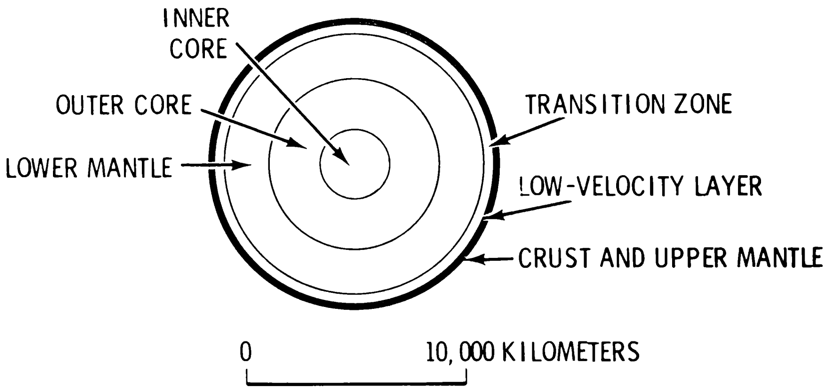
General areas and media that might be concluded to be potentially suitable for waste disposal will require further detailed evaluation at local levels in order to accurately define the most suitable specific locations. These localities will have to be (1) mapped in detail and seismically monitored to delineate active fault zones and areas of crustal unrest, (2) surveyed by geophysical techniques (where applicable) to locate buried faults and to better define subsurface conditions and (3) drilled and hydraulically tested to locate the zones having the lowest permeabilities. Finally, the drill core will have to be analyzed physically and chemically in order to predict the nature of the rock-waste interaction.

4.0.3.1 Basic Description of Earth System

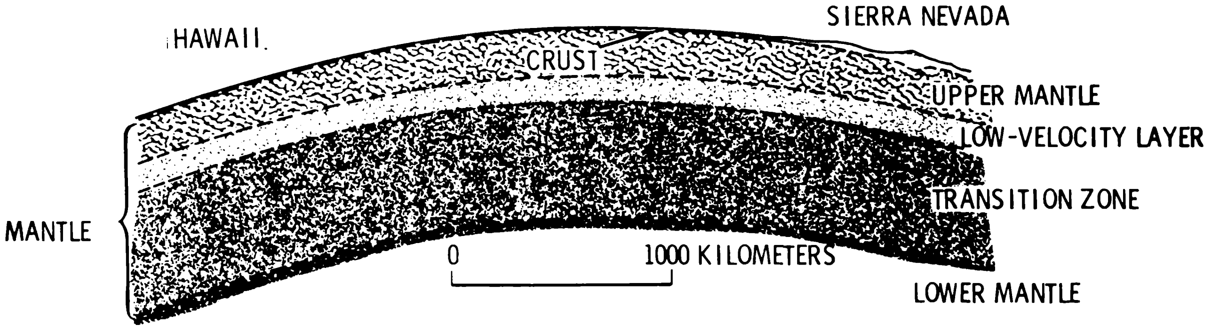
All the geologic waste disposal concepts considered in this investigation involve emplacing waste in the earth's crust, which is the outermost layer or shell of the earth (Figure 4.2). Knowledge that the earth is made up of various layers is based principally on the behavior of seismic or earthquake waves as they pass through the earth. The crust of the earth ranges in thickness from about 5 kilometers in some places under the oceans to more than 50 kilometers under high mountain ranges, such as the Sierra Nevada. In the continental parts of the United States the crust everywhere exceeds the maximum thickness or depth considered for the deep drill-hole concept (16 kilometers).

The continental crust is made up largely of light-colored igneous rocks such as granite, and the oceanic crust is made up almost entirely of basalt, which is darker and heavier than granite. The crust overlies a layer called the mantle which, in turn, overlies the earth's core.

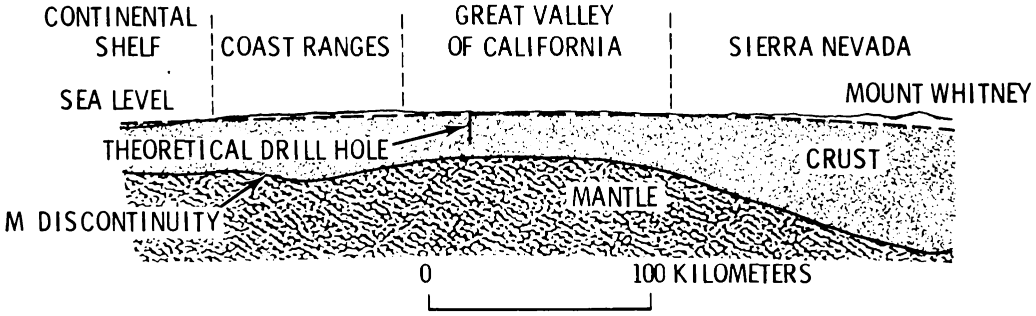
The composition of the mantle as contrasted to the crust is little known. Knowledge of mantle composition is theorized from studies of volcanic lava and of the composition of diamond pipes and from laboratory experiments on minerals and rocks. These studies and seismic data indicate that the rocks of the upper mantle are denser than the crustal material and are composed mostly of iron and magnesium silicate minerals. In the lower mantle, because of very high pressure, only the simple oxides of iron, magnesium and silicon are thought to be present.(2)



CROSS SECTION OF THE WHOLE EARTH, SHOWING CORE, MANTLE, AND CRUST



UPPER MANTLE AND CRUST BETWEEN HAWAII AND CALIFORNIA. THE CRUST IS VERY THIN RELATIVE TO THE REST OF THE EARTH.



CONTINENTAL CRUST UNDER CALIFORNIA, SHOWING CRUSTAL THICKENING UNDER THE SIERRA NEVADA AND 15-KILOMETER DRILL HOLE

FIGURE 4.2. Cross Sections of the Earth and Parts of the Earth's Crust and Mantle (Modified from Robertson, 1966)(2)

Below the mantle is the earth's core, which is divided into an outer part and an inner part as shown on Figure 4.2. The outer core is presumed to be liquid because it does not transmit shear waves (earthquake waves in which particle motion is across, or transverse to, the direction of travel), and because it sharply reduces the velocity of compressional waves (earthquake waves in which particle motion is back and forth parallel to the direction of travel). The inner core, detached because of its higher compressional wave velocity, is considered to be solid. The core occupies about 15 percent of the earth's volume, the mantle about 84 percent, and the crust only about 1 percent.(2)

Of concern to waste disposal in Western United States is the knowledge that the Pacific Ocean and coastal California west of the San Andreas fault system is moving relatively northwestward with respect to the remainder of the United States at a rate estimated at from 5 to 8 cm/yr (2 to 3 inches per year).(3) This movement breeds the earthquakes that shake California and is an example of tectonic activity that affects the entire globe. The science of this global tectonic activity is generally referred to as "plate tectonics."

Not only are southern California and the Pacific moving northwestward with respect to the North American plate, but continents and ocean basins alike throughout the globe are slowly moving across the face of the earth at rates that are extremely slow in terms of a man's lifetime but are exceedingly fast in terms of geologic time.

Knowledge gained on a global scale now allows earth scientists to divide the earth's crust and uppermost mantle into some eight major geological plates or caps.(4) The plates move out from midoceanic ridges and plunge downward into the great deeps or troughs of the ocean (Figure 4.3) in zones referred to as subduction zones. The midoceanic ridges are linear "rift" zones where rock material from the earth's interior wells up to form new crust and then spreads outward on both sides of the ridge. This process is referred to as "sea-floor spreading." That the floor is indeed spreading has been confirmed by magnetic and fossil data which show that the ocean floor is youngest at the midoceanic ridges or divides and becomes progressively older outward in both directions. The continents gradually move away from the spreading ridges. It is inferred that about 200 million years ago the continents were all part of a single land mass or super continent.

Subduction zones (Figure 4.3) and other plate-junction zones are belts of major earthquake and volcanic activity. Of principal concern in evaluating geologic waste disposal in the western United States is the junction of the Pacific and the North American plates along the San Andreas fault, which connects offset segments of the East Pacific Rise. The significance of movement along this junction from the standpoint of waste disposal is the fact that at the present rate southern California west of the San Andreas fault will move northwestward relative to the remainder of the continent at least 50 kilometers (30 miles) in a 1 million year period.

The San Andreas fault projects northward off-shore from California to intercept the east-trending Mendocino fracture zone. It is not clear what happens to the San Andreas at this junction. Neither the Mendocino fracture zone nor the San Andreas system offsets the other.(5) North of

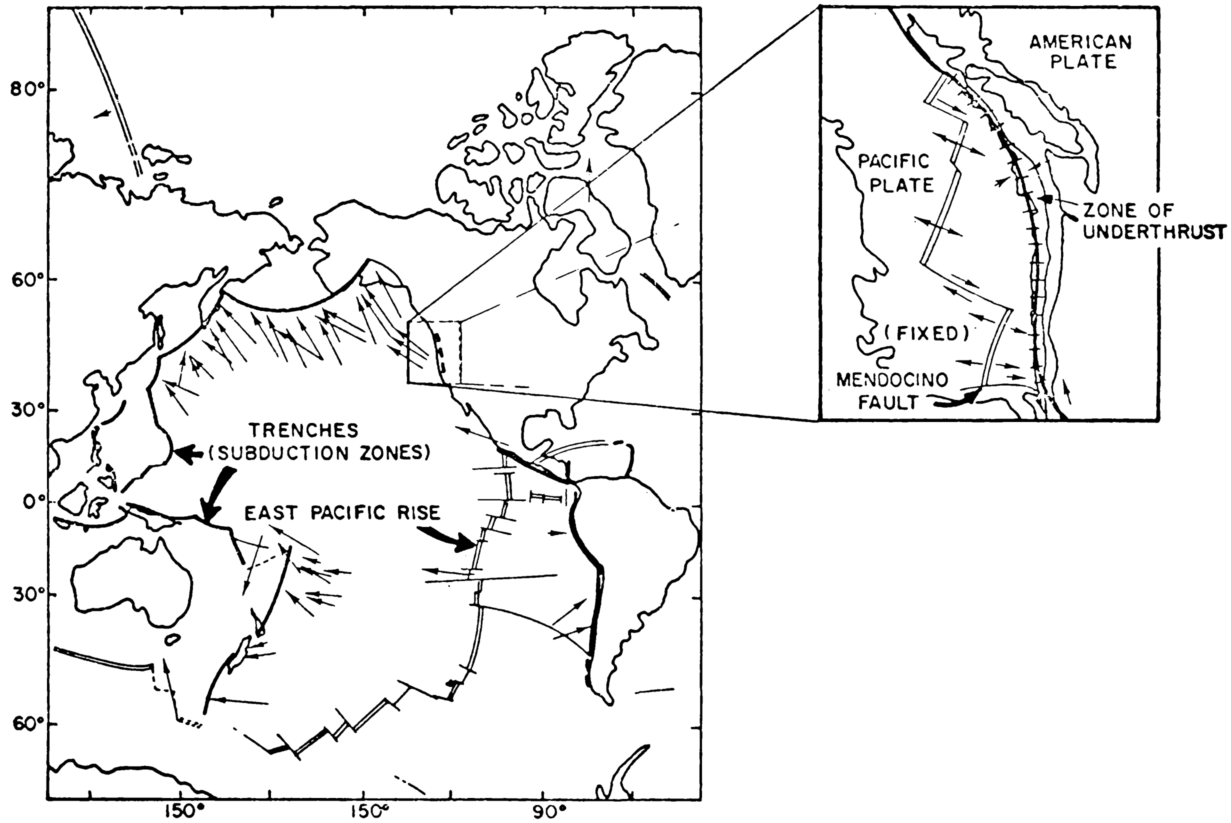


FIGURE 4.3. Summary Map of Slip Vectors in the Pacific Area. (Modified from Isacks and others (1968), Atwater (1970)(3)

the junction, the East Pacific Rise is present (Figure 4.3) and is spreading at a rate of 5 to 8 cm/yr (2 to 3 inches per year).(3) This motion and the possibility that the coasts of Oregon and Washington are being underthrust by the ocean floor(6-8) indicate that the lack of major earthquakes in that locality may not be a permanent condition. The development of tight folds in the Columbia Plateau and the indication of continuing crustal unrest in that region may be related directly or indirectly to the interaction of the oceanic and continental plates, and the next 1 million years could see an increase in tectonic activity in the northwestern part of the United States.

The disposal of waste is a special problem in each environment, and the occurrence of suitable rock types and favorable local geohydrologic conditions will dictate whether a particular area is suitable for waste disposal. However, certain general considerations must be evaluated for all sites and are of primary concern. These considerations are: (1) lithology, (2) hydrology, (3) geochemistry, (4) character of terrain and effects of erosion and rates of denudation (physiography), (5) seismicity, (6) possible climatic changes, and (7) resource potential.[a]

4.0.3.2 Lithologic Considerations

This section briefly describes the principal rocks found in the various geologic environments in the United States and presents tables of physical property data considered significant in evaluating waste disposal. The rocks include all the principal types found in the earth's crust. These are subdivided into three main categories: sedimentary, igneous, and metamorphic.

4.0.3.2.1 Sedimentary Rocks.

Sedimentary rocks are those deposited on the earth's surface by the action of water, wind, accumulation of organic remains, or chemical precipitation. They are formed by the destruction (physical or chemical) of preexisting rocks, either igneous, sedimentary, or metamorphic. The principal sedimentary rocks are shown in Table 4.1.

Among the various sedimentary rocks there are extreme variations in physical properties, but, in general, the sedimentary rocks tend to be the weakest rocks in the crust and, exclusive of salt, have the greatest ability to store and transmit groundwater. Although sedimentary rocks are estimated to constitute only 5 percent of the volume of the earth's crust, they are the rocks most likely to be encountered on the upper surface of the earth.

Sandstone and conglomerate consist of grains of quartz, feldspar, and rock fragments cemented together with silica, calcium, carbonate, clay, or combinations of these ingredients. Sandstone and conglomerate vary considerably in physical properties, but, in general, they are strong rocks that will support unpropped excavations. They are generally drilled with ease and mined with a minimum of problems and hazards. They are often porous, and the pore spaces, commonly interconnected, can allow rapid transmission of water.

Shale is a general term for lithified clay and mud. Most shale contains some sand. Some geologists restrict the term to rock that breaks or weathers to tiny flat fragments a fraction of an inch thick that are parallel to original bedding planes. Most shale is weak and will not support unpropped excavations. It commonly contains swelling clays. It creeps in outcrop and "flows" under loading. It is, in general, a poor foundation rock and it is extremely difficult to drill and mine. The amount of "chimneying" above an underground nuclear blast in shale can be predicted to be extreme unless strong interbeds of sandstone or limestone are present. Shale, however, has the lowest permeability of sedimentary rocks. it has the highest ion-exchange capacity, and, under certain conditions, may be a suitable host for waste disposal.

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[a] Item (7) is included by the staff of Pacific Northwest Laboratories (PNL).

TABLE 4.1. Principal Sedimentary Rocks

Method of formation	Rock	Description
Mechanical	Conglomerate	Almost entirely cemented gravel
	Sandstone	Cemented sand
	Shale	Cemented mud and clay
Chemical	Carbonate (limestone and dolomite).	Chemically precipitated but commonly reworked grains of calcite and dolomite with admixtures of mud and sand
	Salt	
Organic	Limestone, coal	Fossiliferous calcite reconstituted plant remains

Sedimentary carbonate rocks are called limestones if composed predominantly of calcite ($CaCO_3$); they are called dolomite if abundant $CaMg(CO_3)_2$ is present. Carbonate rocks are water soluble in a variety of temperature-pressure conditions in the shallow subsurface and, consequently, form the famous cave areas of the world. In some areas, for example, in the Basin and Range province of the western United States, the carbonate rocks at great depths can be prolific water bearers with extremely high permeabilities. In other areas, for example, the Balmat-Edwards area of New York State, carbonate rocks have very low permeabilities even in the shallow subsurface.(9) They are strong rocks but their local high permeabilities and chemical instabilities would be considered a major disadvantage for waste storage or disposal.

Salt (NaCl) forms in basins that become isolated or partly isolated from the sea. It occurs in relatively pure beds, in thin layers interbedded with sediments and other evaporites, and in domes. Salt has several properties that are favorable for waste disposal. These properties, according to a report prepared by a committee on radioactive waste management of the National Academy of Sciences,(10) are:

1. Natural plasticity that will effectively seal the waste canisters in cells and will relieve stress concentrations produced by the mining operations
2. High compressive strength
3. Thermal conductivities that permit the dissipation of larger quantities of heat

4. Gamma-ray shielding properties similar to concrete

5. Very low porosity and permeability which provide for isolation from man's environment.

In addition to the National Academy of Sciences' National Research Council study(10) many other investigations on the feasibility of using salt for repositories for radioactive waste have been completed (see selected References 11-22). These investigations were generally concerned only with shallow depth burial concepts. At shallow depth (about 1,000 meters or less) the natural plasticity of salt is not considered to pose problems for either cavity construction or long-term disposal of waste. At depths greater than about 1,000 meters, however, the ability of salt to flow may pose problems for waste disposal either in drill holes or in cavities. Many holes have been drilled in salt to depths of at least 4,000 meters.(21) No serious drilling problems have been reported. The possibility exists, however, that large-diameter holes not filled with drilling mud and large mined or explosion-induced cavities would not remain open for any appreciable period at depths much below a thousand meters.

Another consideration regarding the use of salt for waste disposal is the high solubility and the attendant danger of exposing the waste if the salt is attacked by groundwater. Dissolution of salt formations at shallow depths by circulating groundwater is a common phenomenon. To ensure the long-term containment of the waste in the salt, it would be necessary to establish the nature and rates of salt removal near each site.

In principle, salt domes of proven stability should be considered equally as feasible as bedded salt deposits for the disposal of radioactive waste. The National Academy of Sciences' Committee on Waste Disposal(10) made no distinction between salt domes and bedded formations as suitable prospects for waste disposal. Since that time, the studies made by ORNL and others(11-21) on the general suitability of salt for the purpose of radioactive waste disposal have not revealed fundamental reasons for favoring bedded salt over domal structures or vice versa.(a)

There are several potential problems in selecting salt domes and, more importantly, in demonstrating the suitability of any specific dome as a site for radioactive waste disposal. These problems are related to determining the geometry of domes; establishing the tectonics of salt domes (diapirism); the hydrological regime associated with domes; the thermal and temporal effects on the tectonics and hydrology; and the limited geographic distribution of salt domes which would also have the necessary surface conditions suitable for

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a. This paragraph plus the remainder of the section up to <u>4.0.3.2.2 Igneous Rocks</u> presents material prepared by the Pacific Northwest Laboratories' staff.

a waste disposal site (i.e., available land, remoteness, no groundwater).

Salt domes can be very irregularly shaped.(18,21) It would be necessary to accurately establish the geometry of any specific salt dome considered for waste disposal, primarily to assure that the disposal cavity would not too closely approach the dome edge and thereby possibly break through with a resultant inflow of water. To establish the necessary width of the barrier between the salt dome edge and a proposed disposal cavity would require a considerable research and design effort on each specific dome.

In regards to the tectonics of salt domes, it is generally agreed that domes have resulted from the upward intrusion of large volumes of salt from source beds buried at greater depths (diapirism).(18) The average velocity of emplacement is probably no more than a few millimeters per year and some of the domes may still be moving at that rate.(18) Before a particular dome could be considered suitable for waste disposal, it would be necessary to demonstrate that it is presently stable, that past movement had not produced any residual stress concentrations, and that rejuvenated movement affecting the waste disposal system would not likely occur over the next one million years.

Because salt domes occur by intrusion through overlying sediments, they are not generally protected from potential dissolution by circulating groundwater. The anhydrite (calcium sulfate) "cap rock" immediately overlying most salt domes in the Gulf Coast region is believed to be the insoluble residue left by the dissolution of as much as a thousand meters of the original dome.(18) Site investigations for waste disposal in a specific salt dome would have to define the characteristics of the groundwater system around the dome in considerable detail in order to demonstrate that further dissolution would not occur. A further consideration in this respect is the possibility of encountering a zone of higher permeability rock inside the dome that could be hydrologically connected with the groundwater systems.

In order to assure adequate containment of waste products over their toxic lifetime if disposal is made in a salt dome, consideration will also have to be given to the future effects of cavity excavation and added heat from radioactive decay on both the tectonic and hydrologic systems. Salt is quite plastic and when occurring in domes is already in a high potential state of mobility. It would be necessary to demonstrate that renewed diapirism would not occur from movement of salt into the cavity; from response to the wider induced stress field in the case of an explosion formed cavity; or from the stress that would be induced by added heat from the waste products over periods of several hundreds of thousands of years.

Geographically, salt is distributed over several large regions of the United States. Individually salt domes cover a relatively small area within any given basin. Consideration would therefore have to be given to finding a salt dome with suitable subsurface characteristics that also had satisfactory surface features. In the Gulf Coast region where most of the salt domes are known to occur, the surface land is already committed to production of oil and gas, to mining salt from the domes, or to agricultural use because of the shallow and prolific surface water systems.

4.0.3.2.2 Igneous Rocks. Igneous rocks are those formed by the solidification of molten rock. They include intrusive (plutonic) rocks that solidified below the earth's surface at various depths, and extrusive (volcanic) rocks that solidified after being erupted onto the earth's surface. The intrusive rocks are fine, medium, or coarse grained depending upon the depth of intrusion, rate of cooling, and presence of gaseous constituents. The extrusive rocks are fine grained or glassy (with or without crystals) and are subdivided into 1) lavas--rocks formed from liquid magma that flowed directly onto the earth's surface and 2) tuff--rocks that formed from eruptive ash that either flowed directly onto the earth's surface from a volcanic vent (ash-flow tuff) or fell from the atmosphere after being explosively erupted into the air from a volcanic vent (ash-fall tuff). Igneous rocks are commonly classified on the basis of their texture (grain size), minerals present, and the abundance of silica (SiO_2). A general classification and the principal mineral assemblages of igneous rocks are shown in Table 4.2.

The igneous rocks vary individually in hardness and strength dependent upon crystal size, the mode of eruption, and the presence or absence of voids. The plutonic (intrusive) rocks have low porosities and permeabilities, whereas the volcanic (extrusive) rocks vary in these properties from very low to extremely high.

Plutonic igneous rocks which consist of granite, granodiorite, diorite, gabbro, and other varieties can be generally regarded as a single rock type from the standpoint of mechanical strength and overall suitability for waste disposal. The granitic rocks, however, have the lowest melting points and are somewhat weaker than the other rocks in this category. Because of low porosities and permeabilities and high mechanical strengths, the plutonic rocks could be considered favorable for waste disposal.

Volcanic igneous rocks are the fine-grained (extrusive) equivalents of the plutonic (intrusive) rocks. Although some volcanic rocks are chemically identical to some plutonic rocks, their physical properties are, in general, decidedly different, and, although lavas and tuffs may have identical chemical compositions, they generally differ significantly in physical properties.

Throughout the United States lavas occur that vary in composition from rhyolite to basalt, and although the various lavas have many features in common, they display some inherent

TABLE 4.2. General Classification and Principal Mineral Assemblages of Igneous Rocks

Texture	>66 percent silica (acid)	52-66 percent silica (intermediate)		<52 percent silica (basic)
Plutonic (medium- and coarse-grained).	Granite	Granodiorite	Diorite	Gabbro
Volcanic (fine-grained or glassy lava or tuff).	Rhyolite	Quartz latite and rhyodacite.	Dacite and andesite.	Basalt and basaltic andesite.
	Major minerals--quartz, potassium, feldspar, mica.	Major minerals--quartz, sodium-calcium feldspar, mica, amphibole.	Major minerals--calcium-sodium feldspar, mica, amphibole.	Major minerals--calcium-sodium feldspar, pyroxene, olivine.

differences that would be significant to waste disposal. Rocks that are rich in SiO_2 or contain intermediate amounts of SiO_2 are erupted at lower temperatures than the basalts and other similar low-silica lavas, and they are much more viscous. Because of greater viscosity, these lavas move across the earth's surface slowly, congealing and freezing on the flanks, at top, and base and become flow contorted and brecciated (broken fragments cemented by finer grained materials). The brecciation increases the porosity and permeability of the rock, and, consequently, many of the silicic lavas are prolific water bearers. Although they are strong rocks except where they are extensively brecciated, and although they are easily mined and drilled, most silicic lavas would be considered unfavorable for waste disposal or storage. The basaltic and other low-silica lavas are erupted at higher temperatures and are more fluid. They commonly solidify without extensive brecciation except at top and base. Individual flows, however, are often thin (less than 60 meters) and the brecciated contacts between flows are consistently zones of high porosities and permeabilities.

Tuffs solidify from soft ash by a process called welding, which is a result of heat and load pressure, and by bonding of matrix material by secondary processes during burial beneath the water table. The degree of welding is the principal factor that controls the hardness of the tuffs. Densely welded tuffs have physical properties that are similar to those of lavas. Partially or nonwelded tuffs are similar to soft sandstones. Porosity in tuffs is dependent on the degree of welding and the amount of alteration or secondary crystallization that occurred during and after cooling, including zeolitization. Most tuffs have more than 20 percent open pore space (porosity) but they also tend to have lower permeabilities than most lavas because the pore spaces are not extensively interconnected. The tuffs are easily drilled and mined. They have the highest ion-exchange capacities of all the igneous rocks. Where sufficiently thick and not faulted the tuffs could provide potential media for waste disposal.

4.0.3.2.3 Metamorphic Rocks. Metamorphic rocks are formed from original igneous, sedimentary, or other metamorphic rocks through alterations produced by pressure, heat, or introduction of other materials at depths below the surface zones of weathering and cementation. They are more or less reconstructed in place while remaining virtually solid. New minerals and textures come into being and are stable under conditions that produce the change.(23) Grain sizes, compositions, and derivations of the principal metamorphic rocks are given in Table 4.3. Quartzites, marbles, and amphibolites are unfoliated to faintly foliated, whereas the other types are foliated, cleaved, or banded, and some types (especially slate) tend to split in well-defined thin layers. All these rocks are considered to be stronger than their sedimentary equivalents and have lower permeabilities, but, in general, they are weaker and have higher permeabilities than most intrusive igneous rocks.

In general, there are often no sharp boundaries between the various types of metamorphic rocks. Within a small area several rock types may occur; therefore, locating a particular metamorphic type at depth often requires more intense surface and subsurface investigations than is normally required for intrusive igneous (plutonic) rocks.

Quartzites are made up of interlocking grains of quartz. They are essentially extremely well cemented quartz sandstones. When fractured, quartzites break across the grains in contrast to sandstones which break around the mineral grains. Quartzites are very hard, are chemically inert, and have the highest thermal conductivity and thermal expansion of the principal rock types discussed. Most quartzites have very low porosity and permeability. Their susceptibility to fracturing, however, increases their permeability, especially at shallow depths. At greater depths, quartzites could be more favorable for the disposal of waste because fractures would tend to be closed.

Marbles are recrystallized limestones or dolomites, and their chemical and physical properties do not differ markedly from these sedimentary rock types. They have the greatest solubility of the metamorphic rocks and are chemically unstable in an acid environment and at higher temperatures. Because of their chemical instability and potential for locally high permeabilities in most geohydrologic environments, marbles would be generally unsuitable for waste disposal.

TABLE 4.3. Principal Metamorphic Rocks

Rock Type	Grain Size	Chief Minerals	Derivation
Gneiss	Coarse to medium grained	Quartz, feldspar, mica, hornblende	Granite, mica, schist, shale
Quartzite	Coarse to medium grained	Quartz	Sandstone
Amphibolite	Coarse to medium grained	Hornblende, plagioclase, minor garnet and quartz	Basalt, gabbro, tuff
Marble	Coarse to fine grained	Calcite, dolomite	Limestone, dolomite
Schist	Coarse to fine grained	Mica, quartz, feldspar	Shale, igneous rocks
Phyllite	Fine grained	Mica, quartz, kaolinite	Shale, tuff
Slate	Very fine	Mica, kaolinite	Shale, tuff

Most amphibolites are coarse-grained rocks consisting of amphibole and plagioclase and lesser amounts of garnet, quartz, and epidote. They are derived from basalts, gabbros, and rocks of similar composition. Some are derived from impure dolomite. Of the principal metamorphic rock types, amphibolites have the greatest strength and should be less susceptible to fracturing than quartzites, and, therefore, less permeable at shallower depths. Amphibolites also have the highest density and magnetic susceptibility of the common metamorphic rocks, which would be advantageous in determining their distribution through geophysical methods. The potential for very low permeabilites indicates that amphibolites could be suitable for waste disposal.

Gneisses have distinct layers or lenses of different minerals. The mineral composition, although variable, consists of abundant feldspar and moderate amounts of quartz, amphibole, garnet, and mica. Gneisses form from numerous parent rocks, igneous, sedimentary, or metamorphic. They are second to amphibolites in strength and second to quartzites in thermal conductivity. Because gneisses vary considerably in their mineralogy and origin, their physical and chemical properties generally are not consistent. Therefore, some varieties of gneiss could prove to be more favorable for waste disposal than others. Gneisses, in general, have very low permeabilities, but gneisses formed from igneous rocks tend to have lower permeabilities than those formed from sedimentary rocks.

Schists are crystalline metamorphic rocks having closely spaced foliation. They tend to split readily into thin flakes or slabs. There is a complete gradation between schists and gneisses to schists and slates. The names of the varieties of schist are based chiefly on the mineral responsible for the foliation, that is, biotite schist, chlorite schist, and graphite schist. Schists have lower thermal conductivities than quartzites, amphibolites, and gneisses, and have the least strength of any of the principal metamorphic rocks. Because of their wide variation in mineralogy and origin, schists should vary considerably with respect to physical and chemical properties, and their favorability for waste disposal will depend on the rock type in question.

Phyllites are fine-grained foliated rocks that are intermediate between mica schists and slates. Practically all phyllites are derived from fine-grained sedimentary rocks by mechanical deformation and recrystallization. Fracturing is intermediate between the rather splintery fissility of schist and the smooth, even cleavage of slate. Both phyllites and slates are highly foliated and, because of their excellent foliation, split into thin sheets.

Slates are homogeneous metamorphic rocks so fine grained that no mineral grains are visible to the naked eye. Some slates split into slabs having plane surfaces almost as smooth as the cleavage planes of minerals. Slate is harder than shale, although the difference is slight. Slates and phyllites have the greatest ion-exchange capacities of the common metamorphic rocks. Slates may locally be suitable waste disposal rocks from the standpoint of permeability, especially at great depths where open fractures along cleavage planes may be at a minimum. Slates have the least thermal conductivity, and their thermal expansion is nearly as high as in quartzites.

Chemical compositions and additional physical and hydrologic properties of principal rock types (sedimentary, igneous, and metamorphic) are given in Appendix 4.C.

4.0.3.3 Hydrologic Considerations

Hydrology, specifically groundwater hydrology, is one of the most important considerations when planning for the ultimate disposal of high-level radioactive waste, because groundwater flow systems are the primary means by which waste constituents might regain contact with man's environment. Basically, where a hydraulic gradient is developed by difference in head, groundwater has the potential to move from areas of high head toward areas of lower head. If this potential exists and if avenues for movement are open, a groundwater flow system is established.

4.0.3.3.1 Flow Systems. Figure 4.4 illustrates basic patterns of groundwater flow in sedimentary basins under rather uncomplicated conditions and shows how contaminants could regain contact with man's environment even if placed in the deeper parts of the basins. Water enters permeable rock in areas of outcrop and travels downward, then laterally through the rock by gravity. In some basins, if permeable rock is overlain

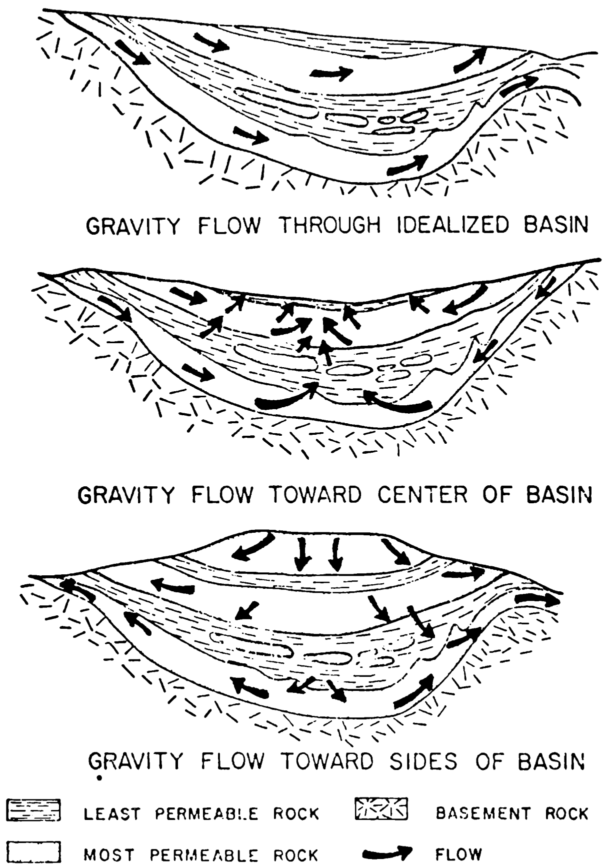


FIGURE 4.4. Idealized Gravity Flow Through Basin (Modified from Drescher, 1965)(24)

by relatively low permeability rock, artesian conditions can develop; this could create especially hazardous conditions for waste disposal.

The sedimentary basins in the United States are far more complicated than these diagrams indicate, and it is apparent that a thorough knowledge of hydraulic conditions in any basin considered for waste disposal is absolutely essential. Figure 4.5 shows the principal consolidated and unconsolidated groundwater systems in the United States and the surface drainage systems that are an important factor in controlling hydraulic conditions. It can be seen that the recharge source for a given basin can come from long distances and be affected by a variety of surface processes not indigenous to the basin.

Damming of rivers for the purposes of flood control, power production, or irrigation has been known to cause significant changes in associated groundwater systems. The major withdrawals of groundwater for irrigation (San Joaquin Valley, California; New Mexico; Texas; and Eastern Washington) has caused a lowering of the water table and an increase in hydraulic gradient. Other areas may show a marked increase in shallow

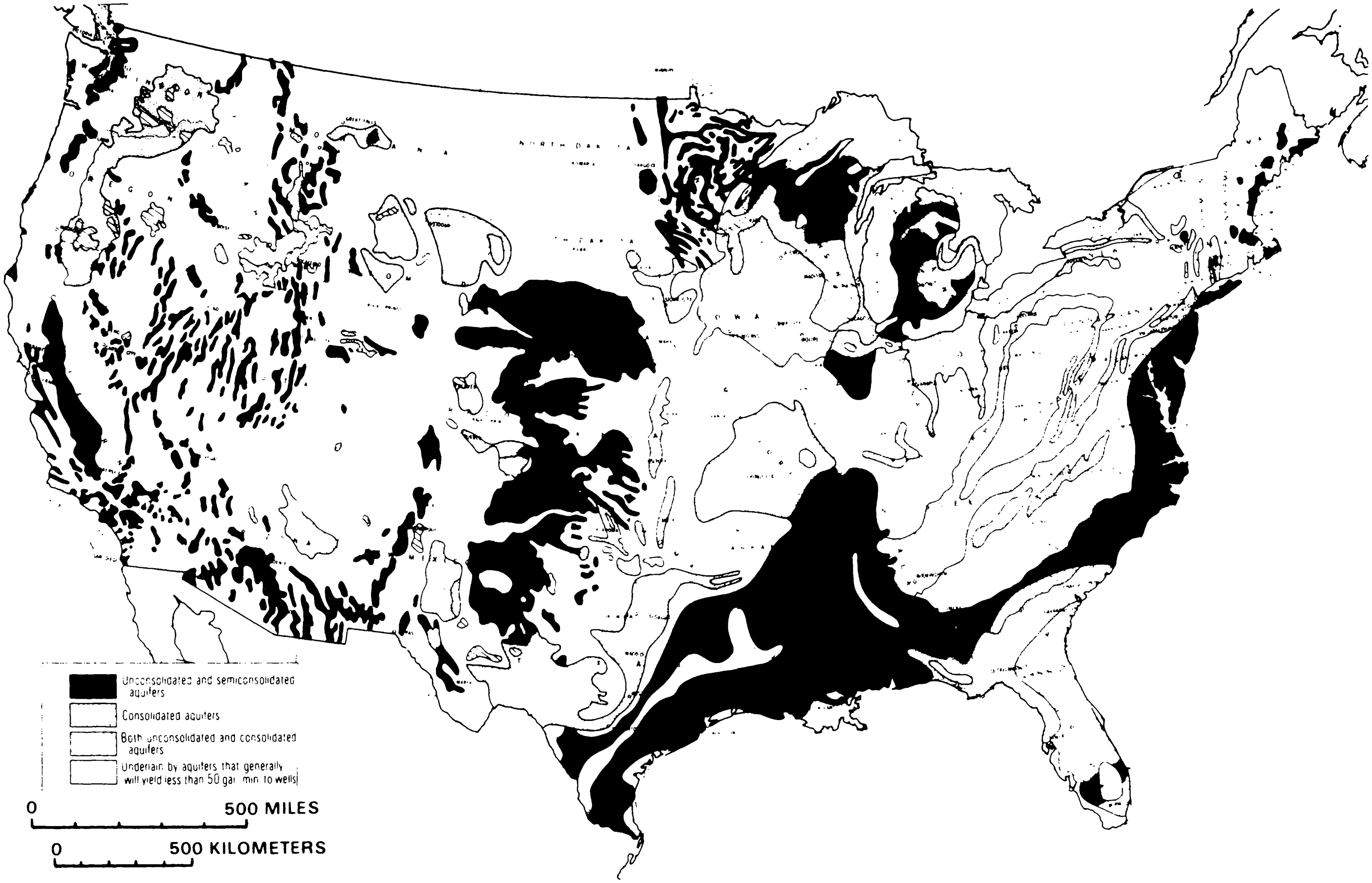


FIGURE 4.5. Groundwater Areas (Major Aquifers) (J. J. Geraghty et al., *Water Atlas of the United States*)(25)

groundwater levels when the soils are impermeable and infiltration rates are too low to readily accommodate the increased water from irrigation and damming. These changes in the hydraulic system caused by man's manipulation of his environment are often difficult to predict because of the relatively slow travel time of groundwater. To foresee the changes that man may enact in the future and also predict the attendant changes in the groundwater systems will be even more difficult.

4.0.3.3.2 Stratification and Faulting. Groundwater flow systems as discussed in the previous section are ideal and can be complicated by a disruption of the geologic framework of the system. The basic flow pattern through a basin usually is complicated, at least locally, by stratification and faulting. Stratification can change the direction of groundwater flow. Faults (fractures along which there has been relative displacement of the rocks) significantly affect flow patterns in any groundwater system. They can either be conduits for flow of water between transmissive zones or be obstructions to flow of water in an aquifer. Faults that are potential conduits of flow have been found at depths of one thousand or more meters. These faults are potentially hazardous to waste containment because they can serve as connections between disposal sites and man's environment even in an otherwise dense rock of very low permeability. Therefore, any site selected for disposal of waste must be hydrologically isolated from permeable fault systems. Thermal springs, commonly associated with volcanic rocks, can be surface expressions of faults. Certainly thermal springs are an indication of permeability and rather rapid groundwater circulation at depth. Conversely, absence of thermal springs does not necessarily suggest impermeable rocks below.

4.0.3.3.3. Permeability. Of principal concern for the safe emplacement of high-level radioactive waste is the permeability of the rock media. Permeability, as used in this study, is a measure of the ability of a rock to allow movement of water through its connected openings. Permeability (hydraulic conductivity) is described by Lohman and others(26) as follows: "If the porous medium is isotropic and the fluid is homogeneous, the medium has a hydraulic conductivity of unit length per unit time if it will transmit in unit time a unit volume of water at the prevailing kinematic viscosity through a cross section of unit area, measured at right angles to the direction of flow, under a hydraulic gradient of unit change in head over unit length of flow path." Permeability is a property of rock that has been measured frequently and, as such, can be discussed with some confidence in terms of general rock types. Table 4.4 defines degrees of permeability for use in later discussion of geohydrologic environments and rock and soil types.

4.0.3.3.4 Liquid-Versus Solid-Waste Disposal. In consideration of

TABLE 4.4. Degrees of Permeability of Various Rock and Soil Types(27)

[By G. A. Dinwiddie, 1973, U.S. Geological Survey]

Permeability, in cubic centimeters per second per square centimeter[(a)]	10^2	10^1	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
Permeability, in gallons per day per square foot	10^6	10^5	10^4	10^3	10^2	10^1	1.0	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}
Degree of permeability	Very high	High		Moderate			Low			Very low		
Soil type(b)	Clean gravel		Clean sands; clean sand and gravel mixtures			Very fine sands; silts; mixtures of sand, silt, and clay; glacial till; stratified clay deposits; etc.				Homogeneous clays below zone of weathering		
Rock type	|←—— shale —— |←—(fractured) —— sandstone ——→| —— (solution cavities) —— limestone and dolomite —— (unfractured) ——→| |←—(fractured or weathered) —— volcanic rocks, excluding basalt —— —— (cavernous and fractured) —— basalt —— (dense) ——→| |←—— (weathered) —— metamorphic rocks —— |←—— bedded salt —— |←—— (weathered) —— granitic-type rocks ——											
Probable yield, in gallons per minute	>3000		1000			100			10			<1.0

a. Multiply by 1.04 x 10^3 to obtain Darcy units.
b. From Reference 28.

groundwater flow systems as limiting factors for planning the ultimate disposal of high-level radioactive waste, it is necessary to evaluate whether underground emplacement of liquid waste is hydrologically feasible in any geologic environment and, if it is, to consider the relative hazards of liquid- and solid-waste emplacement.

Liquid-waste disposal presents some obvious problems. Any plan to inject or place liquid waste within sedimentary rocks could be hazardous even if the waste first melts the host rock and then solidifies with the rock. All sedimentary rock has some permeability--has some degree of ability to transmit water and thus to transmit waste contaminants.

The alternatives to sedimentary rocks for liquid waste disposal are dense, unfractured metamorphic and igneous rocks, including the basement rocks. Most of the metamorphic and igneous rocks are crystalline, and the hydrologic implications are that interstitial porosity and permeability are very low and that any significant permeability established in these crystalline rocks must be fracture permeability. The crystalline rocks are weathered and fractured at shallow depths, but below a depth of about a thousand meters the likelihood of encountering water-bearing fractures, especially in the granitic type rocks, is low because lithostatic pressure generally serves to keep fractures closed and to prevent formation of new tensile fractures. Therefore, the crystalline rocks seem to be much better hosts for all concepts of liquid-waste disposal than do sedimentary rocks. Secor(29) has presented arguments indicating that appropriate fluid pressures in sedimentary rocks of magnitudes observed in deep oil tests could serve both to form tension fractures and to open up previously formed fractures at great depth. Such a process potentially provides paths for the migration of groundwater. Determining the existence of the appropriate conditions would require hydrologic evaluation of the specific area including deep drilling and studies of existing mines.

Fractures might also develop as a result of melting and subsequent expansion of the host rock by high temperature liquid waste whether placed in an exploded cavity or a deep drill hole. Whether or not such possible fracturing would extend far into the rock and form potential avenues for escape of contaminants can only be evaluated by laboratory and small-scale field experiments.

Disposal of high-level radioactive waste as glassy or micro-crystalline solids in the initial phase of disposal appears an advantageous concept to assure waste confinement. The main advantage is that the radionuclides from the first contact with the host media are not subject to aqueous migration until such time that they are leached from the binding solids. An additional advantage is a much greater degree of safety during the period of waste emplacement.

For all of the disposal concepts considered herein it is presumed that the waste canister would be leakproof during the period of waste emplacement and that final sealing of the hole will be complete. The sealant should be of such integrity that it will remain impervious for the long time period of concern. Because of the possibility that the above conditions can not be positively guaranteed, potential site localities containing permeable strata above the emplacement zone must always be regarded as less suitable than those localities where the rocks, from the surface through the emplacement zone, have very low permeabilities.(17)

4.0.3.3.5 Groundwater Transport. Radioactive contaminants can migrate from an underground source of contamination through groundwater systems. Fenske(30) discusses the phenomena of the migration of radionuclides away from sites of nuclear explosions in terms of radionuclide transport in groundwater. Important physical parameters of radionuclide transport include: (1) radioactive decay constants, (2) initial concentrations of contaminants, (3) dispersion and diffusion of radionuclides, (4) retardation of radionuclides by ionic sorption, and (5) velocity of groundwater. These same parameters are pertinent to the problem of transport of radionuclides away from a waste-disposal site.

Dispersion (spreading and dilution) of contaminants in groundwater is caused principally by variations in velocity within a groundwater system. The greatest dispersion will be in a system with the greatest range in velocity wherein movement paths are tortuous. Therefore, dispersion will be greater in heterogeneous, anisotropic host rock than in homogeneous, isotropic media. Certain portions of the groundwater system having velocities greater or less than the average velocity will tend to retard or slightly accelerate the first arrival of contaminants at terminal flow points relative to average groundwater velocity.

Retardation of radionuclides is any means by which the rate of migration of radionuclides is slowed to less than the rate of groundwater movement. The principal retarding effect is that of ion-exchange capacity. The initial effect of ion exchange is reduction of concentration of ions (such as radionuclides) in solution when these ions are exchanged with ions from the host rock. The final effect is elution (desorption) of the radionuclides from the host rock over relatively long time periods compared to initial sorption. The net effect is usually significant dilution of the ions in the water and significant delay in nuclide transport through the rock. Some experiments have been made to determine retarding effects of specific rock types on selected radionuclides. The results of these studies and an expanded discussion of retardation are presented in section 4.0.3.4.

Because radionuclides migrate within groundwater flow systems, the rate of groundwater movement is one of the principal controlling factors of the extent of migration. Velocity of groundwater movement is controlled

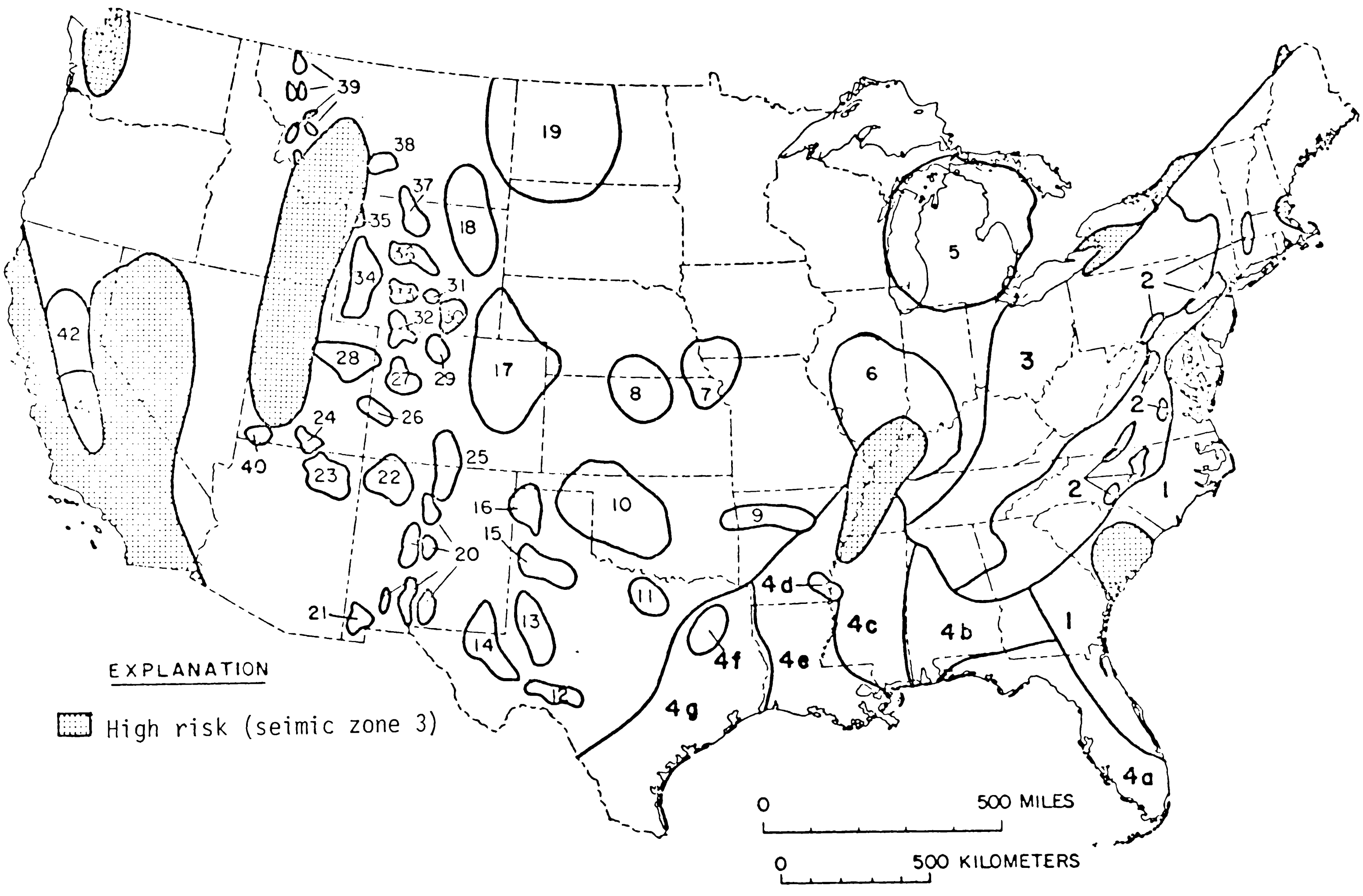


FIGURE 4.6. Locations of Sedimentary Basins (Basins from Love and Hoover, 1961(19) and Seismic Risk from Algermissen, 1969)(31)

Key to Sedimentary Basin Locations in Figure 4.6

Map number (Fig. 4.6)	Basin
1	Atlantic Coastal Plain
2	Eastern Triassic basins, eight
3	Appalachian basin
4	Gulf Coastal Plain:
4a	Florida
4b	Alabama
4c	Mississippi
4d	Desha
4e	Louisiana
4f	Tyler
4g	Texas Gulf
5	Michigan basin, inluding Canada
6	Illinois basin
7	Forest City basin
8	Salina basin
9	McAlester-Arkansas basin
10	Anadarko basin
11	Fort Worth basin
12	Val Verde basin
13	Midland basin
14	Delaware basin
15	Palo Duro basin
16	Dalhart basin
17	Denver basin
18	Powder River basin
19	Williston basin, including Canada
20	Rio Grande basins, six
21	SW New Mexico basins, six
22	San Juan basin
23	Black Mesa basin
24	Kaiparowits basin
25	San Luis basin
26	Paradox basin
27	Piceance basin
28	Uinta basin
29	North and Middle Parks
30	Laramie basin
31	Hanna basin
32	Washakie and Sand Wash basins
33	Red Desert basin
34	Green River basin
35	Jackson Hole
36	Wind River basin
37	Bighorn basin
38	Crazy Mountain basin
39	Western Montana basins, eight
40	SW Utah basin
41	San Joaquin basin
42	Sacramento basin

by effective porosity and permeability of the host rock and by hydraulic gradient. Within the scope of discussion of general rock types and geohydrologic environments, only permeability can be evaluated on a generalized basis.

4.0.3.3.6 Sedimentary Basins. The sedimentary basins throughout the United States (Figure 4.6) all owe their existence to downwarping and (or) downfaulting of the earth's crust. They differ individually in depth to basement rocks, in structure, and in geologic age. They are similar in that they are filled with relatively gently dipping sedimentary and, locally, volcanic rocks. They range in area from 2,500 to 250,000 square kilometers, and they range in depth from about 1,200 meters to more than 15,000 meters. Many of the younger basins in the western area of the United States and in the Coastal Plains contain unconsolidated sediments or slightly consolidated rocks. The older basins in the central and eastern areas of the United States contain mostly well consolidated rocks. Unconsolidated and slightly consolidated sand and gravel deposits are the predominant aquifers, especially in the western basins,(32,33) but consolidated rocks such as sandstone, limestone and dolomite are also important aquifers in many areas.

Most of the sedimentary basins are important producers of oil, gas, or coal. Some produce salt, potash, ceramic clays, and various other nonmetallic and metallic minerals.

A generalized cross section through two typical sedimentary basins is shown on Figure 4.7.

Groundwater. Groundwater occurs under both water-table and artesian conditions. At places where the aquifers are unconfined, groundwater occurs under water-table conditions, and water levels in wells do not rise above the top of the aquifer.(34) At places where the aquifers are confined by strata with very low permeability, such as shale, groundwater can occur under artesian conditions. There the water is under pressure so that the water levels in wells rise above the top of the aquifer. If the pressure is great enough, the well will flow at the land surface.

The water levels found in wells are generally shallower in areas of high precipitation or in areas of low topographic relief, such as basins in the eastern half of the United States. There water levels commonly range from above land surface (artesian) to shallow depths less than 30-60 meters. Water levels are generally deeper in areas of high topographic relief, such as basins in the western half of the United States. In those basins, water levels commonly range from above land surface to depths of 150 to more than 300 meters.

The movement of groundwater generally consists of recharge of water to an aquifer either from precipitation or from seepage from streams. This recharge moves downward and laterally under the forces of gravity and hydrostatic pressure through the aquifer toward points or areas of discharge. Discharge generally occurs in springs, in areas of evaporation and transpiration by plants, or by subsurface

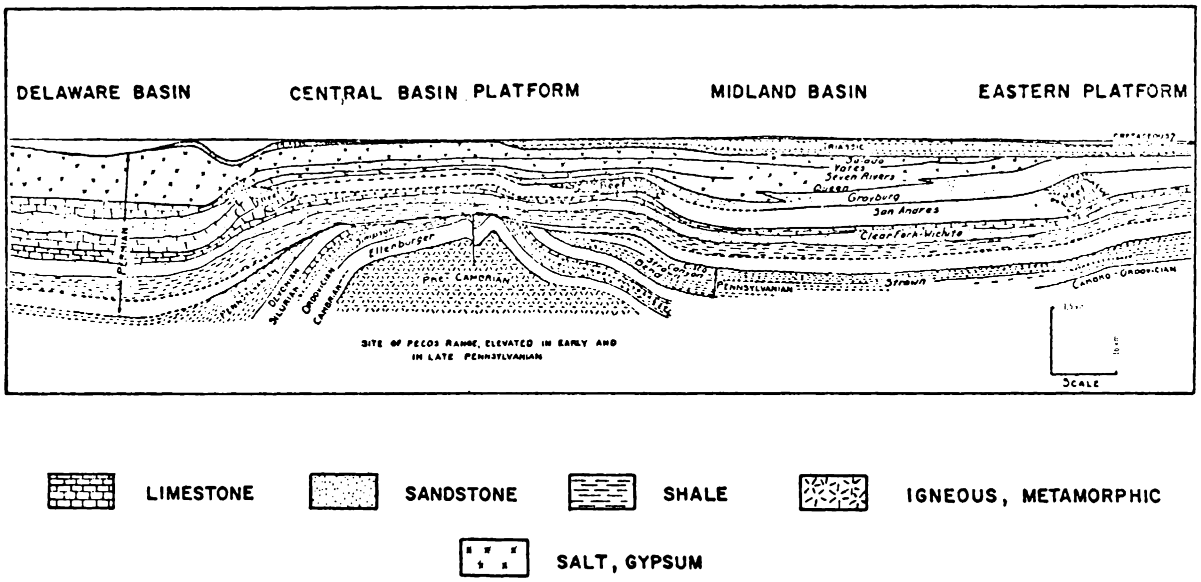


FIGURE 4.7. Geologic Section Through Delaware and Midland Basins, New Mexico and Texas (Modified from King and Others, 1942)(35)

flow out of a basin either into surrounding rock, into flowing streams, or into a body of water such as a lake or an ocean. Figure 4.4 presents examples of groundwater flow under artesian conditions from areas of recharge at the land surface toward areas of discharge at the center or the margins of the basins.

Most sedimentary basins contain geologic structures such as faults and folds. All contain many lateral and vertical variations in rock types and permeability resulting in a complex pattern of groundwater flow. Geologic structures exert considerable influence on the movement of groundwater, and aquifers that are generally separated by rocks with very low permeability may be hydraulically connected along faults and fractures. A decrease in porosity and permeability at great depths may occur due to the compaction of rocks under the great weight they were exposed to during compaction of the sediments. The velocity of water movements related to basin flow systems can be greatly decreased by the occurrence of overlying rocks.(32) If pressures differ between aquifers, flow may occur through either interstices or fractures across the rocks of very low permeabilities that separate the aquifers. In many sedimentary basins the determination of the exact flow path of groundwater movement from recharge area to discharge area may not always be possible.

Several other potential factors of significance in sedimentary basins are abnormal subsurface pressures, the presence of saltwater or highly mineralized water, and the occurrence of thermal springs. Abnormal subsurface pressures may influence the movement of groundwater. Some basins in California and Wyoming and in the Gulf Coastal Plain have subsurface pressures that are higher than normal, probably owing to the compaction of unconsolidated sand and clay deposits.(36) Saltwater or highly mineralized water may affect the movement of groundwater. The aquifers in the Atlantic and Gulf Coastal Plains were filled with saltwater when the sands were deposited under the sea, but now the aquifers have been flushed by freshwater to great depths of from 300 to 1800 meters.(37) In other basins, some deep water is highly mineralized, although shallow water is fresh.

Hot or warm thermal springs (Figure 4.8) that originate at great depths and rise along deep faults or fissures indicate an upward movement of water aided by artesian pressure and hydrothermal activity or both. Nearly all thermal springs are associated with volcanic rocks, possibly indicating that unpredictable upward movement of groundwater may occur in basins that contain hot springs.

Suitability for Disposal. Sedimentary basins represent a significant part of conterminous United States; however, most sedimentary rocks, excluding shale, commonly can have significant porosities and permeabilities to depths as great as 6000 meters. This fact and the common occurrence of important aquifers and (or) oil- and gas-producing strata above, below, and within shale sequences could make the basins generally unsuitable for most waste-disposal concepts except for disposal in salt.

Because shale has very low permeability and high ion-exchange capacity, it has been used as a repository for low-level waste at the Oak Ridge National Laboratory in Tennesssee.(11) Partly as a result of this usage, consideration has been given to using shale as repositories for high-level waste. Shale sequences throughout the United States recently have been generally evaluated for radioactive waste disposal by Merewether, Sharps, Gill, and Cooley.(39) They conclude that, in general, the shale sequences are not suitable for waste disposal but that detailed investigations may disclose some strata that are acceptable.

In most basins where thick shale sequences occur, drill-hole data indicate that few zones exist without thin interbeds of sandstone and (or) limestone that drastically increase the overall permeability of the sequence. In some basins water moves slowly through shale because of permeable interbeds that are cut and displaced by faults and fractures. At shallow depths both water-bearing fractures and faults and permeable interbeds will probably occur in the vicinity of any potential waste-disposal site. It would be difficult, therefore, to assure that waste can be effectively contained for very long time periods if the waste is initially emplaced in shale below existing water tables. There is a possibility, however, that shale can

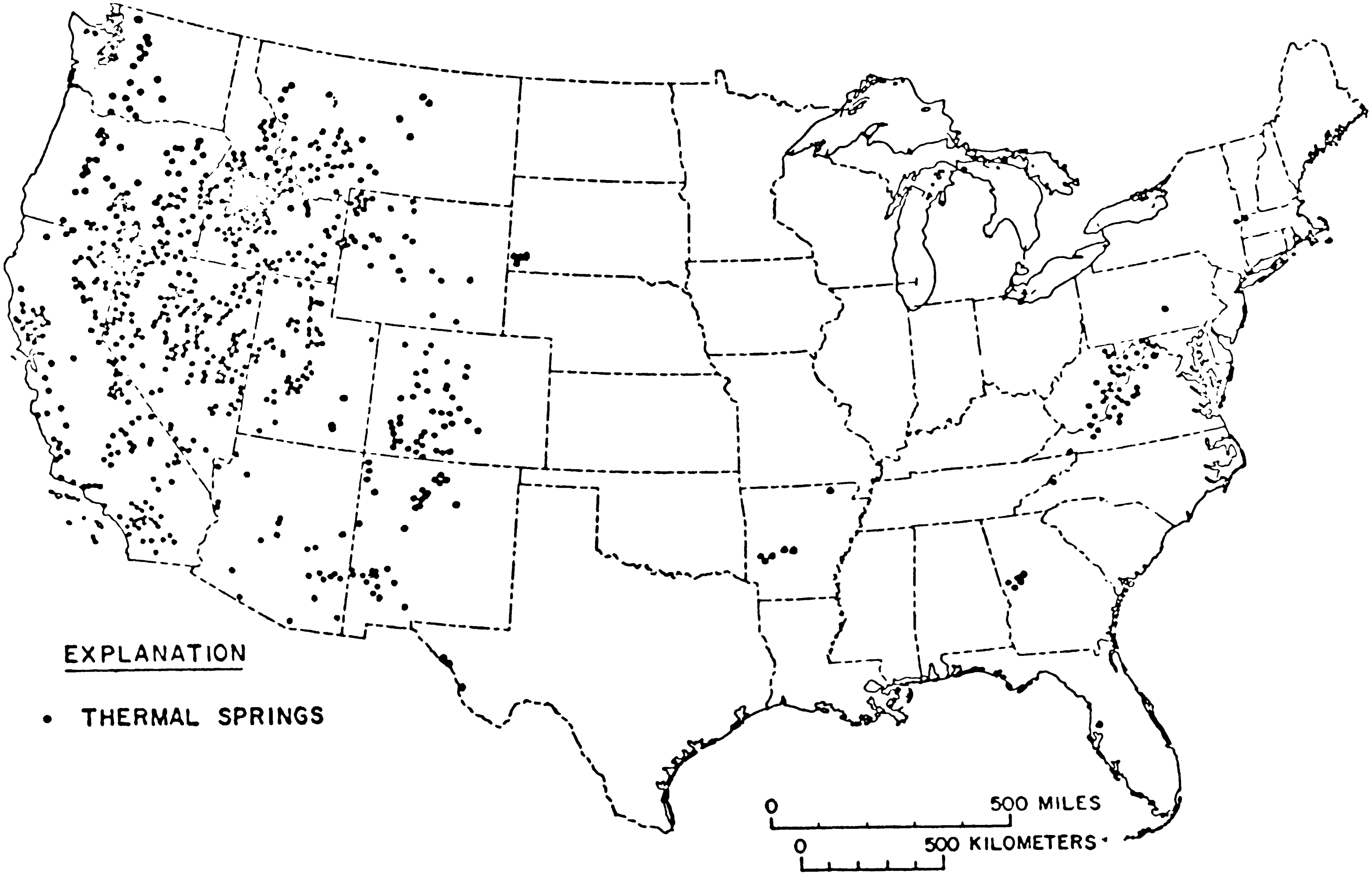


FIGURE 4.8. Thermal Springs in the United States (Modified from Waring, 1965)(38)

be used for shallow-depth mined cavities above the water table provided the water table is deep enough.

At depths below 2000 meters detailed investigations in some basins may define thick shale sequences in which fluid flow can be predicted to be extremely slow. Therefore, this geologic environment could be considered as possibly suitable for the matrix hole and exploded cavity concepts. The basic premise is that at depths below about 2000 meters fractures in shale will probably be tight and porosities and permeabilities of thin interbeds will be diminished. At these depths, however, the structural instability of some shale may prove to be a difficult problem during operational phases.

Geologically and hydrologically, salt may be one of the more suitable media for waste disposal in sedimentary basins (Figure 4.9). Studies so far indicate that salt (bedded or in stable domes) can be potentially suitable for shallow-depth mined cavities and shallow- or moderate-depth explosive cavities. Salt could also be potentially suitable for the matrix of drill holes, but large-diameter drill holes may be unstable and close rapidly in salt at depths below 1000 to 1500 meters.

<u>4.0.3.3.7 Igneous and Metamorphic Systems</u>. Crystalline igneous and metamorphic rocks occur in several large areas in the Eastern, Western, and Northern United States and also in several small areas in the continental interior. Because these rocks have very low porosities and permeabilities (where they are not faulted) especially in the subsurface below depths of about 1000 meters, they are potentially suitable for waste disposal. The principal areas are shown by the stippled pattern on Figure 4.10. The granite and ultramafic bodies and the gneissic rocks seem to comprise the most suitable igneous and metamorphic media for waste disposal. At the Atomic Energy Commission's Savannah River plant, near the boundary of the Piedmont and the coastal plain, hydraulic tests were run in several holes completed in crystalline rock at relatively shallow depths (to 550 meters).(40) All the rock contained fractures, but permeabilities were low, averaging 0.01 liters per day per square meter; this was estimated from transmissivities ranging between 0.025 and 2.5 liters per day per meter. At deeper levels the rocks probably would have even lower permeabilities.

<u>Groundwater</u>. Igneous and metamorphic rocks of the eastern metamorphic belt yield abundant water to wells that average less than 140 meters in depth.(41) Fractures in the rock carry the water, and these logically may be tight and possibly healed in the deeper subsurface. Where sheet mica is mined successfully in the Piedmont at shallow depths, the mines are virtually dry.

Precambrian shield rocks yield little water and usually are explored only for small domestic water supplies. Near the surface, fractures and clayey weathered zones in the igneous and metamorphic rocks yield small supplies of water.(37) Mines in the shield rocks at Sudbury, Ontario, are extremely dry in levels

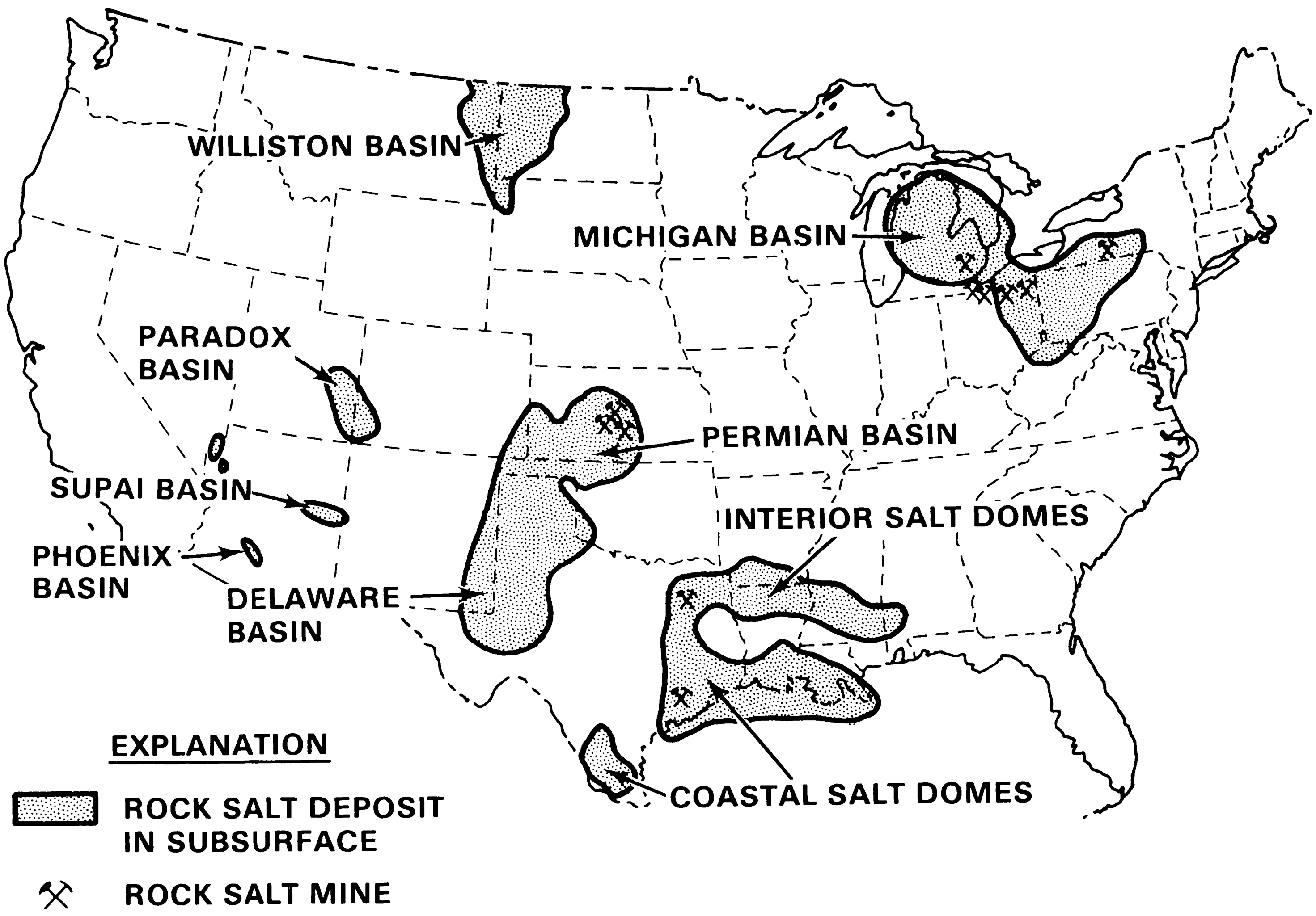


FIGURE 4.9. Rock Salt Deposits in the United States, Parts of Which Are Potentially Suitable for Waste Disposal. (Modified from Pierce and Rich, 1972).[21]

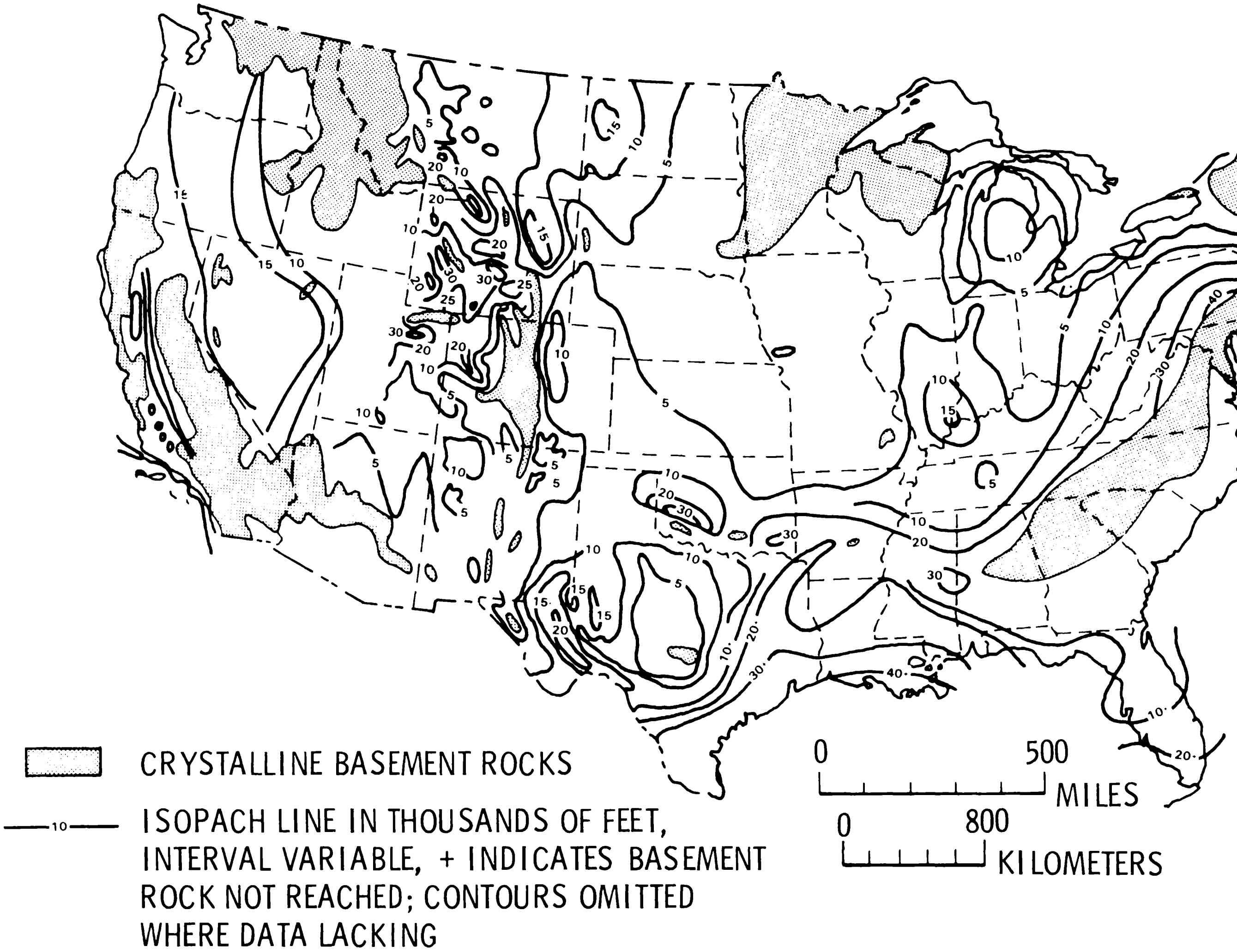


FIGURE 4.10. Principal Areas of Intrusive Igneous and Metamorphic Rocks and Contours Showing Thickness of Sedimentary Rocks in the United States

below a hundred meters of the surface. Mines of the Michigan Copper Company, which have hundreds of kilometers of workings to depths of 1500 meters, encounter such small amounts of water that no pumps are required.

The ability of a metamorphic rock to prevent the escape of liquids within a thousand meters of the surface and the ability of another rock to readily transmit liquids are illustrated by the probable movement of water below the surface at Warm Springs, Georgia (Figure 4.11). Water percolating downward through permeable basal beds of a quartzite underlain by a gneiss with very low permeability encounters a marked fault that offsets the quartzite. The fault acts as a barrier to the movement of the water, causing it to return to the surface through permeable beds in the uppermost part of the quartzite. These beds are overlain by a schist having relatively low permeability, which prevents the escape of the water before it reaches the surface at Warm Springs. The fact that the fault acts as a barrier rather than as a conduit is an example of an old fault encountered at depth being completely healed and not necessarily detrimental.

Suitability for Disposal. It is concluded that metamorphic and intrusive igneous rocks are suitable or possibly suitable for waste disposal in the shield area, the eastern metamorphic belt, and small areas in the continental interior. This conclusion is based on the inference that if faults are avoided these rocks will have very low permeabilities a few thousand or a few hundred meters below the surface. The inference stems from field observations, shallow-well data, and the knowledge that some mines in metamorphic and igneous rocks are dry at shallow depths. Data are scanty, however, and until the areas are drilled and hydraulically tested, the conclusion should be regarded as tentative.

4.0.3.4 Geochemical Considerations

4.0.3.4.1 Ion-Exchange Reactions. Nearly all rocks exhibit the capability of sorbing cations (ion-exchange) such as cesium and strontium from solution. The sorbing capability is especially high in clay minerals. The gross effect of sorption is reduction of the velocity of cation travel to less than the velocity of the transporting water. The degree of retardation of ionic flow depends on the chemical nature of the species, the concentrations of competing species in solution, and the extent and nature of the host rock.

A side effect of sorption is that exchangeable ions are released from the host rock into solution. For instance, sorption of cesium or strontium ions by clay releases sodium or potassium ions into the water, and these released ions, together with ions originally present in the solution, can compete with waste material for available exchange sites. This is the reason that cation movement is only retarded and not stopped. Calcium and magnesium ions tend to affect significantly the retardation of

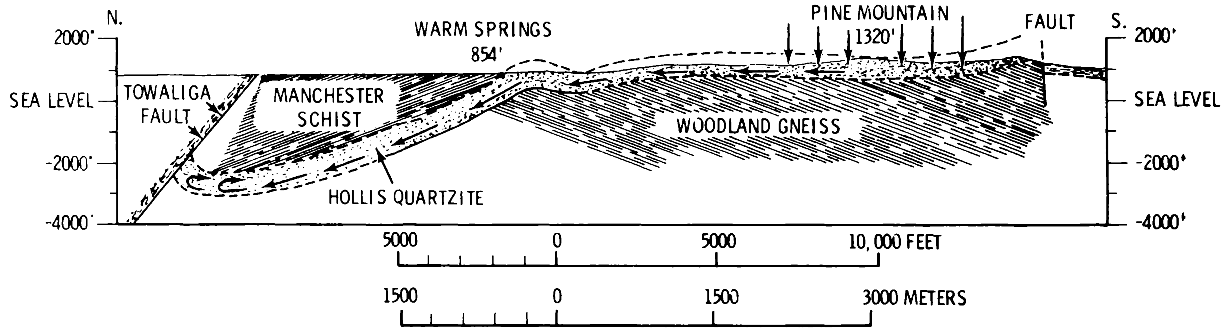


FIGURE 4.11. Cross Section Through Pine Mountain and Warm Springs, Georgia, Showing Geologic Structure and (by Arrows) Probable Course of the Water That Enters Hollis Quartzite as Rain on Pine Mountain and Is Discharged at Warm Springs. (Modified from Hewett and Crickmay, 1937).(42)

strontium ions, and sodium and potassium ions affect strontium retardation very little except at high concentrations. For example, disposal of strontium in dolomite would result in releasing calcium and magnesium ions to solution which then would compete with the remaining strontium ions, and the travel of strontium ions would not be retarded as much as through some other type of host rock.

The degree of retardation also depends on physical parameters such as bulk density and effective porosity of the host rock. Sorption is a phenomenon displayed by all solid substrates. The degree to which these substrates may accommodate sorbants partly depends on the nature of, but more significantly, on the total surface area of the substrate. The larger the surface area per unit mass for a given substrate the greater will be its sorption capacity. If the substrate particles are small enough (e.g., colloidal), they may move with the groundwater together with their sorbed materials, effectively increasing the transport velocity of the sorbents. Should these colloidal materials have a residual electrical charge, however, they in turn may be sorbed on bulkier substrates, thereby decreasing the effective sorbent velocities.

The preceding dicussion has been focused on sorption of cations; however, sorption may or may not have as much effect on movement of anions such as bromides, iodides, and sulfides. Very little study, beyond laboratory conditions, has been conducted on anionic solutions. Most of these studies have been made with iodide. The movement of iodide ions has been measured at significantly higher rates than those of most cations under similar conditions; therefore, it is probable that the mechanisms that control retardation of cations do not readily apply to retardation of anions.

Another group which must be examined is the potential nonionic species of waste constituents. Tritiated water is in the nonionic group. The effect of host rocks on the movement of tritium, as tritiated water, has been studied with varying degrees of success. Although it is not well defined, it is an accepted fact that there is some measurable retardation of tritium; however, the leading edge of a pulse of tritiated water may move at about the same rate as the water.

A distribution coefficient (K_d) is a measure of retardation potential of a host rock. Figure 4.12 illustrates ranges of distribution coefficients for some rock types measured under laboratory conditions. However, the rock samples were in "natural state"--as physically undisturbed as possible.

Ideally, when selecting a geologic environment for waste disposal, the waste constituents and the host environment should be matched for favorable retardation. Movement of cations should be significantly retarded in rocks containing clay or zeolites, which exhibit large surface areas capable of ion exchange. Anionic and nonionic wastes probably should be disposed in water-insoluble forms to minimize leaching by the formation water.

<u>4.0.3.4.2 Rock-Waste Interactions in the Presence of Water</u>. In all geologic disposal concepts, it is most likely that the solid waste forms will eventually come into direct contact with the rocks. Such contact will result in chemical and physical interactions of the waste and the rock. These interactions will tend to be accelerated by the higher-than-ambient temperatures associated with the waste. A brief review is presented of rock-waste interactions possible in the presence of water as pore water in the rocks, as underground aquifers, or as water associated with the waste.

To place glass-waste composition into rock storage with potential or actual water contact is to invite migration of ions, including the radionuclide ions. Boron and the alkalis (Na, K and presumably Cs) are known to have migrated several hundreds of meters under the impetus of a thermal gradient during geologic time spans. Many crystalline phases are theoretically possible under self-heating conditions, but ion migration is just as likely a possibility in any rock type, especially if the waste was originally in aqueous solution.

To examine the ion migration process further, some data are reviewed which were obtained in a study of metamorphic processes most closely resembling the self-heating aqueous waste. A temperature-pressure diagram of the upper crust of the earth summarizes the metamorphic processes(44) in Figure 4.13. In this diagram, the metamorphic processes are considered to extend between diagenesis (processes that occur under the relatively mild thermal conditions of sedimentation and include ion exchange, compaction, pore water migration, etc.) on the one hand (left side) and the minimum temperature for melting of granite on the other. As the rock begins to melt on the other end of the scale, the rock

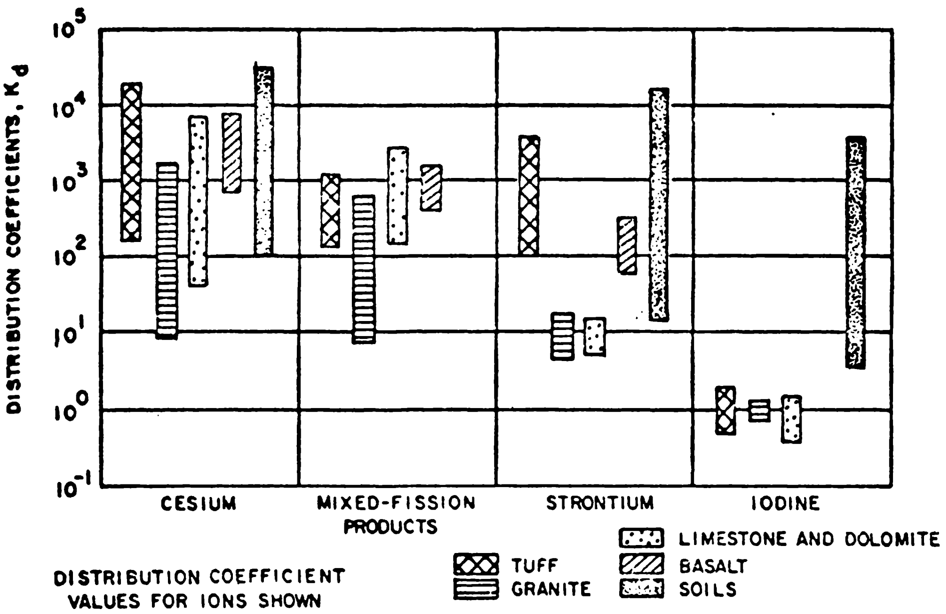


FIGURE 4.12. Ranges of Distribution Coefficients for Various Rock Types (After D. B. Grove, 1970)[43]

becomes igneous, or undistinguishable from an igneous rock. The various rock groups referred to in the diagram comprise a stable group of mineral phases characteristic of given temperature, pressure and compositional conditions.

It is seen from Figure 4.13 that the rocks or minerals change as a function of temperature and pressure. To restate, the minerals recrystallize with increased temperature and pressure to a different group of rocks that is stable under the new pressure-temperature conditions. Recrystallization rates are also greatly affected by the presence or absence of volatile components (water, CO_2 and other gases). Some metamorphic rocks have apparently endured high temperatures and pressures for a span of geological time with little recrystallization. Nonetheless, other compositionally similar rocks at lower temperatures have undergone extensive recrystallization of components. This apparently contradictory behavior is explained by the presence or absence of hydrothermal solutions (warm water solutions) during the metamorphism. With water present, recrystallization is relatively rapid and extensive. These hydrothermal solutions obviously leave the rock after metamorphism. Thus, the rock can show a bulk composition that is nearly the same before and after metamorphism but possess an entirely different bulk composition during metamorphism. The rock bulk compositions before and after metamorphism can also be considerably different due to materials added or removed by the hydrothermal solutions during metamorphism. The composition of these hydrothermal aqueous solutions are of

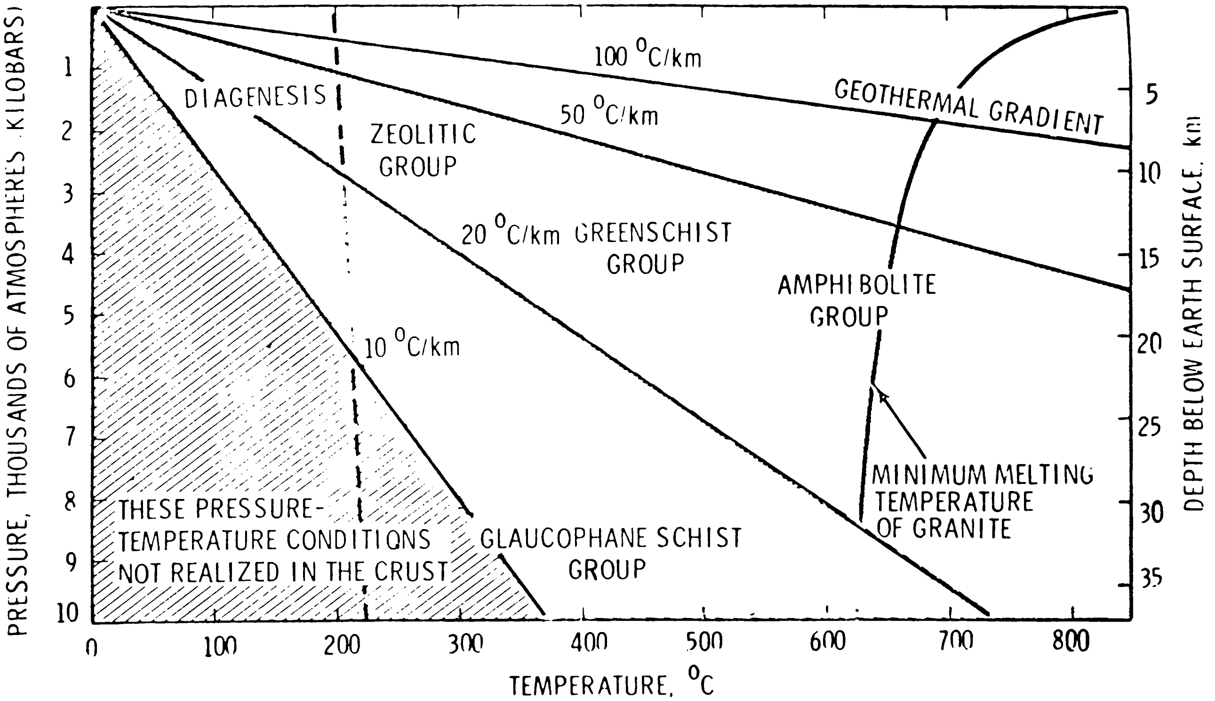


FIGURE 4.13 Distribution of Mineral Groups in a Temperature-Pressure Diagram of the Earth's Upper Crust(42)

interest to us here because these compositions represent ions migrating under the impetus of a thermal driving force that may result in hydrothermal alteration.

Hydrothermal alteration literally refers to the changing of a rock through the agency of hot water. The changes may involve isochemical transformations, or attainment of a new crystal structure without a compositional change, in response to new temperature and pressure conditions. Usually, however, a compositional change occurs as well. The new phases formed are those stable under the new pressure, temperature and compositional conditions. There is usually an increase in altered rock porosity, which means that rock alteration is usually not a constant volume process.

Probably the most important chemical process in rock alteration is that of mineral hydrolysis. Sericitization of orthoclase feldspar in an aqueous solution is a common example of hydrolysis:

$$3KAlSi_3O_8 + 2H^+ = KAl_2AlSi_3O_{10}(OH)_2 + 2K^+ + 6SiO_2$$

(orthoclase) (sericite mica)

Many of the equilibrium activity diagrams for the common mineral phases encountered in hydrothermal alteration have been determined, and they are useful for evaluating the phases stable in a given temperature and compositional environment and how these change with a changing environment.

The process of solution and redeposition of mineral phases by a hydrothermal solution during metamorphism is called metasomatism. During metasomatism, certain elements are mobile and others are immobile as a function of the prevailing pressure, temperature and compositional conditions. No list of relative mobilities of the elements can be given that is valid under all system conditions. However, Korzhinsky(45) has proposed an average list of elemental mobilities after much study, from high to low mobilities: H_2O, CO_2, S, SO_3, Cl, K, Na, F, Ca, O_2, Fe, Mg, Si, P, Al, Ti.

When mineral phases grow or recrystallize in a hydrothermal solution medium, growth irregularities of many kinds trap small portions of the growth solution medium in the solid crystal.(46) These fluid inclusions can be found in most metamorphic mineral rock types, thereby giving evidence for the presence of a fluid phase during metamorphic crystal growth or recrystallization. The inclusions are called fluid rather than aqueous because they sometimes contain liquid CO_2 or petroleum as well as a crystalline solid phase such as pyrite (FeS_2) cubes or halite (NaCl) cubes in aqueous media. They vary in size from the usual microscopic dimensions to several centimeters in a few cases. Fluid inclusions larger than 0.1 millimeter are relatively uncommon, with the majority less than 0.01 millimeter in size. Ordinary white, metamorphic quartz (SiO_2) usually contains about 10^9 fluid inclusions/cm^3. Even the white color in this quartz is due to light dispersion by the inclusions; quartz without inclusions is transparent. In any case, the fluid inclusions represent small samples of the original crystal growth solution medium, or metasomatic solution.

Examples of some analyses of metamorphic quartz fluid inclusion are given in Table 4.5 The total salt content in the aqueous inclusion fluids varied from 3850 to 291,000 ppm (0.38 to 29 wt%) from the more than 800 available analyses with over 100,000 ppm average for total salt content. Twenty weight percent total salts in the aqueous solutions are common. Homogenization temperatures, or temperatures at which the aqueous fluid inclusions became a single liquid phase when more than one fluid phase (e.g., vapor and liquid) was present and completely filled the original cavity in the crystal, were determined by applying heat and assuming a pressure correction. Homogenization temperatures varied from about 100° to 500°C for metamorphic quartz.

Although complete chemical analyses of the fluid inclusions are not available, in general they contain rather large amounts of all the alkali metals including cesium plus many of the alkaline earth metals, presumably including some strontium.

Metasomatic processes have occurred in all rock types with the exception of rock salt, which presupposes the absence of water or other volatile constituents. Placing liquid waste into rock salt formations would negate the one redeeming feature of a nearly anhydrous environment, and dispersive metasomatic

TABLE 4.5. Some Compositions of Metamorphic Quartz Fluid Inclusion

	ppm/10,000 ppm Cl									
Sample	Li	Na	K	Rb	Cs	Mg	Ca	SiO_2	HCO_3^-	$SO_4^=$
1	--	3500	1400	--	--	600	2000	9000	2500	5200
2	60	8000	10100	30	<7	--	--	--	--	800
3	100	8300	8300	32	<3.5	--	--	--	--	2000

1. Quartz crystals from veins in metamorphosed sediments, Dagestan, U.S.S.R. Homogenized at 105 to 200 °C.
2. Microscopic inclusions in massive, white, 3-foot quartz pod in in chlorite schist, Antelope Island, Great Salt Lake, Utah. Homogenization estimated at 200 °C.
3. Massive quartz, Empire Gold Vein, Grass Valley, California. Homogenization at 80 to 185 °C.

processes may once again become operative. A critical evaluation of data and theories about the composition and origin of marine salt deposits was presented by Braitsch.(47) Phase studies prove that the present composition of certain salt deposits may have been formed from low-temperature metamorphism.

The effect of the geothermal gradient on metamorphic processes is another consideration in geologic waste disposal. The average geothermal gradient is about 20°C/kilometer, although this can range from 5°C/kilometer to 200°C/kilometer in the upper crust of the earth. In the latter case, it is safe to assume that the large heat flow is emanating from a radiating, magmatic heat source at greater depth. To minimize the potential for ion migration, it would generally be wise to avoid such areas of high heat flow for waste disposal.

At least some of the chemical ions of elements which have radionuclides in the waste are known to occur in metasomatic solutions that have passed through several hundred meters of nearly impermeable rock during geological time and were eventually dispersed to the environment through groundwater mixing, hot springs, etc. Care must be exercised in the placement of self-heating solidified wastes that can interact with water already present in the environment, to minimize generation of metasomatic solution and dispersion of the radionuclide ions over considerable distances during geologic time spans.

The waste should preferably be in solid form to assure that rock-waste interactions will include recrystallization processes that completely immobilize the fission product ions. Consideration of similar natural processes involving heat and hydrothermal solutions (metasomatism) suggest that dispersive processes are more likely for the alkali and alkaline earth metal fission product ions. In solid form, such as incorporated into a glass, the waste should be kept out of contact with aqueous solutions potentially present in a disposal environment. Hence, to minimize such waste ion migration, long-term disposal in relatively anhydrous rocks is preferred. Such rocks include salt and dry igneous rocks.

Most marine sedimentary rocks contain an aqueous pore solution that approximates seawater in composition.(48) These pore solutions can move about if the sedimentary rock has any permeability and often do so. Placing a heat source such as self-heating waste in a permeable sedimentary rock containing a pore solution is conducive to dispersing this pore solution plus some of the radionuclide ions.

Thus the preferred rock types and waste disposal forms present a trade-off of sorts. If the anhydrous condition of the disposal site can be assured over the required time span, the waste form is less critical. If water contact can be expected, the waste form becomes very critical for safe disposal.

4.0.3.4.3 Molten Rock-Waste Interactions. In all geologic disposal concepts considered, it is most likely that the waste forms will eventually come into direct contact with the rocks. Such contact will result in chemical and physical interactions of the waste and the rock that will tend to be accelerated due to the higher-than-ambient temperatures associated with the waste. A brief review is presented of general rock-waste reactions which could be expected in various disposal schemes.

The reaction of a reference borosilicate glass used in the Waste Fixation Program at PNL (melt number 72-4, Table 4.6) with several rocks is considered. The rocks included a typical basalt, granite, nepheline syenite, graywacke sandstone, shale, limestone and rock salt (Tables 4.7 and 4.8). Three cases of melting of these rocks of average composition with the reference waste formulation were reviewed.

TABLE 4.6. Composition of Melt Number 72-4 Minus the FP Oxides (12.8 wt% in the original composition)

Constituent	Wt %
SiO_2	36.4
Al_2O_3	7.7
B_2O_3	15.9
Fe_2O_3	9.1
CaO	12.8
Na_2O	10.6
U_3O_8	7.4
	99.9

In the first case it was assumed that only the waste borosilicate glass itself would recrystallize upon cooling from the molten phase. Possible phases from this recrystallization include danburite ($CaB_2Si_2O_8$), reedmergnerite ($NaBSi_3O_8$), coffinite ($USiO_4$) or uraninite (UO_2), hematite (Fe_2O_3) and plagioclase feldspar ($Ca,Na_2Al_2Si_2O_8$). The estimates of phases crystallizing from the melt are based on knowledge of similar natural systems.

TABLE 4.7. Range of Minor Constituents of Average Composition Rocks in Parts Per Million (RE = rare earths, PtGr = platinum group)

	Granite	Basalt	Nepheline Syenite	All Igneous Rocks	Sandstone (Graywacke)	Shale	Limestone
Ag	0.02	0.03	0.03	0.07	0.07	0.05	0.05
B	10	1.6	10	10	35	100	20
Ba	430	600	520	425	50	580	120
Cd	0.12	0.19	<0.1	0.2	0.05	0.3	0.035
Co	8	30	8	25	0.3	19	0.1
Cr	10	50-200	4	100	35	90	11
Cs	40	<1	6	1	0.5	12	0.5
Cu	16	149	10	55	5	45	4
Mo	12	3	2	1.5	0.2	2.6	0.4
Ni	2.4	65	2.4	75	2	68	20
P	870	2440	Up to major constituent	1050	170	700	400
PtGr	<0.01	<0.1	<0.01	0.012	<0.01	<0.01	<0.01
RE	225	174	2000-4000	177	118	31	135
Sb	0.2	0.4	0.1	0.2	0.05	1.5	0.2
Sr	120	150	1200	375	20	300	610
Te	<0.01	<0.01	<0.01	0.001	<0.01	<0.1	<0.01
U	3.96	0.83	15	2.7	0.45	3.7	2.2
Zn	60	100-130	50	70	16	95	20
Zr	460	140	1000-3000	165	220	160	19

TABLE 4.8. Composite Analyses of Several Igneous and Sedimentary Rocks

	Granite	Basalt	Nepheline Syenite	Graywacke (Sandstone)	Shale	Limestone
SiO_2	70.18	49.06	54.63	64.0	58.10	5.19
TiO_2	0.39	1.36	0.86	0.5	0.65	0.06
Al_2O_3	14.47	15.70	19.89	14.0	15.40	0.81
Fe_2O_3	1.57	5.38	3.37	1.3	4.02	0.54
FeO	1.78	6.37	2.20	4.1	2.45	---
MnO	0.12	0.31	0.35	0.1	0.40	0.05
MgO	0.88	6.17	0.87	2.9	2.44	7.90
CaO	1.99	8.95	2.51	3.4	3.11	42.61
Na_2O	3.48	3.11	8.26	3.5	1.30	0.05
K_2O	4.11	1.52	5.46	2.1	3.24	0.33
P_2O_5	0.19	0.45	0.25	0.1	0.17	0.04
H_2O	0.84	1.62	1.35	2.1	5.00	0.77
CO_2	---	---	---	1.5	2.63	41.58
	100.00	100.00	100.00	99.6	98.91	99.93

In the second case, mixing and melting of equal weights of the reference rocks and waste form were considered. The resultant compositions of the mixed melts were calculated and compared to the compositions of their nearest, naturally-occurring igneous rock equivalents. The phases crystallizing from the mixed melts were assumed to be the same phases known to occur in natural igneous rocks of the same composition. For example, a mixture of equal weights of granite and the reference borosilicate glass result in a melt very close in composition to an andesitic basalt. The phases normally found in a quartz basalt include andesine (60%), calcium-rich augite (38%), magnetite-ilmenite (5%) and quartz (5%). The limestone-waste mixture was a special case. High pressures must be maintained to avoid the formation of calcium silicate (wollastonite) and CO_2 from calcite ($CaCO_3$) and quartz (SiO_2). With a higher-than-

TABLE 4.9. Synthetic Rocks Produced by Mixing Equal Weights of Melt No. 72-4 and Several Natural Rocks and Closest Natural Equivalents

	Quartz Basalt	Tephrite	Theralite	Shonkinite	Skarn Marble
SiO_2	55.5	39.9	45.6	48.6	
TiO_2	0.9	1.5	1.9	1.0	Calcite
Al_2O_3	16.8	13.6	14.3	12.4	Calcium Aluminum Silicates
B_2O_3	--	--	--	--	Quartz
Fe_2O_3	2.1	6.7	6.2	3.1	
FeO	4.9	6.4	4.0	5.8	
MnO	0.2	0.2	0.2	0.1	
MgO	6.3	10.5	6.1	8.1	
CaO	7.9	12.4	9.5	10.4	
Na_2O	3.3	3.9	5.1	2.7	
K_2O	1.4	1.9	3.7	5.2	
P_2O_5	0.2	0.9	0.7	1.1	
U_3O_8	--	--	--	--	
H_2O	0.6	2.2	2.6	1.5	
	100.1	100.1	99.9	100.0	

normal content of boron, several phases rich in boron may crystallize from such a melt including tourmaline and axinite.

The third case was concerned with melting the waste and a large volume of rock to yield a waste-rock composition that was essentially that of the original rock. Melting the graywacke sandstone, for example, results in a granodiorite, and a shale in a diorite composition. The major mineral phases present and their natural equivalents are listed in Tables 4.9 and 4.10. Uranium, for example, is known to enter the zircon structure ($ZrSiO_4$) in amounts up to one wt% uranium. The dark minerals, pyroxenes and amphiboles, contain the bulk of the rare earths. An exception is the concentration of divalent europium in the calcium-bearing feldspars. Strontium accompanies calcium in the feldspars, and to a lesser degree, potassium in the potash-bearing feldspars. Barium is found predominately in the

TABLE 4.10. Mineral Phases Present in the Natural Equivalents of the Synthetic Waste-Rock Mixtures of Table 4.9

Quartz Basalt	Vol. %	Tephrite	Vol. %
Andesine	60	Labradorite	50
Ca-rich augite	30	Nepheline	40
Ilmenite	5	Analcite	
Magnetite		Pyroxene	10
Quartz	5		

Theralite		Shonkinite	
Labradorite	20	Na-sanadine	50
Nepheline	20	Nepheline	10
Orthoclase	10	Sodalite	
Sodalite	10	Analcite	
Augite	35	Augite	35
Biotite	5	Biotite	5
Magnetite			

plagioclase feldspars, and cesium and rubidium in the potash feldspars (orthoclase and microcline). Molybdenum, zinc, silver, technetium and the platinum group metals prefer a sulfur-rich environment and are not found in the main-stage, silicate minerals.

Tentative conclusions indicate that many of the radioactive elements would be included in the crystal lattices of the relatively insoluble silicate minerals. Exceptions, which tend to prefer a sulfur-rich environment, include molybdenum, zinc, silver, technetium and the platinum group metals. For these waste constituents, some consideration should be given to providing a sulfur-rich addition to the waste glass to prevent diffusion and dispersion of these elements during glass devitrification.

4.0.3.5 Physiographic Considerations

Certain parts of the United States such as the Rocky Mountains and the Sierra Nevada Mountains could be classified unsuitable for waste disposal on the basis of rugged terrain. Although from both the engineering and the economic aspects, the terrain does not present insurmountable problems to waste disposal, other sites will probably be available in terrains that are at least equally suitable.

4.0.3.5.1 Erosion and Denudation Effects. Erosion is clearly the main process going on today on the earth's surface.(49) This process is of obvious concern in planning for waste disposal. The waste should be placed in locations where it will not be exhumed by erosional processes. Additionally, to provide for ease of monitoring and, possibly, site marking, locations are preferred which will not be covered significantly by the ensuing erosion products. The basic underlying cause of erosion is that all materials tend to move downhill. This tendency is shown by landslides, gullies on hillsides, accumulations of rocks (talus) at the foot of cliffs and ridges, and similar examples. Agents of erosion are (1) rivers and streams, which are the most important agents; (2) landslides and other mass movements; (3) rain, which erodes by impact and by flowing over surfaces; (4) glaciers, which erode by grinding and plucking; (5) frost action, which loosens blocks of rock and gradually causes rock to disintegrate; (6) wind, which erodes by deflation and sand blasting; (7) wave action on shorelines; and (8) chemical weathering. The overall effect of erosion is eventually to reduce irregular topography to a level plain.

The rate of erosion of the continents is determined approximately by measuring the amount of material carried by rivers. The overall average rate of erosion in the United States, determined in this way, is about 60 meters per million years. The lowest overall rate of erosion is about 40 meters per million years in the basin of the Columbia River, and the largest is about 165 meters per million years in the basin of the Colorado River. The rates of erosion vary according to specific topographic location, rock hardness, rainfall, evaporation rates, type of vegetation, and other factors The rates are sufficiently slow so that in most areas they do not constitute serious problems for waste disposal, but each site will have to be carefully evaluated.

River Erosion. Common sense dictates that a waste disposal site should not be located in the vicinity of a river or large stream. Examples of rapid erosion in and adjacent to streams are plentiful throughout the world, especially in semiarid and arid climates (Figure 4.14) and also in some humid regions where man's farming and industrial activities have removed forest or other natural cover. In many areas it is not possible to predict erosion rates adjacent to a large stream with any degree of accuracy. This is because catastrophic flooding and rapid erosion may occur only a few times each century or may be initiated by a completely unpredictable climatic change. Such catastrophic flooding may cause a drastic change in the course of a stream or even the complete abandonment of one stream channel in favor of another. Rivers erode by several processes, and rapid downcutting can suddenly take place for a variety of reasons: for example, when a stream bed deepens itself and suddenly gains access to a soluble stratum. Relatively docile streams or those that seem to be completely controlled by

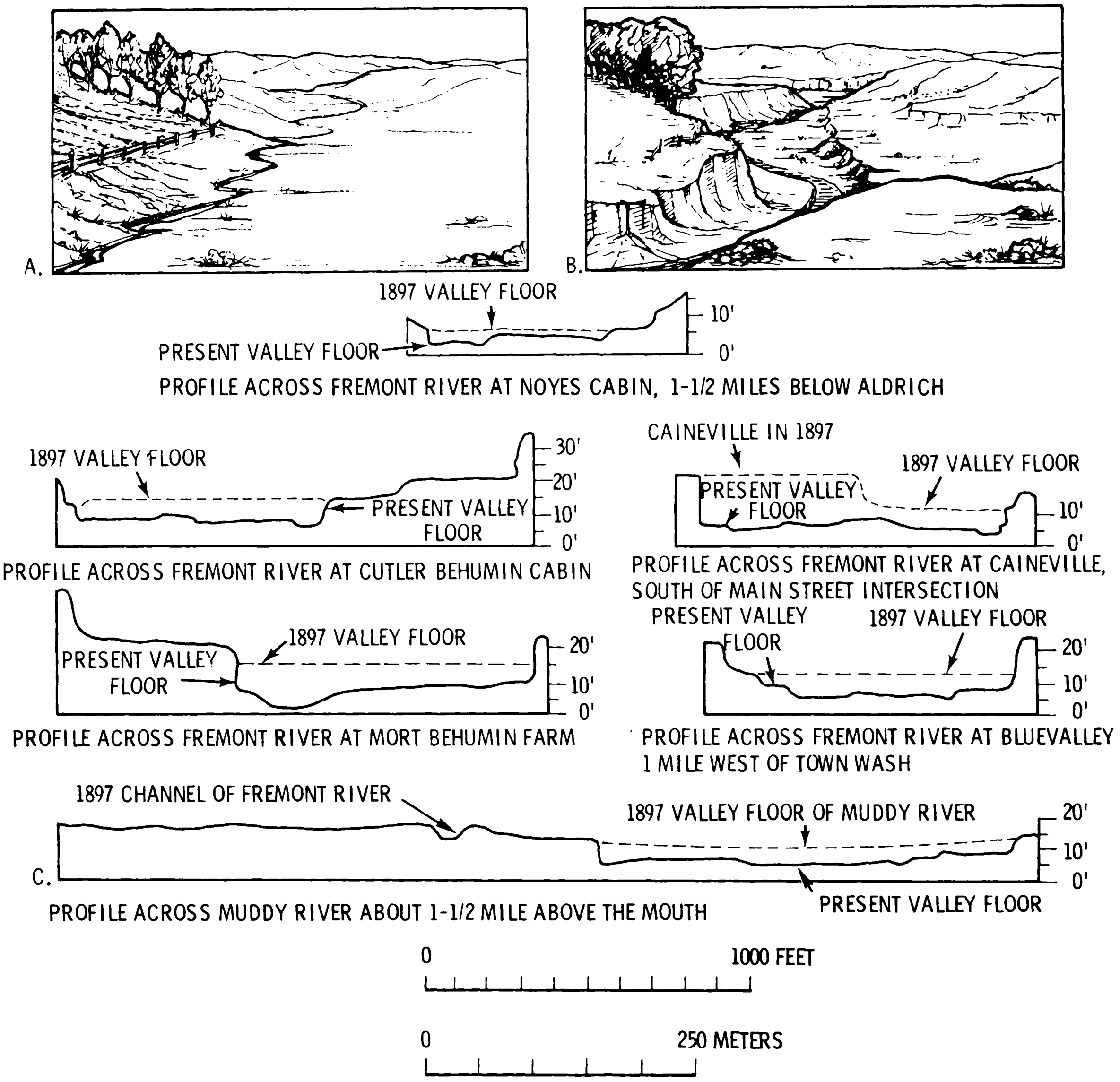


FIGURE 4.14. Examples of River Erosion in Henry Mountains Region, Utah, since 1897. Climate change is the probable reason for this erosion. Parts A and B show Pleasant Creek at Notom. The part B (present day) is 20 feet deep. Part C shows cross sections of Fremont River.[49] (Modified from Hunt and others, 1953).

man may become unmanageable as a result of climatic change or earthquake activity. When a disposal site is considered in an area where man has built dam(s), it must be kept in mind (1) that the life expectancy of these structures, either because of deterioration of the structure itself or because of the complete silting-up of the holding area, is commonly no more than a few hundred years and (2) that the dams may in some areas be vulnerable to rupture by unexpectedly large earthquakes.

Landslides Landslides are of concern to waste disposal planning in areas of moderate and rugged topographic relief. Areas to be avoided include: 1) slopes that may slide or creep, 2) areas that may be covered or exposed by a slide, 3) areas that may be flooded by damming of a river, 4) areas that may be affected by a sea wave resulting from land sliding beneath the sea.

Landslides may be triggered in many ways. According to Foster(50) the most common are (1) undercutting of a slope, (2) overloading of the slope so that it cannot support its new weight and, hence, must flow or slide, (3) vibrations from earthquakes or explosions that break the bond holding the slope in place, and (4) additional water which lessens the cohesion of the material.

Erosional Processes in Arid Regions. The arid and semiarid parts of the United States are affected by erosional processes that differ significantly from those in humid regions. In a particular spot rain may fall only once in many years, but when it does it commonly is a cloudburst. The cloudburst causes flash floods that may erode large areas upslope and bury downslope areas under tons of material. These floods do not necessarily occur along well established stream channels but may occur anywhere adjacent to mountainous areas.

A feature of drainage in desert areas that is especially significant to waste disposal is that in an area of interior drainage, a basin will eventually fill to a level that will allow the ephemeral streams to flow over the lowest divide into an adjoining basin. Soon the divide is eroded and the first basin will be rapidly dissected because of the lowered base level.(50)

Wind erosion is a significant erosional process in desert regions but, except for the possibility of covering a disposal site under dune sand, is of little concern to waste disposal investigations.

A type of erosion of major concern in arid and semiarid climates is the retreating escarpment or cliff. Cliffs, for example, at the edges of mesas may retreat at rapid rates with little or no loss of height. Schumm(51) reported average denudation rates for arid and semi-arid terrain of 100 to 200 meters per million years, and Melton(52) reported slope retreat rates of 60 to 200 meters per million years.

Glaciation. Glaciers are extremely important agents of erosion. They erode by plucking large blocks of bedrock and by abrasion. They deepen and widen valleys previously formed by streams and give rise to valleys with a "U" shape. Where tremendous thicknesses of ice occur, valleys are deepened to great depths; an example is the fiords of Norway. Glaciers also deposit large volumes of material called drift. Drift consists of material deposited in front of, on the sides, and beneath a moving active glacier and deposits that are carried by the glacier and remain after the glacier is melted.

4.0.3.6 Seismologic Considerations

Most of the major earthquakes of the world occur in the belts along the boundaries between the global tectonic plates. One such boundary is that between the Pacific and North American plates along the west coast of the United States (Figure 4.3). The great number of damaging earthquakes that have occurred in California and western Nevada have been attributed to tectonic activity along this belt. Most fault movements in this zone in California are horizontal or strike-slip, rather than vertical or up-down. The most notable fault zone with horizontal movement is the San Andreas fault. Movement along the San Andreas fault system and other major fault systems in the Western United States is sporadic rather than constant because of friction and interlocking of the fault blocks.

Earthquake activity farther east than western Nevada or the Idaho batholith is probably unrelated to the active zone at the boundary between the Pacific and North American plates. This activity includes the earthquakes of the New Madrid, Missouri, area (1811-1812) and Charleston, South Carolina (1886), which were both major damaging earthquakes. Intraplate tectonism and magmatism have been demonstrated in oceanic plates; earthquakes and igneous activity that occur within the North American plate show that intraplate tectonism and magmatism occur in the continental plates as well, though the mechanism for their origin is unknown.(53)

Earthquakes are described in terms of both magnitude and intensity. Magnitude is expressed by a logarithmic scale based on the amplitude of instrumentally recorded seismic waves. Several scales in common use, depending on the type of seismic waves used are:

(1) The Richter or local magnitude scale based on recordings of short-period surface waves recorded at distances of less than 600 kilometers.

(2) The surface-wave magnitude (Ms) scale based on the amplitudes of surface waves with periods near 20 seconds that are recorded at distances greater than about 2,000 kilometers.

(3) The body-wave magnitude (m_b) scale based on amplitude/period ratios and corrections for distance and focal depth for waves recorded at distances greater than about 2,000 kilometers.

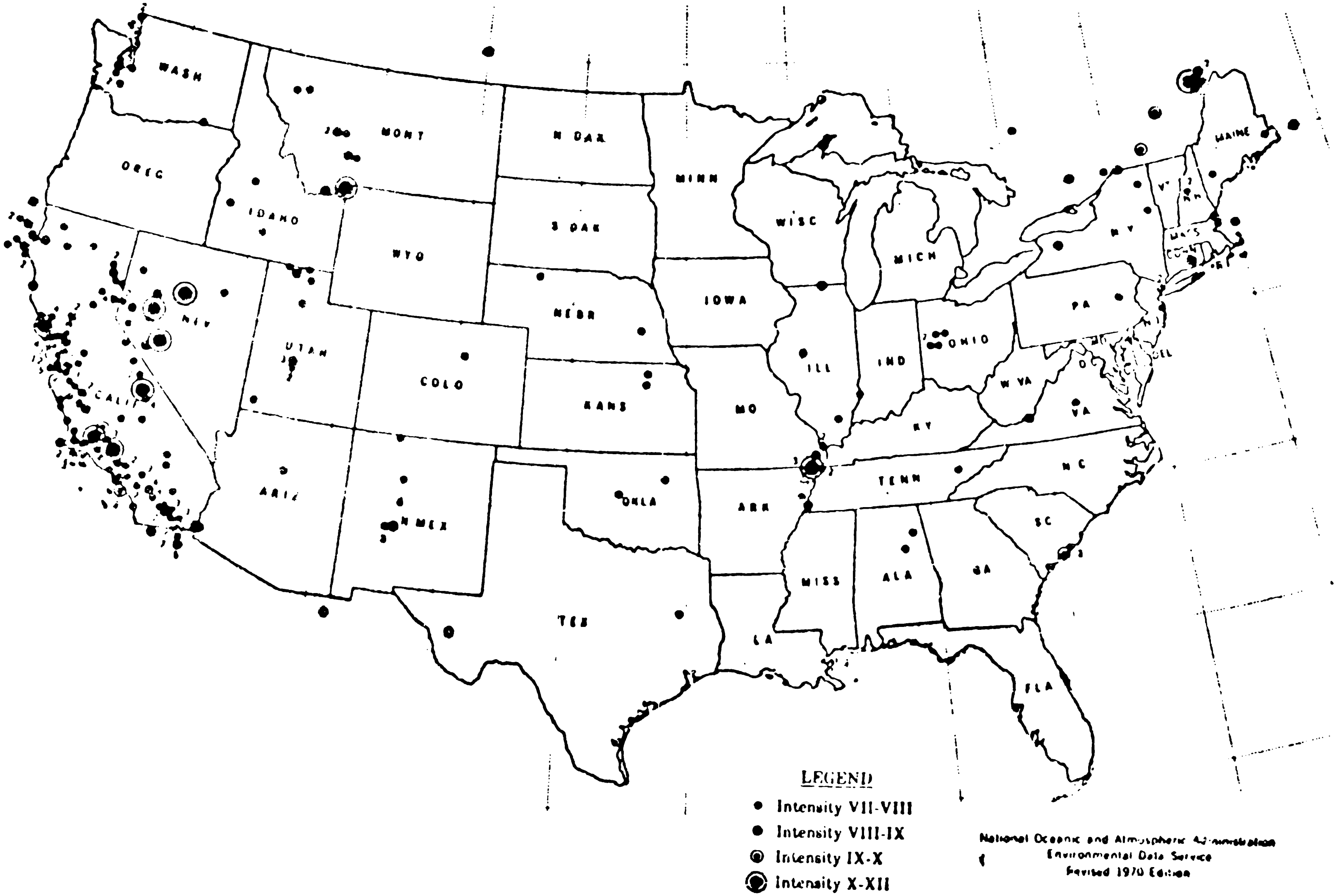
All of the scales result in numbers that are independent of the distances of the recording stations from the earthquake.(54)

In contrast, intensity is a number which expresses various effects of an earthquake at a particular location and thus depends, among other things: on the distance of the location from the earthquake; the magnitude of the earthquake (an indication of the energy released at the earthquake focus); the duration of the quake; and, most significantly, local geology. The intensity scale in use in the United States is the Modified Mercalli Intensity Scale of 1931 (M.M.). Assignment of an intensity value to a particular location is based on the degree of damage and various subjective criteria. (See Appendix 4.D.)

Richter magnitudes of six and greater have been recorded for earthquakes since around 1900, but records for smaller earthquakes are less complete.(31) Modified Mercalli intensities, however, have been assigned by the U.S. Coast and Geodetic Survey and other investigators to nearly all significant earthquakes known to have occurred in the United States. The historical record of seismicity in the country, therefore, does provide some guidelines to the relative seismicity of various regions.(31) Figure 4.15 shows the locations of damaging earthquakes (intensity VII and greater) known to have occurred in the United States from historical times through 1970. Some of the strongest of these earthquakes are listed in Appendix 4.E.

The relative strain release throughout the United States has also been used as an index of current tectonic activity.(31) Strain release is proportional to the square root of the energy released; the energy released is determined from the magnitude of the earthquake. Using this index, Algermissen(31) has divided the conterminous United States into four areas having different rates of strain release, on the basis of data compiled from earthquakes between 1900 and 1965. The areas and number of earthquakes of equivalent magnitude four during this period are listed in Table 4.11. The data in the first column of Table 4.11 show that the strain release in the Pacific West during the 66-year period was approximately six times greater than in the Rocky Mountain area, 86 times greater than in the Central Plains, and 16 times greater than in the Eastern United States. Data of the second column show that the strain release in the Pacific West was respectively 5, 34, and 12 times greater than in the other areas. From the standpoint of strain release, the Pacific West is most active and the Central Plains the least active. Recurrences of earthquakes, as summarized in Tables 4.12 and 4.13, also indicate this.

Although the Eastern United States is an area of relatively low seismicity at present, it is also characterized by low attenuation of seismic waves. According to Nuttli(56) the low attenuation can result in a 100-fold increase in the total damage over the amount that would be expected in California for an earthquake of the same surface-wave magnitude. Unusual attenuation properties of Eastern United States seem to be as much responsible for the large area affected by the Charleston and New Madrid earthquakes as the magnitudes of the quakes.



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Environmental Data Service
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FIGURE 4.15. Damaging Earthquakes in the United States from Earliest History Through 1970 (Modified from Coffman and von Hake, 1972)(55)

TABLE 4.11. Strain Release Index for Four Areas of the United States

Area	No. Equiv. Mag 4 Earthquakes/1000 km^2 66 Years(a)	No. Equiv. Mag 4 Earthquakes/1000 km^2 66 Years(b)
Pacific West - west of long 114° W.	12.	13.
Rocky Mountains- long 106°-114° W.	2.0	2.6
Central Plains- long 92°-106° W.	0.14	0.38
Eastern U.S.- east of long 92° W.	0.74	1.1

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a. Total equivalent number of magnitude 4 earthquakes in each area divided by total area.

b. Only those parts of each area considered in which more than 0.25 equivalent magnitude 4 earthquakes occurred.

TABLE 4.12. Recurrence of Earthquakes in Conterminous United States per 100 ears for Modified Mercalli Intensities V to VIII

Modified from Algermissen, 1969, Table 1(31)

Area(a)	Approximate Seismic Risk Zone	Earthquakes per 100 years			
		V	VI	VII	VIII
California, Western Nevada (combined)	3,2	2,290	646	182	51.3
California	3,2	1,660	479	138	39.8
Western Nevada	3,2	1,510	417	115	31.6
Montana, Idaho, Utah, Arizona	3,2	407	112	30.9	8.5
Mississippi Valley, St. Lawrence Valley	3,2,1	162	51.3	16.2	5.1
Puget Sound, Washington	3,2	224	53.7	12.9	3.1
East Coast	3,2,1	132	34.7	9.1	2.4
Wyoming, Colorado, New Mexico	3,2,1	182	38.0	7.9	1.7
Nebraska, Kansas, Oklahoma	2,1	34.7	11.2	3.6	1.2
Oklahoma, North Texas	2,1	22.4	6.3	1.8	(0.5)

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a. Areas arranged in order of decreasing number of modified Mercalli intensity VII earthquakes.

TABLE 4.13. Recurrence of Earthquakes in Conterminous United States per 100 Years per 100,000 km^2, Intensities V to VIII

Modified from Algermissen, 1969, Table 2(31)

Area[a]	Approximate Seismic Risk Zone	Earthquakes per 100 years[b] V	VI	VII	VIII
California, Western Nevada (combined)	3,2	300	84.6	23.8	6.72
Montana, Idaho, Utah, Arizone	3,2	64.4	17.7	4.89	1.35
Puget Sound, Washington	3,2	68.0	16.3	3.92	0.94
Mississippi Valley, St. Lawrence Valley	3,2,1	24.2	7.65	2.42	0.76
Nebraska, Kansas, Oklahoma	2,1	13.0	4.20	1.35	0.45
Wyoming, Colorado, New Mexico	3,2,1	32.8	6.85	1.42	0.31
Oklahoma, North Texas	2,1	13.3	3.73	1.07	0.30
East Coast	3,2,1	12.8	3.39	0.88	0.23

---

a. Areas arranged in order of decreasing number of modified Mercalli intensity VII earthquakes.

b. The recurrences of Table 4.12 have been divided by the area of each region.

It is interesting to note that the relative amounts of strain release in the four areas of conterminous United States correspond, to some degree, with the distribution of principal horizontal and vertical faults (Figure 4.16). The Pacific West, which has currently active horizontal and associated vertical faults, had the greatest rate of strain release between 1900 and 1965. The Rocky Mountains, which have had relatively less fault movement during historical time, had considerably greater rates than the Eastern United States, in which older, inactive faults, such as the Triassic graben boundary faults, occur. The area east of long 92° W. appears to be seismically more active, based on strain release rates, than the Central Plains region, the greater part of which has deeply buried vertical faults, long since inactive, as indicated by younger undisturbed sedimentary rocks near the surface.

The distribution of damaging earthquakes (Figure 4.15) also corresponds in some degree to the four areas and the distribution of horizontal and vertical faults (Figure 4.16). The seismic activity in the Mississippi Valley, for instance, may be associated with the vertical faults in the region. Apparently little is known about the origin of damaging

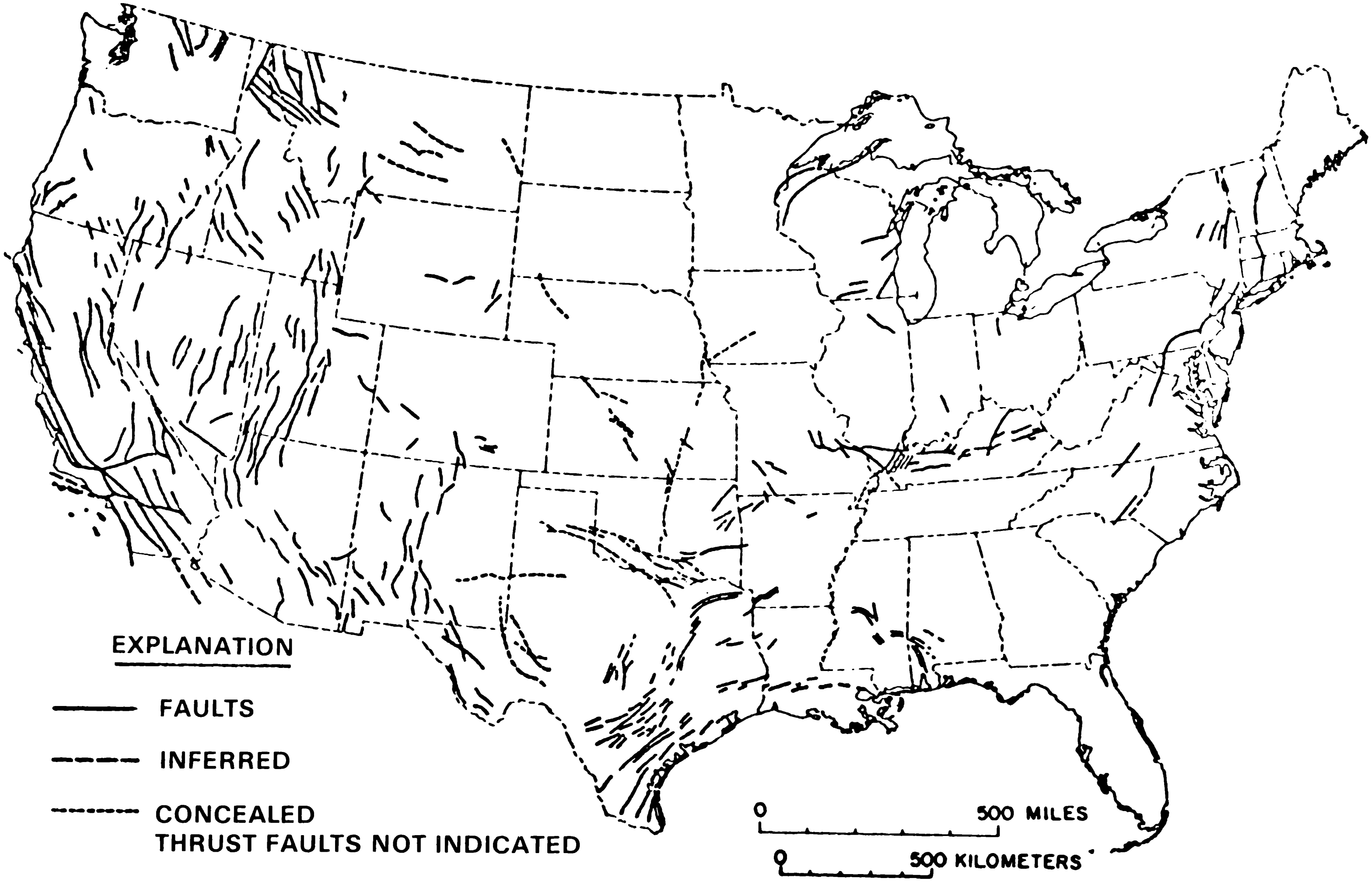

FIGURE 4.16. Principal Faults Located in the United States (Modified from P. B. King, 1967)(58)

earthquakes in coastal plain areas in the Eastern United States, such as those recorded at Charleston, South Carolina. Zietz and Zen(57) speculated that the Charleston earthquake may be associated with a continental extension of a fracture zone apparently active in the early opening of the Atlantic Ocean.

The seismic risk map, Figure 4.17, is based on the distribution of Modified Mercalli intensities associated with the known seismic history of the United States, strain release in the United States since 1900, and the association of strain release patterns with large-scale geologic features believed to be related to recent seismic activity.(31) Zones of seismic risk, rated 0-3, in order of increasing risk, based on no damage to major damage, are shown on this map. Areas of seismic risk 3 correspond to areas that have had the most numerous and most damaging earthquakes.

It is important to note that "...frequency of occurrence of damaging earthquakes was not considered in assigning ratings to the various zones on the risk map..." (Algermissen, 1969),(31) and thus, the seismic risk map indicates the maximum expected events and not how often such events are expected to occur. Difficulties in evaluating the adequacy of historical seismic data as the basis for assigning risk have made seismic zoning a controversial subject, but most workers seem to agree that reliable assignment of risk requires an understanding of local and regional tectonic processes responsible for earthquakes. Papers in the proceedings of the International Conference on Microzonation for Safer Construction, Research, and Application, 1972,(59) give an idea of currently recognized difficulties and methods of evaluating seismic risk.

It is also necessary to note that the seismic risk map depicts the estimated damage potential at the ground surface. For seismic waves arriving nearly normal to the surface, motion is about twice that of points within the earth.(60) Because of these and other probable differences between the characteristics of seismic waves at the surface and at the depths considered in this study of waste disposal concepts, additional studies should be made to determine the response of underground facilities to seismic waves and to define criteria for acceptable ground motions.

In lieu of more comprehensive seismic risk studies and criteria for acceptable ground motions, it is necessary to consider that areas of seismic risk zone 3 are unsuitable for underground as well as surface facilities. Areas in seismic risk zone 2 and less are considered to be potentially suitable if zones of active faulting are avoided.

4.0.3.7 Climatic Changes

Strong evidence is available that indicates extreme climatic changes in the geologically recent past.

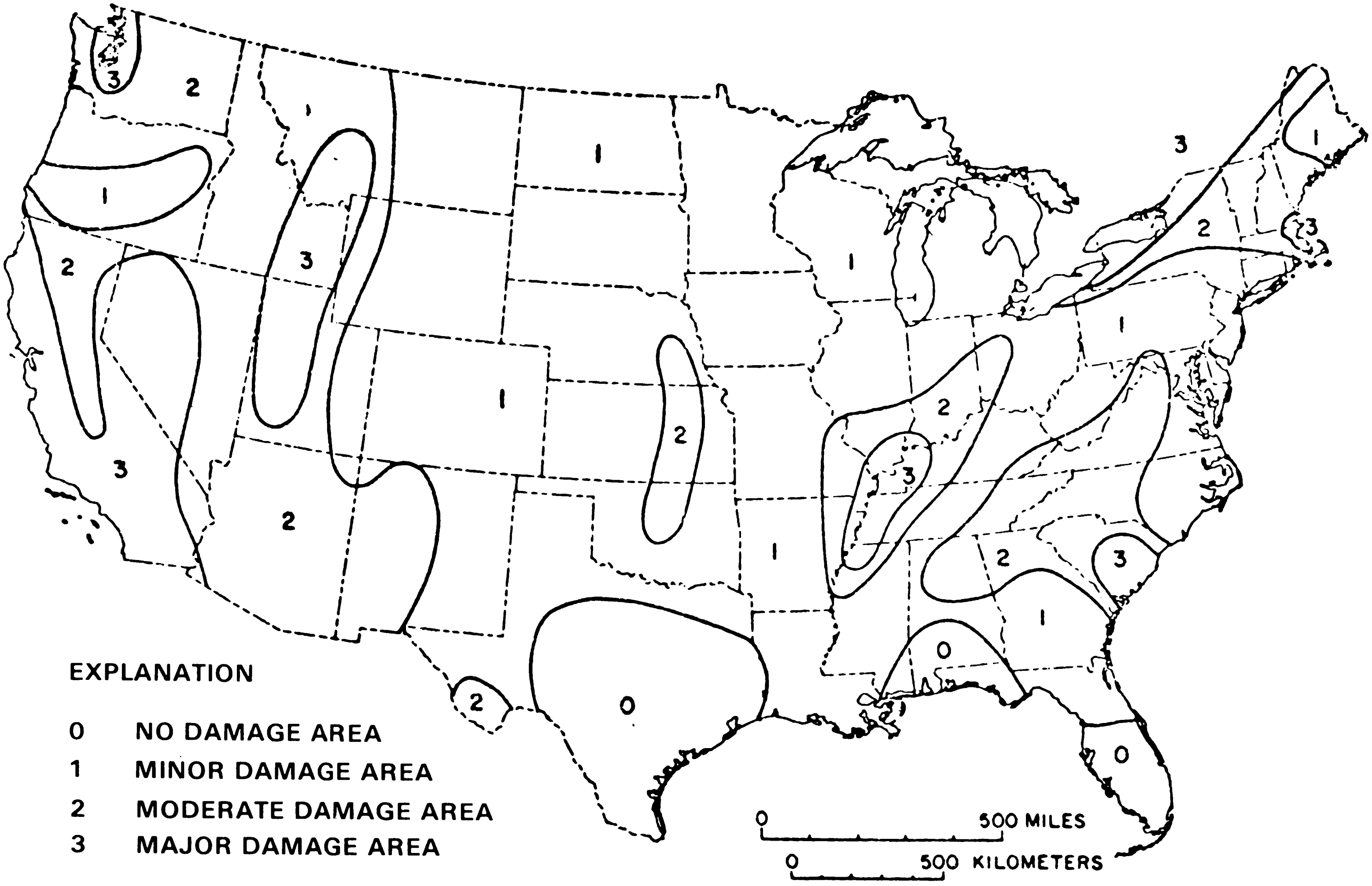

FIGURE 4.17. Seismic Risk Map of the United States (Modified from Algermissen, 1969)(31)

Therefore, the possibility of climatic changes in the future must be considered when selecting a site for waste disposal. Of principal concern are those climatic changes that will drastically alter the present-day hydrologic regime. These changes include: (1) a possible return of glaciation; (2) a warming trend that would cause a melting of polar ice caps and cause a subsequent rise in sea level; and (3) a return of pluvial climate to arid regions.

4.0.3.7.1 Effects of Glacial Climate. Many geologists and climatologists are agreed that the present-day interglacial period will eventually end and an ice age will return. This conclusion is based on the apparent cyclic pattern of glacial activity during the past million years and on evidence from pollen studies that indicate that warm intervals like the present one have been short lived in the geologic past.

Some investigators believe that we are in the final phase of the present interglacial period. Their conclusion is based on a comparison of the last interglacial with the present one. For example, pollen diagrams of the preceding interglacial lake beds so closely parallel the present interglacial records in composition and thickness that basically the same duration could be expected for both intervals.(61) Kukla and Matthews(61) point out that cooling on a global scale is evident in certain key regions in arctic and subarctic latitudes. They feel that man's heat-generating activities are insufficient, at present, to alter the natural climatic changes, although continuing human input may eventually trigger or speed climatic change. Whether these activities, which include production of dust and CO_2, will cause cooling or heating appears to be an unresolved but very important question to the disposal of radioactive waste.

The causes of past climatic changes are unknown. Theories include changes in the earth's magnetic field related to precessional torques, astronomical motions of the earth,(61) volcanism, changes in solar activity, veils of cosmic dust, and changes in atmospheric/ocean curculation.(62) Whatever the causes, only slight changes in temperature are apparently required to cause a shift from interglacial to glacial climates. According to Flint,(62) extreme glacial-interglacial temperature ranges over lands in low altitudes near coastlines may have been as little as 1.7°C in mean annual temperature, increasing to 7°C or more inland.

It is evident that one or more possible returns to ice ages must be considered in evaluating potential sites for waste disposal. Areas covered by glaciers during past glacial epochs should either be avoided entirely if continued monitoring of the site is required or considered only for concepts that would have at least 1 thousand meters of burial. Areas covered by ice during maximum advances of continental sheets and alpine glaciers are shown in Figure 4.18.

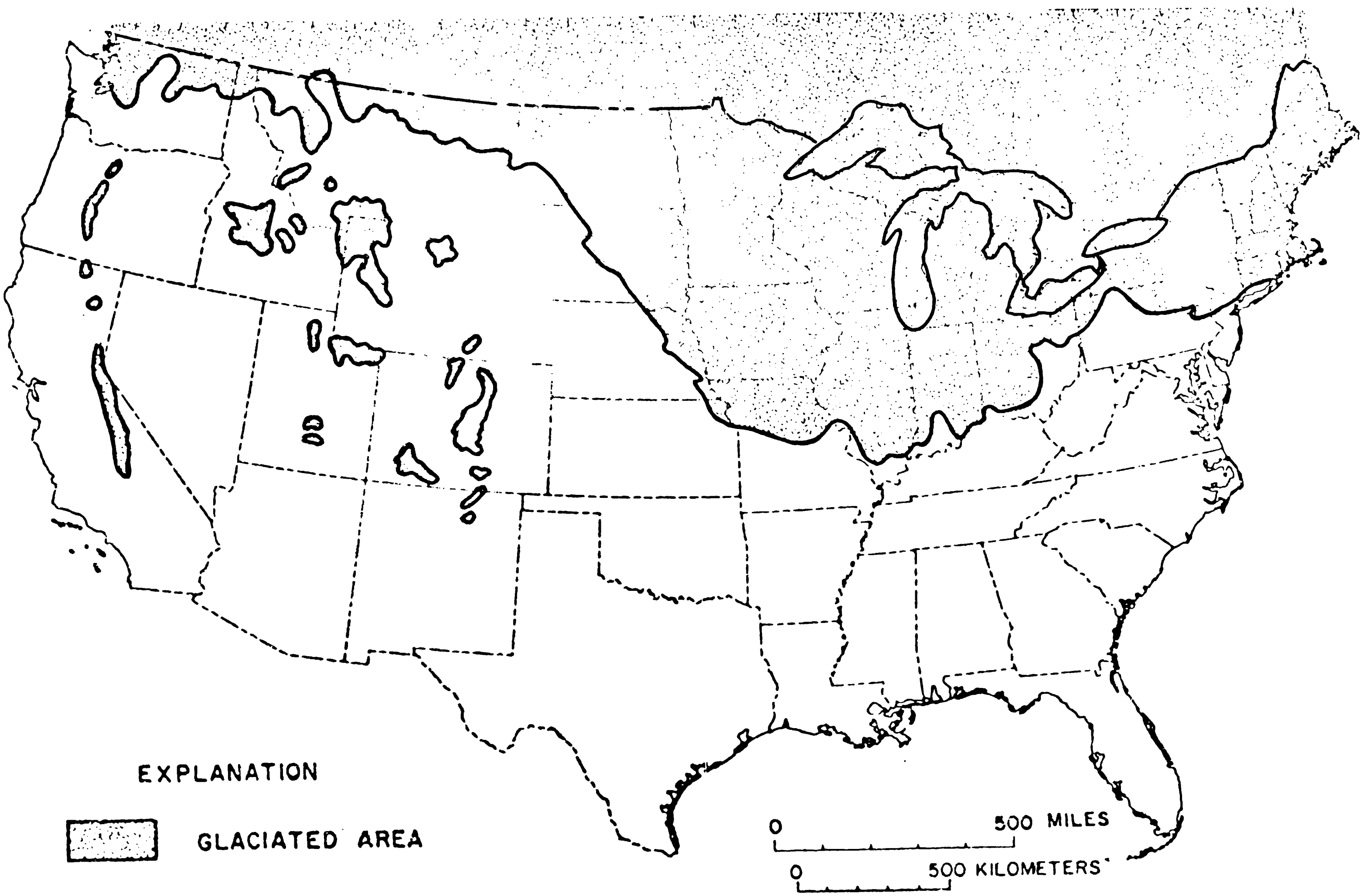

FIGURE 4.18. Maximum Extent of Glaciation in the United States (Modified from Flint and Others, 1945)(58)

In addition to possible occurrence of ice cover, changes, according to Flint,(62) that could affect potential sites in these areas include (1) drastic changes in drainage patterns including complete obliteration of pre-existing valleys and creation of new ones, (2) overall changes in the hydrologic cycle, (3) creation of new lakes by glacial damming and/or ice melting, (4) cutting and filling of terrain adjacent to glaciers by glacial outwash streams, (5) disastrous flooding by bursting of glacial dams, and (6) burial of vast areas under windblown sand and silt.

4.0.3.7.2 Effects of Sea-Level Change. The sea coasts of the world display a variety of erosional and sedimentary evidence that indicates sea levels have changed dramatically in Quaternary time (Figure 4.19). Tide gages indicate that changes are presently in progress.(62) In most areas it is not possible to determine whether the changes recorded on land or below the sea resulted from actual rise or fall of the sea or from crustal rise or fall of the land. However, coastlines that appear to have been stable for long periods display sea-erosion terraces as much as 150 meters above the present level(64) and as much as 120 meters below the present level.(65) In addition to the obvious effect of advance and retreat of glacial ice, other significant causes of sea level rise include: (1) movement of crust beneath the sea, (2) creation of volcanic masses beneath the sea, (3) draining of inland seas and lakes as a result of crustal movements or erosional processes.(62)

The processes listed above are all capable of causing significant

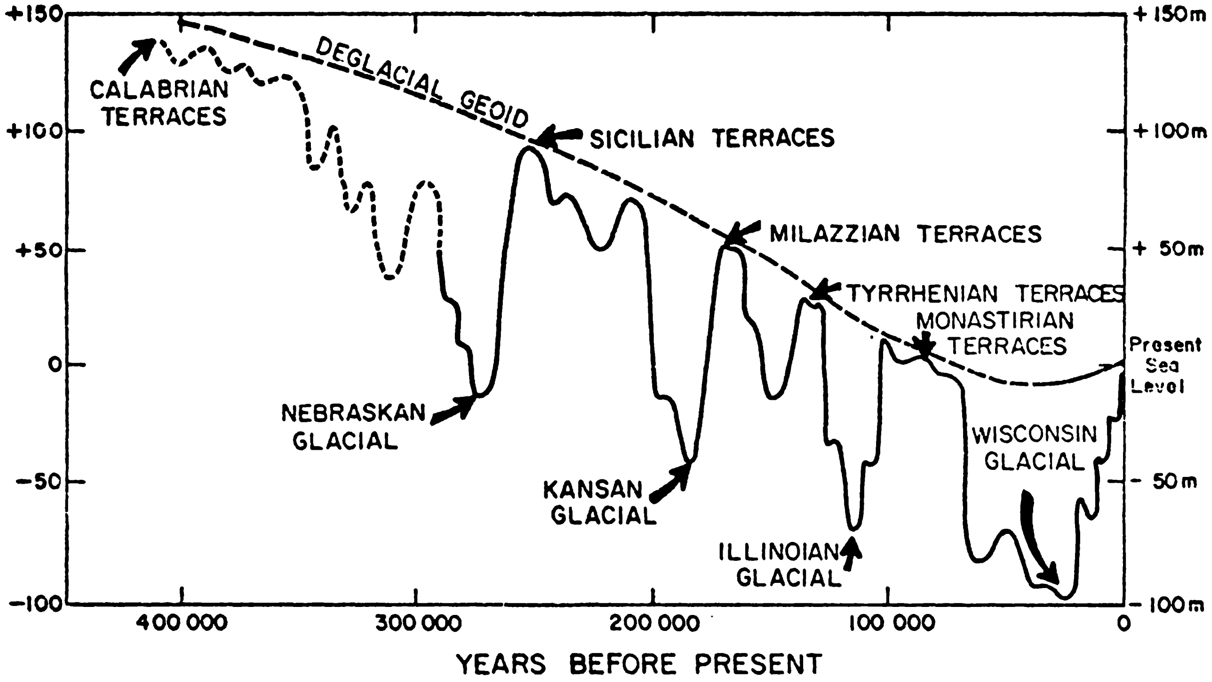

FIGURE 4.19. Quaternary Sea-Level Oscillations (Modified from Fairbridge, 1961)(59)

changes in sea level, but for the next million year period the process of principal concern to waste disposal will be the possible melting of glacial ice. If all the ice now stored in the Arctic and Antarctic ice caps were melted, the sea level would rise about 60 meters.(50,62) Although many investigators feel that this possibility is unlikely, others(66) feel that it is almost a certainty, and all the ice could be melted by the year 2050. In view of the overall disagreement among expert climatologists and the lack of firm factual data for predicting climatic change, it is necessary at this time to consider the possibility that large parts of the coastal areas of the United States will be inundated during the next million years. Areas that will be inundated by 60-meter and 150-meter rises are shown in Figure 4.20. All potential sites for waste disposal in these areas, especially those below the 60-meter level, should be reviewed critically.

4.0.3.7.3 Effects of Pluvial Climate. The arid and semiarid climate prevailing today in large parts of the Southwest creates conditions that could be hydrologically attractive for waste disposal; however, the possibility of a return to pluvial climate (abundant precipitation) should be considered when planning a site in these areas. A return of pluvial climate will predictably alter the present-day rates of erosion, but more significantly, a return will mean an abundance of, or at least a significant increase in, surface and near surface groundwater. Such an increase would result in greater runoff and the possible development of new and "permanent" rivers and streams, development of lakes in topographically closed areas, and greater recharge to the groundwater reservoirs. Winograd(67) concluded that valley floors of topographically closed basins could become flooded and should be avoided as sites for waste disposal. He further concluded that topographically high areas would continue to receive the most precipitation and that the water table is controlled more by geologic conditions and hydraulic parameters that by climate. The significance of Winograd's conclusions is that a return of pluvial climate presents some problems for waste disposal but that these problems can be overcome by adequate evaluation of hydrogeologic conditions and careful selection of sites for waste disposal in arid or semiarid areas.

4.0.3.8 Resource Potential

In any geologic concept for disposal of high-level waste, a conflict will arise between the use of the earth for disposal and for development of the resource potential that could be available in other forms such as geothermal energy, minerals (i.e., oil, gas, water, salt), surface space and subsurface space. Because disposal will essentially limit the land to exclusive use for geologic periods of time, it must be assured that this portion of the earth is being utilized in the best possible way. It should be considered

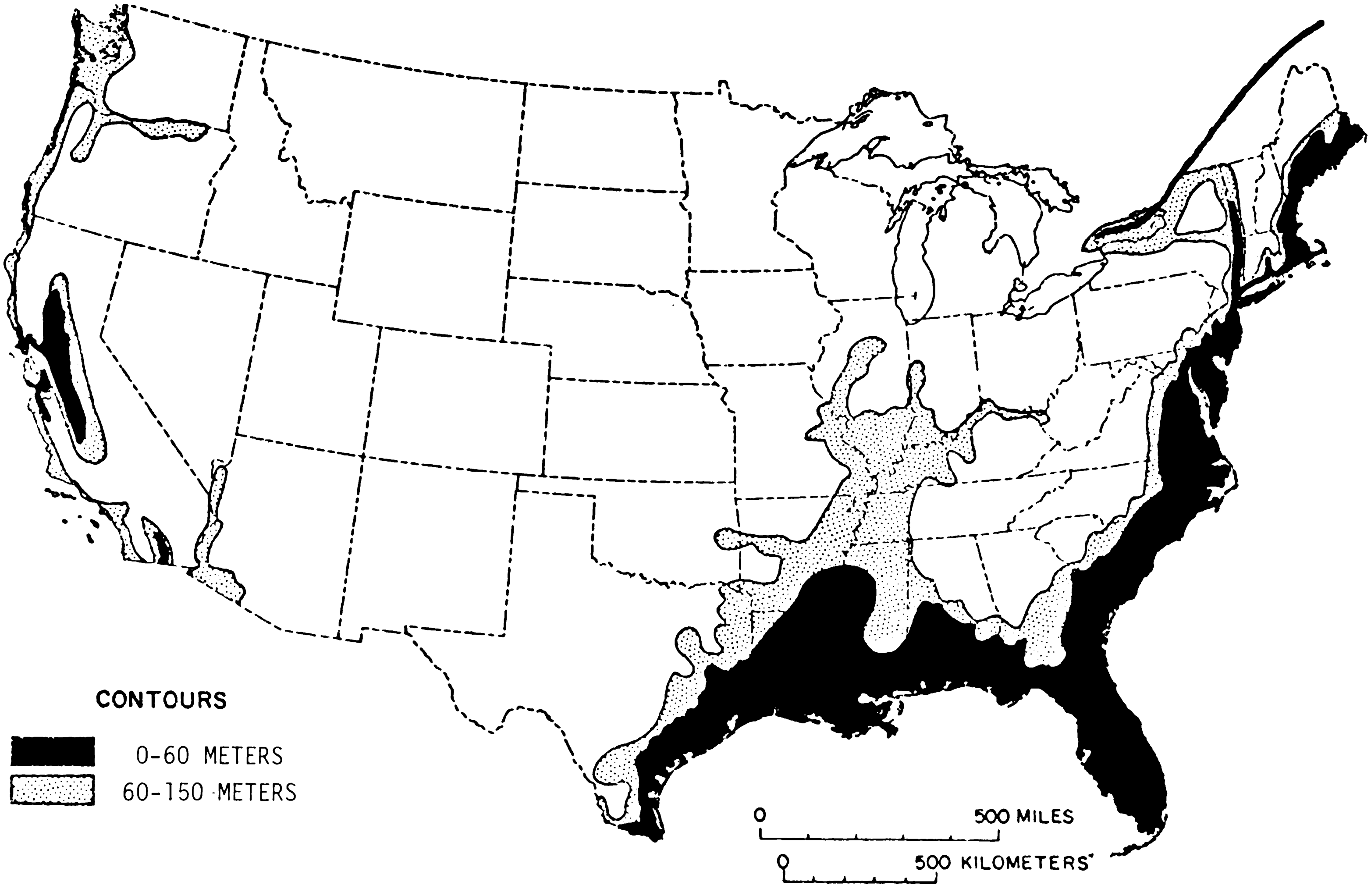

FIGURE 4.20. Areas of the United States that Would be Inundated by 60- and 150 Meters Sea-Level Rise (Modified from U.S. Geological Survey Maps)(1)

that man may not be able to monitor or control the disposal area for the total time period required to render the bulk waste harmless. Any geologic disposal concept, therefore, must provide maximum isolation of the waste and present the least possibility of inadvertent intrusion by future generations of man during the development of other potential resources.

Further discussion of resource potential related to the cavity, drilled hole and deep hole concepts will be covered in Sections 4.0.3.9.

4.0.3.9 Resume of Preferred Geohydrologic and Related Characteristics

All the geologic concepts for disposal of radioactive waste considered in this report are aimed at isolating the waste from man's environment for periods up to about 1 million years. To achieve this, many requirements will have to be met, and although all the disposal concepts have many similarities (e.g., all entail emplacement of waste at some depth within the ground) they nevertheless differ sufficiently that the best location for one mode of disposal may not necessarily be the best location for another. This section of the report outlines the geologic and hydrologic conditions that appear to provide "optimum" or preferred sites for each disposal concept and outlines reasons why a certain environment(s) would be more suitable than others.

4.0.3.9.1 Mined Cavity Concepts. Geology and Hydrology. These concepts will probably require a zone of strata with very low permeability at some interval within 3000 meters of the surface. The interval must be sufficiently thick to include zones of very low permeability, over 100 meters thick, both above and below a potential waste disposal cavity to assure that the cavity can be effectively sealed from man's environment.

The mined cavity enables the use of strata insufficiently thick to be practical repositories for drilled hole disposal sites. Of the various rock media potentially favorable for this concept, the most suitable appear to be igneous intrusives, tuffs, shale, and rock salt either in relatively thick beds or in stable domes.

Salt has very low porosity and permeability, which should allow virtually complete hydrologic isolation. In addition, salt has a relatively high thermal conductivity, which should allow good dissipation of heat from the chamber. Mined cavities in salt may be limited to depths of about 1000 meters owing to the natural plasticity of salt and the potential for serious flowage problems at greater depth.

Favorable properties of tuff, some metamorphic rocks, and intrusive igneous rocks include low permeabilities and porosities, and high mechanical strengths. They can be mined with a minimum of structural problems. In tuff at the Nevada Test Site cavities have been mined successfully to depths of as much as 1500 meters. Mined cavities in metamorphic and igneous rocks are feasible as is clearly indicated at Sudbury, Ontario, and in deep copper mines in Michigan. In both of these areas the rocks have such low permeabilities that the mines are dry, even in the lowest levels. Thermal conductivities of metamorphic and igneous rocks vary considerably from values less than that of salt to levels slightly higher.

The possibility of using shale for mined chambers is attractive from the standpoint of placing waste in rock having both high ion-exchange capacity and low permeability. Shale sequences, however, are rarely without thin permeable interbeds of sandstone and (or) limestone, and the possibility of finding zones sufficiently thick to assure complete hydrologic isolation of a mined chamber may be limited. In addition, shale is one of the most difficult rocks to mine because of its plasticity. Perhaps the only areas where shale can be safely used for waste disposal are areas where the chamber can be mined well above an existing water table or where evaporation exceeds precipitation. The possibility of eventual water table rise must be considered in these areas because of potential climatic or manmade changes.

Any such natural changes, if they did occur, would probably be slow, and the possibility of the repository remaining above the water table for many thousands of years is likely. During this period the level of radioactivity would be reduced; when (and if) the groundwater would reach the emplacement zone, the high ion-exchange capacity and very low permeability of the shale would impede the outward movement of radionuclide contaminants.

The possibility of using tuff for an above-the-water-table repository is also appealing for the same reasons as outlined for shale. Tuff probably has the highest ion-exchange capacity of the igneous rocks. This property and its low permeability would probably assure slow outward movement of radionuclides in the event that climatic change would cause groundwater to reach the emplacement zone.

The use of metamorphic, intrusive igneous, or volcanic rocks other than tuff is less attractive for above-the-water-table repositories because these rocks have lower ion-exchange capacities than either tuff or shale and, in general, somewhat greater potentials for high permeabilities at shallow depths. Lavas of all kinds are generally unsuitable for this concept because of high permeabilities.

Seismicity and Faulting. Areas of seismic risk zone 3 must be precluded from consideration for mined cavity disposal, and areas in lower seismic zones (especially zone 2) must be carefully mapped and seismically monitored to assure that active fault systems are avoided. The principal danger is that fault movements could rupture either the emplacement zone or the rocks surrounding the chamber and create passageways for groundwater to carry potential contaminants to man's environment. For sites above the water table, in areas where evaporation exceeds precipitation, earthquake rupturing of the chamber or vicinity would not create an immediate hazard, but the possibility of eventual groundwater encroachment during a period of a million years should be considered.

Climatic Changes. Climatic setting is one of the more critical factors in selecting a suitable location of a site for a mined chamber. To insure the safe long-term containment of radioactive waste in salt, for example, it would be necessary to establish the nature and rates of present-day salt removal by surface waters near the site and the underground dissolution rates by circulating groundwaters. Careful studies must then be made to determine how the rates would be affected by increased (or decreased) rainfall and how changes in regimes of nearby streams might affect groundwater flow systems.

For cavity disposal in these rocks, above present-day water tables, rock-erosion rates including both denudation and escarpment-retreat rates must be established. Estimates of how these rates will be affected by possible changes in rainfall must also be made. Calculations must be made to estimate how rapidly a groundwater table could rise with increasing rainfall and how large an increase in rainfall would be necessary to cause precipitation rates to exceed evaporation rates. For cavity disposal in these rocks below about 600 meters in depth, there is relatively small potential danger from climatic changes.

Resource Potential. Areas considered for mined cavity repositories in salt or shale should be evaluated for potential exploitation and/or contamination of oil, gas, and water reservoirs, and of salt, potash, and other valuable or potentially valuable commodities. Areas of tuff, metamorphic, or intrusive igneous rocks that contain known metallic deposits or where extensive hydrothermal alteration suggests the possible presence of such deposits should, in general, be avoided.

Geographic Setting. A site for mined cavity disposal should generally be (1) as far removed from oceans and major lakes and streams as is practicable to extend as long as possible the transit time of contaminants to man's environment in case of accident during transport, loading, or emplacement of waste, (2) the site locality should be as far removed from human population centers as is practicable, and (3) the site should be in as gentle terrain as possible in order to avoid steep drainage gradients that would allow rapid distribution of contaminants in case of an accident.

Advantages and Disadvantages of Mined Cavity Concepts. The principal geohydrologic advantage of the mined cavity concept compared to drilled hole concepts is the potential ability to provide safe emplacement of high-level radioactive waste in a wider variety of media, including salt beds, shale and tuffs that are too thin for drilled hole emplacement. Metamorphic and intrusive igneous terranes which are suitable geologic settings for drilled holes or exploded cavities are also suitable for the mined cavity concepts.

Potential geohydrologic disadvantages of mined cavity concepts compared to deeper disposal concepts include (1) shorter possible flow paths of waste constituents to man's environment in the event the integrity of the geologic environment is violated, (2) somewhat higher potential of exhumation of waste by erosional processes, (3) somewhat higher susceptibility to flooding, including rising sea levels, and (4) the higher susceptibility of being inadvertently penetrated by man in the future.

4.0.3.9.2 Mined Cavity with Separate Manmade Structures. From the standpoint of geology and hydrology, this concept is essentially the same as the mined cavity concept discussed above. The manmade structures will be designed to allow a greater degree of retrievability of the waste and to greatly restrict or inhibit movement of radionuclides beyond the cavity for a limited time after the waste is emplaced. Terranes and rocks that are best suited for this concept are the same as those outlined for the mined cavity.

4.0.3.9.3 Exploded Cavity Concepts. Geology and Hydrology. Developing an underground cavity by means of nuclear devices or possibly conventional explosives provides a means of creating a sizeable waste-holding facility without the depth limitations of conventional mining techniques. Cavities have been created by nuclear devices in a variety of rock media at Nevada Test Site and other parts of the United States. A concept for using a deep nuclear cavity (chimney) for the incorporation of nuclear fuel-reprocessing waste in molten silicate involves in-situ melting of rubble and wall rock by the high-level radioactive liquid waste.(68) Strata of very low permeability, at least 200 meters thick, are required for the model to contain the molten rock at its maximum dimension.(68) In addition, at least 100 meters of rock having very low permeability and completely surrounding the potential molten zone would be essential for safe confinement of waste constituents. The chances of finding such a sequence in sedimentary environments is limited except possibly in shale at depths of 2000 meters or more in deep sedimentary basins. The need for drill hole connections to the cavity for the introduction of waste and the release of volatile constituents for a period of about 25 years(68) further adds to the potential of introducing contaminants to the overlying strata.

The preferred environment, therefore, must satisfy the need for (1) a thick sequence of rock having very low permeability to effectively contain the exploded cavity and the molten mass of waste and rock and (2) rock having very low permeability around the emplacement zone to avoid introducing contaminants into water or oil and gas reservoirs during the period of waste injection and steam release. These requirements are most likely met in metamorphic and intrusive igneous terranes. The optimum locality would be one where metamorphic and (or) intrusive igneous rocks having very low permeabilities extend from or near the surface to great depths. A potential problem that might be hazardous, however, is posed by the knowledge that a volume increase due to rock melting and the possible accompanying production of gaseous constituents could result in significant fracturing in these low porosity rocks. Other terranes that appear suitable for this concept are those where thick sequences of tuff form the surface rocks and extend to great depth.

Experiments in Mississippi and New Mexico have shown the feasibility of creating stable cavities in salt by small nuclear devices. The nuclear shot near Carlsbad, New Mexico, for example, (project Gnome) formed a cavity about 20 meters high and more than 45 meters across by means of a 3 kiloton device.(69) Post-shot studies at project Gnome indicate that blast-induced fractures and faults were mainly confined to a radial distance of about 40 meters from the shot point(69) and indicate that setting off nuclear devices in salt may not necessarily create hazardous fractures around the shot point.

Seismicity and Faulting. Areas of seismic risk zone 3 should be precluded from consideration for emplacement of waste in explosion-induced cavities for essentially the same reasons as outlined for the other disposal concepts. The principal danger is that fault movements could create passageways for groundwater to reach the contaminated zone and carry contaminants to man's environment. An additional consideration is the possibility of earthquake activity rupturing the drill holes and creating potential passageways between overlying aquifers and the emplacement zone. Small amounts of water entering the emplacement zone may not pose an immediate hazard because the water would tend to be driven away by the intense heat.(68) Large amounts of water, however, flowing into the emplacement vicinity could create explosive conditions causing complete loss of emplacement holes and possible loss of the chimney itself.

These potential dangers from fault movements indicate that a site must be mapped in detail to assure that known or projected fault systems are avoided. If buried faults are encountered in exploratory drill holes either in or above the potential cavity, they must be carefully tested hydraulically to determine that they are completely healed. If testing reveals that they are permeable, a new locality should be selected.

Climatic Changes. Except for the need for continuous monitoring of the site there is little danger from potential climatic changes if the cavity is 600 meters or more beneath the surface in rock other than salt. To eliminate possible adverse effects of another variable, it seems advisable that areas of potential sea-level rise or areas occupied by former pluvial lakes should be avoided.

For disposal in an exploded cavity in salt, the same evaluations outlined for the mined cavity apply.

Resource Potential. Areas considered for exploded cavities in salt should be evaluated for potential contamination of oil, gas, and water reservoirs, potash, salt, and other valuable or potentially valuable commodities. Areas of tuff, metamorphic, or intrusive igneous rocks that contain known metallic deposits or where extensive hydrothermal alteration suggests the possible presence of such deposits should, in general, be avoided.

Geographic Setting. A site for emplacement of liquid waste in an exploded cavity must be in the same location as the reprocessing plant. Therefore, selections of geographic locations for reprocessing plants would have to await geologic and hydrologic analyses to determine the most suitable locations for underground nuclear cavities or other disposal modes. As will be pointed out in the discussion of the deep drill hole concept, the depth involved allows for the possibility of disposing of waste at existing reprocessing plants. An exploded cavity at depths of as much as 6000 meters might also be suitable at some existing reprocessing plant sites, depending on local geologic and hydrologic conditions and the proximity to damage-prone manmade structures.

The main geographic requirement appears to be remoteness from human population centers. Also, because of the potential for release of contaminated steam from the underground facility prior to final sealing, it seems advisable to locate the site as far from oceans, major lakes, and streams as is practicable.

Advantages and Disadvantages of Exploded Cavity Concept. The principal geohydrologic-related advantage of the exploded cavity over the mined cavity is the ability to create cavities at relatively shallow depths (1500-3000 meters) where high underground temperatures or, perhaps, dangerous mining conditions preclude manpower techniques. The main advantage over the deep drill hole and matrix holes is the ability to obtain much larger disposal volumes in one cavity.

The development of radial and other fractures around an exploded cavity compounds the problem of potential hazards from fracture porosity and permeability. For disposal in salt the nuclear device conceivably could trigger diapirism or other deleterious plastic movement. In-place conversion of waste in salt is expected to result in formation of a molten mass of chloride salts of the radionuclides which, when solidified, will exhibit a solubility of the same order as the salt rock. In general, however, terranes and rocks that are suitable for a mined cavity are suitable also for a shallow-depth-exploded cavity, and terranes and rocks suitable for deep drill holes are suitable for a deep nuclear cavity.

4.0.3.9.4 Matrix Drilled Holes (300 to 6000 meters). Geology and Hydrology. A matrix of drilled holes to depths of as much as 6000 meters provides a potential means of disposing of waste where mining a cavity, forming a nuclear cavity, or drilling a very deep drill hole may be impractical. A thick sequence of rock having very low permeability is required to obtain the necessary waste-holding capacity without drilling an impractical number of holes, each of which must be considered as a potential avenue for communication with man's environment. The principal geohydrologic requirement for low permeability is similar to the deep drill hole discussed later. The main difference is a need for rock having very low permeability to be present at shallower depths than is necessary for the very deep drill hole (9,000 to 16,000 meters) and the potential need for a larger surface area to accommodate additional holes. This latter requirement may not be a critical factor because, in an average environment where a vertical column of thick, very impermeable rock is present, areas can probably be found where such rock is contiguous over lateral distances of many kilometers. The spacing of holes would be controlled by local terrain and drilling conditions, the temperature and chemical properties of the waste, rock conductivity, and other physical characteristics of the host media.

The requirement for a thick sequence of homogeneous rock having low permeability is most readily found in terranes where metamorphic or igneous rocks are near or exposed at the surface or where such rocks are at shallow depth. The possibility of using beds of salt only a few hundred meters thick or sequences of shale for matrix hole emplacement may be possible but is likely to be impractical. Drilling a large number of holes into a thin salt bed to achieve the necessary waste-holding capacity would greatly increase the potential connections to man's environment. The possibility exists that stable salt domes could be used for matrix drill hole disposal if it can be proven that salt will be stable in large-diameter holes drilled to depths of more than about 1000 meters.

Thick sequences of shale occur in several sedimentary basins.(39) Shale commonly contains many interbeds of permeable sandstone and limestone. Because of the interbeds and the common occurrence of faults and other fractures in the basins, there is limited possibility that waste emplaced in a large vertical column could be effectively contained in shale, especially at shallow depths where porosities and permeabilities of interbeds and fractures could be high. Because of the general decrease of porosity and permeability with depth, exploratory drilling may define shale sequences at some interval within 6000 meters of the surface that could be suitable hosts for matrix drill hole waste emplacement. The fact that the thick, deeply buried shale sequences occur only in sedimentary basins that are the principal producers of oil and gas indicates that extensive exploratory drilling and hydraulic testing will probably be necessary to prove hydrologic isolation of the potential waste emplacement zone.

Seismicity and Faulting. Crustal stability is essential for safe disposal of radioactive waste in a matrix of drill holes. Because of shorter total hole length, the problem of keeping the hole open if earthquakes should occur is less for the matrix hole than it is for the deep hole concept. Unless hydraulic testing demonstrates conclusively that they are completely healed and "water tight," faults within the waste-emplacement zones are undesirable because of the potential for groundwater access and the threat of earthquake activity causing movements to occur along these planes of weakness. A potential site area would have to be mapped in detail and seismically monitored. Exploratory drill holes are economically feasible and should be drilled and hydrologically tested to delineate lithology having the lowest permeability and to locate areas free of buried faults.

Climatic Changes. The setting for matrix drill holes should be carefully evaluated if the top of the waste column is within 600 meters of the surface. If the disposal site is in an area of gentle relief, there is little possibility that erosion will actually exhume the waste even in areas that may be covered by glaciers. However, if a climatic change should cause a radical change in precipitation, there is the potential for surface and groundwater regimes to be changed. The site, therefore, must be so selected that the most realistic potential hydrologic change will not create foreseeable avenues for communication of the disposal area with man's environment. Because climatic changes cannot be predicted with any degree of accuracy, it seems advisable to place the top of the waste at least 1000 meters below the earth's surface in any potential site locality having integrated surface drainage.

All areas that conceivably could be inundated by rising sea levels or covered by glaciers or pluvial lakes must be considered less suitable for matrix drill hole disposal than areas that are free from those potential hazards.

Resource Potential. Careful evaluations must be made to avoid areas where mineral deposits are known or where extensive hydrothermal alteration suggests the possible presence of mineral deposits. If terranes are selected where the principal rocks are metamorphic or igneous, the potential exists for drilling into economically valuable metallic or nonmetallic mineral deposits.

If terranes are selected where sedimentary rocks either mantle the surface or are the principal rocks at depth, the potential exists for water, oil, and gas resources. These possibilities would have to be evaluated prior to any exploratory study.

Because of the modest drilling depths under consideration for this concept, there is relatively little likelihood of locating a matrix drill hole repository within a potential source of geothermal energy. Nevertheless, it will be necessary to avoid areas having high geothermal potential.

Geographic Setting. The optimum geographic setting for a matrix drill hole disposal site is a large area of gentle relief. If it is necessary to locate a site in terrane with locally high or moderate relief, the topography may become the principal factor in choosing a suitable site because of the increased potential for landslides and erosion.

The sites should also be located (1) in areas as far removed from population centers, major drainages, lakes, and oceans as practicable and (2) in areas of gentle relief to avoid steep drainage gradients.

Advantages and Disadvantages of Matrix Hole Concepts. From the standpoint of concept implementation, a sequence of holes drilled to depths of as much as 6000 meters has the following advantages compared to the very deep drill hole: (1) The shallower holes can be drilled to larger average diameters and can have larger ratios of waste capacity per total length of hole drilled; (2) conceptual preemplacement pilot or exploratory holes are more economical for this mode; (3) drilling problems due to earthquake activity are less likely with shallower holes, and (4) drilling times per unit of hole depth will be much less and several rigs could be employed simultaneously.

Whether a sequence of holes or a mined or exploded cavity would be preferred in any given locality would depend on the geologic and hydrologic information obtained from detailed investigations. For example, if exploratory drilling reveals that rock having low permeability and other acceptable physical and chemical properties exists from 1000 meters below the surface to 6000 meters, then economics and the safety considerations related to access to the disposal location may determine whether a cavity at the 1200-1500 meter depth is preferable to several large-diameter drill holes. Laboratory or actual field tests would have to be made to determine the effects of a concentration of solidified waste in a cavity at 1200-1500 meters or in a series of drilled holes, from the standpoint of heat transfer for the particular rock at the potential site locality.

If exploration revealed that rock at a proposed site with acceptable low permeability and other physical and chemical properties is present only down to about 1500 meters, then that location would generally be more favorable for a cavity concept than for drilled holes (assuming other factors are approximately equal).

4.0.3.9.5 Deep Drilled Hole (9000 to 16,000 meters). Geology and Hydrology. Because of the depth involved in this concept and the great physical separation of waste from man's environment that it will provide, it will generally be of little consequence what climatic or other changes might eventually occur that could affect surface conditions. The principal geohydrologic requirement is the necessity for a fairly thick sequence of rock having low permeability to occur below a depth of about 9000 meters. This requirement can be found in a variety of terranes, but the preferred setting is one where homogeneous, low permeability, metamorphic, and intrusive igneous rocks persist from on or near the surface to great depths. Metamorphic and intrusive igneous rocks have high mechanical strengths and can be drilled with a minimum of risks such as caving of the drill hole walls.

Deep sedimentary basins of interbedded rocks having varying degrees of permeability are generally not suitable for this concept because of the typically high potential for regional aquifers and (or) oil-bearing strata. Some basins at depths of

9000 meters or more may have such low porosities and permeabilities that they may be suitable for deep hole waste disposal, but this would have to be proven by exploratory drilling and extensive hydraulic testing.

Because the characteristics of the upper several thousand meters are relatively unimportant for the deep hole concept, many parts of the United States that are mantled by thin (1500 meters or more) layers of permeable sedimentary rocks but are underlain by metamorphic or igneous rocks may provide suitable sites for the deep drill hole. The concept, therefore, offers the possibility of safe disposal of waste at or near processing plants where suitable rock media are not available at shallow or moderate depths.

An important consideration if liquid waste is emplaced in the drill hole is whether or not extensive fractures will develop as a result of the expansion of molten rock due to radiogenic heat. Laboratory and field tests are necessary to determine the nature and extent of such fracturing.

Areas of high heat flow such as coastal California, the Basin and Range Province, Columbia Plateau (including the Snake River Plain) must be regarded as less suitable for the deep drill hole than areas of normal flow. Volcanic activity has occurred in all these areas in the past few million years, and, locally, molten rock may even exist at levels considerably above 16,000 meters.(70)

Seismicity and Faulting. Crustal stability is of extreme importance when evaluating terranes for any waste disposal concept. For deep drill hole disposal, the most important geohydrologic consideration for long-term waste confinement, assuming the waste is emplaced in suitable media, is the potential for fault movement rupturing the zone in or near the waste column and creating passageways for groundwater to enter the disposal area. Good crustal stability is required in order to even drill such a hole. Several years are likely to be required for the actual drilling and preparation of a 9000 to 16,000 meter hole and several more for disposal operations within a given hole. Even moderate earthquakes, if in close proximity to the drill hole, could cause collapse of the hole walls. Therefore, all areas of high seismic risk (zone 3) must be precluded from deep drill hole consideration. The selection of sites in other seismic zones would have to await seismic monitoring and detailed geologic mapping to establish the existence of fault systems and the locations of seismically active zones.

The emplacement zone of the hole should be virtually free of faults, whether currently active or not, because faults could provide potential avenues for fluid movement. Great depth should contribute to sealing of faults. However, great depth may not necessarily guarantee that faults and fractures will be closed and healed despite the knowledge that porosity and permeability generally diminish with depth, (Figure 4.21).(71) Hydrologic testing at the Nevada Test Site revealed that fractures had low to moderate permeability at least to 4160 meters,(72) and fractures below 6000 meters in a drill hole in the Delaware

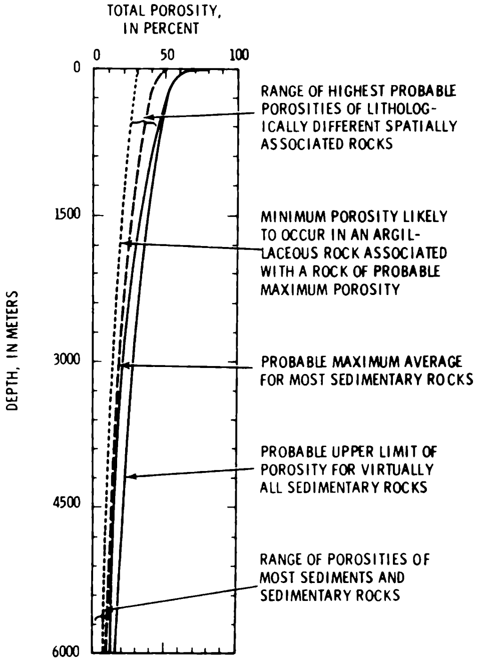

FIGURE 4.21. Total Porosities of Sedimentary Rocks Versus Depth (Modified from McCulloh, 1967)(71)

Basin of Pecos County in Texas were found to be permeable. Potential sites must also be carefully evaluated to ascertain the possible presence of buried low-angle or thrust faults. Areas known to be characterized by such faults or areas where they have been logically inferred should be avoided.

Resource Potential. The possibility of damaging or destroying a potential resource must be evaluated for all concepts, but for the deep drill hole the possibility of damaging a potential source of geothermal energy must be especially evaluated. Areas of high heat flow such as coastal California and the Basin and Range province, are areas where the probability of penetrating an economic source of geothermal energy is very high. Volcanic activity has occurred in both of these areas in the past few million years. A close spatial and temporal relationship between volcanic activity and geothermal activity has been outlined by Grose.(73) Active hot spots in the crust are generally known by the occurrence of geysers, hot springs, etc.; other hot spots probably are present at depth but will be found only by deep drilling. Therefore, in deep drill holes the disposal of high-level waste must be regarded as less suitable in areas of high heat flow than in areas of normal flow. In some areas of high heat flow, molten rock may even exist at levels considerably above 16,000 meters.(70)

As previously discussed, valuable oil and gas bearing strata are commonly found in sedimentary environments. This potential for connection between a deep hole disposal site and such resources in sedimentary basins may be possible, even at great depth. Natural gas is now being produced at depths as great as 7500 meters in Oklahoma.(74)

Geographic Setting. A site for deep drill hole disposal should be (1) as far removed from oceans and major lakes and streams as is practicable, (2) as far removed from human population centers as is practicable, and (3) in as gentle terrain as possible in order to avoid steep drainage gradients that could allow rapid distribution of contaminants in case of accident.

Advantages and Disadvantages of Deep Drill Hole Concepts. The principal advantages of the deep drill hole concept compared to other geologic concepts include (1) a wide variety of potential sites with the ability to provide safe emplacement of high-level radioactive waste in desirable geographic locations where suitable rock media do not exist at shallow or moderate depths and (2) the ability to place the waste as far from man's environment as possible.

Other attractive features of the deep drill hole are (1) elimination of danger of exhumation of waste by any erosional process, including glaciation, and (2) elimination of dangers from flooding, including rising sea levels (assuming complete sealing of unused portion of drill hole).

The principal disadvantages of the deep drill hole appear to be largely operational. Probable high drilling expense and long drilling times would be required especially in hard metamorphic and igneous rocks. In addition, exploratory or pilot holes to assure suitable rocks at the depths under consideration would also be limited by time and expense.

4.0.4 Radionuclide Migration in Soils

One of the major considerations associated with either storage or geologic disposal concepts will be the selection of sites where the possibility of groundwater or surface-water intrusion is essentially nil. However, even if water somehow contacted the waste, the remoteness and the characteristics afforded by certain geologic formations could significantly delay the time of arrival of dispersed radionuclides into man's immediate environment. Obviously, radioactive decay associated with any delay retardation of nuclide migration could reduce radiological consequences of an unexpected release. Furthermore, chromatographic separation of radionuclides could segregate radiological doses that would otherwise be additive. The nuclide retention and separation results from the fact that many of the species that might be leached from solid products during an incident involving water contact would subsequently react with and be retained by the host media or surrounding sediments.

Mechanisms for retention and separation (fractionation), as the result of radioactive solutions percolating through the sediments, include ion exchange, precipitation, and replacement. Ion exchange is a special case of sorption where species moving in or out of the sorbing media are ions rather than molecules. Many solids, when placed in contact with solution, simply exchange ions with similar chemical species that are present in solution. "Fertilizers contain soluble ammonium and nitrate ions. One reason these ions are not washed away from the surface of the soil is that they exchange with other ions in the soil and are then held by insoluble minerals."(76) In layered silicates and zeolites of the silt and clay size fractions of sediments, cation exchange can be the predominant reaction for the removal of radionuclides.(77)

The formation of gelatinous, insoluble aluminum hydroxide during water treatment is a good example of a precipitation reaction. Many chemical salts remain in solution primarily under acidic conditions. However, when an acid waste solution enters calcareous soil, free carbonate tends to neutralize the acid in the water, resulting in the precipitation of various nuclides as insoluble hydroxides. Additional details concerning soil sorption reactions are presented in Reference 77 where emphasis is placed on retention mechanisms for Sr-90, Cs-137, Co-60, Ru-106, plutonium, transition metals and rare earths.

Evaluation of the extent of confinement afforded by the retardation and separation potentially associated with geologic formations obviously requires the definition of a particular site. The depth and mineralogy of the host media and the surrounding sediments as well as the areal climate must be described to evaluate the relative importance of the above sorption reactions in relation to a particular waste constituent. Ion-exchange capacity and the thickness of the unsaturated zones of arid or semiarid regions of the southwest are qualitatively discussed in relation to the retardation of nuclide transport in Reference 67. It should also be noted that any final evaluation of a specific site must consider the possibility that the dispersed but sorbed nuclides could conceivably become a contamination source, e.g., as the result of changes in water chemistry. Methodology for providing quantitative estimate of the orders of magnitude of retention and retardation that could be expected from reactions in a typical desert soil following a postulated release incident was presented in Section 3.

4.0.5 Excavation and Sealing Information Relevant to Waste Disposal

All of the geologic storage or disposal concepts require some form of excavation to provide access to the region selected for waste emplacement. After waste emplacement the access must be closed and sealed from man's environment for hundreds of thousands of years. The techniques and technology for hole forming, cavity formation, and access sealing relevant to waste disposal are summarized in the next two paragraphs. The sections following give a brief review of these areas.

In general, technology and methods seem to be adequate to produce the excavation needed for the waste disposal concepts under investigation. The one notable exception is the lack of demonstrated capability and technology to form a modest sized drill hole up to 16 kilometers deep. One study suggests that forming such a hole may be feasible with existing equipment and technology for locations having low geothermal temperature increases with increasing depth.(78) Unpredictable conditions at depths below those explored (about 9 kilometers) could cause major complications and delays in an attempt to reach full depth and/or desired diameter at full depth. Bigger equipment and select technological improvements are likely to be required.

Technology for sealing cavities and drill holes is reasonably well developed for seals which maintain integrity on a short-term basis. Existing seals have accomplished their goals for the time they have been in place. Unfortunately, these test times are on the order of 10 to 50 years rather than the hundreds of thousands of years required for waste disposal. A carefully planned development program should lead to seals having a high assurance of a predictable long life.

4.0.5.1 Hole Forming

As referred to here, this is simply a method of forming a hole, usually near vertical, with all man's activities performed at the earth's surface. Drilling is the most frequently used method for holes over a few hundred meters in depth and no larger than a few meters in diameter.

4.0.5.1.1 Conventional Drilling. In conventional drilling a rotating drill bit is used within the hole. The bit is powered from the surface through connecting drill pipe. Great depths could perhaps require techniques which eliminate the rotation of the shaft. Promising ways of doing this include locating the motor for rotation near the hole bottom or using graduated drilling or melting techniques. A few details about these methods are given below. The general information presented was obtained from Reference 79 unless otherwise noted.

The boundaries of drilling experience such as depth, diameter, and drilling rates are of interest in indicating when development would be needed for a particular concept. Depth is discussed first. The most recently reported depth record is 9135 meters.(80) This record hole required about 2 years to drill and is now producing gas at the 5180 meter depth. The particular geologic formation thought to lie at about the final depth was not reached. The reason for terminating the drilling is unknown but appears to be economic. The hole diameter is stepped in size as follows: 44 centimeters to 4700 meters, 32 centimeters to 7300 meters, and 20 centimeters to 9135 meters.

During 1972, 506 holes were drilled to deeper than 4600 meters and 49 holes were drilled to deeper than 6100 meters(80) in the United States. The numbers of holes greater than these depths have been generally(79,80) increasing yearly. An attempt at an 8800-meter hole is under way.(81)

The depth boundaries described above are adequate for all needs identified in this report except that of the 16,000-meter hole. In this case the most relevant data is a study by Fenix and Scisson, Inc.(78) Direct quotes excerpted from their conclusions are:

- "It is feasible to drill a hole to 16,000 meters.
- Equipment required to drill the projected hole is available at this time (May, 1969). Some items of equipment should be subjected to additional development to improve performance and safety. Specifically

the items needing development are: drill pipe, downhole motors, and bits.

- Casing, cement and cementing services, along with circulating fluids for use at the assumed temperature and anticipated depth are available.
- The estimated time to drill the hole is from 4 years, 9 months to 6 years, 6 months, dependent upon the area selected.
- The estimated total cost of the hole is from 19.5 million dollars to 26.7 million dollars depending upon location and intermediate casing strings required. These cost estimates, along with others shown in this report, do not include a contingency allowance, nor do they include the cost of administrative overhead or an architect/engineer. (Note: The cost of subsequent holes should be in a lower range because of experience gained on the initial hole.)
- The most expedient and economical method of drilling would be to penetrate the upper 6000 to 9000 meters with a currently operational drilling system. Depending upon final criteria the drill rig could continue the drilling to depth or be replaced completely, or in part, with components of greater capacity. Development and testing of special tools for the project should be completed during the drilling of the upper portion of the hole.
- A possibility exists that fractured formations, caving hole, seismic activity or other conditions may be so severe that it will be impractical to proceed. In this eventuality the project should be moved to a more favorable location or abandoned."

Based upon these and other studies, it is concluded that a small diameter (less than 10 cm) 16,000 meter deep hole is feasible with today's equipment in areas of low geothermal gradient (i.e., where down-hole temperature are lower than typical). For holes of the diameter required for radioactive waste disposal and for areas with nonlow downhole temperatures, necessary equipment is not yet available, and considerable research and development may be required.

To provide perspective on the size of deep-drilling equipment the rig description for the 9135 meter hole is given below:(82)

> The largest in the world, Rig 32 is equipped to drill below 9,100 meters.
>
> The 2,235 kilowatt drawworks is powered by three 1,000 kilowatt electric motors. The 43 meter mast has a gross nominal capacity of 910 metric tons, rotary capacity of 730 metric tons and a setback capacity of 500 metric tons. The crown block is the world's largest, with a capacity of 860 metric tons. Hook and traveling equipment are rated at 680 metric tons.
>
> Other equipment includes two 1,230 kilowatt mud pumps, a 431 cubic meter active mud system, and 632 cubic meters of reserve mud capacity. A 1020 atmosphere working pressure BOP (blowout prevention) system is the largest ever fabricated.

Certain items in drilling experience have bearing upon the potential for drilling a 16,000-meter hole. They include rotating drill table capacity, drill pipe strength, bit strength and design, and downhole temperature, pressure, and rock competence. Each is briefly and independently discussed with respect to its effects on drilling 16,000-meter holes. All factors could possibly combine to defeat such an effort short of the point each might cause failure separately.

The mechanical connection between large engines and the pipe is made by a device called a rotating table. It is designed to transfer power at some maximum rate. The largest table in use within the United States is rated at 14,000 kilogram-meters of torque. Downhole friction must be overcome to rotate the bit. The total friction increases with depth until ultimately a point may be reached where the bit cannot be turned. Present rotary tables are expected to have the needed capability for 16,000-meter holes.

A table with twice the capacity of the current maximum appears technically feasible but there presently appears to be no incentive to build such a table in the oil industry. The larger table could allow an increase in the drilling rate at any instant by about 40 percent. To the extent that maximum depth is friction limited and that friction depends upon the total rotated surface area, the possible hole depth could be doubled for each drill diameter used. Thus the rate at which hole size decreases (by steps) with depth could be reduced. Applying the same logic, the diameter could be doubled at a given depth. Note, however, that both cannot be done simultaneously and that these simple estimates are only absolute upper bounds rather than actual experience.

Drill pipe strength also has significant bearing on the achievable hole depth. Adequate drill pipe is available for drilling a small diameter hole to 16 kilometers. The safety margin, however, is not as great as usually used, and the chance of twisting off the drill pipe is greater.(78) A broken drill pipe is frequently not recoverable. The tensile loading on the pipe is made up of two major components: 1) the twisting load in turning it and 2) the static load of the pipe, bit, and the drill collar.[a]

Presently available drill bits may be adequate for a 16-kilometer, 70 centimeter diameter hole or a 2.6-kilometer, 3-meter hole.(78) Better bits, however, would speed up the average drilling rate by reducing the number of times they have to be changed.

The earth's temperature typically increases with depth at a rate of about 15 to 30°C per kilometer depending on the location. Extrapolation of this rate of increase suggests that there are areas where a 16-kilometer hole can be drilled without exceeding the temperature limits of existing equipment. Currently, drilling muds are limited to use at up to about 260°C. Higher temperatures can cause increased drill bit wear, drill bit failure, decomposition of muds, problems with premature cement setting, and reduction in downhole material strengths. This implies that for a 16-kilometer

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[a] A drill collar is a series of weights which load the bit for optimum drilling pressure.

hole either an area having an average geothermal temperature increase of about 16°C per kilometer must be chosen, or higher temperature drilling muds must be developed.

Denser muds are required for the higher temperatures and pressures encountered in deep drilling. These muds are more difficult to handle than conventional muds, causing an overall increase in drilling costs.

Hole collapse, water invasion, and drilling mud loss are three related and currently encountered problems which may be anticipated in a 16-kilometer hole. All can be minimized by either casing the hole or locally cementing the formation.

At some depth for a given diameter, the hole cannot be cased using existing equipment because of equipment and casing strength limitations. A depth limit of 12 kilometers for 70-centimeter casing has been estimated.(79) A proposed 8.8-kilometer hole has already a record 4.3-kilometer, 36-centimeter casing weighing about 680 metric tons.(82)

Diameter can be discussed at least partially exclusive of depth. The record large diameter holes drilled are shown below in Table 4.14 as a function of depth.

These limits are adequate for almost all large diameter needs of the identified concepts. The possible exceptions are those concepts requiring manned access at the hole bottom for holes deeper than about 1830 meters. Fenix and Scisson(79) feel 2400 meters is the maximum depth for a larger than 180-centimeter diameter hole using existing equipment. They believe larger equipment is possible.

The generally inverse relationship between maximum hole depth and maximum diameter makes it necessary to consider what the maximum depth is for a diameter which is suitable for a solid waste canister. Forty-three centimeters is considered the reference hole diameter for the drilled hole concepts in this study. The record hole (80) described previously reached 4700 meters at this diameter. Data on drilling a 43-centimeter diameter hole to depths greater than the record 4700 meters has not been generated, primarily because the oil and gas industry has apparently not had either the technical need or economic justification for it.

Drilling rates are an important factor in the cost of drilling holes. For waste disposal they are additionally important in the logistics of

TABLE 4.14. Large-Diameter Drill Hole Depths(79)

Location	Hole Depth, (meters)	Hole Diameter, (meters)
Amchitka Island, Alaska (conventional rig)	1,900	2.3
Central Nevada (conventional rig)	1,700	3.0
Nevada Test Site (conventional rig)	90	4.1
Location Unknown (special rigs)	210-240	>4.0

implementing a selected disposal concept. Rates vary extensively with rig size, drilling depth, and material being drilled. A significant factor affecting rate as depth increases is the time required to change drilling bits (trip time) since increasingly more drill shaft sections must be handled. In recognition of these variations, "average" drilling rates have been tabulated in Table 4.15.(79) Shown also is a record fast time drilling rate for a 5300-meter hole. The demonstrated drilling rates do not appear to place a controlling burden on the geologic disposal concepts under investigation.

Drilling typically requires recirculation of a fluid (drilling mud) as a means of lubricating the shaft and bit, cooling the drill bit, transporting the hole drillings to the surface, and equalizing hydraulic and lithologic pressures at depth. Drilling muds normally consist of various materials dissolved in or slurried with water. Cleaning the drilling mud and water out of the holes after drilling is important for waste disposal. Holes have been cleaned for a wide array of underground nuclear tests, such as the 1900-meter hole at Amchitka Island, Alaska, and for liquified petroleum gas (LPG) storage cavities. A gradual reduction of drilling mud density to that approaching clean water while maintaining fluid circulation may be a possible technique of hole cleaning. The water could then be pumped out; the hole cased and cemented; and finally residual water pumped out, resulting in a clean dry hole.

Deviation of a drilled hole from the vertical is an important consideration as it affects hole location. Two types of drill deviation can be encountered. One is geology dependent; the other a random effect controlled by other aspects of the drilling process. The first type,

TABLE 4.15. Typical Drilling Rates Versus Hole Depth in Relation to Time(79)

Hole Depth (kilometers)	Data Basis	Estimated Drilling Rate (meters/day)	Total Drilling Time (days)
5.3	Experience	53[a]	100[a]
0 to 4	Experience	18	250
6	Experience	18	350
8	Experience	18	470
10	Extrapolation	15	600
12	Extrapolation	10	800
14	Extrapolation	4	1300
16	Extrapolation	1	2700

a. Record fast drilling job.

geology dependent, occurs rather reproducibly in adjacent holes and is caused by such features as tilting in the rock bedding planes. Thus it occurs to about the same extent in the same direction at the same depth in adjacent holes. Two solutions to the geology dependent deviation are thus apparent. First, as drilling proceeds, compensation for the deviation can be made at known points in a planned fashion based upon past experience. The second alternative would permit the hole to deviate from vertical if none of the design goals are compromised. For example, a design goal that all holes must have uniform spacing can be achieved if each hole deviates in a like manner. Correcting this type of deviation may require several trial and error holes to develop an adequate system, but the oil industry routinely moves in the direction of straight holes as they proceed to drill a field.

The second type of deviation, random, can only be controlled in a particular hole by frequent monitoring followed by corrective directional drilling. The monitoring can be done as often as desired, but does increase the cost of drilling. Directional drilling is a well developed art, but does require more time to accomplish and to monitor the results. A hole can be redirected from 1/2 to about 5 degrees over about ten feet of drilling.

A quantitative measure of the nominal deviation from vertical has not been established. However, it appears that 1/2° to 2° is not an unreasonable goal. Typical specifications for oil well drilling are 3 to 5° off vertical overall, with no sharp "dog legs."

4.0.5.1.2 Advanced Hole Forming Technology. Work upon advanced drilling and cavity forming techniques has been reported.(83-87) Nonconventional or novel forming techniques can be classified by the basic mechanism utilized for rock removal.(83) The various mechanisms include: 1) fusion and vaporization, 2) thermal spalling, 3) chemical reactions, and 4) mechanically induced stresses. The specific novel methods reviewed for this study have been classified according to these rock-removal mechanisms and are presented in Table 4.16. Conventional drilling falls in the last category.

Fusion and Vaporization Drills. Fusion and vaporization drills must operate at the rock melting temperature. The melting temperatures of most rocks range from 1000 to 2000°C, and the specific energy required to fuse rock range from 4,000 to 5,000 joules per cubic centimeter. Strong igneous rocks such as granite and basalt have lower fusion energy requirements than weaker sedimentary rocks such as sandstone and limestone. This suggests that fusion drills will find initial application for drilling these strong igneous rocks.

Electric heater drills(88) and nuclear drills(89) are similar except for heat source. Both melt the rock and remove it as a liquid which is solidified to "popcorn-like" particles which are blown out of the hole. The subterrene, a particular hole

TABLE 4.16. Classification of Novel Drills

Fusion and vaporization drills

- Electric heater (subterrene)
- Electric arc
- Electron beam
- Nuclear
- Plasma
- Laser

Thermal-spalling drills

- Jet piercing
- Forced flame
- High-frequency
- Fluid contact
- Electric disintegration
- Microwave
- Induction

Chemical drills

- Fluorine

Mechanical drills

- Explosive
- Erosion
- Turbine (single stage)
- Pellet
- Implosive
- Continuous penetrator
- Ultrasonic
- Spark

melting device, shows potential for applications in the future and is one of two drills under active development at the Los Alamos Scientific Laboratory. The device bores holes in rocks by progressively melting them instead of chipping, abrading, or spalling them away. The energy requirement for melting rock is relatively high, but may not be prohibitive. Common igneous rocks melt at about 1200°C and, in being heated from 20°C to just above their melting ranges, they absorb about 4300 joules of energy per cubic centimeter. In comparison, the corresponding figures for rotary drilling in most igneous rocks is about 2000 to 3000 joules per cubic centimeter. Even for a penetrator of very large diameter advancing at a high rate, the melting energy can easily be provided by a compact, high-temperature, nuclear reactor. Energy transfer from the reactor to a melting tool at the rates and densities required will be by means of heat pipes.

The rock-melting drill has so far been developed only to the stage of a small, functional, electrically heated prototype. Tested in this form, it has been shown to penetrate basalt and other igneous rocks at usefully high rates and with moderate power consumptions. As it advances, the penetrator forces molten rock laterally into voids in the unmelted rock around the bore, and backward around the periphery of the penetrator. The molten rock freezes in these locations, producing an obsidian-like glass lining on the wall of the hole which helps to seal and support it. The lining also forms a seal around the penetrator, tight enough to permit high pressures to be developed in molten rock ahead of it.

The formation of holes up to 25 meters deep and 7.5 centimeters in diameter has been demonstrated in field tests.

Electric arc drills operate at 5,000 to 17,000°C and can fuse holes in any rock. Work has been done by several organizations.(83) As an example, Drilling Research, Inc.,(90) used an electric arc to spall and fuse craters in flint, limestone, and sandstone. Craters ranging in volume from 13 to 16 cubic centimeters were formed in 6 to 15 seconds in air. In one underwater test, a crater having a volume of 14 cubic centimeters was fused in sandstone in 120 seconds. No spalling occurred in this underwater test.

Plasma generators or plasma arc drills produce temperatures up to 17,000°C and are capable of fusing holes in any rock. Plasmas are produced by passing electrical current through a gas such as helium or argon which is passing between electrodes at velocities of 200 to 7,500 meters per second. Plasma drills are high-velocity, high-heat-transfer devices. Bouche(91) used a plasma arc to spall and fuse holes in various rocks. This plasma had a 7.5-centimeter flame having a temperature of 5,000°C at the electrodes and 1,800°C at a distance of 2.5 centimeters from the electrodes.

Electron-beam drills(92) produce power concentrations up to 1.5×10^9 watts per square centimeter, sufficient to fuse holes in any rock. Electron beams are produced by accelerating electrons from a cathode toward an anode using potentials of 5 to 150 kilovolts. The electrons emitted from the cathode are focused against the rock by means of a bias grid along with electrostatic and electromagnetic lenses. Electron beams have been used to drill holes in rubies and other minerals, but no large-scale drilling tests have been performed.

Laser drills(93) can produce power concentrations of 1.5×10^{12} watts per square centimeter, which is sufficient to fuse holes in any rock. A laser beam is produced by exciting or "pumping" a group of atoms in a crystal or gas to their higher energy state and then dropping them back to their lower energy state. As this drop occurs, the atoms emit photons of the same frequency, producing a coherent light beam. Flash tubes are used to excite ruby crystal lasers. These crystal lasers can be used only in short bursts because over 99 percent of the pumping energy is lost to the cooling fluid, and heat dissipation is a problem.

At this time it is not possible to predict if any of the fusion and vaporization concepts will work on a commercial scale and if so, which are best. However, the concepts provide a wide range of power outputs. Thus, if a number of concepts work, presumably the final choice would be that method which is the most effective and does not use excessive power. The media used for transporting the drilling energy varies from a solid to photons, which provides for a considerable range of application. All fusion and vaporization methods will require a number of downhole cables and complex equipment.

Thermal Spalling Drills. When the surfaces of some rocks are rapidly heated to 400 to 600°C, thin flakes or "spalls" of rock break off the surface. This process, called thermal spalling, produces long, thin flakes. These spalls are produced by thermal stresses resulting from differential thermal expansion of the constituent crystals and grains.

Jet-piercing drills,(94) which were introduced into the mining industry in 1946, are widely used for drilling taconite and other silicate ores. They burn oxygen and fuel oil to produce a flame having a temperature of 2400°C and a velocity of 1800 meters per second. Water is used to cool the combustion chamber and the burner nozzles. This water also solidifies the molten rock and is converted to steam, which assists in removing the disintegrated rock from the hole bottom. Jet-piercing-drilling rates range from 0 in limestone to 12 meters per hour in some taconites and quartzites.

Forced-flame(95) or rocket-exhaust drills are similar to jet-piercing drills except that they use nitric acid as the oxidizing agent instead of oxygen. Nitric acid produces a faster reaction, resulting in higher power output and faster drilling rates. A field-tested, forced-flame drill penetrated iron quartzite at 18 meters per hour, compared to 5 meters per hour for a jet-piercing drill.(84)

Numerous tests have shown that high-frequency electric current can be used to break and crush conductive rocks such as iron ore.(95) This technique could be used to drill rock. These devices heat rock by dielectric heating and by resistance heating. Dielectric heating occurs due to the rapid switching back and forth of the dipoles, while resistance heating is produced by electric current passing through the rock between the electrodes.

Kravchenko(95) used 240 kilocycles/second current to heat and break blocks of iron quartzite weighing up to 9 metric tons. A conducting channel formed in these rocks after 1 to 10 seconds, and they broke into 3 to 8 pieces after 1 to 3 minutes.

Ross(96) has patented a thermal drill (called the Terra Jetter) which cyclically heats and cools rock. As conceived, superheated steam (250 to 500°C) would heat the rock for 3 minutes and then liquid nitrogen (-134°C) would be sprayed on the heated rock to thermally shock and pulverize it. Low-pressure steam would be circulated through the drill to remove the pulverized rock from the hole bottom and to reheat the rock. In addition to heating the rock, the high-pressure steam would assist in removing rock by eroding it and by flashing water in pore spaces into high-pressure steam. Ross reports the Terra Jetter should drill granite at 3 to 6 meters per hour and medium-strength rock at 11 meters per hour.

Sarapuu(97) has used the electric-disintegration drill to drill limestone, taconite, and concrete. This drill heats and spalls rock by passing low-frequency electric current (60 cps) into the rock through a sharp bit. The bit is rotated at 90 rpm and air is sprayed on the rock to thermally shock and break it. In field tests a 150-kva electric-disintegration drill made 12-centimeter-diameter holes in top soil faster than conventional bits. The heating process dried the top soil and made it easier to remove from the hole bottom. Drilling rates in limestone were low, apparently because of the low resistivity of this rock.

Laboratory tests have shown that microwaves (1000 to 3000 MHz/sec) can effectively heat and break rock. Microwaves produce dielectric heating, which is proportional to the frequency of the field. This technique could be used for drilling wells. Steudel(98) used two magnatrons (2.5 kW) operating at 2400 MHz/sec to spall sandstone and slate. Thin spalls began to flake off the sandstone surface after 20 to 120 seconds, and the rock was broken after 3 to 10 minutes. Cracking sounds emanated from these rocks prior to the appearance of fractures in the rocks. In some tests, spalls were explosively thrown off the rock surface.

Of the thermal spalling techniques, jet piercing appears most promising for forming deep holes since it has seen commercial use in the mining industry. Each of the first two spalling methods discussed above appears to be somewhat restricted by the need for injecting explosive and corrosive materials deep within a long shaft. The other spalling methods discussed suffer from the lack of testing in "hole like" geometries and from physical restrictions which appear to make focusing for "hole like" cases difficult.

<u>Chemical Drills</u>. Chemical drills use highly reactive chemicals such as fluorine to drill rock at high rates. These drills have successfully drilled sandstone, limestone, and granite in laboratory tests. They have limited potential because of the difficulty in handling large quantities of highly reactive chemicals and because of the high cost of these chemicals.

<u>Novel Mechanical Drills</u>. Novel mechanical drills are those which remove rock by mechanically induced stresses. Energy sources for these drills are not necessarily mechanical since explosive, erosion, and spark drills fall in this classification. These drills induce mechanical stresses in the rock by impact, erosion, and abrasion. When these stresses exceed the tensile or shear strength of the rock, the rock fails in a brittle or plastic manner.

An explosive drill which shows promise of providing a method to drill either very deep holes and/or drill into hot environments has been developed and extensively tested by the Russians.(99) This drill pumps explosive capsules within a drilling mud slurry to the hole bottom. Each capsule is finned and contains two nonexplosive liquids separated by an impermeable membrane. As the capsule passes through a constriction near the bottom of the drill pipe, the membrane is broken, and the liquids mix to form an explosive mixture. Near the hole bottom, the fins actuate a percussion pin which strikes a detonator that initiates the explosion. The chips and rubble are carried out of the hole by the drilling mud.

In numerous Soviet field tests, explosive drills have drilled over 3000 meters of 25- to 40-centimeter-diameter holes in oil wells ranging in depth to 4000 meters. Drilling rates of 2.5 to 11 meters per hour have been achieved in limestone and dolomite in these tests. The explosive drills have drilled hard rocks such as hard quartzite or chert at higher overall drilling rates than rotary drills. Rates of 15 meters per hour have been obtained.

Waste disposal concepts consider areas of high rock strength which pose problems using conventional drilling methods. Rock strength has less effect on explosive drilling rates than on rotary-drilling rates. Holes have been drilled in granite and concrete at equal rates using explosive drills even though the granite was seven times stronger. Work on optimization of explosion rate is also reported.

The turbine drill(100) has been extensively tested in oil wells. A single-stage turbine is used to rotate a diamond-faced cutter wheel at speeds of 5,000 to 10,000 rpm. The drill pipe is rotated at 30 to 75 rpm, producing a hemispherical hole bottom. Part of the thrust applied to this drill is transmitted to the spring-loaded cutter wheel, and part is transmitted to the rock through diamond reamers at the bottom of the drill. Several turbine drills were field tested from 1953 to 1956. One serious limitation of this turbine drill is that single-stage turbines are inherently inefficient, and only 10 to 20 percent of the hydraulic power is transmitted to the cutter wheel as mechanical power. Work is currently inactive on this drill, and no commercial tools are available. The method has potential for deep hole application since the drill does not require a rotating shaft at the surface.

Carter Oil Company(101) developed a pellet drill. This drill breaks rock by impacting it with steel pellets which are recirculated through the bit. Following impact, the pellets are lifted by the rising fluid to an opening near the top of the drill where they reenter the bit. "Gauge-feeler" feet at the bottom of the drill maintain proper standoff distance between the bit and the rock. This bit is rotated to expose the rock under these feet. A 23-centimeter-diameter pellet drill penetrated hard quartzite at 15 centimeters per hour, limestone at 1.2 meters per hour, and marble at 2.3 meters per hour. Pellet wear was noticeable only in quartzite, where a 200-kilogram charge lost 5.5 kilograms of steel during a 3.5-hour drilling test. In tests, pellet drills demonstrated they can drill even the hardest rocks; but the drilling rates were low due to low power output.

Howe(102) has proposed the continuous penetrator. A high thrust would continuously push the penetrator through the rock, crushing the rock ahead of it and pushing it aside. Since no bit is used, it would eliminate pulling drill pipe to change worn bits. It would also eliminate the need for circulating mud to remove cuttings from the well. The thrust would be applied by drill collars, by impact loads, or by wall anchors that grip the borehole walls and hydraulically load the penetrator. Data from impact tests indicate that thrusts of 25 to 140 metric tons would be required to push a 20-centimeter-diameter penetrator through an average-strength sedimentary rock. The high thrust makes the continuous penetrator impractical except for drilling very weak rocks.

Ostrovskii(99) has proposed using implosions to drill. These drills would produce implosions by pumping hermetically sealed capsules to the holes bottom and breaking them against the rock. The high hydrostatic pressure existing in oil wells would produce intense implosions. Thus far, the concept has been untested.

Ultrasonic drills(103) are used commercially for drilling hard materials such as diamonds and ceramics and can be used to drill rock. These drills use magnetrostrictive or electrostrictive cores to vibrate emitters at frequencies of 20 to 30 kHz/sec. These ultrasonic vibrators are only 40 to 50 percent efficient, so it is necessary to circulate water to remove the excess heat. Ultrasonic drills remove rock by cavitation and abrasion. Energy transmitted to the water by the vibrating emitter forms "cavities," or bubbles, in the water; the cavities impact and crush the rock.

Spark, or electrohydraulic drills(104) use high-energy sparks to break and remove rock from the hole. Sparks, which last from 1 to 50 microseconds, are produced by high-voltage capacitors charged to 30 to 70 kilovolts. The capacitors are fired from 1 to 10 times per second, producing pressure pulses in excess of 6900 atmospheres. Spark drills can produce higher power outputs than rotary drills. For example, a 4-microfarad condenser (70 kilovolt) firing 10 sparks per second produces a power output of 100 kilowatts. This is much higher than the 15 to 400 kilowatts which oil-field rotary drills using roller or drag bits can transmit to rock. Yutkin(104) developed the radial spark drill. This drill fires sparks from a rotating center electrode to stationary electrodes located around the periphery of the drill. Drilling rates in 4-to 5-centimeter-diameter holes equaled 18 centimeters per hour in diabase, 60 centimeters per hour in marble and 300 centimeters per hour in shale. This drill fired two sparks per second (25 to 30 kilovolts, 0.1 to 0.2 microfarad), producing a power output of 90 to 130 watts.

Erosion drills using high-pressure water jets can drill hard rocks at high rates, provided a threshold pressure drop is exceeded across the nozzles. This threshold pressure, which is a function of rock strength and hydrostatic pressure in the well bore, ranges from less than 140 atmospheres for weak materials such as coal to over 1400 atmospheres for hard rocks such as granite or basalt.

Zelenin used a four-nozzle erosion drill (990 atmospheres) to drill an 8-centimeter-diameter hole in granite at 9.1 meters per hour. Zelenin also traversed blocks of rock with water jets (990 atmospheres) at a speed of 0.9 meters per hour, cutting slots 3 to 5 millimeters wide and ranging in depth from 1.8 centimeter in granite to 16 centimeters in limestone.

4.0.5.2 Cavity Forming

Cavities or tunnels can be formed by four basic methods: 1) conventional face drilling, blasting, and mucking (rubble removal); 2) horizontal rotary drilling with a tunnel boring machine; 3) blasting with high-yield explosives; and 4) solution mining in suitable rock. Each has different requirements for access and different ranges of applicability.

In conventional mining, small holes (up to several centimeters in diameter) are drilled several meters into the face to be removed. Explosive charges are placed in the holes and detonated. The rubble is then loaded onto conveyors or into mining cars and transported to the surface. This technique requires manned access, and therefore the necessary life support systems must be provided. This includes ventilation, lighting, and service facilities. Temperature control facilities would probably be required at depths over 1,500 meters, although manned operations exist without temperature control at depths to 3,000 meters.

The size of the access from the earth's surface frequently depends upon the amount of cavity forming or tunneling to be done. For removal of large amounts of material a large access is needed to allow the use of large equipment having high material removal rates. Cavities of 56,000 cubic meters have been mined through a 110-centimeter cased drill shaft.(105)

Horizontal rotary drilling has been used mostly for near surface tunnel boring; however its use in deep cavity formation is feasible. The principal feature limiting its use at this time is the significant size of the machines. A large access shaft is needed to introduce pieces of the machine into the mine for in-mine assembly. Once the equipment is in place, the cavity is formed by rotating the large drilling bit, continuously loading rubble onto mine cars or conveyors, and removing it with a lift at the mine shaft. For certain rock types, this technique may be used to form cavities more economically than use of more conventional mining tecniques. Tunnels up to at least 7 meters in diameter have been made using horizontal rotary drilling.(105) This technique also requires manned access and is subject to the resultant need for the life support system previously discussed.

Blasting with sufficiently high-yield explosives to irreversibly compact and lift overburden may also be used to form a cavity. One advantage of this type cavity is that it can be made at the bottom of drill holes too small and too deep for manned access. In most materials the resultant cavity is full of rubble and has a 30 to 50 percent void fraction. The explosives may be either conventional chemical explosives or plowshare explosives.

Chemical explosives are not normally used for this type of cavity forming because the volume needed for placement of the explosives is 20 to 50 percent of that ultimately desired.(106) Stepping up to the desired volume by a series of progressively larger explosions is a possibility, but may not be practical.

Plowshare explosives avoid the problem of placement volume. However, they may introduce problems of possible radiation leakage during the forming stage. The smallest size, probably about 5 kilotons of equivalent TNT, is also quite large for a pilot plant test, and the nonlinearity in cost per explosion size favors larger sizes. Note, however, that the needed explosions are all very small on the plowshare scale and the depths are all very deep in relation to that required to minimize surface motion and damage. In general, a ton of explosives will produce a cubic meter of volume in the range of 5 to 30 kilotons. The cavity height is usually about 4 times the cavity diameter. Cracking is extensive out to at least this same distance. Surface motion may require the cavity be formed before the surface facilities are built.

Solution mining is applicable for rocks which can be conveniently dissolved. Water is a suitable solvent for rocks such as salt and sylvite. Dilute acid may also be used for rock such as limestone, dolomite, gypsum, and anhydrite. This technique can be quite economical, providing the cavity formed is a satisfactory geometry. Conventional experience has been almost totally confined to dissolving salt by water apparently because the use of solvents other than water is generally uneconomical.

Potential problem areas include control of cavity shape during production and detailed information about the interior and walls of the cavities produced. Apparently no cavity has ever been entered primarily because the production and access have been through small holes and the desire for inspection has been low. Cavity shape is claimed to be controlled if the rock formation is homogeneous and uniform in composition. The concentrated working solution also must be disposed of, which can be a major problem for concepts requiring large volumes. Experience has shown that the cavities are sealed to the usual measuring levels of commercial interest, generally 1 to 5 percent of the inventory. Careful testing would be necessary to prove tightness to better than 1 percent. Two 400-million-cubic meter cavities have been made in salt.(105)

The extent of cavity lining required depends upon the use of the cavity and the type of material in which it is formed. The extent and form of internal support depends upon the material used, the depth of the cavity, and the time it must be kept open. Three types of support are available: 1) natural material can be left behind in the form of pillars or the cavity itself can be a series of tunnels, 2) the cavity can be open with manmade beams and poles (special forms for this are called "sets") inserted for support of the roof, or 3) the roof can be made self-supporting by systems such as that using rock bolts[a] and fencing or other lining materials. The type of cavity lining possible is influenced by the need for, extent of, and type of support. Conversely the type of lining utilized may well dictate the supporting system. A multilayer totally sealed lining is mechanically done best in the shape of a sphere or a cylinder with elliptical ends. Thus a support system such as rock bolts must be provided external to the tank, and/or a manmade support sytem must be placed within the tank.

Cavity lining can be in the form of a tank as mentioned above or can be sprayed on layers of concrete and other materials. The interior may then be covered with a steel or plastic lining, if needed. For tunnels, liner plates may be inserted.

In summary, cavities or tunnels that meet requirements identified for the geologic concepts evaluated can be constructed given an adequate engineering design and adequate materials considerations. The formation of stable tunnels and mines has been demonstrated in materials from salt and coal to hard rocks like granite at depths from the surface down to 3,000 meters.(79) Solution-mined cavities of large size have been formed in soluble materials.

In all cases, however, the mining and cavity forming experience is based upon short time periods compared to storage/disposal times required by the concepts employing disposal of waste in manmade structures within a geologic formation. If the tunnel or cavity must stay open for greater than about 100 years, engineering beyond present practice is required.

4.0.5.3 Borehole Sealing

Placement of solidified waste canisters in geologic formations, whether placed individually into boreholes or placed as a group in a rock cavity, will result in a penetration of the geologic environment with potential for contact with man's environment. In order to assure the containment of nuclear waste by the geologic environment, these penetrations must be completely sealed in a manner that will afford the same level of integrity as the geologic environment prior to drilling the borehole.

The only positive method to neutralize the boreholes or entrances is to restore the stratum to essentially its original strength, permeability and compatible chemical characteristics. This basis suggests that the complete plugging of the penetrations (boreholes) throughout their entire length should be considered.

Setting reliable plugs in the boreholes is difficult. General experience in plugging gas and oil wells with various cements and clays to seal off water formations and to fix well casings in place indicates that these plugs may be reliable from only a few years (about 10) up to about 100 years, which is as long as industry has been interested. With proper

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[a] Long bolts are inserted and cemented into holes in the ceiling and walls to provide support of the cavity surface.

care during installation the seals may be suitable for longer periods of time. Therefore, with today's plugging technology little confidence can be placed in these plugs for more than 100 years. A problem that has been encountered during borehole plugging is the failure of the cement to completely set when plugging is not carried out properly.

Phillips Petroleum Company successfully plugged a 7,700-meter well, which in 1959 was the world's deepest well. The bottomhole temperature was 157°C.(107)

A good knowledge of the borehole conditions is required for plugging operations. This includes well temperature and drilling mud characteristics. The temperature effects will control the chemical reaction and the resulting characteristics of the cement. Cement slurries are subjected to progressively higher temperatures from mixing to pumping into the hole and final cement curing. The cements must be able to withstand the temperature encountered during pumping and the static temperature after the hole is filled. These temperatures will affect the ultimate cure of the cement.

The quality of the plug is also influenced by the nature of the mud used in the drilling operation. This mud lines the walls of the formation and will likely weaken the bonding strength of the cement to the formation. Therefore, it is essential to achieve maximum removal of all the circulatable mud before plugging begins. This cleanout will help produce a stronger bond between the cement and the rock formations. Example methods to reduce the mud problem include thinning the mud with water, jet blasting cement against the wall, preflushing with water before cementing, using cements not affected by the mud, and use of excess cement for the scouring action of the cement itself.

The plugging techniques used for sealing oil and gas wells are generally specified by the state regulatory bodies who must approve placement of the plugs. The normal practice of plugging is to place a minimum-cost plug that will be acceptable to the state regulatory body. Usually the placement of rotary mud between Portland cement plugs is required, and, as such, mud becomes volumetrically the most important plugging material. Mud helps inhibit or prevent movement of water from one porous zone into another porous zone of lower pressure. Probably the most important common conventional plugging material is therefore mud.

There are two broad classifications of hole plugging: 1) plugging of holes immediately upon completion of the hole while the drilling tools are still on location and 2) the reentry and plugging or replugging of old boreholes. The industry-accepted practice for plugging new boreholes involves cleaning out the hole and pumping a cement slurry down the well. Generally an inner casing, commonly the drill pipe, is used for filling the borehole with cement. As the cement is placed in the hole, the inner casing or drill pipe is removed as cementing proceeds, since in time the casing may corrode away, allowing a path to man's environment. It is still common in the oil industry to leave all or part of the casing in the hole. Most states require that casings opposite fresh water zones be left in place when the borehole is plugged. Also, removal of casings is very expensive. Laboratory tests have shown that bonding of cement to a rock formation for a seal is considerably improved when cements are used which expand when they cure.(108) The permeability and pressures of expanding cements are generally equivalent to standard Portland cements. The threshold pressures for expanding cements are generally greater than 68 atmospheres.

Expansion of the cement can be increased by addition of expansive aids such as sodium sulfate, sodium chloride, pozzolan (a naturally occurring siliceous or siliceous and aluminous material) or combinations of these to basic Portland cement.

Laboratory tests have been conducted on several selected cements and clay-sand mixtures to plug boreholes in salt formations.(109) During initial tests two types of expanding cements were used, including Type S expanding cement from the Ideal Portland Cement Company and Type III Stress-Ex cement from Portland, Colorado. Standard Portland cement (Type I) was used for comparison.

Clay-sand mixtures have been tested for water permeability.(109) Clays expand as water is absorbed, thereby reducing permeability. Clays also have much lower solubilities than certain original hole materials such as limestone, gypsum, etc. Preliminary results of these tests, including those for cements, are shown in Table 4.17.

The data show that both Type S and Type III have lower water penetration rates than the standard Portland cement. Type III Stress-Ex appeared to be extremely impermeable, since in three out of four tests no water

TABLE 4.17. Water Penetration through Cement and Clay-Sand Plugs at Pressure of 6.8 Atmospheres(110)

Plug Type	Curing (days)	Flow Rate ml/min	Area cm^2	Penetration Rate mm/min
Type I Portland	5	0.256	7.54	0.34
	7	0.035	7.54	0.05
	19	0.006	7.54	0.008
Type III	5	No flow for 24 hrs	---	---
Type S Expanding	5	0.032	7.79	0.04
	7	0.027	7.79	0.03
Cement	19	<0.001	7.79	<0.001
Stress-Ex	7	0.02	---	---
10% Clay-Sand	--	---	5.06	0.0036
	--	0.00015	5.06	0.0003

flowed through the plug after 24 hours and at pressure of 6.8 atmospheres.

The results also indicate that clay-sand plugs may be useful in borehole plugging operations. The penetration rate for the clay-sand mixture, about two orders of magnitude better than Portland cement, is still somewhat higher than the penetration rate for the best expanding cements cured under similar conditions.

More recent laboratory tests have been initiated on Portland cements and specialty sealants. The results of these tests are presented in Table 4.18. Except for El Toro H and Tijeras C, which were dropped from consideration due to problems encountered in compressive strength and permeability tests, the remaining cements are considered to have reasonable strengths, permeabilities, and sulfate resistance.

Initial tests on specialty sealants indicate that their usefulness may be limited. These sealants and their properties are shown in Table 4.19. Nukem 200, a sodium silicate-silica flour sealant, is not suitable due to high shrinkage. Basolit 600, a sulfate sealant, suffers from two disadvantages: 1) it requires heating to 120°C to be poured, and 2) the linear shrinkage is greater than 1 percent when the set material cools from 90°C tp 30°C, which would prevent good bonding. A polyester sealant set with a peroxide catalyst

TABLE 4.18. Portland Cement Characteristics(110)

Type Cement[a]	Brand	Wt% of Cement Water	Wt% of Cement Salt	Compressive Strength (psi)[b] 1 day	Compressive Strength (psi)[b] 3 days	Permeability millidarcy x 10^{-3}	Salt Bond kg/cm^2	Linear Expansion (%) 1 day
T-2	El Toro 2	46	19	677	1637	<1.0	17.4	
			101	172	2700	<1.0		
Cl-C	El Toro 35	56	19	1287	2637	<1.0	20.2	
			113	245	2856	<1.0		
T-5	El Toro 5	46	19	830	1662	1.0	18.3	
			103	165	2850	2.3		
T-K	El Toro Chem Comp	56	19	962	2156	<1.0	18.8	
			125	130	2500	<1.0		
Cl-H	El Toro H	46	19	6	3187	3.4		
			97	48	3275	1.8		
Cl-C	Tijeras C	56	19	1248	6125	5.2		
			121	17	7062	<1.0		
T-5	Tijeras 5	46	19	283	4712	<1.0		+0.03
			121	266	5125	2.7		+0.07
T-K	TX1 Chem Comp	56	19	505	3750	1.1		+0.29
			121	655	4275	0.2 (1 day)		+0.33

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a. T refers to type cement according to ASTM; Cl refers to class according to API; T-K refers to type K expanding as referred to by ACl.

TABLE 4.19. Specialty Hole Sealant Characteristics(110)

Sealant	% Liquid	% Salt	Temp (°F)(a)	Compressive Strength kg/cm² 1 day	3 days	Permeability millidarcy x 10^{-3}	Linear Expansion (%) 1 day
Nukem 200	50	0	80	21.4	125	7 to 32	-1.75
	40	0	80	85.4	172	4	-1.35
	33	(Not pourable					
	40	Salt - Instant gel)					
Basolit 600	Heat	0	250	485	534	--	-1.1
		68	250	288	--	0.03	-1.0
Epoxy	100	0	80	Soft	439	1.0	-0.09
		70	80	Soft	364	0.01 (3 day)	+0.01
Phenol formaldehyde	90	0	80	Soft	218	0.1	--
		70	80	Soft	209	0.1	--
Polyester	--	0	80	868	--	--	--
	--	69	80	434	788	0.1	
Polyacrylamide	60	0	80	Not tested		0.1	--
		64	80	Not tested		0.1 (3 day)	--

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a. °C = (°F-32)/1.8

b. 1 psi = 0.07 kg/cm²

proved to be difficult to handle under field conditions and was removed from further consideration. The phenolformaldehyde resin sets by a condensation process which releases water and results in some shrinkage.

Epoxy sealant using an amine catalyst and Dowell Seal Ring are still undergoing tests.(110) The epoxy shows no apparent shrinkage on setting, excellent adhesion to surfaces, and good strength with no water permeability. The Seal Ring (a 35 percent crosslinked polyacrylamide in glycol) is a rubberlike material, so the usual compressive strength and linear expansion tests were not run. Water permeability tests indicate that the material is essentially nonpermeable. The material resists water encroachment pressures of several thousand psi (several hundred atmospheres). Both of these sealants seem quite promising but long-term durability is the major question.(110)

The 150°C maximum temperature to be expected at depths up to 4,600 meters has little effect on the strength of cement. The effect of temperature due to geothermal gradients is relatively small for depths up to 9,000 meters. The compressive strengths of cements range from about 2,100 to 3,500 kg/cm² when under a confining pressure of 970 atmospheres.(111) These are comparable to the strengths of sedimentary rocks under similar conditions. Thus the strengths of plugging cements under downhole pressure-temperature conditions are at least as good as those of sedimentary rock generally found in surrounding formations. The ultimate compressive strengths of rocks rise with increasing depth.

Dowell Company of Tulsa, Oklahoma, under contract to ORNL, has provided an in-depth investigation pertaining to the evaluation of materials and technologies for borehole plugging. A literature search and demonstration of borehole sealing techniques has been emphasized. Information on sealing of boreholes in salt, gypsum and anhydrite was reviewed. Laboratory tests including compressive strength, permeability, expansion sulfate resistance, and shear bond strength have been made on several cements. Tentative results show that the use of sulfate-resistant Portland cement as the primary sealant and epoxy cement in critical areas should provide a good sealant in salt formations. No published information is yet available on this work.

The cost of plugging or replugging old boreholes by conventional techniques is estimated to be on the same order of magnitude as the drilling cost, which ranges from \$10,000 for a depth of up to 1,500 meters to greater than \$100,000 per hole for depths up to 6,100 meters. These costs are high because of the problems of locating the old hole, the hazards of re-entry, the possibility of drilling out the old hole and the unknowns about the condition of the hole. The cost of plugging some gas wells was recently reported to be in the range of about \$8,000 to \$14,000 for a well about 600 meters deep.(112,113) Routine plugging to state specifications of newly drilled oil test holes with the drilling tools still on location can probably be done for less than one-tenth the cost of drilling the hole.(114)

Borehole plugging must be critically evaluated before the relative merits of the various possible methods of geologic disposal can be realized. Borehole plugging may be the limiting factor for a disposal concept. Geologic disposal of high-level radioactive waste implies containment for time periods up to one million years; hence, borehole seals must be maintained for the same time frame. Clay minerals are among the best plugging materials for preventing fluid flow into otherwise permeable rocks while remaining stable in the upper earth's crust for long periods of time. Portland cement, presently the second most commonly used material, in some cases remained in excellent condition for time periods of at least 2000 years.

4.0.6 Heat Removal Relative to Waste Disposal

Heat transfer analysis of buried radioactive waste is required to determine the amount of external cooling needed to maintain design structural temperatures or, if no cooling is provided, to determine the limit on the heat that can be conducted into the surrounding geologic formation or the amount of melting that will occur around the repository. Determination of the thermal stresses in the surrounding rock and the heat load on the surface environment also requires information obtained from the heat transfer analysis.

4.0.6.1 The Nature of the Heat Transfer Problem

If a concentrated radioactive heat source is placed in a fluid cooling medium such as flowing air or water, it will typically reach a steady-state temperature within a few hours with its center far below its melting point. As time passes, the center temperature will decrease as the rate of heat generation decreases.

In disposal of radioactive waste in geologic formation, when an active means such as forced air convection, natural air convection, or forced and natural convection water cooling is present to remove heat from the waste to a heat sink such as the atmosphere, a lake or a river, the temperature of the waste soon reaches a steady-state value below its melting point. When these means are not present or are interrupted, conduction through the surrounding rock or soil itself is the only means to remove heat. The heat must be transferred into the geologic formation, where it is stored and dissipated. Terrestrial materials in general are poor heat conductors and act to some extent as insulators.

The time-temperature relationship of a radioactive heat source perfectly insulated from its surroundings is a function of the rate of radioactive heating per unit volume of source, the thermal properties of the source, and the rate of decay of the radionuclide involved. For example, assuming a highly radioactive source such as pure strontium-90 fluoride, the temperature will increase in an approximately linear fashion, reaching the melting point in a few minutes. The source will remain at the melting point for a few hours, rise in temperature to the boiling point in a few more hours, and eventually increase in internal pressure until it explodes. On the other hand, if the source is diluted manyfold with non-heat-generating material (such as the case with bulk waste), the temperature of the source may rise only a few degrees, first linearly with time and then more slowly at times approaching the 30-year half-life of strontium-90. Eventually after many half-lives, the temperature will remain constant as nearly all of the strontium-90 is converted to stable zirconium-90. Of course, in an imperfect insulator such as a geologic formation, the temperature will rise until the rate of heat generation equals the rate of heat dissipation and then will decrease as the source decays.

In geological formations such as shale, basalt, granite or salt, the magnitude and time of occurrence of the maximum temperature of the source are highly dependent upon the source geometry. Heat transfer analysis in underground disposal or storage of radioactive waste is primarily concerned with estimation of transient conductive heat transfer associated with exponentially decaying heat sources to determine the maximum source temperature and the temperature of the surrounding formation as a function of source geometry and the thermal properties of the geologic formation.

The geometries used to develop the results presented here are the point source, the spherical shell source, the long line source, and the finite array of short line sources. Analytical solutions for each geometry source, assuming an infinite geologic formation with constant thermal properties, were developed to provide rapid design data for concept evaluation. The effect of mixtures of radionuclides with differing half-lives and the effect of nearness to the earth's surface are also included by using the method of superposition.

Each geometry has a special use. The spherical shell source can be applied to a mined cavity with a cubical, short cylindrical or spherical geometry. It has been modified to include extended filling time periods and melting of the surrounding rock to enlarge the cavity. The point source is useful in estimating temperatures at appreciable distances from a source. A cavity tends to become spherical as it melts and the temperature field becomes spherical around any finite source as the distance from it increases.

The long line source is applicable to tunnels, as an asymptote for the short line source, and to the initial stages of the deep hole concept. Systems of tunnels have been simulated by superposition. The short line source is directly applicable to the wall of a direct-buried canister itself or to the region immediately surrounding it. The short line is a satisfactory model for the more complex short cylindrical canister because the thermal capacity of the canister is small compared with the surrounding rock and at the time the maximum temperature occurs the resistance to heat flow is dispersed over a large volume without being concentrated near the canister wall. Finite arrays of non-identical canisters or clusters of canisters oriented in various ways with respect to each other and toward grade can be built up by superposition to give the effects of spacing and canister diameter on the local temperatures.

It is time consuming to build up arrays larger than about 50 to 100 canisters by superposition. Another approach, first used by ORNL,(115) is to assume a bounded unit cell around a single buried canister of an array of identical canisters. The analytical solution for this problem is somewhat complex and is often unstable. It is used here only where no other approximation will work.

The plane source and the disc source give the average rock temperature in the plane of distributed heat sources such as arrays of canisters, the allowable heat generation per unit area (e.g., per hectare) of the array, and the heat flux into and temperature gradients in surrounding formations. The disc source has been used to estimate the temperature in hydrofractures with two dimensional spreading of the waste.

Each geometry has its own peculiar limitations. The temperature is infinite at the point source and the line source, but it is finite at the plane, disc, and spherical shell sources. If the heat generation rate is constant without radioactive decay, the regions around the point, spherical shell, short line, and disc reach steady-state temperatures, but the temperatures around the long line and the plane sources increase without limit with time.

The example results presented in the following sections are based on the assumption of homogeneous media with temperature independent properties (specific gravity of 2.5 and a specific heat of 0.2 cal/(g)(°C) are assumed as reasonable average values for geologic formations), a single half-life of 30 years (typical of 10-year-old waste), and heat transfer by conduction only. Within the limits discussed, the calculation techniques used to develop these data can be used in rapid evaluations for most potential geologic disposal concepts. For many specific applications, more exact results may require refinement of these study models.

4.0.6.2 Arrays of Heat Sources

Whether the waste canisters are arranged vertically or horizontally, if they are equally spaced in an infinite array, the gross behavior results in a temperature versus position or distance from the plane of the waste similar to that shown in Figure 4.22. For a power density of 247 kW/hectare (100kW/acre) in a rock medium with a thermal conductivity of

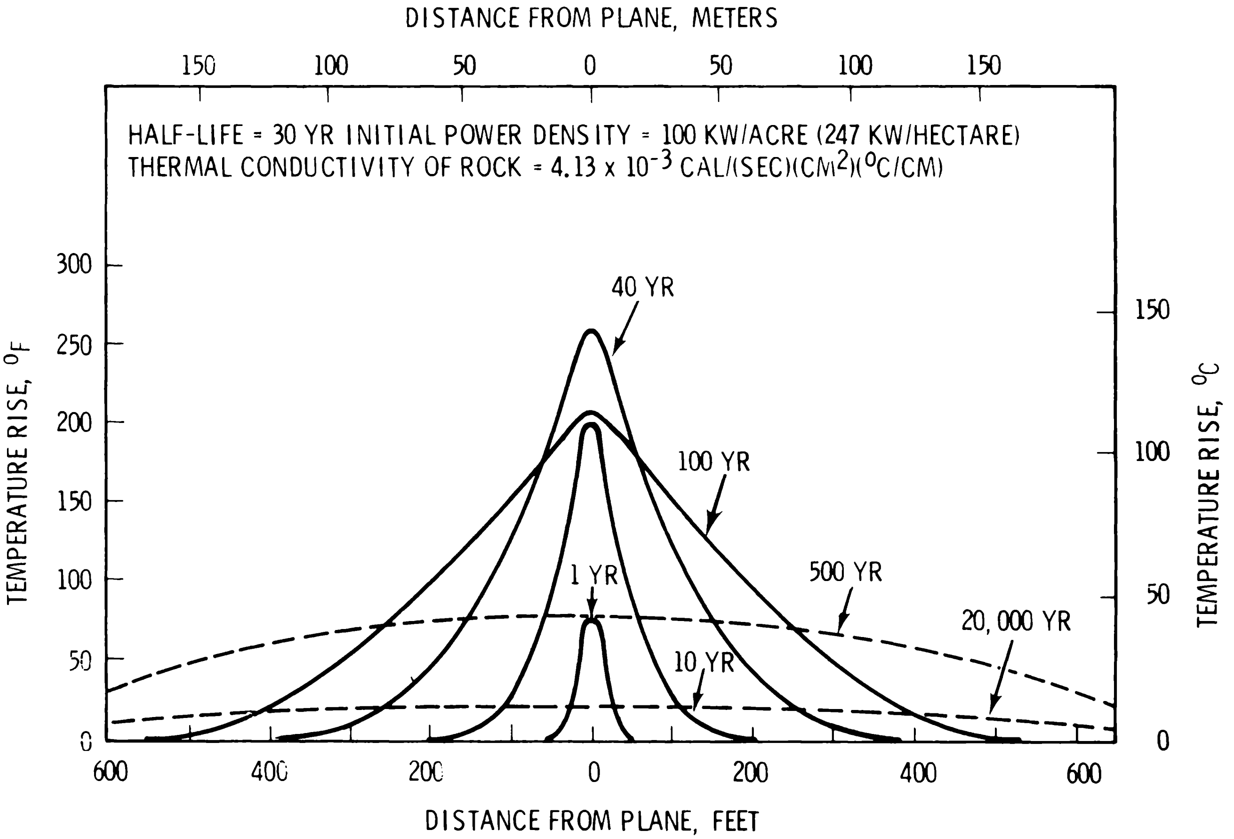

FIGURE 4.22. Transient Temperature Around an Exponentially Decaying Infinite Extent Plane Source

4.13×10^{-3} cal/(sec)(cm^2)(°C/cm), or 1.0 Btu/hr(ft^2)°F/ft, the average temperature rise in the plane of the array reaches a maximum of 144°C in 40 years and decreases thereafter. The effect on the surrounding rock reaches greater and greater distances as the temperature wave expands and subsides. If the array is at a depth of 1525 meters where the average geothermal temperature is 50°C, the maximum average temperature of the array is 194°C.

A comparison of the temperature rise for geologic formations with thermal conductivities varying over a tenfold range is given in Figure 4.23. The temperature rise is greater for lower thermal conductivity rock but does not quite vary inversely with the conductivity. For example, with a power density of 274 kW/hectare, the maximum temperature rises in the plane of the array are 83°C, 144°C, and 262°C for salt [k=1.24×10^{-2} cal/(sec)(cm^2)(°C/cm) or 3 Btu/hr(ft^2)(°F/ft)] crystalline rock [k=4.13×10^{-3}] and loose sand [k=1.24×10^{-3}], respectively. The temperature rise is, however, directly proportional to the heat generation rate so that temperature limits resulting in lower power densities can easily be imposed.

The effect of burial depth is shown in Figure 4.24. Generally, depths less than 60 meters are required to affect the maximum temperature at the plane of burial. For example, shallow burial at a depth of

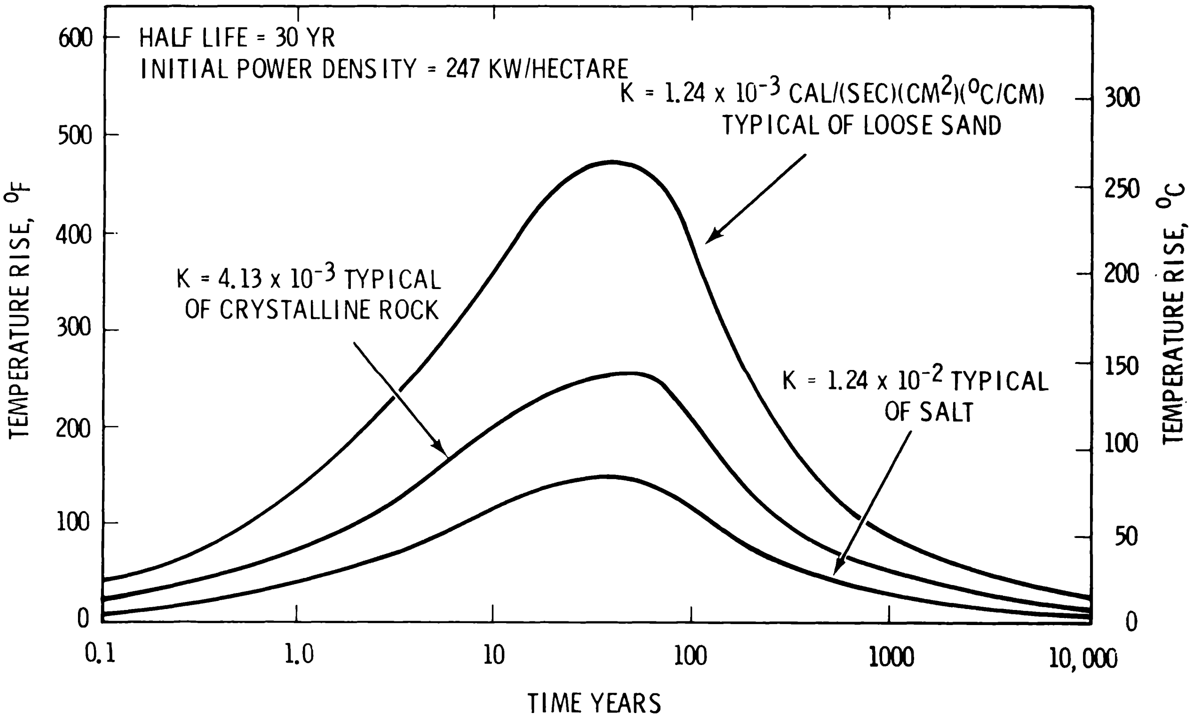

FIGURE 4.23. Transient Temperatures in an Exponentially Decaying Plane Source - Effect of Thermal Conductivity

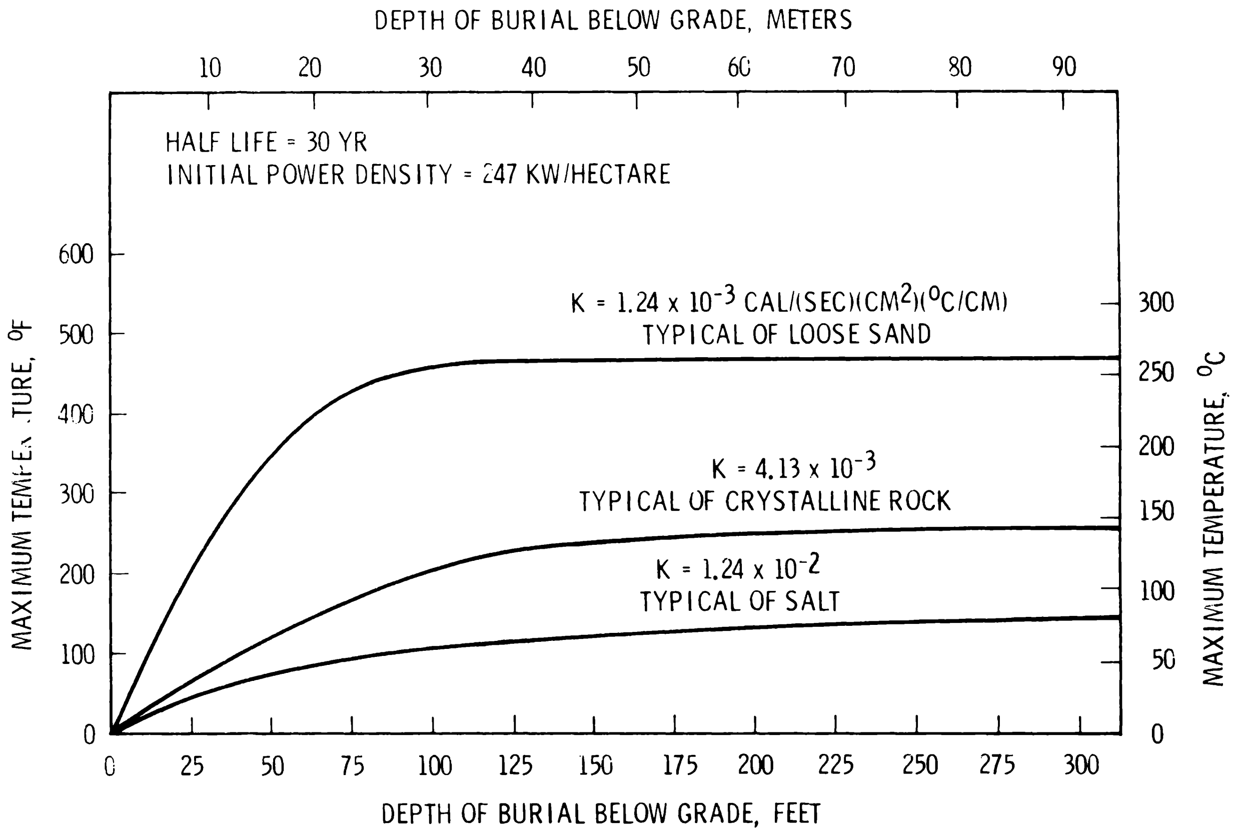

FIGURE 4.24. Effect of Burial Depth on Maximum Temperatures in an Exponentially Decaying Plane Source

30.5 meters reduces the temperature rise from 144°C to 132°C for a plane source in a rock medium with a thermal conductivity of 4.13×10^{-3} cal/(sec)(cm^2)(°C/cm), or 1 Btu/hr (ft^2)(°F/ft). The effect of burial depth is approximately the same for all geometries.

Figure 4.25 shows the effect of the size of the array upon the maximum temperature at its center. If the radius of a disc representing the array gets larger than about 60 meters, there is no effect of size upon the maximum temperature. This size corresponds for example, to a field of 37 vertical cylinders arranged on a triangular pitch with a spacing of 20.4 meters between neighboring cylinders.

Even in an array of buried canisters the highest local temperature in the surrounding rock is at the canister wall. This temperature is the sum of two effects: the local temperature rise, which is a strong function of the canister radius, and the temperature rise due to its neighbors, which is independent of canister radius but strongly dependent on spacing between neighbors. When either the rock temperature or the temperature of the canister structural material is limiting, the wall temperature is often used as the design basis maximum temperature. If

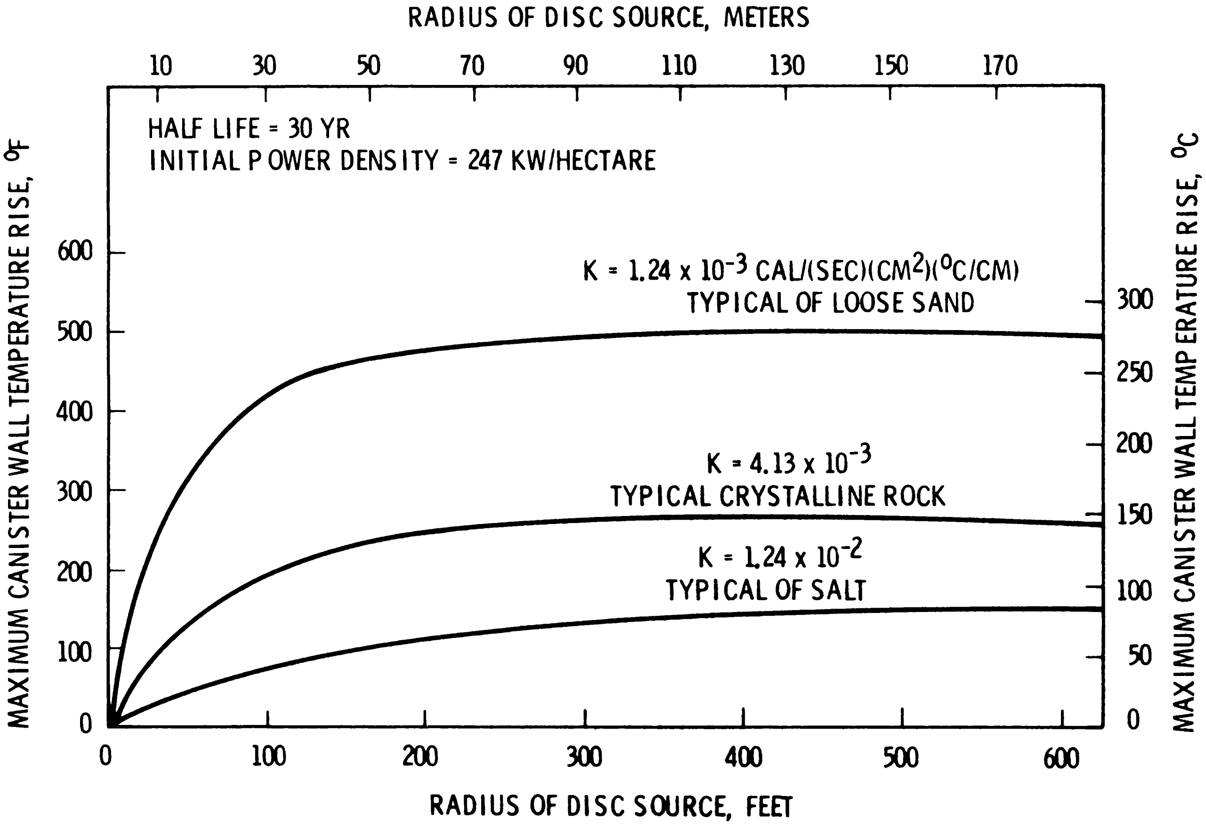

FIGURE 4.25. Effect of Disc Size on Maximum Temperature of an Exponentially Decaying Heat Source

an internal canister condition such as the center-line temperature is limiting, it is sufficient to neglect the internal canister temperature transients and add on a steady-state temperature rise to the canister wall temperature with allowance for slow variation of the heat generation rate with radioactive decay. Nevertheless, additional variables such as waste thermal conductivity and the presence of internal fins, composites or annuli greatly complicate heat transfer considerations in the waste storage/disposal design when canister center-line temperatures are limiting.

The maximum wall temperature in an array of 3-meter-length cylinders as a function of spacing is given in Figure 4.26 with cylinder radius as parameter. The same information is compared with the average rock temperature in the plane on Figure 4.27 as a function of the power density. The local wall temperature is clearly much higher than the average plane temperature. For a 30-centimeter-diameter canister, Figure 4.28 shows the wall temperature versus the power density as a function of the rock thermal conductivity. With low thermal conductivities the temperature at the wall of a single canister with no neighbors is still much above the design limits of the materials of construction.

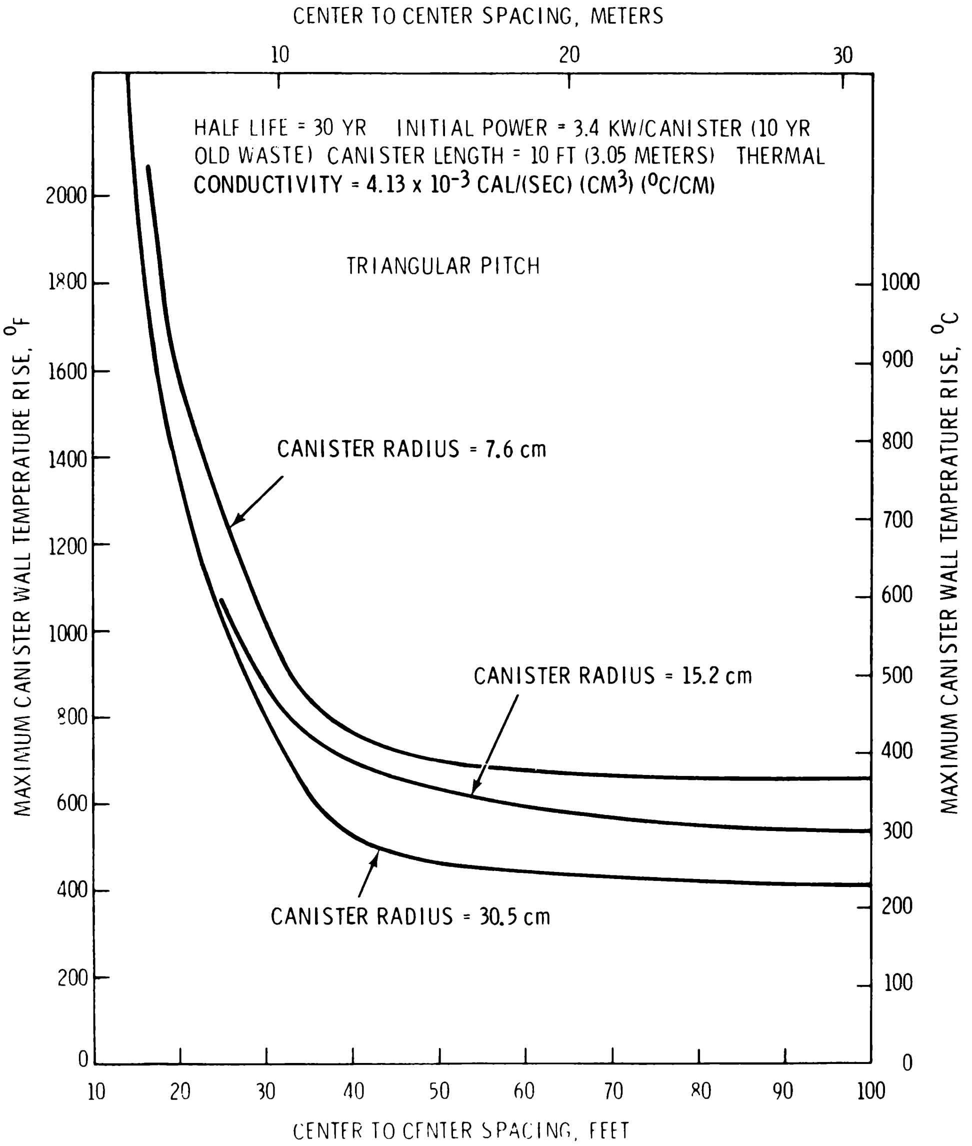

FIGURE 4.26. Effect of Spacing and Canister Radius on Temperature in Arrays of Buried Waste Canisters Containing Exponentially Decaying Heat Sources

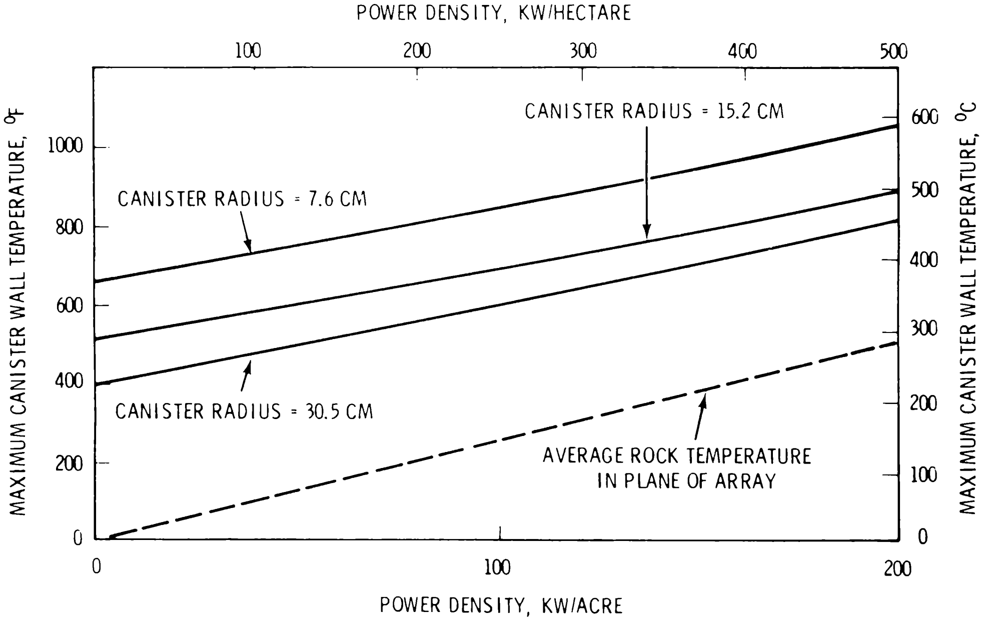

FIGURE 4.27. Effect of Power Density and Canister Radius on Temperature in Arrays of Buried Waste Canisters Containing Exponentially Decaying Heat Source

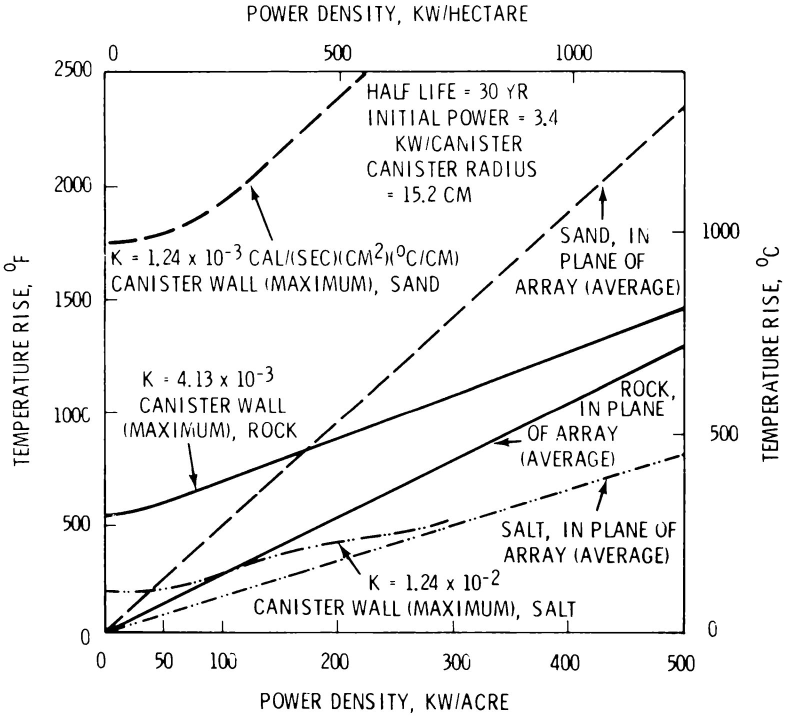

FIGURE 4.28. Effect of Rock Thermal Conductivity and Power Density on Temperature in Arrays of Buried Waste Canisters Containing Exponentially Decaying Heat Sources

The temperature rise in salt is generally less than in most other geologic materials. But the allowable temperature rise may also be much less in salt. Salt temperatures may be limited to below 260°C because of moisture content and plastic flow. Temperatures in some types of dry crystalline rock may be limited only by cracking of the rock due to thermal stress. Allowable temperatures in sand are much higher, but the unconsolidated medium may shift the design limiting factor to the integrity of the canister wall itself, which may be above the crystalline rock temperature limit.

4.0.6.3 Single Heat Sources

The analysis of solitary heat sources is usually associated with intentional melting of the surrounding rock or with analysis of accidents resulting in melting. High temperatures may also be associated with burial of short-cooled waste still containing appreciable quantities of Ru-106, Cs-134, and Ce-144. Figure 4.29 shows the effect of lowering the age of the waste on the temperature of the canister wall. For 10-year-old waste with an initial heat generation rate of 3.4 kW with 86 percent of the power due only to about 30-year half-life radionuclides (Sr-90 and Cs-137), the maximum canister wall temperature rise is 282°C at 1.78 years after burial. The same waste with an age of 5.7 years initially generating 5 kW of which 65 percent is Sr-90 and Cs-137 reaches a maximum wall temperature

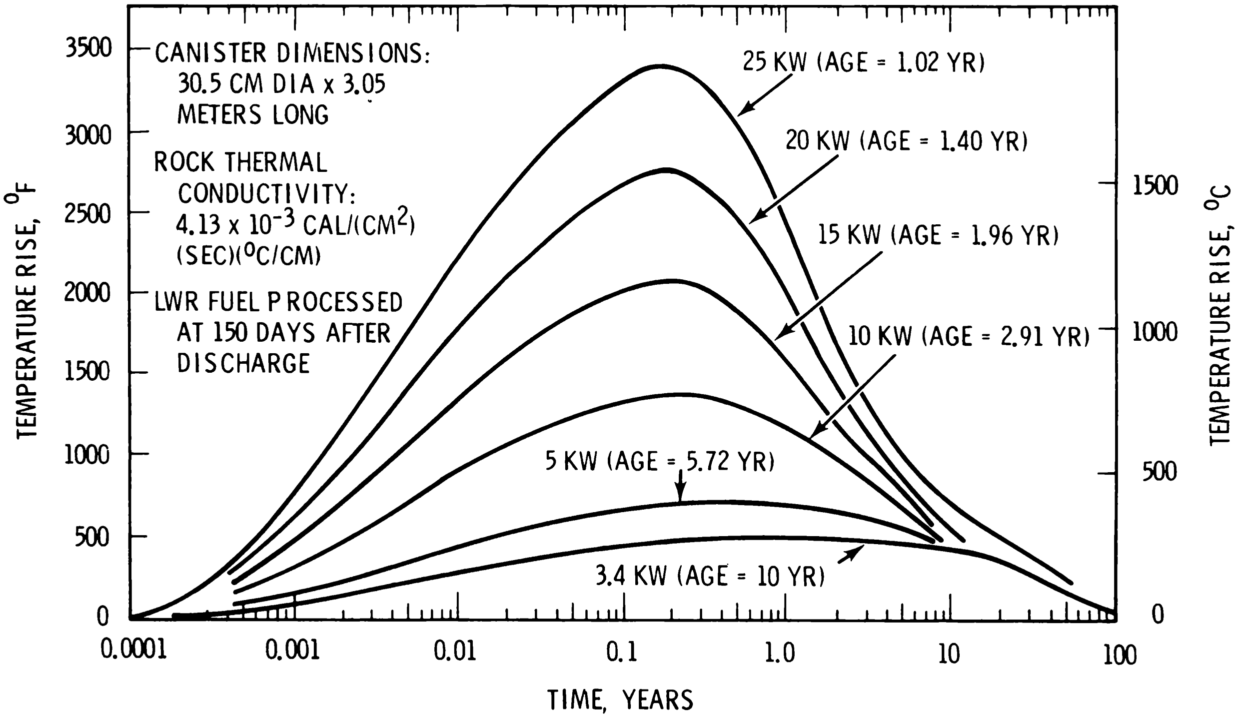

FIGURE 4.29. The Effect of Waste Age on the Maximum Wall Temperature of Single Buried Canisters

rise of 392°C. The same waste with an age of 2.9 years generating 10 kW of which 35 percent is Sr-90 and Cs-137 reaches 742°C, and waste with an age of 1.96 years generating 15kW of which 23 percent is Sr-90 and Cs-137 reaches 1153°C. Thus tripling the heat generation rate by adding short half-life fission products increases the maximum temperature rise by about the same factor.

Lowering the age of the waste or increasing the quantity of heat in the hole results in melting of the surrounding rock, as suggested in one of the deep-hole concepts. As the rock begins to melt, the shape of the pool changes from cylindrical to spherical because temperature is a potential function.

In one mined cavity concept, the aqueous waste is continuously poured into a 10-meter-radius cavity for 25 years and then allowed to heat and melt a pool of rock. Shown in Figure 4.30 are the results of calculations made for spherical pools formed under the conditions given by Lawrence Livermore Laboratory for their nuclear cavity concept.(116) The properties for the three types of geologic formations are given in Table 4.20 along with the calculated mimimum power at 25 years to enlarge the cavity by melting. The maximum size of the molten cavity, occurring

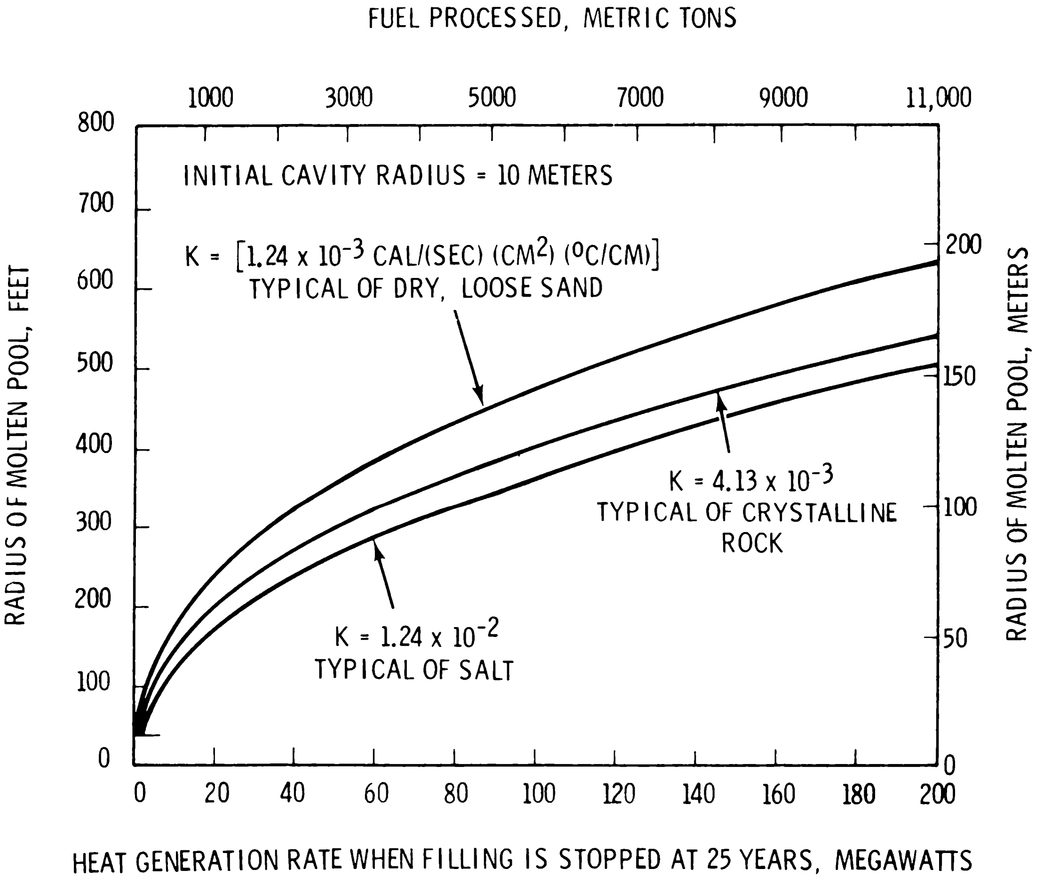

FIGURE 4.30. Size of Molten Pool as a Function of Heat Generation Rate

TABLE 4.20. Properties Used in Molten Pool Calculations

	Thermal Conductivity[a] cal/(sec)(cm^2)(°C/cm)	Melting Point, °C	Heat of Fusion, cal/g	Specific Heat, cal/g/cc	Minimum Power to Enlarge Cavity by Melting, kW
Salt	1.24×10^{-2}	808	116	0.2	1300
Crystalline Rock	4.13×10^{-3}	1100	80	0.2	800
Loose Sand	1.24×10^{-3}	1100	80	0.2	340

a. Arbitrarily selected from within a range of values for each specific material.

at times less than 200 years after filling, is shown as a function of the power at the end of the 25-year filling period. It is apparent that the low thermal conductivity and high heat of fusion of salt is nearly compensated for by the low melting point of salt in lessening the differences in the maximum size of the molten mass for three types of geologic formations.

4.1 DESCRIPTION OF GEOLOGIC DISPOSAL CONCEPTS

Ten concepts for disposal of high-level radioactive waste in geologic formations were considered in this study. The ten concepts are listed with their key operational characteristics in Table 4.21.

In all concepts the final waste form is a solid. Concept 1 is based on the placement of canisters filled with solidified waste in excavations formed by conventional mining techniques. A regular, dispersed storage array is specified to minimize waste-rock reactions. Concepts 3 and 4 are also based on underground cavities, but fluid cooling is used to permit a close-packed storage array while minimizing reactions. In Concept 7 a dispersed storage array is attained from the surface via a matrix of drilled holes.

Concept 2, also a mined cavity concept, is based on fluid cooling for an interim period, but, as indicated in Table 4.21, after a time canister cooling is stopped and the waste permitted to react with the host rock. Waste-rock melting can either be permitted or not permitted for Concept 8, which is based on placing solid waste in a deep drilled hole.

For Concepts 5, 6, and 9 the self-generated heat within the liquid waste is used to dry and melt the waste and some of the surrounding rock which, when cooled, forms a solid waste-rock matrix. In Concept 10, the liquid waste is incorporated within a self-curing cement. Because of the large volumes generated and the potential hazards of shipping aqueous high-level waste, the liquid emplacement concepts require locating the disposal site at

TABLE 4.21. Characteristics of Geologic Disposal Concepts

Concept	Type of Cavity	Waste Form at Time of Emplacement	Fluid Cooling	Waste-Rock Reactions
1	Mined	Solid	No	No
2	Mined	Solid	Water	Melt
3	Mined[a]	Solid	Air[c]	No
4	Mined[a]	Solid	Water[c]	No
5	Mined	Liquid[b]	No	Melt
6	Exploded	Liquid[b]	No	Melt
7	Matrix of Drilled Holes	Solid	No	No
8	Deep Hole	Solid	No	No/Melt[d]
9	Deep Hole	Liquid[b]	No	Melt
10	Hydrofracture	Liquid[b]	No	No

---

a. Includes underground manmade structures.
b. All liquid emplacement concepts involve in-place conversion to a solid form.
c. Cooling is provided for an interim period of tens of years until the heat generation rate has decreased to a point that melting will not occur.
d. This deep hole concept is studied for both melting and non-melting cases.

the fuel reprocessing plant. The solid emplacement concepts involve transportation of the waste, which has been converted to a solid form at the fuel reprocessing plant, cross-country to a separate disposal site.

4.1.1 Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting

One method of placing waste in appropriate geologic formations is the burial of waste packages (canister filled with solidified waste) in excavations formed by conventional mining techniques. The concept for a Federal Repository developed by Oak Ridge National Laboratory (ORNL) is based on the placement of waste canisters in mined voids in bedded salt deposits; Figure 4.31 is similar to the ORNL concept.(116) Salt domes and intrusive igneous, argillaecous, and metamorphic formations are other examples of candidates for disposing of solidified high-level radioactive waste into geologic formations by this method.

Waste canisters are buried in the floor of rooms or tunnels excavated in the geologic formation. Floor area required is determined by the

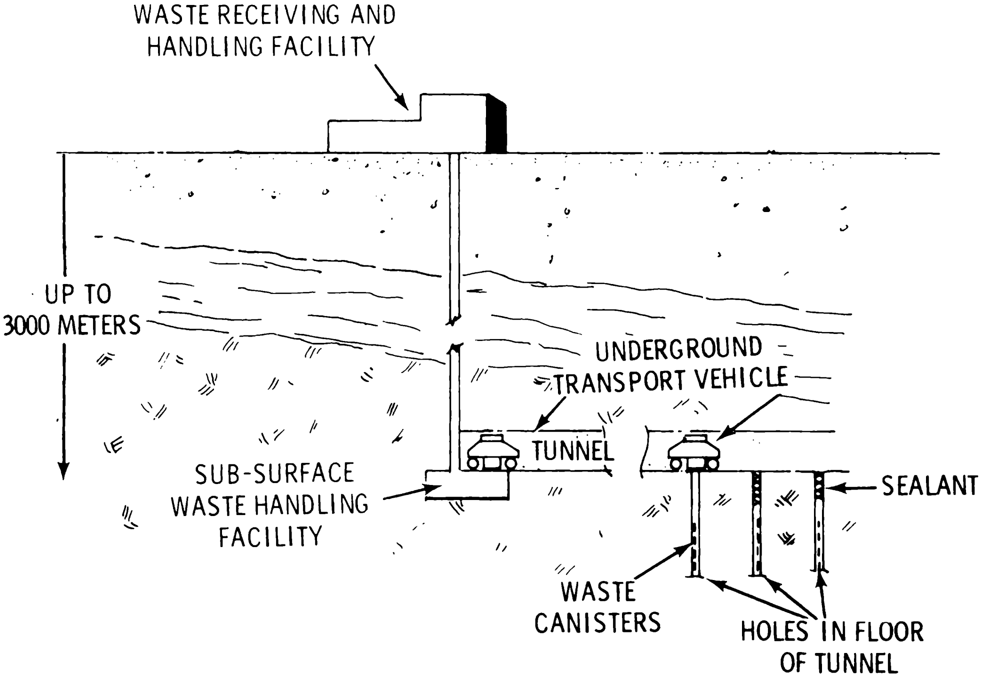

FIGURE 4.31. Solid Waste Emplacement in a Mined Cavity - No Fluid Cooling or Melting

total number of canisters, the number of canisters placed vertically in individual burial holes, the heat generation rate of individual canisters, and the heat dissipation characteristics of the formation. The height and width of rooms and tunnels are determined primarily by the size of subsurface transfer vehicles, overhead requirements needed for the formation of individual burial sites or holes, and rock mechanics. However, typical values would be about 4.5 to 9.0 meters high and 4.5 to 25 meters wide. The need for shoring and linings to prevent tunnel subsidence and convergence would be determined by the rock mechanics of the geologic formation.

The tunnels or rooms would be in a regular array such as shown in Figure 4.32. Prefiltered ventilation air is supplied to the uncontaminated tunnel areas and, by controlling pressures, flows toward the potentially contaminated areas (where waste is contained). Here, the ventilation air is exhausted through a high efficiency filter into a separate ventilation tunnel. The air is then directed to the surface and sent through another bank of high efficiency filters before being routed to a stack that is continuously monitored for radioactivity. The ventilation tunnel and ducts are arranged to assure that air which has passed a potentially contaminated mine area can be isolated from any further contact with personnel.

Other required features such as provisions for mining in one area while disposing of waste in other

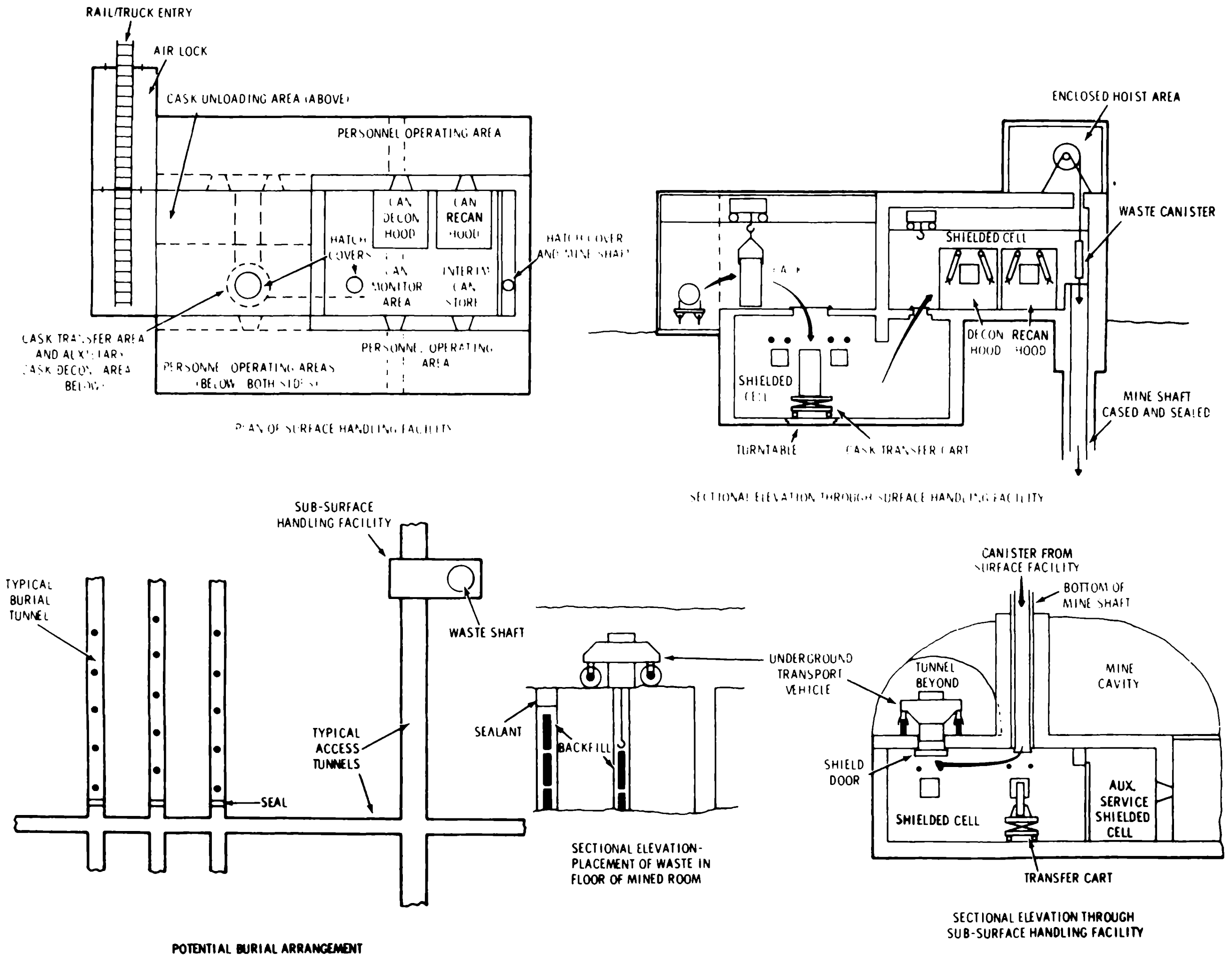

FIGURE 4.32. Overall Facility Needs - Solidified Waste in Mined Cavity

areas, additional shafts and tunnels (e.g., for ventilation, mining, emergency), and auxiliary provisions such as mechanical, electrical, and ventilation equipment, laboratory and office areas, etc., are not shown in Figure 4.32.

It is estimated that about 90 kilometers of burial tunnel, 4.6 meters on a side, would be required to dispose of the 14,700 canisters of high-level waste produced by the reference reprocessing plant. In addition, nearly 11 kilometers of access tunnel will be required.

Overall characteristics of the concept for placing solid waste directly in a mined cavity with minimum interaction between the waste and the formation are summarized in Table 4.22.

4.1.2 Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix

The major features of this concept for disposing of waste in a mined cavity with waste-rock melting are: 1) the waste is in solid form contained in canisters in a large mined

TABLE 4.22. Summary of the Overall Characteristics; Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting

Waste Form	High integrity solid waste form and canister.
Waste Concentration	Moderate; inversely proportional to heat content of waste.
Operational Features	Significant canister handling but relatively straightforward; direct "hands-on" control of each canister.
Candidate Geologic Environment	Might include bedded or domed salt, tuff, intrusive igneous, crystalline metamorphic or possibly shale formations.
Retrievability	Relatively good for 50 to 100 years or until operation shutdown; more difficult with time depending on plasticity of formation, corrosion resistance of canister, and maintenance of repository before final sealing.
Monitorability	Limited; direct monitoring of waste impractical, can monitor gross radioactivity release within each major tunnel during operation; can detect radioactivity in nearby water-bearing formations if it should occur; can monitor temperature increase in shallow observation wells.
Extent of Knowledge	Fair to good; mining techniques and remote handling techniques established; waste-formation interaction evaluated on short-term data when considering geologic times; unknown effects of burial of radioactive heat source on geologic formation.
Isolation	Moderately deep geologic isolation, 300 to 3000 meters or maximum mining depths, depends on geologic formation as the primary containment barrier for geologic times; relatively few manmade penetrations to the surface require sealing.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.

cavity; 2) the canisters are cooled by evaporation of surrounding water while the cavity is being filled; 3) the waste canisters are in a close, randomly stacked array; and 4) the waste is ultimately allowed to melt. The time at which the melting phase starts may be varied. Melting might be postponed for up to 100 years by continuing liquid evaporation cooling of the waste. This concept of solid waste placed in a mined cavity is a variation of that proposed by Clark.(117)

A pictorial description of the concept is shown in Figure 4.33. Waste canisters are removed from shipping casks in the waste receiving facility, lowered through a drill hole into a lined cavity, and deposited on the cavity floor in a random array. Waste within the cavity is immersed in a boiling water bath, and the resultant steam generated is condensed in a surface facility and returned to the cavity for cooling the waste. Operation of the surface cooling system must be continued until the cavity material is permitted to melt and the waste fixed.

In the reference version of this concept, the cavity is doubly lined with high-integrity, corrosion-resistant liners to assure containment of the cooling liquid. The cavity and its tank liner are proposed to be

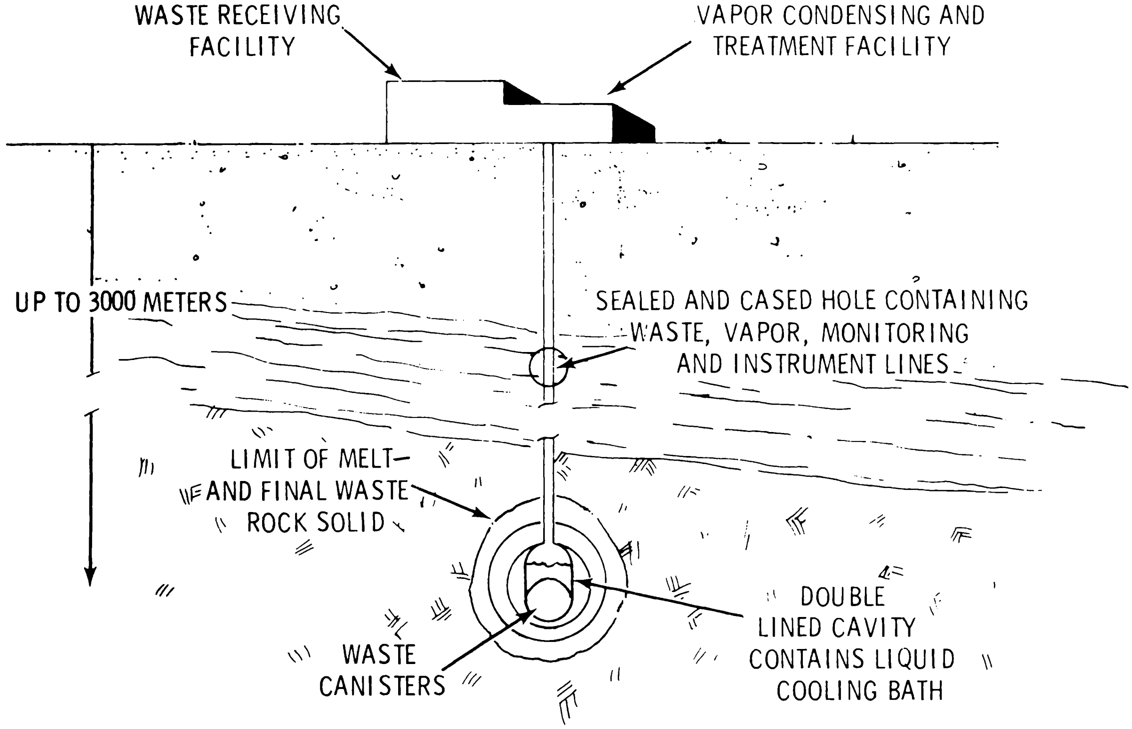

FIGURE 4.33. Solid Waste Emplacement in a Mined Cavity - Interim Liquid Cooling and Waste-Rock Melting

either spherical or cylindrical with near spherical ends to provide for maximum structural strength and minimum surface-to-volume ratio. Depending upon specific circumstances, more than one cavity may be used at a site.

In time all the canisters will fail, exposing the solidified waste directly to the boiling water coolant. If cooling is continued, the water within the cavity will gradually leach the radionuclides from the solid waste form. An increase in the radioactivity of the boiling water will result until, in the limit, the solubility of the radionuclides is reached. At the same time, the radioactivity of the condensate and the noncondensable gases will increase. The noncondensable gases will require processing and handling by alternative methods.

The reference case for this concept allows waste-rock melting after shutdown of the liquid cooling phase of cavity operation. Shutdown of the liquid cooling phase of operation will be initiated when 1) the cavity is no longer needed for waste additions or 2) the cavity is full.

An option of this concept is to limit the extent of the melting phase by continuing the condensate recycle step for some time after stopping waste additions. The time required for the condensate recycle to completely eliminate melting of the waste is believed to be in the order of 500 years. To accomplish reliable cooling for this extended period would require very high integrity system components, including the mined cavity, access piping, surface facility, and canisters.

A flow diagram showing the waste emplacement and the coolant cycle is presented in Figure 4.34. The Figure 4.34 indicates the possibility that other wastes such as low-level waste and fuel cladding waste could be disposed of in the same cavity after suitable pretreatment and encapsulation. In this study, however, only high-level waste is considered.

A conceptual diagram of the canister insertion area and well-head shielded cell room is shown in Figure 4.35. Adjacent pipes of corrosion-resistant material project through the floor into the well-head shielded cell and extend downward to the top of the cavity. The piping includes the main well casing, four intermediate-sized pipes located within it, and several smaller pipes contained inside one of the intermediate pipes.

In the concept shown, the interiors of all of the pipes are made accessible through covers in their tops. Access is for system needs such as inspection, monitoring and repairs and for canister insertion through an intermediate-sized pipe. The steam risers are each routed to more than one of the condensers to provide redundancy for reliability and maintenance. The steam or the condensate may optionally be treated to remove undesirable vaporized and radioactive constituents in the coolant. Recycle water is returned to the cavity through a pipe located within one of the intermediate size pipes. Any noncondensable gases from the condensers will likely be vented to a waste off-gas system for cleanup.

In the concept shown, the annulus between the large outer casing and the intermediate sized pipes will be filled with a monitoring fluid to detect outward leaks from the inner pipes. This fluid can be either a gas or liquid. A similar system

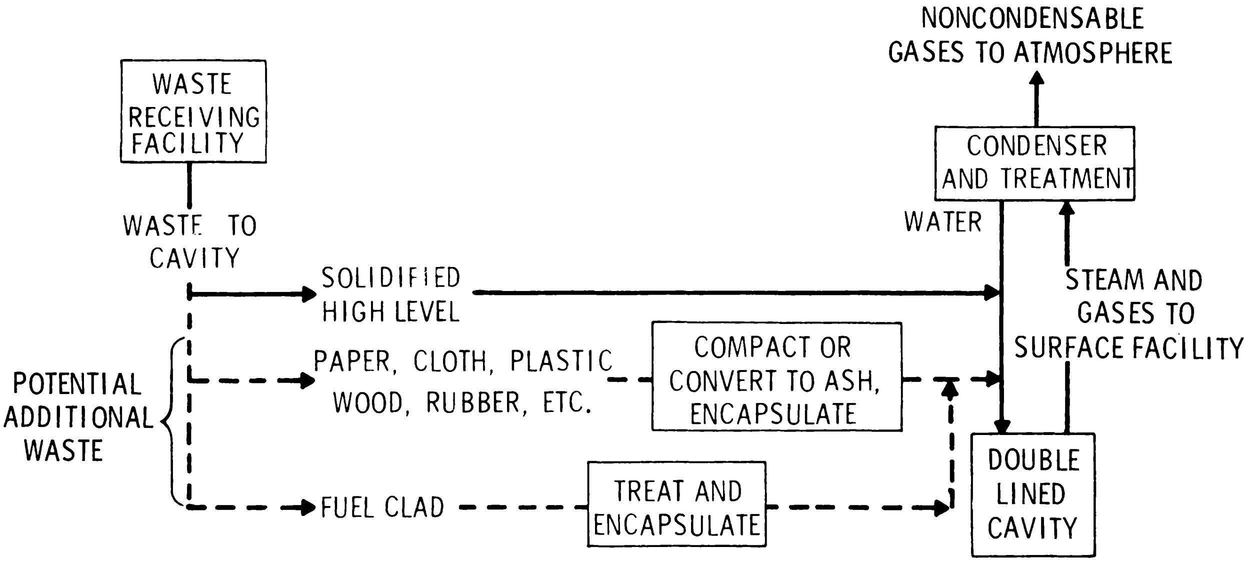

FIGURE 4.34. Flow Diagram Showing Emplacement of Solid Waste in a Mined Cavity - Interim Liquid Cooling and Waste Rock Melting

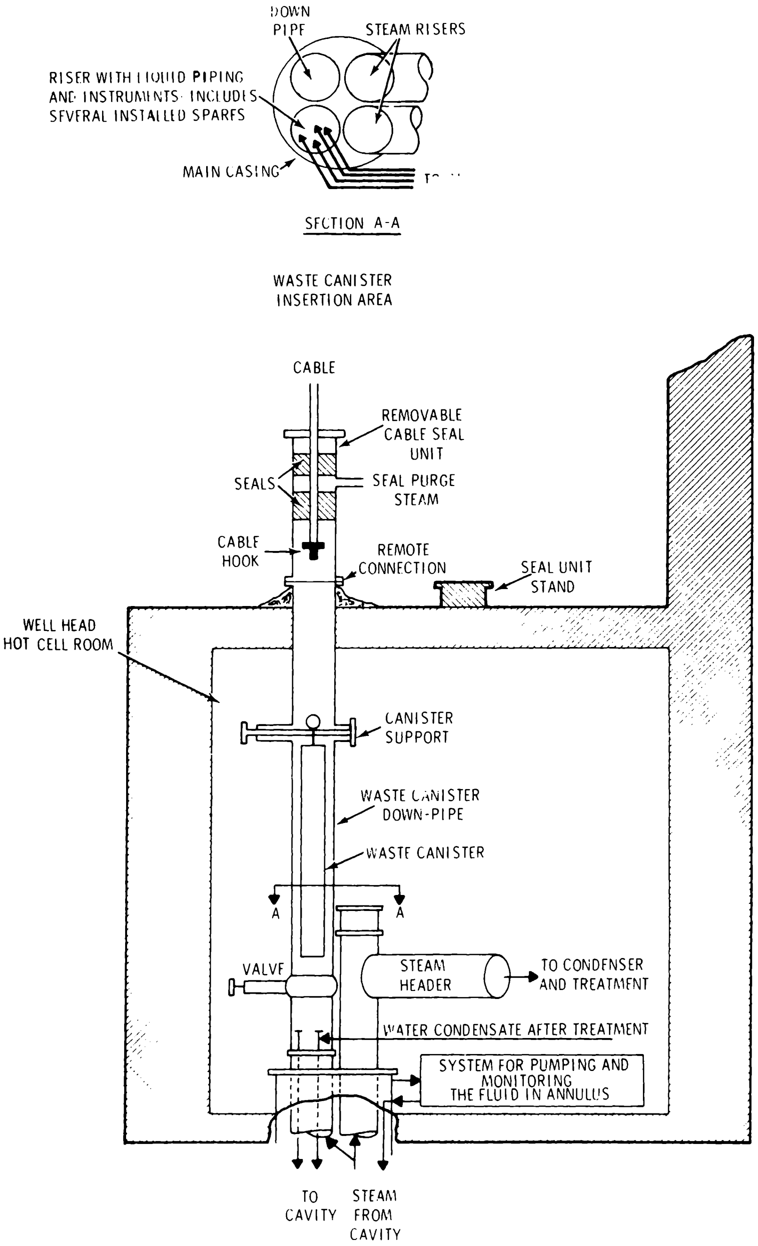

FIGURE 4.35. Well-Head Concept for Solid Waste Emplacement in a Mined Cavity - Interim Liquid Cooling and Waste-Rock Melting

using chromated water as the monitoring fluid has been used successfully as a part of a chemical waste disposal system.(118-120) Double encasement is provided for the liquid handling and instrument pipes by being located within an intermediate sized pipe. The inner annulus of these doubly encased pipes could also contain monitoring fluid systems for leak detection.

Casing repairs or modification could be accomplished using downhole packers, which are devices used to plug well pipes from the surface. Packer insertion is done routinely in the oil industry in wells with higher surface pressures than required by this concept.(81) Special packing elements are available for service up to about 700°C. Bottom sealing of the intermediate and smaller pipes would be done with well cements or packers.

A cavity volume of about 13,000 cubic meters would be required to receive and serve as a repository for the high-level waste generated by the reference reprocessing plant.

The overall characteristics of the concept for storing solid waste in a mined cavity with interim water cooling followed by waste-rock melting are presented in abbreviated form in Table 4.23.

TABLE 4.23. Summary of the Overall Characteristics, Solid Waste Emplaced in Mined Cavity; Initial Water Cooling; Melting

Waste Form	High integrity solid waste form and canister in a water bath; later allowed to dry and perhaps melt
Waste Concentration	High in waste form in canisters. High to moderate when waste-rock melts.
Operational Features	Mining of cavity; surface cooling system by steam-water recycle; surface operations for perhaps hundreds of years. In-place drying and perhaps some conversion to melt; eventual self-cooling to solid.
Candidate Geologic Environment	Might include bedded or domed salt, tuff, intrusive igneous, crystalline metamorphic or possibly shale formations.
Retrievability	Difficult as waste in canisters; extremely difficult as rock-waste matrix.
Monitorability	Limited. Can measure temperatures and released radioactivity within cavity, fluid streams, outer casings annuli, and monitor holes; can detect radioactivity in nearby water-bearing formations if it should occur. Direct monitoring of waste is impractical after melting.
Extent of Knowledge	Fair. Boiling water stage is somewhat similar to surface liquid storage tank operation. Little is known about random stacking or in-place conversion and its heat transfer effects on geologic environment.
Isolation	Moderately deep geologic isolation, 300 to 3000 meters or maximum mining depths, depends on geologic formation as the primary containment barrier for geologic times; relatively few manmade penetrations to the surface require sealing.
Possible Pathways to Man's Environments	Natural pathways such as fractures if flowing water present, volcanism seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Incorporates temporary manmade barrier of tank-type cavity lining.

4.1.3 Solid Waste Emplaced in Manmade Structures in Geologic Formations--Interim Air Cooling:

A major consideration in the disposal of high-level radioactive waste in geologic formations is the removal of heat generated by the waste. Waste temperatures can be kept low by placing the waste in a relatively dispersed array to allow natural heat removal. Or, the waste can be closely spaced in manmade structures within geologic formations with some form of artificial heat removal until the radioactivity decays to a level where natural heat removal methods can be used. The concept discussed here involves the latter situation utilizing air cooling.

Air cooling by natural convection rather than forced convection was chosen for detailed review as the base case because it is a passive system. The reference concept is shown in Figure 4.36. A waste canister is sealed inside a thick-walled metal pod. The pod is then buried in the floor of the tunnel to shield operating personnel from radiation. Radioactive decay heat is conducted along the metal pod wall and is dissipated to the cooling air from a finned surface.

The pod also provides secondary containment and retrievability. An unwelded closure or lid is placed in the pod just above the canister. The space inside the pod above the closure is filled with crushed rock at least to the level of the tunnel floor. The burial trench is also backfilled with crushed rock to provide radiation shielding. The unwelded closure prevents the crushed rock from entering the space between

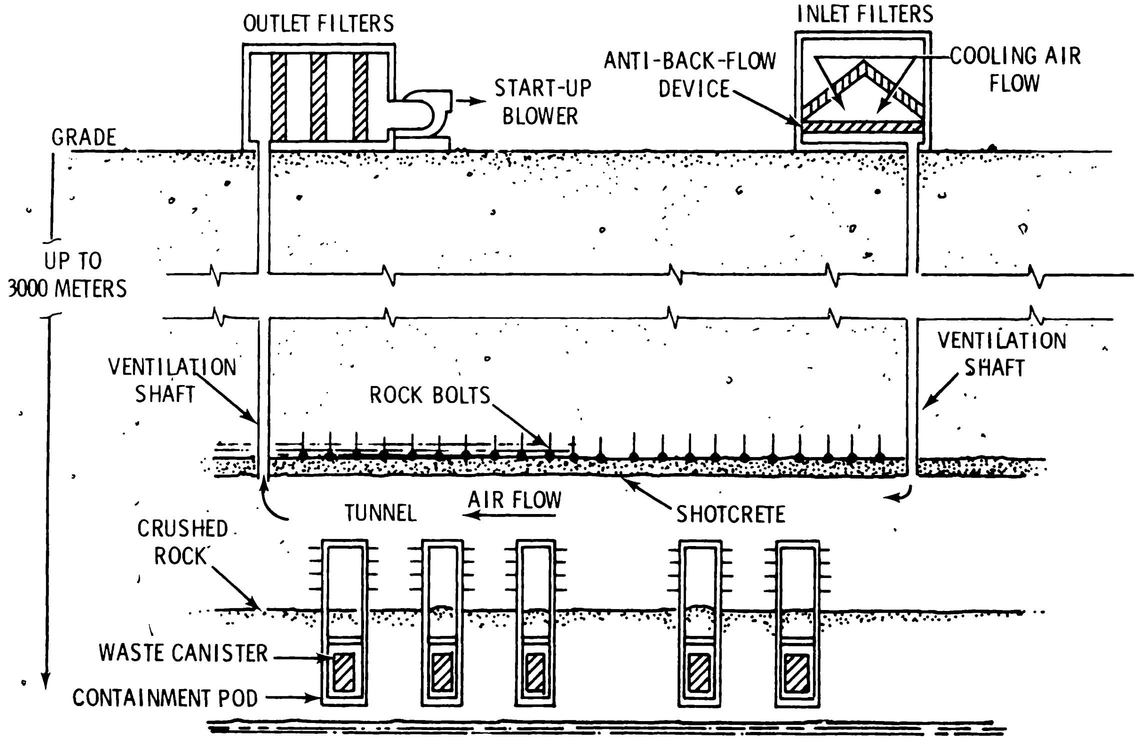

FIGURE 4.36. Solid Waste Emplacement in a Mined Tunnel - Interim Natural Convection Air Cooling, No Melting

the canister and the pod wall so that heat transfer is not impeded. The top of the pod is sealed by a closure weld to provide secondary containment. The welding can be performed using contact methods because of the shielding afforded by the crushed rock.

The tunnel size is determined by the size of the equipment required to place the canister in the pod. Rock bolting and shotcreting may be required for strengthening the tunnel walls and ceilings.

In this concept inlet air from the atmosphere is first filtered to prevent excessive dirt buildup in the waste disposal area. The incoming air flow is then divided to ventilate the personnel access area and to air cool the waste canisters. Upon leaving the waste disposal area, the air rises up the outlet shaft through a high-efficiency filter system where it is cleaned before being released to the atmosphere. A blower is used to initiate the draft but is not needed once the draft is established.

Waste canisters are spaced to permit heat removal by the geologic formation so as to maintain waste and rock temperature below melting after termination of the natural draft cooling in about 100 years. After access areas are sealed, waste heat is conducted to the rock. Canister spacing determined in this manner requires a large disposal area. Alternatively, the canister spacing could be relatively small at the time of placement and then, with additional tunneling, increased when use of the cooling system is terminated.

About 5.5 kilometers of burial tunnel, 9 meters in diameter, would be required to dispose of the high-level waste produced by the reference reprocessing plant.

Other air-cooling methods reviewed and compared with natural convection cooling include single-pass forced convection, recirculation and evaporative air cooling.

Single-pass forced convection air cooling requires the same equipment as natural convection cooling. However, the blower must be operated continuously and, because of the higher available pressure, the shaft or stack diameter can be made smaller than in the case of natural convection. The optimum shaft diameter for single-pass forced convection cooling would be determined by balancing drilling or mining costs against blower costs. Several parallel blowers and emergency power supplies may be needed to provide high reliability. In the case of a power failure, the rise in air temperature would induce a natural draft which would keep the waste at a tolerable temperature for the relatively short time required to restore the blower operation.

A forced convection concept utilizing finned-tube coolers for cooling recirculated air would require more complex equipment.(121) A fan recirculates air past a finned-tube heat exchanger which removes the decay heat and discharges it either directly to the atmosphere or indirectly through circulating cooling water. In this latter case, the water is cooled in an evaporative or wet cooling tower. The water coolant would be isolated from the waste to assist in preventing an accidental release of radioactivity.

Another approach to heat removal is air cooling by evaporative cooling of the air. Here the equipment requirements would be similar to the preceding system except that the water coolant system including the finned-tube heat exchanger and cooling tower would be absent. Instead, the recirculating air would pass through an underground evaporative cooler. The major advantage of this system would be the reduction in net cooling air flow compared with single-pass air cooling. Another variation of this concept would be single-pass air cooling using evaporative cooling of the air. Such evaporative cooling methods may be attractive for storage sites in hot, arid regions.

Overall characteristics of the mined cavity concept with heat dissipation to the geologic formation and minimum interaction between the waste and the formation with fluid cooling are summarized in Table 4.24.

TABLE 4.24. Summary of the Overall Characteristics; Solid Waste Emplaced in Manmade Structure in Mined Cavity; Initial Air Cooling; No Melting:

Waste Form	High integrity solid waste form and canister.
Waste Concentration	Moderate; inversely proportional to heat content of waste.
Operational Features	Significant canister handling but relatively straightforward; direct "hands-on" control of each canister.
Candidate Geologic Environment	Might include bedded or domed salt, tuff, intrusive igneous crystalline metamorphic or possibly shale formations.
Retrievability	Relatively good for 50 to 100 years or until operation shutdown; more difficult with time depending on plasticity of formation, corrosion resistance of canister, and maintenance of repository before final sealing.
Monitorability	Limited; direct monitoring of waste impractical; can monitor gross radioactivity release within each major tunnel during operation; can detect radioactivity in nearby water-bearing formations if it should occur.
Extent of Knowledge	Fair to good; mining techniques and remote handling techniques established, waste-formation interaction evaluated on short-term data when considering geologic times; unknown effects of burial of radioactive heat source on geologic formation.
Isolation	Moderately deep geologic isolation, 300 to 3,000 meters or maximum mining depths, depends on geologic formation as the primary containment barrier for geologic times, although several manmade penetrations to the surface require sealing.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.

4.1.4 Solid Waste Emplaced in Manmade Structures in Geologic Formations--Interim Water Cooling

Use of water cooling to remove the heat generated by radioactive decay is an alternative to the air cooling concept described in the previous section. For this concept, heat removal by radiant heat transfer to boiling water was selected as the base case. A schematic cross section diagram of a system is shown in Figure 4.37. The underground facility is a manmade structure designed to withstand earthquakes and shifting of the rock formation. The waste is placed in the shielded lower part of a cylindrically shaped storage area. Water coolant is placed in a sealed pressure vessel which surrounds the water canisters. Steam generated by the waste is piped to the heat exchange system at the earth's surface where it is condensed and returned to the waste storage area. A side stream of the coolant is treated to remove radioactivity.

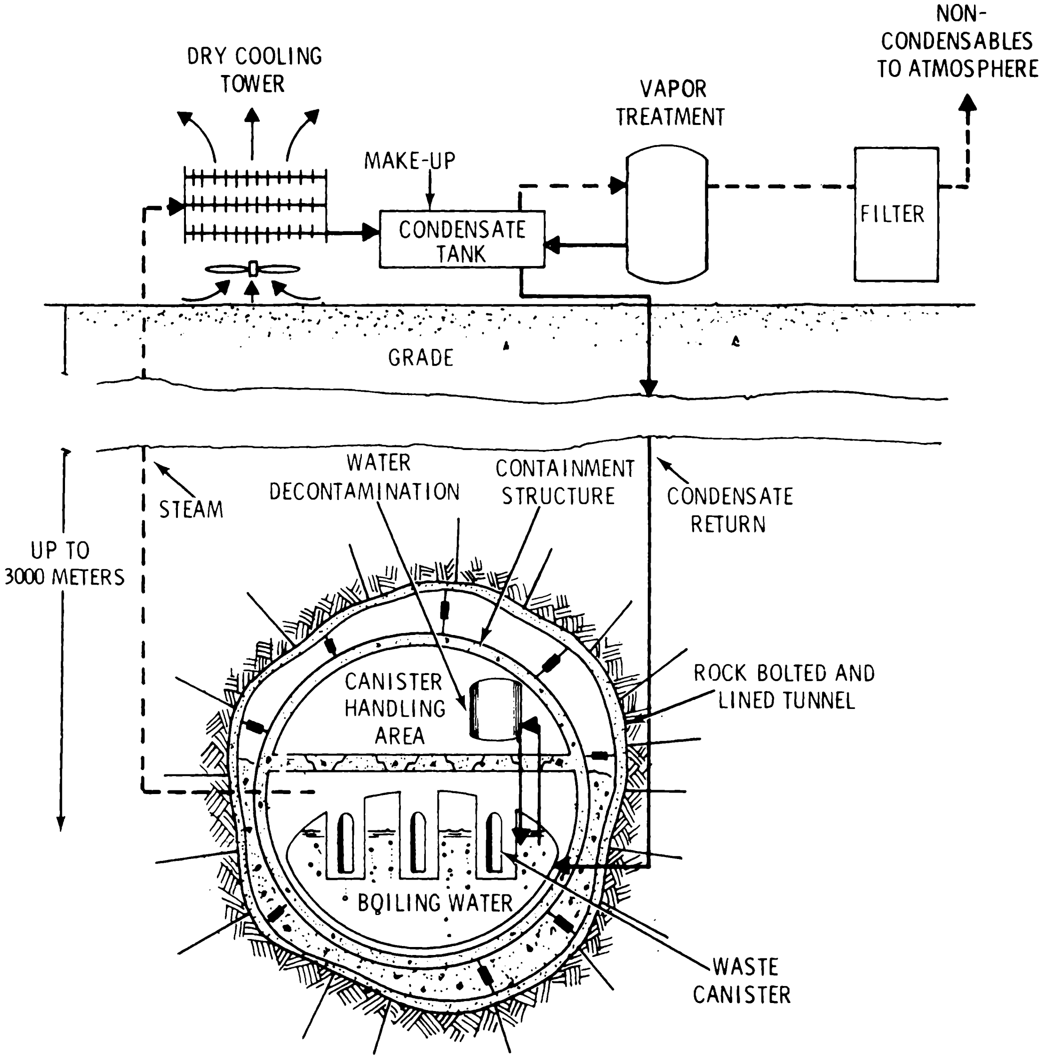

FIGURE 4.37. Solid Waste Emplacement in Manmade Structure with Interim Boiling Water Cooling, No Melting

The stream could be treated at the surface or underground as shown.

Heat is transferred from the waste canister to the walls of its surrounding "thimble" within the water-filled vessel by radiation and free convection and then to the water by boiling heat transfer. The heat is carried to the surface as steam, condensed in a dry cooling tower and returned. If the steam is generated at a pressure of two atmospheres, a pressure tank of elliptical cross sectional dimensions of 7.6 and 15 meters would require a wall thickness of about 1 centimeter of low-alloy steel. Alternatively, the concept could use a boiling water vessel at near ambient pressure and depend on vapor pumps to transfer the vapors to the heat removal system at the surface.

Assuming a heat load of 2.5 megawatts for each cooling unit (2.5 megawatts is about five percent of the total heat removal requirements in the year 2000 if 5-year old waste is shipped to the disposal site), the pipe diameter required for steam flow to the surface without pumping would be about 50 centimeters if the steam pressure in the disposal cavity is 2 atmospheres. The condensate may be returned in the same line without an appreciable increase in flow resistance.

Overall characteristics of the mined concept with heat dissipation to the geologic formation and minimum interaction between the waste and the formation with fluid cooling are summarized in Table 4.25.

4.1.5 Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix

In this concept the high-level liquid waste is managed by a system whose main feature is a mined cavity located below the surface and isolated from mobile groundwater (Figure 4.38). The liquid waste is placed initially into the cavity and stored for an interim period of time. During this time heat is removed from the self-boiling waste by routing the vapors to a surface facility for condensing, treatment, and recycle to the cavity. Essential to this concept is the location of the fuel reprocessing plant at the waste disposal site. The management of the waste by this concept is divided into three distinct time steps:

1. Interim storage as a boiling liquid for the life of the reprocessing plant and perhaps somewhat longer;
2. In-place conversion and melting; and
3. Solidification to a monolithic solid resulting in ultimate disposal away from man's environment for geologic time periods.

The principal steps in the disposal process are shown with a time scale in Figure 4.39. The process operation during the liquid storage phase, Step 1 above, is shown diagrammatically in Figure 4.40. The waste is allowed to boil and the condensate is recycled. Also indicated in Figure 4.40 is the possibility that other types of waste from the fuel reprocessing plant might be

TABLE 4.25. Summary of the Overall Characteristics; Solid Waste Emplaced in Manmade Structure in Mined Cavity; Initial Water Cooling; No Melting:

Waste Form	High integrity solid waste form and canister.
Waste Concentration	Medium; inversely proportional to heat content of waste.
Operational Features	Significant canister handling but relatively straightforward; direct "hands-on" control of each canister. Fluid cooling allows more flexible and positive control of temperature of waste and rock.
Candidate Geologic Environment	Might include bedded or domed salt, tuff, intrusive igneous, crystalline metamorphic or possibly shale formations.
Retrievability	Relatively good for 50 to 100 years or until operation shutdown; more difficult with time depending on plasticity of canister, and maintenance of repository before sealing.
Monitorability	Limited; direct monitoring of waste impractical; can monitor gross radioactivity release within each major tunnel during operation; can detect radioactivity in nearest water-bearing formations if it should occur.
Extent of Knowledge	Fair to good; mining techniques and remote handling techniques established; waste-formation interaction evaluated on short-term data when considering geologic times; unknown effects of burial of radioactive heat source on geologic formation.
Isolation	Moderately deep geologic isolation 300 to 3,000 meters or maximum mining depths; depends on geologic formation as the primary containment barrier for geologic times, although several manmade penetrations to the surface require sealing.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.

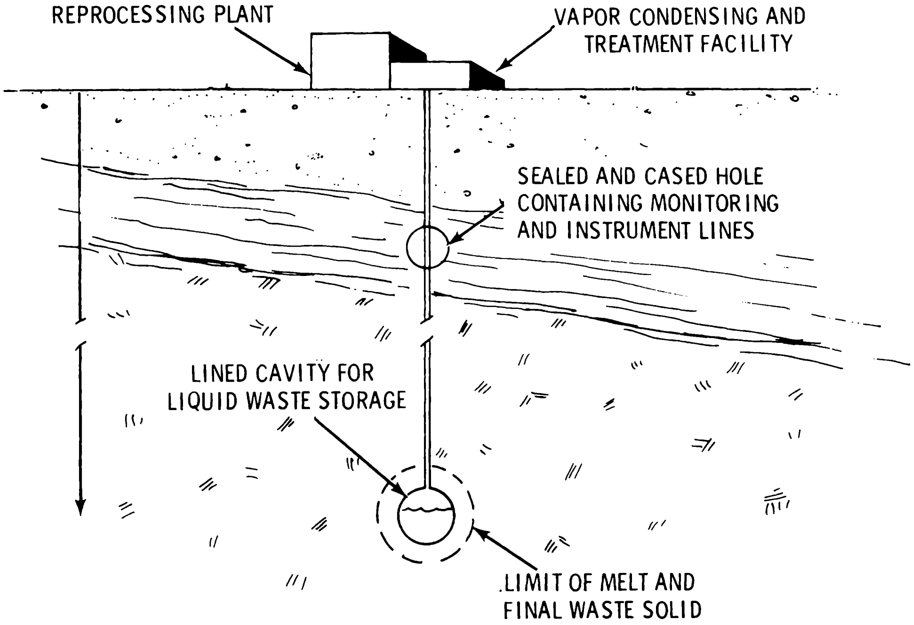

FIGURE 4.38. Liquid Waste Emplacement in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix

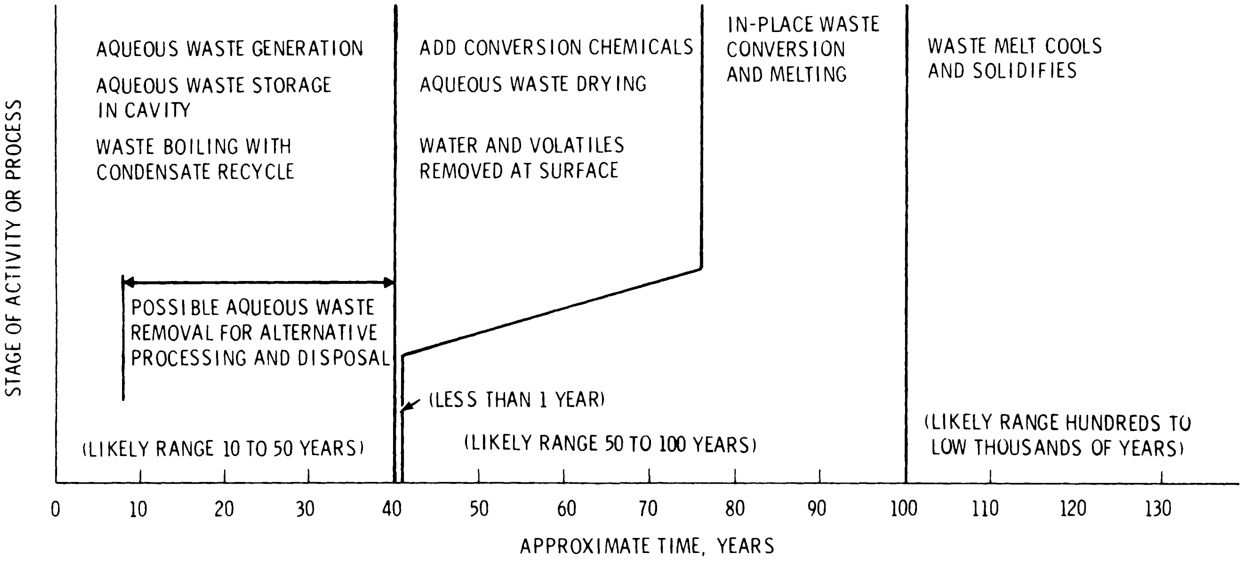

FIGURE 4.39. Time Scale for Steps in Liquid Waste Emplacement in a Mined Cavity

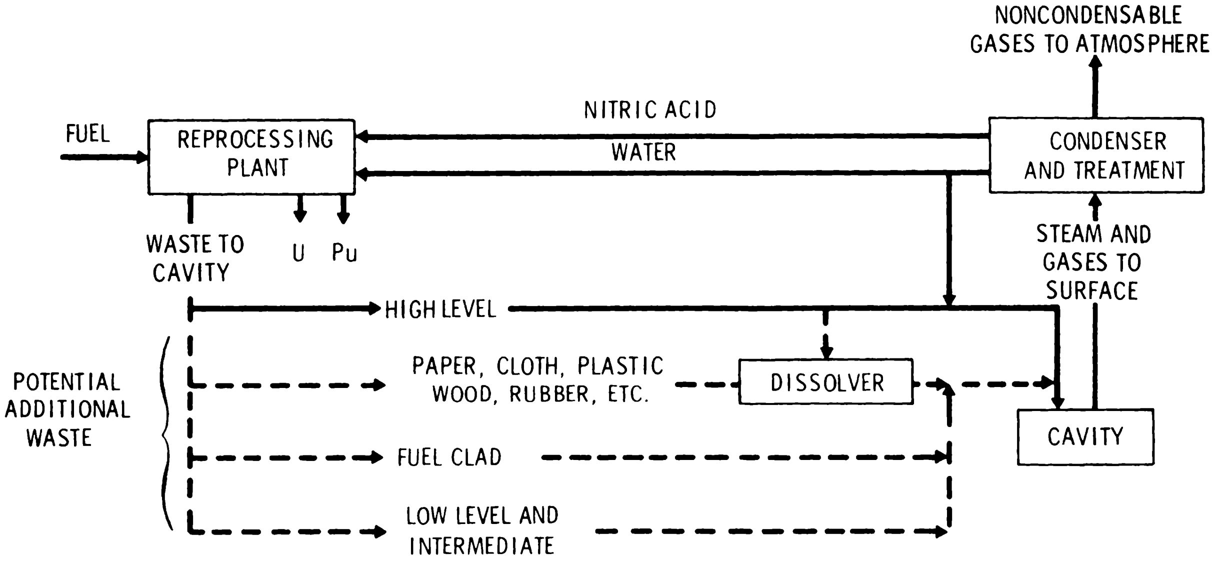

FIGURE 4.40. Flow Diagram for Liquid Waste Emplaced in Mined Cavities - In-Place Drying and Conversion to Rock-Waste Matrix

disposed of with this concept: high, intermediate, and low-level liquid waste; fuel clad; and other contaminated solid or liquid materials. In this study, however, only high-level liquid waste is considered.

The cavity can be mined and the shaft drilled using conventional techniques. The cavity is lined with a high-integrity and corrosion-resistant liner to assure containment during the liquid operating state (the concept may succeed without a lining). The cavity and its tank liner are proposed to be either spherical or cylindrical with nearly spherical ends to provide for maximum structural strength and minimum surface-to-volume ratio. Depending upon specific circumstances, more than one cavity may be used at a site. About 4,000 cubic meters are required for the cavity volume to dispose of the high-level liquid waste generated by the reference reprocessing plant. In operating with liquid waste, the cavity provides the same function as a near-surface liquid storage tank.

A conceptual diagram of what might be contained within the well-head shielded cell is shown in Figure 4.41. Pipes of corrosion-resistant material project through the floor into the well-head shielded cell and extend downward to the top of the cavity. The piping includes the

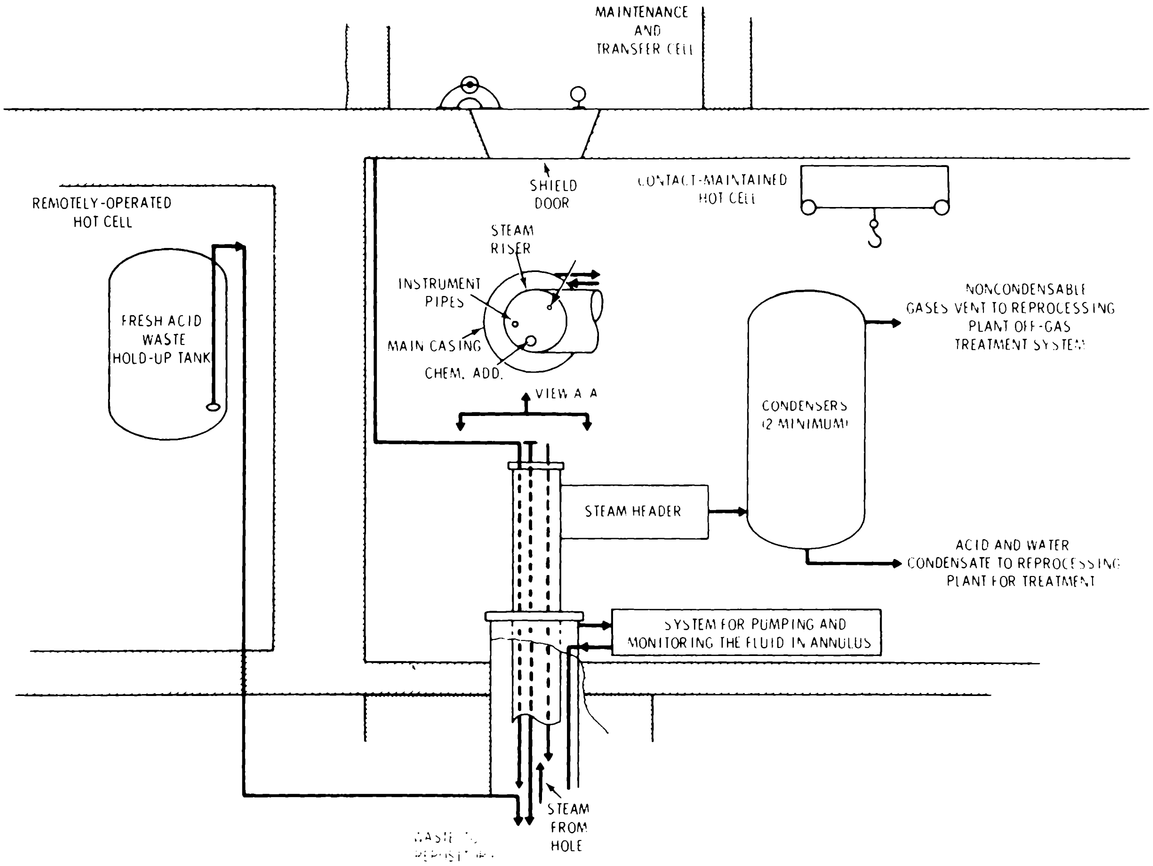

FIGURE 4.41. Facility Requirements at the Well Head - Liquid Waste Emplaced in Mined Cavities

large-diameter main well casing, a steam pipe concentric within the casing, and several smaller pipes contained inside the steam pipe.

In the concept, the interiors of all of the pipes are made accessible through covers in their tops. Access is for system needs such as inspection, monitoring, and repairs. The steam risers are each routed to more than one of the condensers to provide redundancy for reliability and maintenance. The steam or the condensate is treated to remove undesirable, vaporized, and radioactive constituents from the coolant. The condensate may require chemical processing prior to returning it to the cavity. Recycle condensate is returned to the cavity through a pipe located within one of the intermediate size pipes. Liquid high-level waste is added to the cavity through a separate small pipe which is shielded from the well head and the steam-condensate system. Any noncondensable gases from the condensers will likely be vented to a waste off-gas system for cleanup.

In the concept shown, the annulus between the large outer casing and the intermediate-sized pipes will be filled with a monitoring fluid to detect outward leaks from the inner pipes. This fluid can be either a gas or liquid. A similar system using chromated water as the monitoring fluid has been used successfully as part of a chemical waste disposal system.(118-120) Double encasement is provided for the liquid handling and instrument pipes by being located within an intermediate-sized pipe. The inner annulus of these doubly-encased pipes could also contain monitoring fluid systems for leak detection.

Casing repairs or modification can be accomplished using downhole packers as discussed in Concept 2.

Overall characteristics of the concept for placing liquid waste in mined cavities with in-place drying and conversion to a rock-waste matrix are summarized in Table 4.26.

4.1.6 Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix

High-level liquid waste is emplaced in an exploded underground cavity isolated from mobile groundwater,(68) see Figure 4.42. The cavity is formed at depths greater than 3000 meters. The process is similar to that for a mined cavity (Concept 5), except for the form of the cavity. Because in most materials the ceiling of an explosion-produced cavity collapses, the cavity will be rubble-filled rather than open. Unless otherwise stated, the characteristics are similar to those of Concept 5.

The explosive method of cavity formation produces differences in the utility and technical feasibility, but the concept description is not significantly altered from that of the mined cavity. These differences are:

1. The exploded cavity can be formed at greater depths than can the mined.
2. Piping installation into the exploded cavity is more difficult.

TABLE 4.26. Summary of the Overall Characteristics; Liquid Waste Emplaced in Mined Cavity; Initial Reflux Cooling; Melting:

Waste Form	Liquid during emplacement; rock-waste matrix after in-place melting and solidification.
Waste Concentration	High as liquid; low to moderate as final solid.
Operational Features	Surface operations only. Surface vapor condensing and recycle system. In-place, self-conversion to melt; eventual self-cooling to solid.
Candidate Geologic Environment	Might include bedded or domed salt, tuff, intrusive igneous, crystalline metamorphic or possibly shale formations.
Retrievability	Some difficulty as liquid; very difficult to nonretrievable as a matrix.
Monitorability	Can monitor temperatures in and adjacent to cavity and in access holes during aqueous storage; can monitor radioactivity in access annuli and test holes; cannot monitor precisely some events occurring meltdown and cooling stages; can detect radioactivity in nearby water-bearing formations if it should occur; can monitor surface support.
Extent of Knowledge	Aqueous stage operation is similar to surface liquid storage tank operation. Meltdown and cooling knowledge is largely inferred.
Isolation	Moderately deep geologic isolation, 300 to 3,000 meters; depends upon mobility of molten sphere of rock-waste; depends partly upon effective manmade sealing of modest number of manmade penetrations.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Ability to control melt stage must be predicted before starting melt.

3. The exploded cavity cannot be lined or well inspected, and contains cracks in the walls.

4. The chance of hot-spot formation, unwanted local decomposition and offgasing, local melting, and sudden cooling by water contact are all greater in the exploded cavity than in the mined cavity.

Cavity forming using Plowshare techniques is well established. Cavity formation using chemical explosive volumes can be achieved utilizing stepped charges. Depending upon specific circumstances, more than one cavity might be required at a single site.

Typical shielded cell facility requirements are basically the same as those for Concept 5 shown in Figure 4.41.

An arrangement for the piping downhole into the cavity is presented in Figure 4.43. The cavity is penetrated by each of the main casings. The steam up-flow pipes are located within and concentric to the main casing. Condensate return lines and mon-

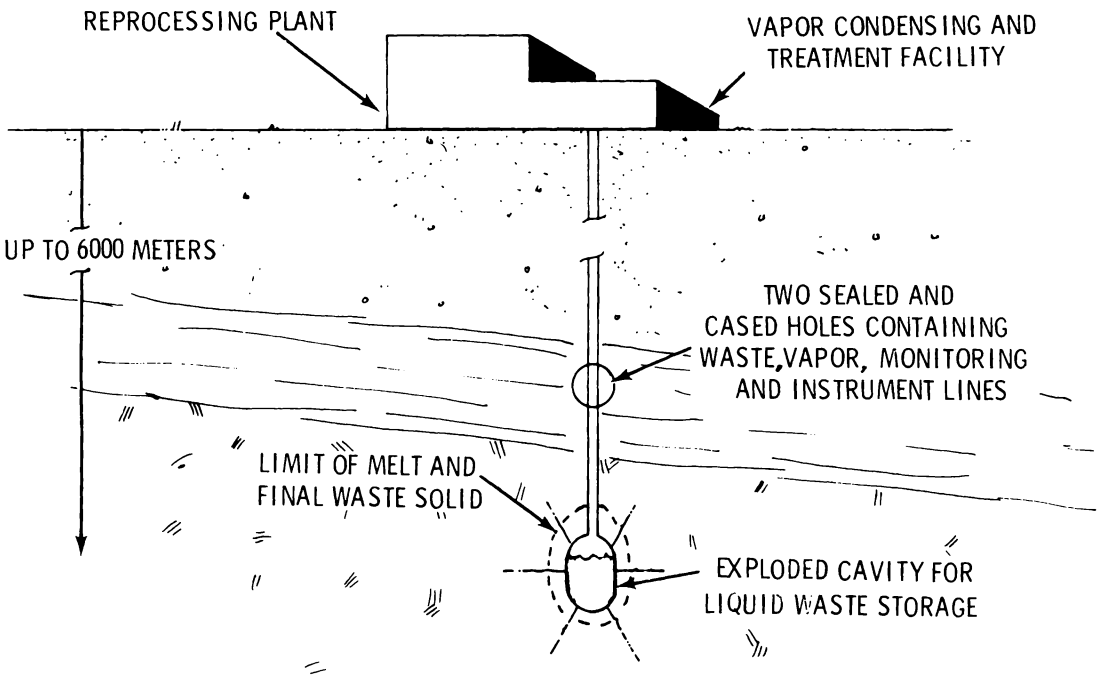

FIGURE 4.42. Liquid Waste Emplacement in an Exploded Cavity - In-Place Drying and Conversion to Rock-Waste Matrix

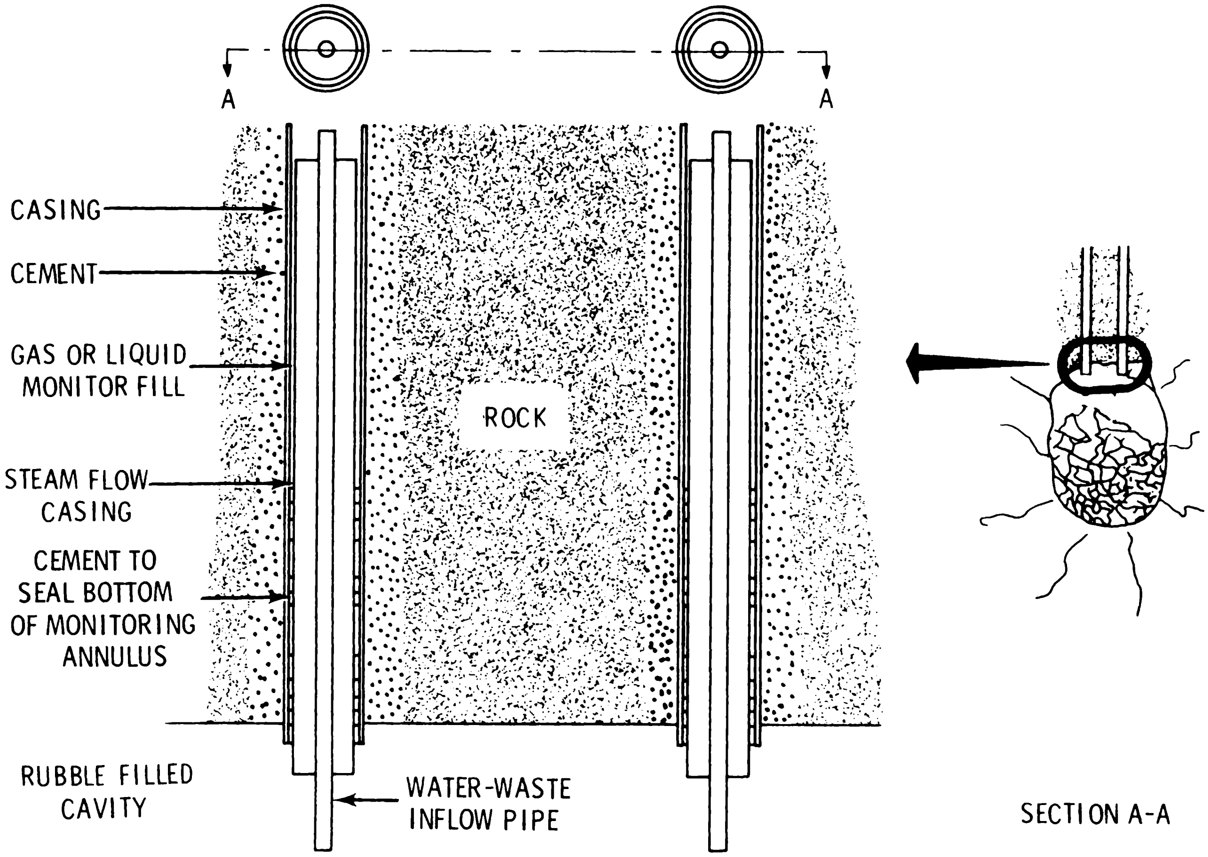

FIGURE 4.43. Pipe and Bottom Hole Configuration for Exploded Cavity Concept with Liquid Waste

itoring instrumentation leads will be contained inside the steam pipe.

Overall characteristics of the concept for placing liquid waste in exploded cavities with in-place drying and conversion to a rock-waste matrix are summarized in Table 4.27.

4.1.7 Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting

The method of placing wastes in appropriate geologic formations, shown in Figure 4.44, is based on lowering waste packages (canisters filled with solidified waste) into an array of holes that have been drilled into the formation from the earth's surface.(122) This concept was originally proposed as a method for placing waste canisters in bedded salt deposits and as an alternative to the mined cavity concept for a Federal Repository.(123) The primary feature of the drilled hole concept is that all operations are conducted from the surface. Salt domes, argillaceous, intrusive igneous, and metamorphic

TABLE 4.27. Summary of the Overall Characteristics; Liquid Waste Emplaced in Exploded Cavity; Initial Reflux Cooling; Melting:

Waste Form	Aqueous waste during emplacement; rock-waste matrix after in-place melting and solidification.
Waste Concentration	High as liquid; low to moderate as final solid.
Operational Features	Surface operations only. Surface vapor condensing and recycle system. In-place, self-conversion to melt; eventual self-cooling to solid. Nuclear explosion produced cavity.
Candidate Geologic Environment	Might include intrusive igneous, crystalline metamorphic, possibly shale or salt (bedded or domed) formations.
Retrievability	Very difficult to nonretrievable.
Monitorability	Limited; can monitor temperatures in cavity and in access holes during aqueous storage; can monitor radioactivity in access annuli and test holes; cannot monitor precisely some events occurring in meltdown and cooling stages; can measure radioactivity in nearest water-bearing formations; can monitor surface support.
Extent of Knowledge	Aqueous stage is inferred from nuclear cavity work and to surface liquid storage-tank operation. Meltdown and cooling knowledge is largely inferred. Uncertainty about effect of wall cracking.
Isolation	Deep geologic isolation, down to about 6,000 meters; depends upon mobility of molten sphere of rock-waste; depends upon extent and degree of cracking of geologic formation; depends partly upon effective manmade sealing of modest number of manmade penetrations.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attriuted to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Ability to control melt stage must be predicted before starting melt.

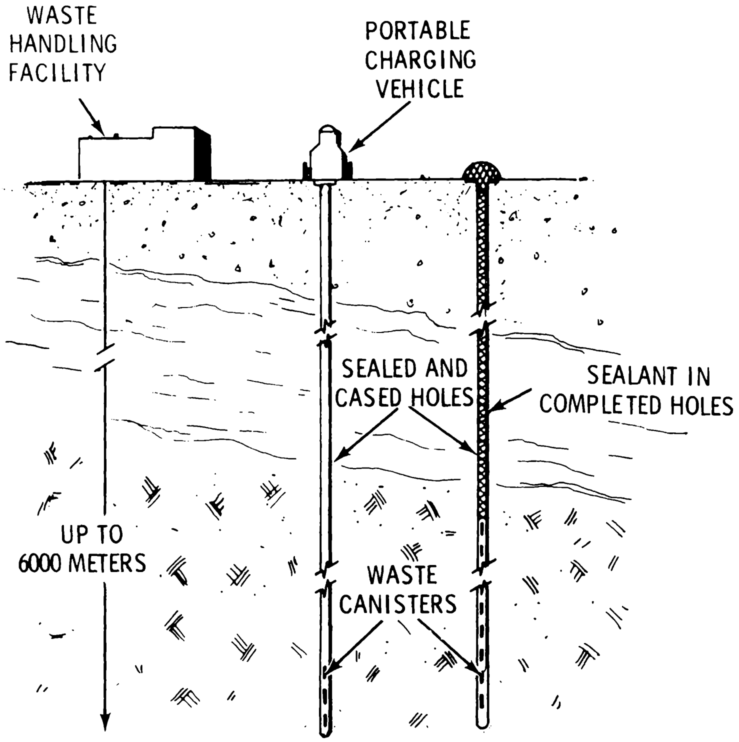

FIGURE 4.44. Solid Waste Emplacement in a Matrix of Drilled Holes - No Melting

formations are other examples of geologic candidates for the drilled hole concept. The concept is currently envisioned as being appropriate for depths ranging from about 300 to 6000 meters.

The number of holes required will depend primarily on the number of canisters and the thickness of the geological strata or formation. Assuming a 10 year hold-up time at the reprocessing plant, about 3000 waste canisters, each having a diameter of 0.3 meters and a length of 3 meters, would be available annually by the year 2000.(124) This quantity corresponds to a vertical space utilization rate within a single hole of about 25 meters per day; relatively thin geologic formations could require an immense number of drilled holes. Spacing of the drilled holes will depend on the heat generation rate of individual canisters and the heat dissipation characteristics of the geologic formation. Water-bearing formations must be sealed off by setting and cementing a casing. To provide a hole which can be freed of all water before waste is emplaced, it is probable that the casing will be required all the way to the bottom of the hole.

As shown in Figure 4.45, surface facilities consist of a handling facility (cask unloading area and shielded cells), drill rig, and charging vehicle. The latter is a self-powered vehicle for lowering the canisters into the drilled holes. The vehicle will probably travel on rails and will be equipped with run and jog

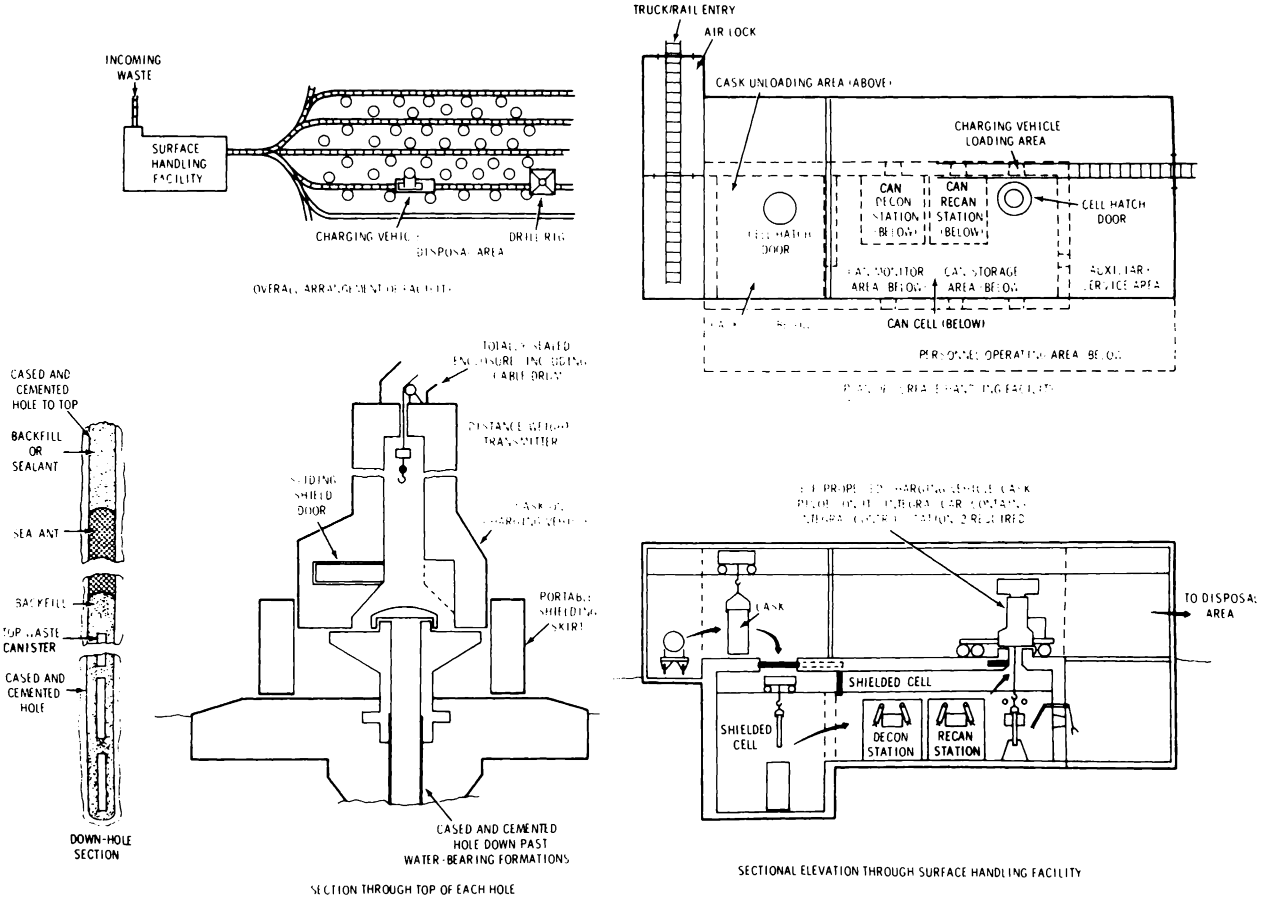

FIGURE 4.45. Conceptual Facilities for Solid Waste Emplaced in a Matrix of Drilled Holes

drives. Canisters are transported inside a lead-filled cask mounted on the vehicle operating platform. In addition to position read-out, instrumentation to indicate vehicle velocity, cable tension and elevation are installed at the operating console. Large, elaborate high-speed hoists, similar to those used on oceanographic research vessels, would be required for high capacity in deep-hole formations.

The surface shielded cell complex should be equipped with facilities for canister decontamination, inspection and recanning. Slightly negative pressures must be maintained in potentially contaminated areas of the unloading area-shielded cell complex. Exhaust ventilation air from areas confined in this manner is passed through prefilters and high-efficiency filters before being routed to a stack that is continuously monitored for radioactivity. In addition to ventilation equipment and provisions for back-filling and sealing, other required features include auxiliary service equipment and laboratory and office areas.

The characteristics of the concept for placing solid waste in a matrix of drilled holes are presented in abbreviated form in Table 4.28.

TABLE 4.28. Summary of the Overall Characteristics; Solid Waste Emplaced in Matrix of Drilled Holes; No Fluid Cooling or Melting:

Waste Form	High-integrity solid waste form and canister.
Waste Concentration	High in waste form; high to low when canister fails. Hole spacing is flexible.
Operational Features	Surface operations only. Relatively simple.
Candidate Geologic Environment	Might include intrusive igneous, crystalline metamorphic, or possibly shale or salt (bedded or domed) formations.
Retrievability	Moderately difficult for initial period (up to about 100 years); more difficult with time; might require overboring technology beyond current state-of-the-art.
Monitorability	Limited; can measure temperatures and released radioactivity within holes for limited time; can detect radioactivity in nearby water-bearing formations if it should occur.
Extent of Knowledge	Fair. Hole drilling is generally state-of-the-art. Exceptions are long-time proven cementing and casing systems and some hole diameter-depth limits.
Isolation	Moderately deep to deep geologic isolation, 300 to 6000 meters, or nominal reasonable drilling depths. Depends considerably on effective manmade sealing of numerous manmade pentrations into holes.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathways attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	---

4.1.8 Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix

One method of placing solid waste in appropriate geologic formations is with the deep-hole concept. In this concept, holes about 16 kilometers in depth are drilled into a suitable geologic formation from the earth's surface. Solid waste is then disposed of in the lower portion of the hole. When the waste reaches a predetermined level, the hole is filled with sealant. Figure 4.46 presents the basic features associated with the deep-hole concept.

The base case for the concept incorporates melting of the waste and surrounding rock. However, the concept could be directed toward the nonmelting case if it is decided that in-place melting should not be permitted. Except for the need to reduce the heat dissipated to the rock, all the steps required for the nonmelting option are common to the melting case. The reduced heating load for the nonmelting case could be achieved by decreasing the can size, reducing the waste concentration while maintaining the reference can size, storing the waste for an interim period of time, spacing the waste canisters farther apart, or adopting a combination of these methods. A flow diagram depicting

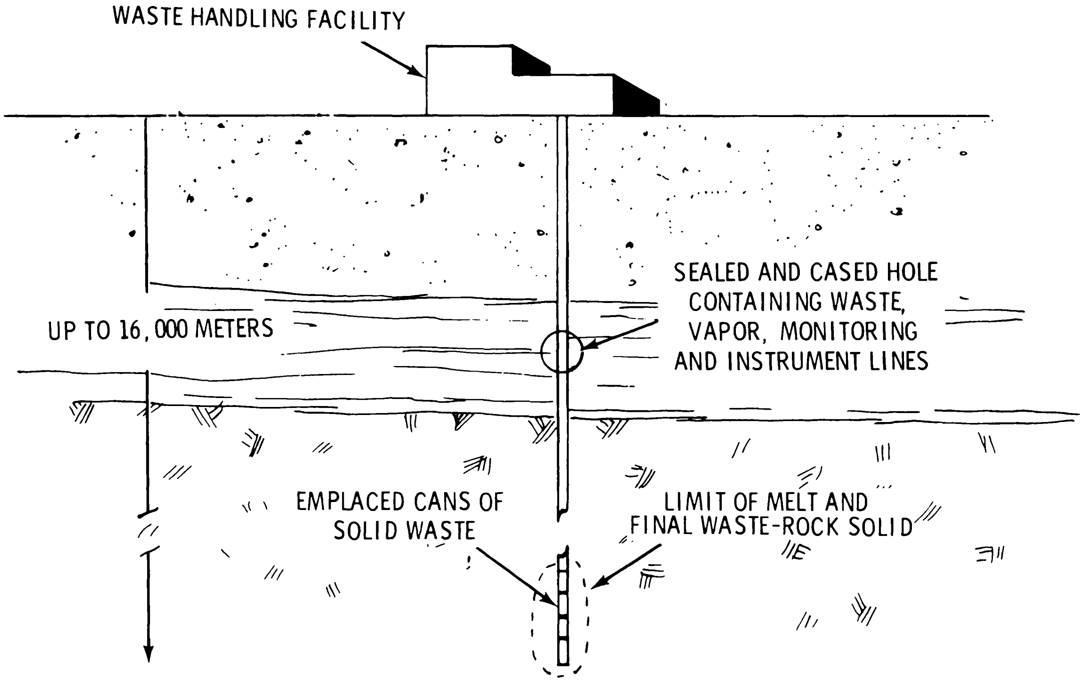

FIGURE 4.46. Solid Waste Emplacement in a Deep Hole with In-Place Conversion to a Rock-Waste Matrix

disposal by emplacing solid waste in a deep hole is shown in Figure 4.47.

The concept incorporates a very deep drilled hole encased with corrosion-resistant material for the length of hole above the final waste level. For the reference example taken here, each hole would be capable of holding about four years waste from a 5 MT/day reprocessing plant (assuming canisters with diameter of 0.3 meters and length 3 meters). Waste is assumed to be disposed into the lower 8 kilometers of the 16-kilometer deep hole. For the reference case in this study, 2,500 canisters were assumed to be in the lower 7,500-meter portion of each hole requiring a total of six holes. The drilling operation of a single hole will require about six years using the largest rigs and equipment currently available.

The processes occurring within the hole, the facilities and equipment, and the resulting waste product form depend upon the waste type placed into the hole. For low-heat waste, no significant changes in the waste or geologic formation will occur. Drying of the rock, some small amount of gas release, and chemical reaction may occur from intermediate-heat source waste. Rock melting will occur for high-heat source waste. The total range of waste concentration could potentially take place at varying depths in the same hole. For example, below the level of the most recent canister addition would be solids which get progressively hotter with depth until melt-

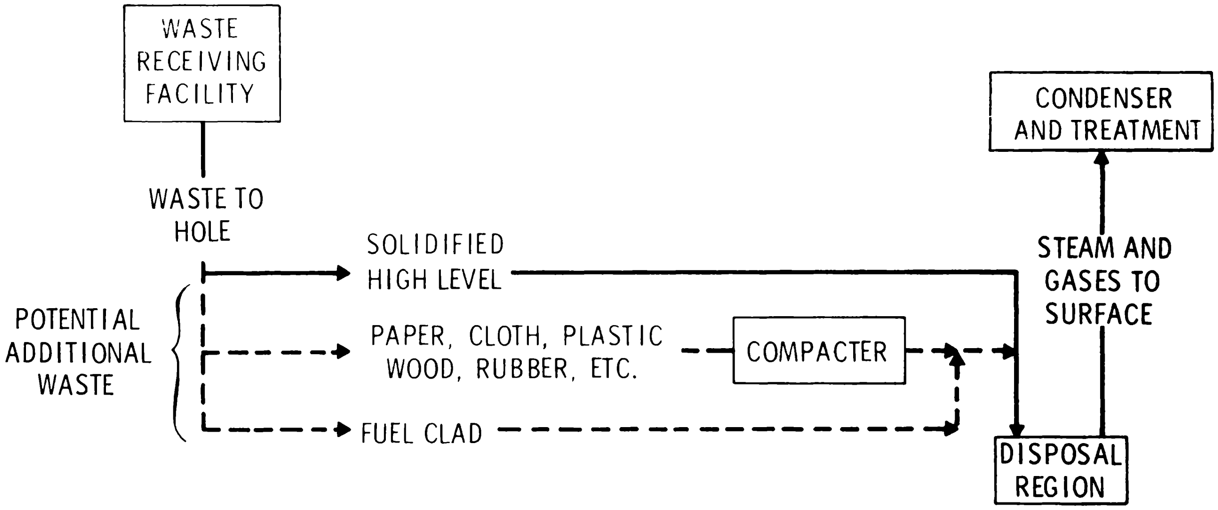

FIGURE 4.47. Flow Diagram for Solid Waste Emplacement in a Deep Hole

ing occurs. The melting forms a pool of melted waste, canisters, and rock. Below this melt level would be resolidified rock-waste melt. Chemicals can be added with the waste canisters if needed to control the chemistry of the final molten pool.

Addition of waste is discontinued when a predetermined level is reached, and the rest of the hole is then plugged with a sealant.

A concept of the key equipment within the shielded cell at the wellhead is shown in Figure 4.48. The main casing projects through the floor into the shielded cell. An intermediate-sized pipe and several smaller pipes are contained within the main casing. The interiors of all the pipes are accessible through covers in their tops. Access is for system needs such as inspection, monitoring, and repairs. The intermediate-sized pipe inside the large casing serves as a waste canister down-pipe and a steam outflow pipe.

The annulus between the large outer casing and the intermediate-sized pipe is filled with a monitoring fluid to detect outward leaks from the inner pipe.

Overall characteristics of the concept for placing solid waste in deep drilled holes are summarized in Table 4.29.

4.1.9 Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to Rock-Waste Matrix

One method for disposing of liquid waste in appropriate geologic formations is in a deep hole. In this concept, holes about 16 kilometers in depth are drilled into a suitable geologic formation from the earth's surface. Liquid waste is then disposed of in the lower portion of the hole and converted in-place to a solid.

As shown in Figure 4.49, a very deep hole is drilled. The hole is encased with a corrosion-resistant material for the length of the hole above the final waste level. A shielded

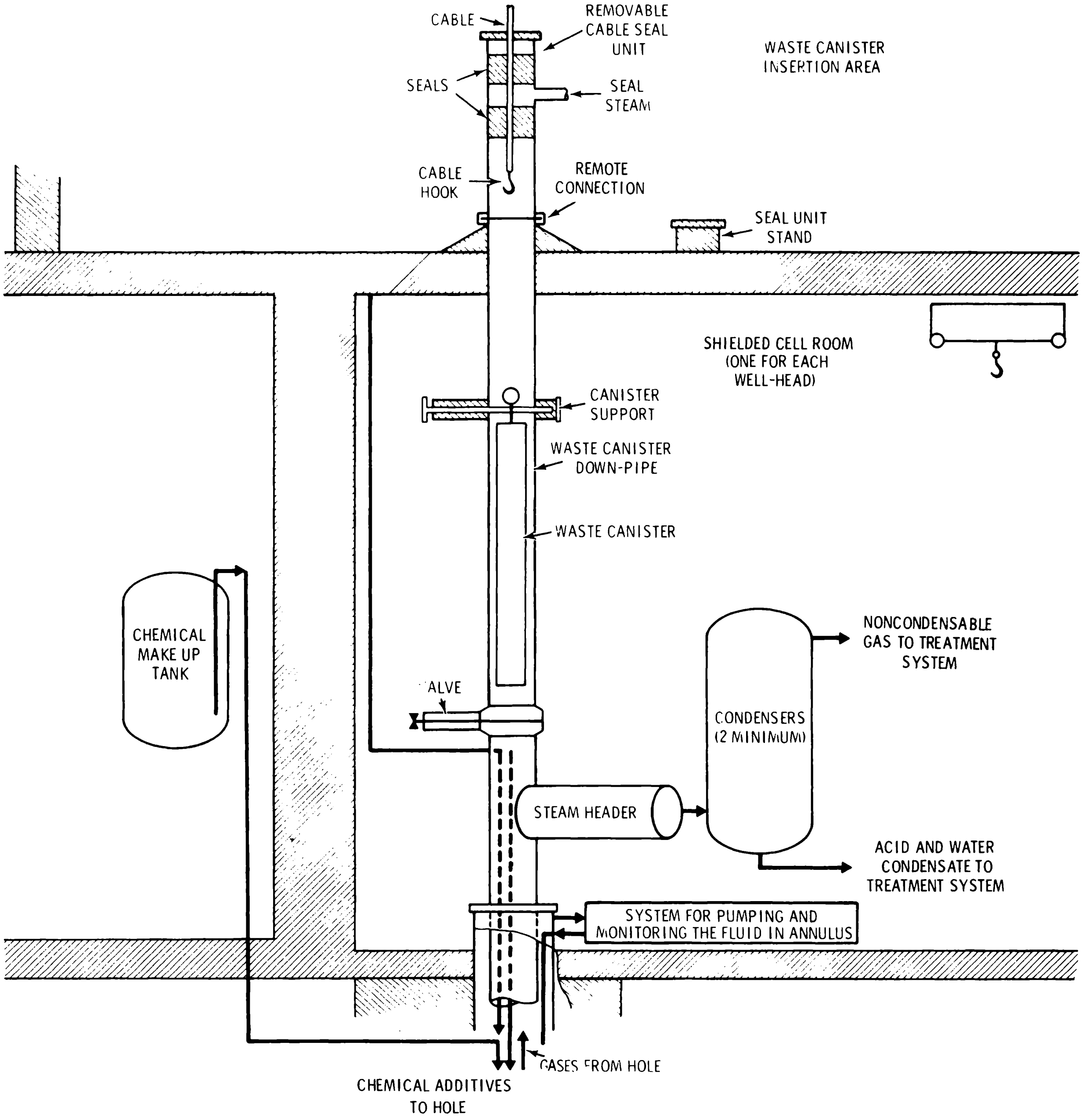

FIGURE 4.48. Facility Requirements at the Well Head - Solid Waste Emplaced in Deep Holes with Melting

TABLE 4.29. Summary of the Overall Characteristics; Solid Waste Emplaced in Deep Holes; No Fluid Cooling; Melting or Nonmelting:

Waste Form	High integrity solid waste form and canister. Rock-waste matrix for melting case.
Waste Concentration	High in waste form; high to low when canister fails.
Operational Features	Surface operations only. Very difficult to drill to great depth.
Candidate Geologic Environment	Might include intrusive igneous or crystalline metamorphic formations.
Retrievability	Difficult for initial period (up to about 20 years); very difficult to nonretrievable thereafter. Requires overboring technology beyond current state-of-the-art.
Monitorability	Very limited; can measure temperatures and released radioactivity within holes for limited time; can detect radioactivity in nearby water-bearing formations if it should occur. Can monitor surface support.
Extent of Knowledge	Limited; hole depth beyond current state-of-the-art in many rocks. Melt-down and cooling knowledge is largely inferred.
Isolation	Very deep geologic isolation from surface, below about 7000 meters. Depends partly on effective manmade sealing of moderate number of manmade penetrations.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathway attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Ability to control melt stage must be predicted before starting melt.

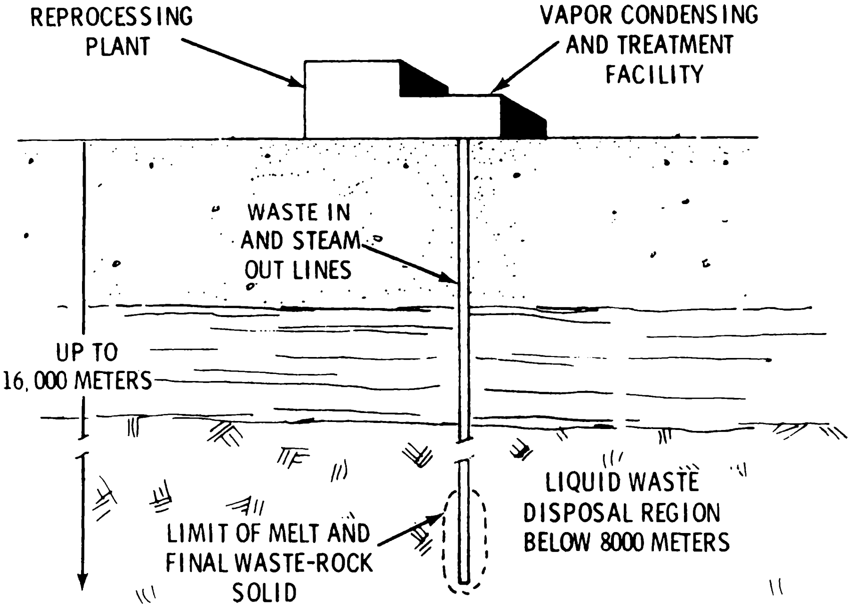

FIGURE 4.49. Liquid Waste Emplacement in a Deep Hole - In-Place Drying and Conversion to Rock-Waste Matrix

cell type of facility for processing volatile constituents issuing from the hole is located adjacent to the fuel reprocessing plant at the surface.

Aqueous waste is discharged from the nearby reprocessing plant into the deep hole. Steam and any non-condensable constituents generated by the boiling and drying waste are routed from the hole into the condensing facility. The waste boils to dryness shortly after it reaches the bottom of the hole. Hence aqueous holdup in the system is minimal.

In-place conversion of the concentrated aqueous waste to a solid will proceed in a continuous fashion at rising levels within the hole. Below the level of current liquid additions will be solids which get progresively dryer and hotter with depth until melting occurs. The melting is expected to form a pool of molten waste and rock. Below this level will be resolidified rock-waste melt. Within the boiling zone, the height of the aqueous portion of the waste column must be maintained at a controlled value to prevent surging of the liquid surface.

Addition of waste will be discontinued and the contents of the hole permitted to dry when a predetermined level is reached. This level is expected to be in the range of 6 to 10 kilometers below the surface. It is estimated that three deep holes are required to contain the waste produced by the reference reprocessing plant. When all the waste is dry, the remaining part of the hole will be plugged with a sealant and perhaps some rock backfill.

The typical shielded cell facility requirements are basically the same as those for Concept 5, shown in Figure 4.41.

The characteristics of the concept for placing liquid waste in a deep drilled hole with in-place drying and conversion to a rock-waste matrix are presented in abbreviated form in Table 4.30.

4.1.10 Liquid Waste Emplaced By Hydraulic Fracturing - In-Place Conversion to a Solid

In disposal by hydraulic fracturing, liquid waste is mixed with dry solids to form a cement grout slurry which is then pumped down a well and out into a fracture or fractures in the subsurface rocks where the cement-waste mix hardens. For this concept, the reprocessing plant must be located at the waste disposal site.

Acting upon recommendations from a 1955 special committee of the Earth Science Division, National Academy of Sciences-National Research Council, a group from the American Petroleum Institute(125) reviewed the technological problems associated with waste disposal in the earth, outlined the technology in use that might be adapted to disposal, suggested approaches to the problems and listed related Research and Development requirements. One suggested method of disposal of low-level waste, hydraulic fracturing, was subsequently dedeloped and tested at Oak Ridge National Laboratory (ORNL).(126-131) From 1960 to 1966, seven experimental injections were made, involving a total volume of about

TABLE 4.30. Summary of the Overall Characteristics; Liquid Waste Emplaced in Deep Holes; Initial Reflux Cooling; Melting:

Waste Form	Aqueous waste during emplacement; rock-waste matrix after in-place melting and solidification.
Waste Concentration	High as liquid; moderate to high as final solid.
Operational Features	Surface operations only. Surface vapor condensing and recycle system. In-place, self-conversion to melt; eventual self-cooling to solid.
Candidate Geologic Environment	Might include intrusive igneous or crystalline metamorphic formations.
Retrievability	Essentially not retrievable.
Monitorability	Limited; can measure some temperatures and released radioactivity within parts of hole for limited time; can detect radioactivity in nearby water-bearing formations if it should occur. Can monitor surface support.
Extent of Knowledge	Limited; hole depth beyond current state-of-the-art in many rocks. Melt-down and cooling knowledge is largely inferred.
Isolation	Deep geologic isolation from surface, below about 6000 meters. Depends upon mobility of molten column of rock-waste; depends partly upon effective manmade sealing of modest number of manmade penetrations.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathway attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Ability to control melt stage must be predicted before starting melt.

2,500,000 liters of low-level liquid waste. Results of the experimental program were successful to the point that routine disposal of selected low-level liquid radioactive waste by hydraulic fracturing was begun in December 1966. Details of the hydraulic fracture disposal concept developed by ORNL for disposal of low-level radioactive waste have been previously documented.(126-134)

Figure 4.50 shows the basic concept developed at ORNL as a radioactive waste grout sheet spreading laterally through an artificially created fracture in a shale bed. The total volume of waste that can be injected at any one site is determined by the lateral extent of each horizontal fracture and the vertical rise (uplift) of the overlying formations. Surface elevation measurements are taken after each injection. When the amount of vertical rise reaches a specified level that indicates no further horizontal injections can be made, the well is sealed and a new well drilled at another location.

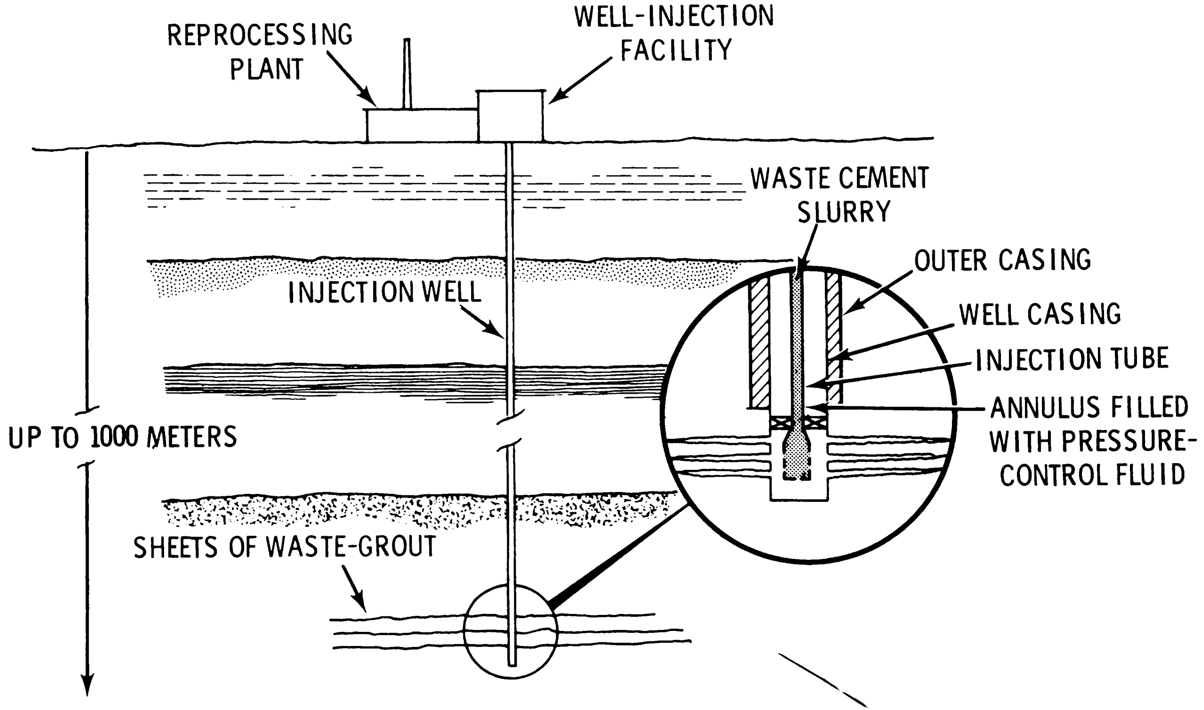

FIGURE 4.50. Liquid Waste Emplacement by Hydraulic Fracturing - In-Place Conversion to a Solid

Figure 4.51 shows the details of a typical waste injection well that might be drilled and prepared prior to disposal.(135) The cased well is prepared for injection by perforating the casing at the desired depth. The initial fracture is induced in the disposal formation through the well casing by pressurizing with water at about 130 atmospheres. Figure 4.52 shows a flow diagram where liquid low-level waste is mixed remotely in a shielded surface facility with pre-blended dry solids (principally cement). The resulting slurry then is pumped down the well and out into the disposal formation. The surface facility contains the shielded cells, which in turn contain pumps, mixers, injection head, storage tanks, etc.

Pumping pressure and rate of injection are sufficient to cause the performed fracture to extend and accept the waste-grout mix. Pressure is maintained on the waste-cement slurry while it hardens to form a thin horizontal grout sheet of about 3 millimeters thickness and 180 meters radius for each 300,000 liter waste batch. Subsequently, pre-drilled monitor wells are logged and precise surface measurements taken to confirm the emplacement position, distribution, and physical status of the injected waste. As soon as solidification has been achieved, in 8 to 24 hours, further disposal injections can be made by repeating the procedure successively at higher elevations up the well, thereby creating a stack of horizontal grout sheets. After the prescribed number of injections are made, the well is sealed.

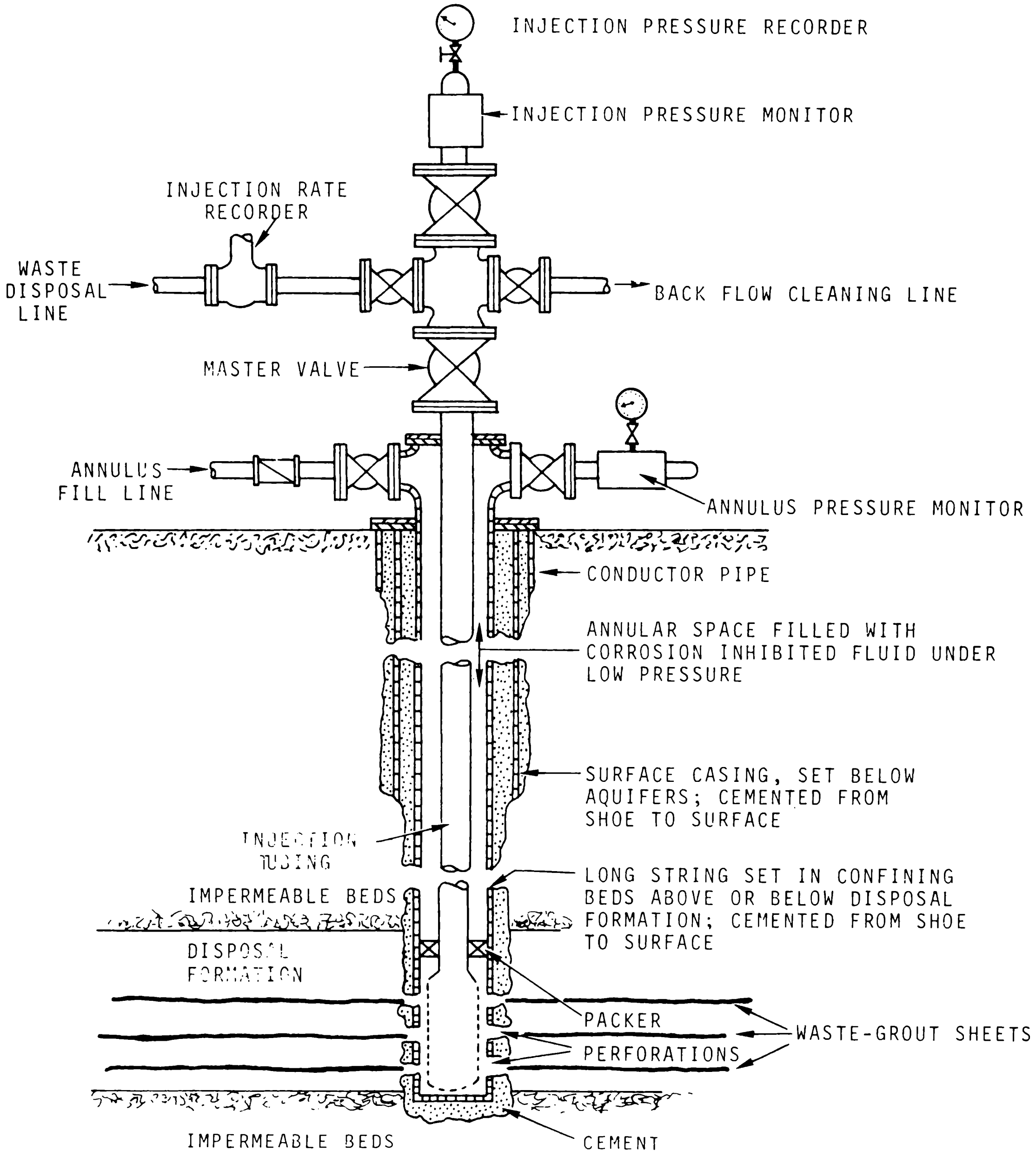

FIGURE 4.51. Waste Injection Well for Hydraulic Fracturing (Source: Reference 135)

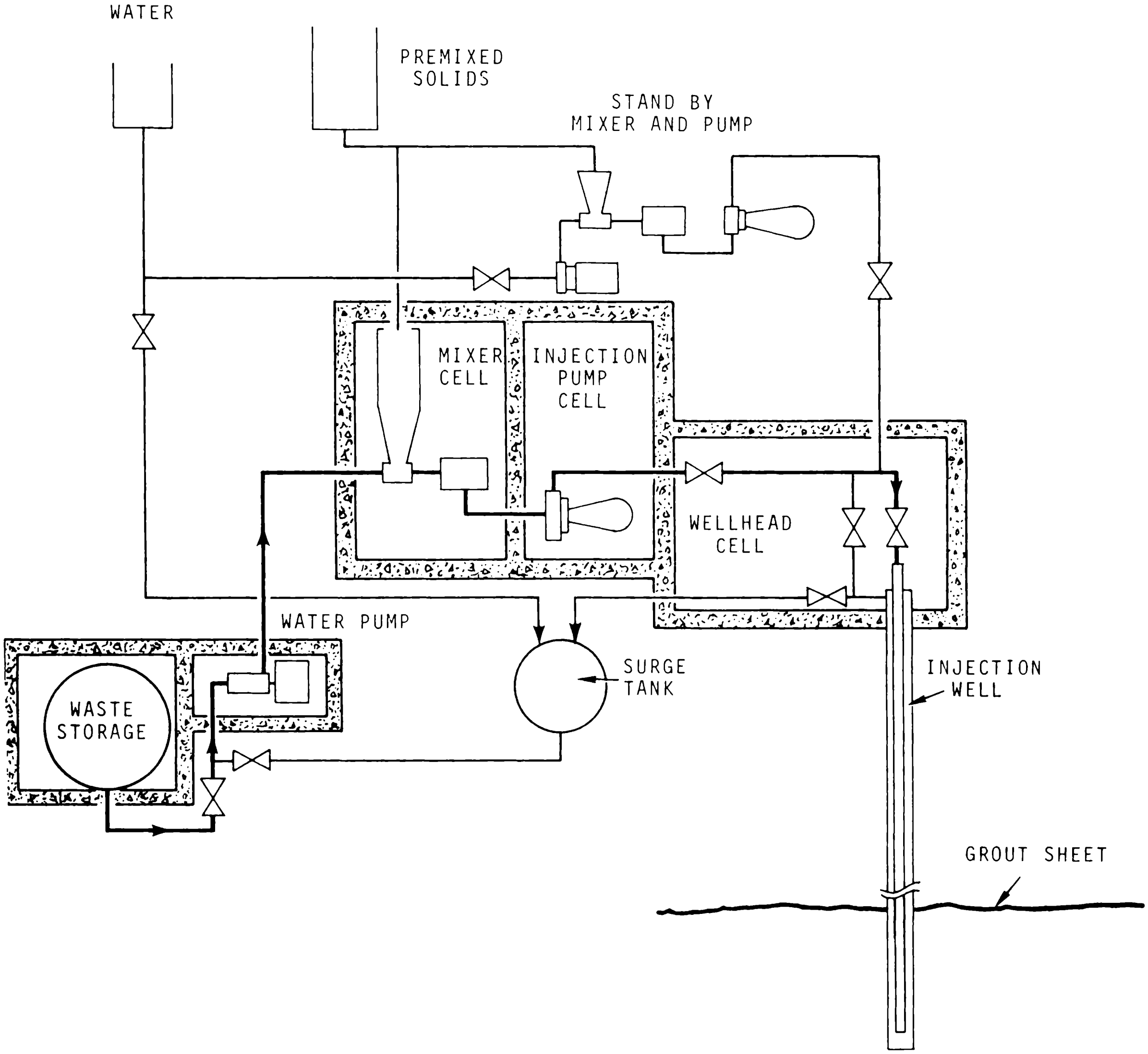

FIGURE 4.52. Flow Diagram of Surface System for Hydraulic Fracturing--Grout Mix-Waste Disposal (Source: Reference 131)

The volume of subsurface space required for disposal by hydraulic fracturing of all high-level radioactive waste expected to be generated by the year 2000 will depend primarily on the temperature rise that can be tolerated without affecting the physical properties of the hardened grout or causing release of natural fluids from the disposal formation. An additional limitation will result from the quantity of waste that can be mixed with the grout and still permit rapid solidification. For shales with a large amount of the clay mineral montmorillomite present, a comparatively large amount of water might be released if heated much above 100°C. It is roughly estimated that the grout can safely contain up to about 40 Ci/liter at a grout sheet spacing of 4.5 meters without reaching the 100°C limit. Further evaluation of temperature limits are needed before a concentration limit and distance between grout sheet layers can be more accurately defined.

Existing disposal operations at ORNL handle waste concentrations up to about 0.25 Ci/liter. With additional shielding of their present surface injection system, it has been estimated that radioactive waste concentrations could be readily increased to above 3 Ci/liter.

For a five-year interim storage period for the liquid waste, the inventory of waste generated by a 5-MT/day fuel reprocessing plant operating 25 years will total about 2×10^4 megacuries. Assuming a dilution of the waste into a slurry containing 40 curies per liter, a minimum volume of 5×10^8 liters would be generated for the reference fuel reprocessing plant.

Experience with the existing disposal facility at ORNL indicates that a minimum of about 1.5×10^7 liters of waste grout can be injected for each well with a high degree of assurance that a potential breach of containment will not occur. The maximum volume for injection cannot readily be calculated beforehand, but it is expected to be about 5×10^7 liters for the ORNL site, which is several times greater than expected for most potential sites. The spacing of the individual disposal wells would have to be approximately 1.5 kilometers apart to preclude any uncontrolled added stress on the confining rock formation. For the reference case of 40 Ci/liter, a surface area of about 65 square kilometers, or about 8 kilometers on a side, would be required for disposal. Therefore it is essential that the maximum concentration of radioactivity be used to reduce the area for disposal. Table 4.31

TABLE 4.31. High-Level Waste Disposal by Hydraulic Fracturing - Waste Injection Data

Concentration, Ci/liter	0.25	3	40	100
Waste volume per fuel reprocessing site, liters[a]	8×10^{10}	6.7×10^9	5×10^8	2×10^8
Injection wells per site (18×10^6 liters/well)	4,400	380	30	11
Total injections per well	60	60	60	60
Total area (kilometers^2) wells on 1.5 km center	10,000	850	65	25

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[a] Data based upon reprocessing 45,625 metric tons of irradiated fuel and holding the waste for a five-year period. This is the waste from processing 5 MT/day of fuel for 5 years. Reprocessing this quantity of fuel will generate waste with 20,000 μCi of radioactivity.

summarizes the data for waste mixes with variations in radioactivity concentrations.

Overall characteristics of the concept of hydraulic fracturing and grout injection of high-level radioactive waste in geologic formations are summarized in Table 4.32.

4.2 SYSTEM REQUIREMENTS FOR THE CONCEPTS

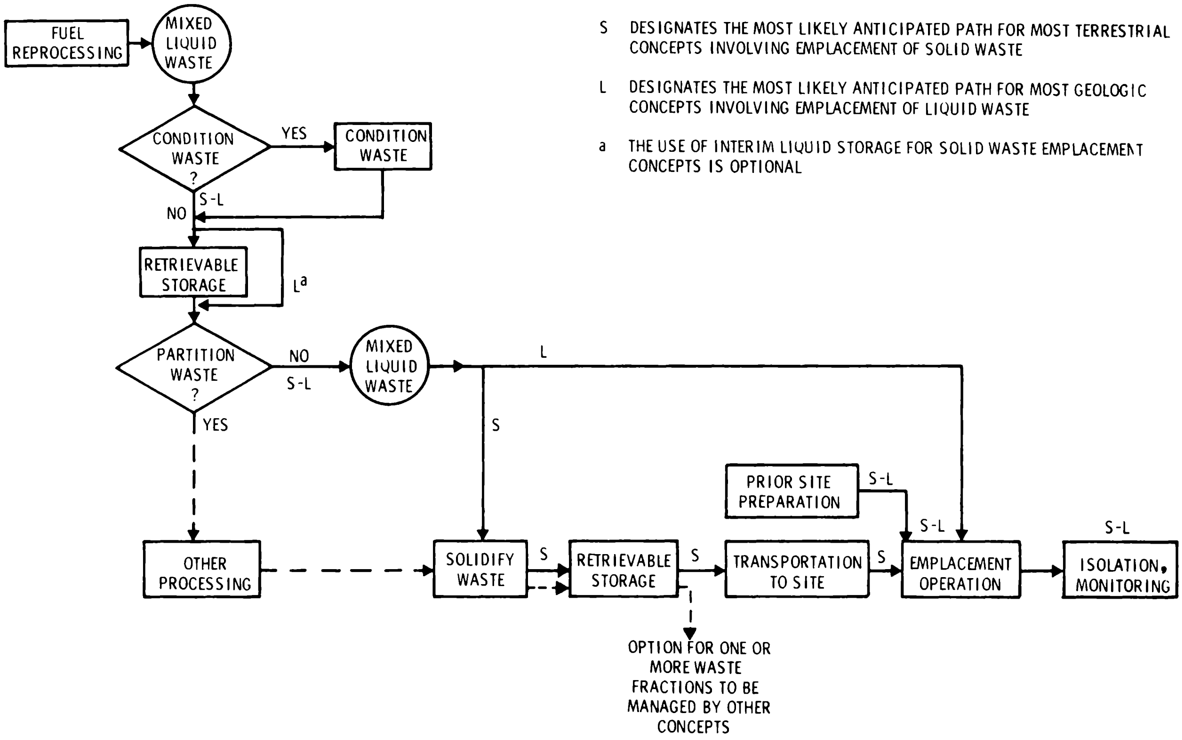
Basic system requirements for the ten concepts are summarized in Figure 4.53. This figure shows that in disposal of solid waste, optional interim retrievable storage of unconditioned high-level liquid waste arising from chemical reprocessing of spent fuels is expected to be followed by solidification and encapsulation; retrievable storage of the resulting canisters; transportation to the disposal site; and, finally, by emplacement in the geologic formation.

For most concepts to dispose of waste in the liquid form, the most likely anticipated path does not include interim retrievable liquid storage. The aqueous waste would be transported directly to the nearby disposal site by pumping the waste through pipes.

In the hydraulic fracturing concept, high-level liquid waste arising from the chemical reprocessing of "spent" fuels, after receiving some

TABLE 4.32. Summary of the Overall Characteristics; Liquid Waste Emplaced by Hydrofracture; In-Place Curing:

Waste Form	High-level liquid waste mixed with dry cement to form slurry during emplacement; in-place solidification 8 to 24 hours after injection.
Waste Concentration	Moderate as solid after dilution with cement.
Operational Features	Surface operations only on site of fuel reprocessing plant.
Candidate Geologic Environment	Expected to be suitable only in low permeability, thick, horizontal shale beds.
Retrievability	Essentially not retrievable.
Monitorability	Very limited; can measure initial spread of grout sheet; can measure some temperatures and radioactivity release for limited time; can detect radioactivity in nearby water-bearing formations if it should occur.
Extent of Knowledge	Technique of hydrofracturing well developed; each site will require extensive geologic study. Temperature effects of waste on host rock inferred.
Isolation	Moderate depths of 300 to 1000 meters below surface provides primary isolation by impermeability of host rock. Secondary confinement provided by ion exchange capacity and cement waste form.
Possible Pathways to Man's Environment	Natural pathways such as fractures if flowing water present, volcanism, seismic activity, erosion, etc. Pathway attributed to man's actions such as drilling into repository, sabotage, etc. See also Volume 1, Section 3.
Other	Chemical and thermal compatibility must be verified prior to each injection.


S DESIGNATES THE MOST LIKELY ANTICIPATED PATH FOR MOST TERRESTRIAL CONCEPTS INVOLVING EMPLACEMENT OF SOLID WASTE

L DESIGNATES THE MOST LIKELY ANTICIPATED PATH FOR MOST GEOLOGIC CONCEPTS INVOLVING EMPLACEMENT OF LIQUID WASTE

a THE USE OF INTERIM LIQUID STORAGE FOR SOLID WASTE EMPLACEMENT CONCEPTS IS OPTIONAL

FIGURE 4.53. System Requirements for High-Level Radioactive Waste Management in Geologic Locations

conditioning, is sent to retrievable liquid storage, optionally allowed to age up to five years, and finally injected as a waste-grout mixture into a selected geologic formation. Since the high-level waste is liquid, the fuel reprocessing site must be located near the injection site.

Details concerning the specific system requirements of waste treatment and handling prior to emplacement at the disposal site, site preparation, transportation, operation of the site, and final sealing of the repository are presented below.

4.2.1 Prior Waste Treatment and Handling

The anticipated needs for the concepts currently do not require any special reprocessing restrictions, chemical treatment of the waste such as neutralization, or chemical separations such as fractionation of the waste.

For solid disposal concepts the bulk high-level radioactive liquid waste is solidified and placed in canisters suitable for transporting from the reprocessing plant to the disposal site. Before final emplacement, retrievable storage of the canisters by alternative concepts is likely and could be done for time periods in the order of 100 years. Such storage will comply with present policy. Canister transport, repair, decontamination, and recanning could be required steps during such interim retrievable storage of the canisters.

For concepts which dispose of waste in the liquid form, the bulk high-level radioactive liquid waste is supplied by the reprocessing plant. Optionally the waste may be conditioned and stored retrievably by alternative concepts for an interim time period. Chemical adjustment, such as neutralization, and storage as liquids in tanks for up to five years are examples of these options. The waste could be chemically separated into an actinide stream and one or more fission product streams. Such separations may be desired to permit management of selected components of the waste (e.g., isotopes with short-or long-term biological hazards) by alternative concepts; to adjust heat generation rates; to recover useful constituents; also, in the case of hydraulic fracturing, to provide a compatible waste-grout-rock mix for a particular site. However, it was assumed in this study that all concepts have the potential to handle the total high-level waste without separation of waste constituents.

For hydraulic fracturing the primary waste treatment and handling steps expected to precede injection disposal would be interim liquid storage and liquid conditioning. Prior liquid storage would be highly beneficial to allow necessary heat decay. The maximum allowable heat level in the injected waste depends on the chemistry and physical properties of the host rock and the waste. The host rock chemistry determines to some extent the type of grout mix that can be used, which in turn will impact the conditioning required by the waste stream.

4.2.2 Site Preparation

The geology and hydrology of potential sites must be thoroughly investigated to assure that the requirements for waste disposal are satisfied. The existing knowledge of the geology and hydrology of each potential site must be studied and evaluated thoroughly at locations all around that of the proposed cavity. This information must be checked with information available from any existing nearby wells. New test holes would likely be required at the proposed site and at selected locations around the site to supplement available information on the hydrology and geology and to provide future monitoring capability. In addition, evaluations must be made of the geochemistry and potential chemical interactions between the host rock and the waste constituents. Detailed information about thermal and mechanical properties of the host rock will be required and thermal and mechanical models of the system developed and confirmed.

Site evaluation will include detailed analysis of population centers and densities, transportation facilities, and the potential for natural resources. The latter must include location and status of known resources and the potential for future resource development.

Additionally, for concepts involving disposal of liquid waste, the site must meet the requirements for a fuel reprocessing plant as well as for an underground disposal system because the concept involves disposal of the high-level waste at the site of the fuel reprocessing plant. It is assumed here that the basic site requirements for the fuel reprocessing plant (e.g., meteorology, seismology, geology, and hydrology, topography, demography, site exclusion etc.) are considered and that candidate sites meet these requirements.

Because the characteristics of the upper several thousand meters are relatively unimportant for the deep-hole concept, many parts of the United States that are mantled by layers (1 to 10 kilometers thick) of permeable sedimentary rocks but are underlain by metamorphic or igneous rocks may provide suitable sites for the deep drill hole concept. The concept, therefore, offers the possibility of safe disposal of waste at or near processing plants where other suitable rock media may not be available at shallow or moderate depths.

The main requirements of a site for waste disposal by hydraulic fracturing are a suitable geologic formation at a reasonable depth that will fracture horizontally (or nearly so) under pressure. However, control by formational dip or bedding planes appears to be such an advantage in the forming of horizontal fractures that it may be desirable to restrict hydraulic fracturing waste disposal to thin-bedded formations such as shales. More massively bedded shale formations, mudstones and some volcanic rocks may be suitable in other respects and would be worth testing for horizontal fracture potential.

The site evaluations would be followed by site selection, design and general surface facility construction. Facility construction may in certain cases be preceded by the construction and operation of a pilot facility.

For concepts 1, 3 and 4 (mined cavities) site preparation is basically similar: surface and underground facilities, drilling of monitoring holes, installation of monitoring equipment, and initial mining or drilling will be completed prior to the burial of the first canister. Subsurface facility construction would begin with drilling the main hole and excavating the tunnels. The tunnels would then be prepared structurally, cracks would be plugged, additional small holes radiating from the cavity would be drilled, and temperature and other monitoring instruments would be installed and back-sealed. Monitoring instruments would be installed and piping and instrumentation within the drill hole completed. The surface facilities would be completed and the piping and instrumentation connected to the below-ground facility.

Concepts 2 and 5 (involving waste-rock interaction) resemble each other in site preparation requirements. Subsurface facility construction would begin with drilling the main hole and excavating the cavity. The cavity would then be prepared structurally, cracks would be plugged, additional small holes radiating from the cavity would be drilled, and monitoring instruments would be installed and back-sealed. The cavity liners would be fabricated and installed. Monitoring instruments surrounding the cavity liner would be installed and piping and instrumentation within the drill hole completed. The surface facility would be completed and the piping and instrumentation connected to the below-ground facility.

The site for Concept 6 must be suitable for a 5-kiloton nuclear explosion carried out at depths typically more than 3 kilometers. Cavity formation would precede facility construction. One of the main holes would be drilled and the cavity produced by a nuclear explosion. The hole plug would be redrilled and the cavity checked for suitability. The second main hole is drilled if all cavity checks are affirmative. Piping and instrumentation within the drill hole is to be installed and the surface facility constructed. The site is ready for operation once the surface and below-ground piping and instrumentation is connected. It is possible that the nuclear explosion must be completed before construction of the fuel reprocessing plant is permitted to start.

Concept 7 (matrix of drilled holes) would include in initial facility plans layout of the hole array. When the array was established, equipment would be assembled and the first set of holes drilled. After this, the concept has the same basic steps in site preparation as Concepts 8 and 9. Surface facilities, drilling of waste disposal and monitoring holes, installation of monitoring equipment, and nonradioactive testing would be completed prior to burial of the first canister. It is expected that hole drilling, burial, and final sealing can proceed simultaneously in separate areas of the site after proof testing the system.

For Concept 10 (hydraulic fracturing) the preparation of the disposal site consists of drilling, casing, and testing for the disposal well. All monitoring holes and equipment installations will be completed prior to commencement of disposal operation. Each individual well disposal site may require a complete demonstration experiment using "non-radioactive" simulated waste. When conditions are considered satisfactory, a surface pipe would be connected to the radioactive waste in preparation for injection operations on a batch basis. A surface facility is needed for each well consisting of shielded cells for handling the high-level waste. Surface hardware, shielding, and mixing facilities would be designed and installed. A backup storage system in the form of a tank (see Figure 4.52) would be installed to handle the aqueous waste contaminants which result from backflushing and cleanout of the well and equipment after each injection.

4.2.3 Transportation to the Site

Waste solidification facilities or interim retrievable storage facilities and the disposal site are likely to be separated by large distances. Transportation to the disposal site would be accomplished by placing the canisters into massive, heavily shielded shipping casks weighing up to 100 tons. The shipping casks are then loaded onto special rail cars, trucks, or possibly barges for transportation to the site.

At the disposal site, transportation is accomplished by mechanisms such as cranes and shielded vehicles.

The concepts for liquid disposal are considered to be applicable only on the site of a nuclear fuel reprocessing plant. Transportation requirements, therefore, would involve pumping aqueous waste through direct pipelines within the boundaries of the exclusion area to the surface facility above each well site. The pipelines used for transporting the radioactive waste to the repository would be heavily shielded and double-contained.

4.2.4 Operation of the Site

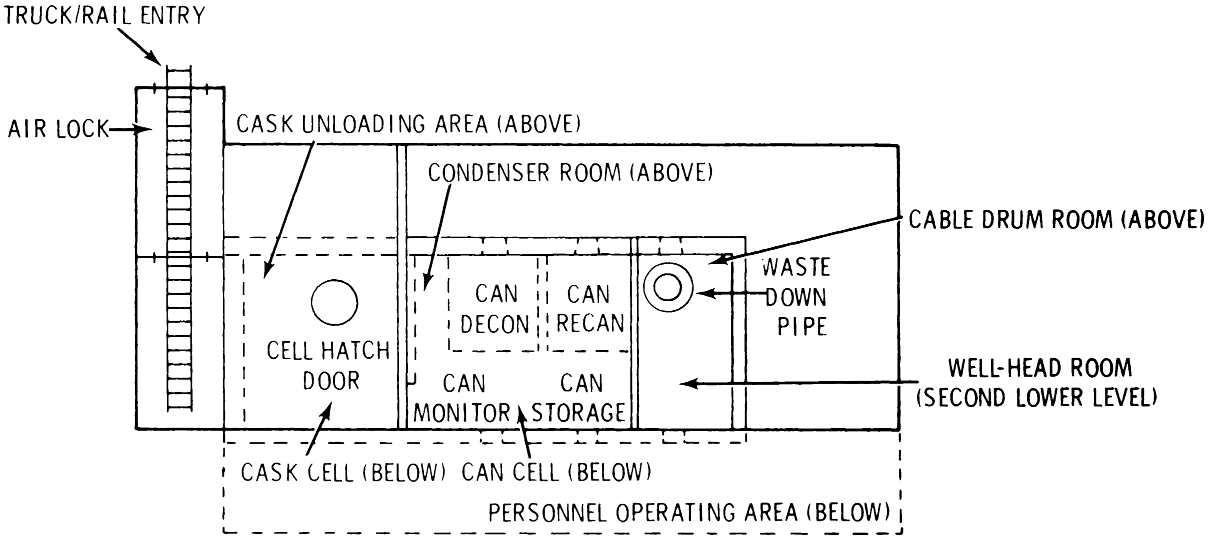
Normal site operation can be initiated when construction is complete and the facility has been thoroughly tested and operated under simulated conditions to assure that all components perform as designed. Liquid waste concepts would initially require the addition of some water or nitric acid to the repository to bring the liquid volume to an operable level. Waste is then added over a period of a few months until steady-state boiling has started.

Operation of the site can be categorized into waste receiving and handling; waste emplacement in the repository; and auxiliary or support functions.

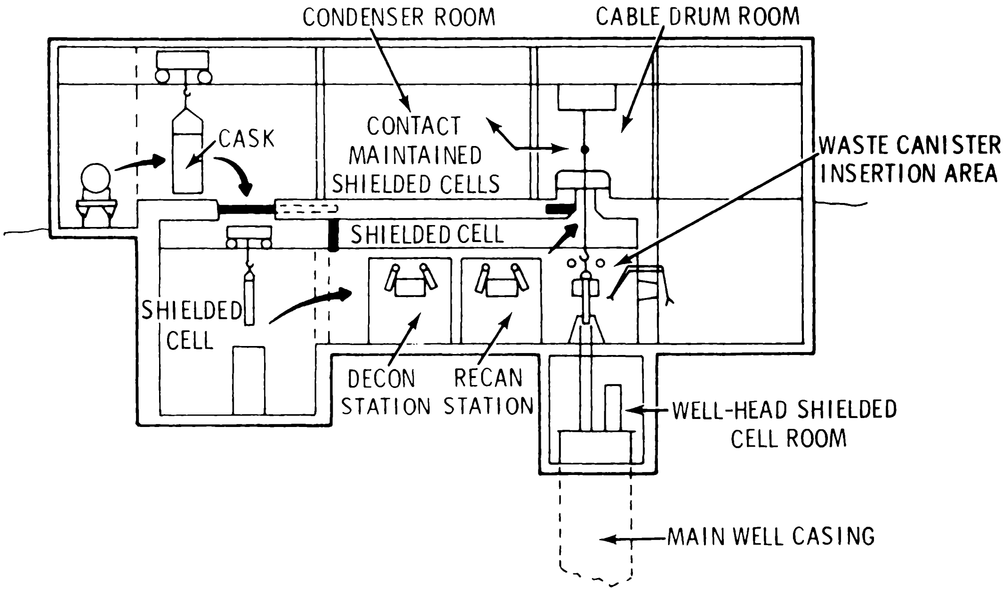
Waste Receiving and Handling. Concepts for waste receiving and handling were developed in this study. This section treats those concepts for receiving high-level radioactive waste at the surface facility and the handling steps required prior to emplacement in the repository. Obviously, other concepts could be used, but those described here are believed to be representative of potential concepts.

Solid waste would arrive at the site by truck, rail, or possibly barge. Upon arrival at the site, the shipping cask and its carrier truck or rail car are moved via an air lock into the cask unloading building, which is equipped with cask cooling and decontamination equipment. A typical surface facility for handling solid waste is presented in Figure 4.54. The cask atmosphere is sampled and the cask decontaminated if required. The cask is removed from its carrier and lowered into a shielded cell by a large, permanent bridge crane onto a cask transfer cart. The cart is used to move the cask below the hatch of a second shielded cell located above the first shielded cell. Individual canisters are removed from the cask by a remotely operated crane, inspected, repaired or recanned if necessary, and then transported to a transfer shaft where they are lowered by cable into the repository. The "surface" shielded cell complex is equipped with facilities for canister examination, decontamination, and recanning.

The steel cased and cemented transfer shaft is essentially an extension of the "surface" hot cell. The lower end of the shaft terminates in a transfer vault or shielded cell that is located in the geologic formation at the repository level. All manipulations in the "surface" and subsurface hot cells and the transfer shaft are conducted remotely using cranes, manipulators, and shielding windows.



PLAN OF SURFACE HANDLING FACILITY



SECTIONAL ELEVATION THROUGH SURFACE HANDLING FACILITY

FIGURE 4.54. Surface Facility Layout for Receiving Solidified High-Level Radioactive Waste

The matrix of drilled holes is similar to other solid waste disposal concepts except for use of a charging vehicle located in the surface facility. Canisters are received in the second shielded cell and, after inspection, lifted into the shielded cask of the vehicle for transport to the desired disposal hole. (See Figure 4.45.)

For all liquid disposal concepts except hydraulic fracturing, liquid waste is pumped through shielded lines directly from the reprocessing plant to the repository located in the geologic formation.

The essential components of a hydraulic fracturing disposal plant and their function are illustrated in the schematic flow diagram Figure 4.52. Each batch of approximately 300,000 liters of waste is analyzed and a mix formulation established that will assure a pumpable slurry and a grout that will cure to the desired solid after injection. Prior to the injection, the dry solids are blended and temporarily stored at the site. After the equipment has been checked, the well is prepared by jet perforation at the depth and the fracture initiated using water at high pressure, 130 atmospheres.

Waste Emplacement. For solid waste disposal concepts 1, 3, and 4, individual waste canisters are moved from the subsurface shielded cell into a shielded transfer vehicle at the repository level. This transfer could be accomplished by lowering the canister onto a transfer cart, moving the cart horizontally by a built-in device, and raising it with a device which is part of the transfer vehicle, (see a graphic presentation of a typical subsurface facility in Figure 4.32). Upon receiving the canister, the subsurface transfer vehicle transports the waste package to its final storage location.

The vehicle used in Concept 1 is equipped with hoppers and mechanisms for backfilling the hole after the waste package has been deposited. The hole may be backfilled with crushed rock that was removed, with sand, or with some type of cement. In the event a waste canister fails, this backfill provides a partial barrier against escape of radionuclides into the tunnel area as well as providing some shielding to the tunnel area. After the last canister is placed in a hole, the top 1.8 to 2.4 meters of the hole are filled with a sealant to provide additional isolation and shielding.

After all holes have been filled and sealed, individual burial tunnels or rooms are sealed from the rest of the repository by a bulkhead. The tunnel or room may be backfilled immediately, at some later time, or perhaps not at all; backfill could be crushed rock material previously removed, cement, a combination, or other materials.

The process for placing the pods and canisters described in Concept 3 is similar to Concept 1. The main differences are: 1) the vertical travel of the shielded carrier must be greater to accommodate the finned surface extending above the tunnel floor; 2) the unwelded closure or lid must be placed inside the pod above the canister; and 3) the top of the pod must be sealed by a welded closure.

Concept 4 waste emplacement differs from Concept 1 only in that 1) cover blocks must be removed and replaced during emplacement of the canister, and 2) no backfilling of holes is required.

When placing waste canisters for final disposal in Concepts 2 and 8, seals on the transfer shaft access port are opened and the canister lowered through the access port. Provision must be made for airlocks and cable seals to prevent gases generated down the hole from escaping at this time. The canister is lowered into the repository in a controlled manner to minimize damage to the canisters and the hole.

Routine operation of the system described in Concept 2 will involve either continuous or frequent batch addition of the canisters to the cavity, addition of recycle water to the cavity at a rate to maintain the liquid volume in the cavity at the desired level, and operation of the steam condensing and treatment system at the surface as long as cooling of the waste is allowed.

Canister emplacement is initiated in Concept 7 by moving the charging vehicle to the desired hole. The vehicle is accurately positioned over the hole. Any portable shielding required is moved into place and any couplings required for seal purposes are made. The hole sealing cap is opened and the canister lowered into the hole in a controlled manner to minimize damage to the canisters and the hole. The area surrounding and immediately above the canister may then be backfilled. The above processes are repeated until the hole is filled to the desired level. When the hole is filled to a predetermined level, the void space above the string of waste canisters is filled with permanent sealants.

Waste emplacement and routine operation of aqueous systems described by Concepts 5, 6 and 9 will involve either continuous or frequent batch addition of high-level aqueous waste to the repository, addition of recycle water or nitric acid to the repository at a rate to maintain the liquid volume in the repository at the desired level, and operation of the steam condensing and treatment system at the surface as long as boiling aqueous waste exists in the cavity.

Referring to the hydraulic fracturing concept flow diagram, Figure 4.52, the dry solids and liquid waste are vigorously mixed, at a constant flow rate, by the jet mixer. The slurry is then pumped to the wellhead, down the well, and out into the prefractured shale. After all the waste batch has been injected, a "nonradioactive slug" of water-grout is emplaced to partially clean the well. Pressure is maintained on the system until the grout mix has solidified (8 to 24 hours).(121) The system is then flushed and decontaminated as necessary. The jet mixer, the high-pressure injection pump, and the wellhead are enclosed in individual radioactive processing cells to provide shielding and for ease in decontamination.

During injection operations, close monitoring of injection pressures is required to assure that vertical fractures do not form during injection. The waste-cement mix temperatures are monitored to assure that the heat limit of the mixture is not exceeded.

When the waste disposal limit is near for a disposal well, operations would be terminated, the well would be sealed, and a new disposal well and surface facility constructed at an appropriate distance.

Concepts 2, 5, 6, 8 and 9 permit melting of the waste and surrounding geologic formation resulting in a rock-waste matrix. When the decision is made to proceed with in-place fixation of the waste, drying of the repository contents is initiated by reducing the quantity of recycled condensate. The aqueous level gradually decreases in the repository until the liquid is evaporated. At some point before or during the drying stage chemicals could be added to the repository if needed to control the chemistry of the final molten pool of waste and rock. When the drying has progressed to a predetermined state, the drill hole and any other penetrations into the repository will be quickly sealed by a predesigned, high-integrity seal system and the steam condensing system will be shut down. Incomplete removal of volatile constituents from the repository before the final sealing should not pose a problem if the final repository pressure does not exceed lithostatic pressure.

After the repository is sealed, the waste will continue to melt, and over a period of tens of years the surrounding rock will melt to a predetermined extent. After 50 to 100 years the molten rock and waste will begin to cool and solidify. The time period required for solidification to be complete has not yet been calculated, but will likely be hundreds to perhaps thousands of years. During the melting and solidification periods the only operation required will be monitoring various conditions around the disposal area.

If it is decided that in-place melting should not be permitted, operation of the steam condensing and recycle system can be continued until the waste has decayed to a point that melting will not occur or until the waste is removed from the repository. Concept 5 permits most of the waste to be pumped to liquid storage facilities at the surface where it can be dealt with as desired. The sludge in the bottom of the repository is removed by slurrying and/or dissolution techniques. Depending on the extent of cleanout and decontamination required, final decontamination and restoration activities could be extensive.

Auxiliary or Support Functions. Auxiliary or support functions associated with emplacement operations include radiation monitoring, maintenance and repair of facilities, quality assurance control, security surveillance, engineering support, equipment decontamination and the management of any new waste that is generated.

Hole drilling and preparation is essentially a continuous operation for the deep drilled hole and matrix of drilled hole concepts because of the interaction between reasonable drilling rate, depth of the holes, and the number of holes required. Holes are drilled and casings set to the depth required. In-hole instrumentation is added and tests made to confirm that each hole is suitable for use. Each of the deep drilled holes may require up to six years for completion.

For all concepts, site monitoring will continue throughout normal operation and for some currently unknown time in the future but is expected to decrease in frequency as data are accumulated. Monitoring will involve measurement of radioactivity in monitoring holes surrounding the site and surveillance of the position and status of the repository. It may also be desirable to install temperature monitors in some selected holes. In addition, the site will be controlled with respect to other uses for a time which depends upon the long-term toxicity of the waste.

Monitoring may be carried out using radiation detection in small-diameter cased wells to identify the position, extent and radioactivity of the solidified waste. Initial data would come from the recovered core of the test wells. Subsequently, the core holes could be logged with a variety of geophysical tools at regular intervals to verify the repository stability. Some monitoring wells would be drilled prior to the disposal as part of the site evaluation, some to monitor the disposal as it progresses and some for final evaluation. Each monitor well would be sealed when it no longer serves its purpose.

4.2.5 Final Sealing from Man's Environment

Final sealing of the waste from man's environment involves plugging the hole(s) into the waste-bearing area of the rock. Depending upon the particular disposal concept, isolation is provided by the waste form, waste canisters, and/or cavity linings as well as the geologic formation until final sealing is completed.

Sealing of the access hole to the waste will depend on a man-emplaced sealant. Sealing techniques used by the mining and drilling industry(81) have only been demonstrated for the time range of about 50 years. These conventional sealants are generally forms of cements or clays.

4.3 GEOLOGIC CONSIDERATIONS FOR SPECIFIC CONCEPTS

Viable concepts for disposing of radioactive waste in appropriate geologic formations will be governed by the following geologic considerations to assure safe disposal and effective long-term containment of the waste:

- Thermal properties of the host rock
- Engineering properties of the host rock
- Water content of the rocks and water movement
- Mineral resources potential
- Geothermal resource potential
- Geographic characteristics
- Seismicity, and faulting
- Depth of disposal
- Dimensions of the host rock

The following discussions of the above geologic considerations are of a general nature. Although general, information contained within the discussions is sufficient to allow identification of large geologic areas having potential for use as sites for disposal of high-level radioactive waste. After identifying specific candidate sites located within the larger areas all the geologic factors of the sites will be considered in great detail and examined with respect to the needs of a waste disposal site.

The most suitable rock media for the various concepts considered appear to be 1) <u>intrusive igneous</u> rocks (e.g., granite) or <u>crystalline metamorphic rocks</u> (e.g., quartzite) because of their low permeabilities and high mechanical strengths, 2) <u>salt</u>, either in stable domes or thick beds because of its low permeability and self-sealing property, and 3) <u>tuff</u> (welded volcanic ash) and <u>shale</u> because of their very low permeabilities and high ion-exchange capacities. No order of preference was established in this study, nor is it meant to be implied here. Sedimentary rocks other than shale and salt, and volcanic rocks, exclusive of tuff, are considered generally unsuitable for waste emplacement because of their potential for high permeabilities. Rock types which appear attractive for specific disposal concepts are enumerated in sections 4.0.3.9.1 through 4.0.3.9.5.

The concepts based upon emplacement of liquid radioactive waste in underground cavities with in-place conversion of the waste to solids would have more stringent geological restrictions than those for solid waste emplacement concepts. The restrictions are needed because of (1) the higher mobility of the waste in its interim liquid form, (2) interim manmade barriers (a canister) are not present, and (3) the concentration of waste and its heat are significantly higher than for initially solidified waste.

An important consideration for emplacement concepts incorporating in-place conversion to a rock-waste matrix is whether or not extensive fractures will develop as a result of the expansion of molten rock due to radiogenic heat. Such fracturing may not extend far into the medium but provides some potential, nevertheless, for leakage to adjacent, possibly permeable, saturated zones. Also, there is some potential for geysering (expulsion of fluid material from the repository) resulting from the buildup of heat after final sealing of the hole.

A relatively large amount of information is available on the geology of conterminous United States. However, the knowledge of the geologic environment at great depth (to the order of 16 kilometers) is only inferred from geophysical measurements. Only a few drill holes have penetrated to depths of 9 kilometers and no drilling deeper than 9.3 kilometers has been done.(136)

Regulations governing the acceptability and operational safety of sites for handling radioactive materials are found in Code of Federal Regulations, Title 10 (10CFR), Chapter 1, Part 20, "Standards for Protection Against Radiation"; 10 CFR, Part 50, "Licensing of Production and Utilization Facilities"; 10 CFR, Part 100, "Reactor Site Criteria"; and their appendices, in particular, Appendix A, 10 CFR 100, "Seismic and Geologic Siting Criteria for Nuclear Power Plants." In addition, guidance can be found in AEC Manual Chapter 6202, "Site Selection," Chapter 6203, "Site Development Planning," and their appendices.

4.3.1 Thermal Properties of the Host Rock

The rock thermal property of primary importance to radioactive waste disposal is thermal conductivity. Values for thermal conductivities of some potential host rocks are listed in Table 4.33.

TABLE 4.33. Typical Thermal Conductivity of Potential Host Geologic Rocks

Rock	Average Thermal Conductivity(137) millical/cm-sec-°C
Quartzite	9 - 19
Salt	13 - 17
Granite	6 - 9
Shale	3 - 7
Tuff	0.6 - 1[a]

a. Value estimated from similar materials

For all concepts a relatively high thermal conductivity of the host rock is desirable to efficiently and steadily dissipate the heat of radioactive decay from the chronic heat source. Good conduction of heat will generally allow for minimizing the extent of disposal areas and minimizing cost.

It is desirable for the melting point of the host rock to be greater than the melting point of the waste material. When the waste canister fails, a higher melting point rock would generally tend to minimize interaction between waste and the host rock.

For concepts with in-place conversion of the waste to a solid, the melting point of the host rock should be less than the melting point of the waste material to provide rapid incorporation of the waste into the host rock. The lower melting point would tend to mobilize the rock and promote interaction between the waste and the host rock. It may also be desirable to fill the space between the canister and the cavity with crushed host rock that readily melts and facilitates the waste-rock interaction.

4.3.2 Engineering Properties of the Host Rock

It would be desirable for the engineering properties of the host rock to be such that the open walls of the repository can be sustained with minimum additional structural support until the waste has been emplaced. In the case of mined cavities, safety considerations indicate strong desirability for competent rock with compressive strength greater than about

3×10^6 kg/m^2.(138) In the instances of deep drill holes or exploded cavities, the requirement is merely that the working remain open until waste emplacement. For disposal in salt, depths in the range of one kilometer evidently result in flowage at a rate that may be unacceptable without major additional structural support. At depths below 10 kilometers, rock properties are little known. Certainly flowage of shale can be expected, and rock bursts will take place under many conditions in most rocks.

The host rock can be either massive or laminated(138) as long as it is linear-elastic, isotropic and homogeneous. Isotropy and homogeneity imply uniformity of material and absence of defects such as joints or partings. All rocks generally exhibit some defects when mined. However, the host rock would generally be considered massive if the spacing between joints or partings is comparable to or larger than the critical dimensions of the cavities, or if the strength of the bond across joints is comparable to the rock strength. Typical rock types in the competent, massive elastic class are granites, gabbros, quartzites, massive marbles, jointed igneous or metamorphic rocks in which the joints are bonded, thick bedded sandstones, and limestones. The capability of the host rock to withstand thermal stress without significant new fracturing or extension of existing fractures must be demonstrated for any disposal scheme.

For deep drilled holes (Concepts 8 and 9), the principal geohydrologic requirement would probably be a thick sequence of rock with low permeability below a depth of about 3 kilometers. This requirement can probably be met in a variety of terranes. It would be even more preferable in a setting where such rocks (e.g., metamorphic and intrusive igneous rocks) persist from on or near the surface to great depths. These rocks have high mechanical strengths and therefore would present the least problems in maintaining the drill hole open during emplacement operations.

Deep sedimentary basins of interbedded rocks having varying degrees of permeability are generally not suitable for geologic disposal because of the higher potential for productive aquifers and (or) oil-bearing strata in the region above emplacement depths. Some basins at depths of about 9 kilometers or more may have such low porosities and permeabilities that they could be suitable for deep hole waste disposal, but this characteristic would have to be proven by exploratory drilling and hydraulic testing.

To be suitable for hydraulic fracturing waste injection (Concept 10), it is generally considered that a geologic formation must produce essentially horizontal fractures under pressure. A fracture at any steeply dipping angle could represent a possible containment breach of the overlying strata and could lead to deposition of the waste-grout mix in a zone subject to leaching. Vertical fractures could also potentially open channel ways for circulating water and permit the leaching of grout which was originally beyond the reach of these waters.

It is generally agreed that hydraulically induced fracture orientation is primarily controlled by the state-of-stress in the earth at the point of fracturing.(139,140) In the absence of other factors, the primary fractures will always be oriented normal to the direction of least principal compressive stress.(139) A horizontal fracture develops only when the vertical stress (overburden stress) is less than the two horizontal stresses.(139)

Results from the ORNL disposal of low-to-intermediate-level wastes by hydraulic fracturing indicates that horizontal fractures will follow bedding planes even with minor folding of a few feet.(126) Zero slope of a formation would be ideal but not controlling. Depending on the size of each injection, the maximum radius of the grout sheet would be in the order of 200 meters. If all the points in the fracture horizon at the maximum distance still satisfy the requirements for isolation from potentially circulating groundwater, the amount of formation slope is inconsequential.

A reasonable estimate of the vertical stress component can usually be made from a knowledge of the depth and density of rocks at any particular point. Horizontal stresses are difficult to estimate, however, and practically impossible to measure with present technology.(141)

Some fracture orientation may be controlled by the injection well operation. Stress concentrations around a well drilled in a stressed medium appear to favor elastic formation of horizontal fractures for a distance of about three diameters from the borehole.(138)

Oriented stress concentrations can also be effected by the control of well casing perforations. If a horizontal slot is cut in the well casing and the well pressurized, vertical tension shear stress will develop which in turn favors horizontal fractures. This influence will also die out rapidly away from the well unless otherwise controlled.

Petroleum industry experience using hydraulic fracturing as an oil-well stimulation technique indicates that vertical fractures will probably be more common than horizontal fractures at depths greater than about 1 kilometer.(130)

Although interpretation of the data is still mostly theoretical, there also appears to be a valid indication that vertical fractures will predominate over horizontal fractures under most conditions.(130,142)

Once a potentially acceptable disposal formation is identified, the question of total capacity for injected grout is difficult to determine with present technology. Each injection deforms the rocks slightly by uplift of the overlying formations.(126) Eventually, if injections continue, a failure could occur in the overlying surfaces that could represent a breach of the primary isolation. The most probable failure mode will be development of vertical fractures. Although the failure could be identified after it happens, present techniques have not been used to attempt to predict with certainty such a failure.(133,142)

4.3.3 Water Content of the Host Rock

Moisture available as free water, including connate water and fluid inclusions, should generally be as low as possible. Less than two percent available water by volume has been suggested in considering salt as the host rock for high-level radioactive waste disposal.(143) Higher water content should not necessarily exclude other rock formations as potential disposal media. For example, an average shale may contain up to about 12 percent water by volume but, in general, will have a very low permeability which greatly restricts water movement within the formation. Other rock types considered (e.g., intrusive igneous, cyrstalline metamorphic, and tuff) generally exhibit a free water content less than two percent.

Sites containing aquifers both active and potential in the disposal horizon, will be avoided for all the waste disposal concepts. However, in many locations unconfined aquifers may be encountered by shafts or drilled holes. Unconfined (water table) aquifers are those in which the water table is the top of the water-saturated material and the pressure at the top of this material is atmospheric. Depth to the water table may vary from less than a meter to hundreds of meters.

Confined aquifers may also be penetrated by the disposal operations. A confined aquifer is one where water-bearing material is confined above and below by impermeable material and the water is at a pressure greater than atmospheric. Confined aquifers may be found at any depth where the proper geologic conditions exist but generally are found at greater depths than unconfined aquifers.

Drilled holes and shafts which penetrate aquifers will be cased and sealed off to prevent movement of material into or out of the penetrations.

For the deep drilled hole concepts (8 and 9), the probability is small that much water will be encountered at depths greater than about nine kilometers, but this remains to be verified.

The hydraulic pressure within the disposal horizon should be equal to or less than the hydrostatic pressure of a column of water open to the atmosphere. If confined aquifers are present above or below the disposal horizon, it is desirable that the hydraulic pressure be less than or equal to the pressure within the disposal horizon. This condition indicates a higher degree of confinement in the disposal horizon than in the aquifer.

The water chemistry of any fluids present should be such that there is limited potential for undesirable chemical or physical reactions with the waste or containers. For in-place waste conversion concepts, the waste and the formation water should have chemical compositions that will assist in their interaction and precipitation of the waste constituents. The chemistry of essentially immobile formation waters reflects the chemistry of the enclosing rock masses. Hence, in this case, the rock will continue to provide those constituents that helped to initially precipitate the waste.

4.3.4 Mineral Resources Potential

Mineral production inevitably involves some type of subsurface operation which could compromise the geologic confinement offered by any geologic waste disposal site. Areas of existing mineral production and significant exploration, therefore, should be avoided if possible. Any mineral in the host rock or formations above or below the host rock having obvious potential for economic development should be seriously considered as a threat to long-term geologic containment. Minerals such as clays or zeolites in the host disposal rock or in the formations overlying the disposal rock that can absorb radionuclides would be considered beneficial as long as the concentrations are low enough not to be economically recoverable. Any existing or abandoned mining or drilling operations and exploratory boreholes within the general area of a candidate disposal site represent potential hydraulic pathways between the host rock and man's environment. Consequently, all existing mines and boreholes should be located and evaluated as to their potential to form hydraulic connection to the disposal site. Where such penetrations exist, repairs may include reentry, cleanout, and replugging or sealing in a permanent and verifiable manner.(143)

4.3.5 Geothermal Resource Potential

As man's need for energy increases, the use of geothermal heat may become common and widespread. As with mineral potential, exploration or development of geothermal power poses a definite threat to the long-term integrity of any geologic waste disposal site.

Moreover, many areas and depths where the geothermal potential is significant are undesirable for waste disposal because of thermal and tectonic stresses and high temperatures. For periods in the order of hundreds of thousands of years, igneous (volcanic) action or reaction with volcanic fluids also is possible.

It can be shown, however, that unless the existing geothermal gradient for an area is well above average, it is doubtful that an efficient energy conversion could be made.(144) Therefore, it is believed that only areas with a geothermal flux greater than the general average value of 1.5 μcal/cm^2/sec(144) would be undesirable for waste disposal because of potential geothermal resource conflicts.

4.3.6 Geographic Characteristics

A site for disposal of high-level radioactive waste should be 1) as far removed from oceans and major lakes and streams as is practicable; 2) as far removed from human population centers as is practicable; and 3) in as gentle terrain as possible in order to avoid steep drainage gradients that could allow rapid distribution of any surface contaminants.

4.3.7 Seismicity and Faulting

The earth's crustal stability is of extreme importance when evaluating terranes for any waste disposal concept. Tectonic action could rupture the disposal zone and create passageways for groundwater to carry waste materials into man's environment. Therefore, all areas of high seismic risk (Zone 3) should be precluded from consideration. The selection of sites in other seismic zones would have to await seismic monitoring and detailed geologic mapping to establish the lack of fault systems or seismically active zones. With all other conditions comparable, sites with the lowest seismic risk would be preferable.

For the deep drilled hole concept low seismic risk is especially important during the operational stage. Several years are likely to be required for the actual drilling and preparation of a very deep hole and several more for disposal operations within a given hole. Even moderate earthquakes, if in close proximity to the drill hole, could cause premature collapse of the hole.

The emplacement zone of the repository should be virtually free of faults whether currently active or not. The location of any faults within the area of the site, the boundary of the buffer zone, and particularly inside the disposal cavity could be sufficient cause to abandon the site for disposal due to the potential for hydraulic or chemical transport of the waste material. Any fracture or jointing patterns that exist should be locally confined to the disposal cavity area and preferably oriented horizontally. Any vertical fractures or jointing must be shown not to extend continuously for a distance greater than about twice the cavity dimensions. This arbitrary and possibly conservative proposed guideline would probably vary with each potential geologic host environment. The rationale for the proposed guideline is to minimize the potential for a permeable connection between the waste disposal area and man's environment. Horizontal permeability is similarly not desirable, but pathways to man's environment are generally longer in this direction. Therefore, higher permeability may be acceptable in the horizontal direction.

Great depth should contribute to self-sealing of faults. However, depth may not necessarily assure that faults and fractures will be closed and healed despite the knowledge that porosity and permeability generally diminish with depth.(71) Hydrologic testing at the Nevada Test Site revealed that fractures had low to moderate permeability at least to about 4200 meters (the maximum depth reached),(72) and fractures below six kilometers in a drill hole in the Delaware Basin of Pecos County in Texas were found to be permeable. Potential sites must also be carefully evaluated to ascertain the possible presence of buried low-angle or thrust faults. Areas known to be characterized by such faults or areas where they have been logically inferred should generally not be considered for deep disposal.

4.3.8 Depth of Disposal

Based on conservative judgment, a depth greater than 300 meters is proposed as a minimum to assure isolation from man's environment. In many localities important water wells already penetrate to depths of 300 meters and more. Where those conditions prevail or where excessive surface mass wasting processes such as erosion or denudation may occur, still greater depths may be the minimum allowed.

The maximum depth for mined-out cavities is primarily a function of the temperature at which man can work. Greater depths can be used for other concepts not requiring human entry. With a surface temperature of 20°C and a typical geothermal gradient of 20°C/kilometer a working temperature of 60°C would be generally reached at depths less than 2000 meters without artificial cooling.

Limiting conditions for other concepts are the maximum temperatures for accelerating or retarding waste-rock interactions (whichever is desired), the physical and chemical conditions present, and, for the deep-hole, the ability to drill to suggested depths in the order of 16 kilometers. At the greater depths, significantly different characteristics can be expected, including a much reduced possibility of sedimentary rocks, lower rock porosity, an increasing probability of at least low-grade metamorphism, and physical characteristics of the rocks. Depths of disposal for the concepts studied are presented in Table 4.34.

TABLE 4.34. Depth of Disposal

	Concept	Depth, Kilometers
1.	Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting	0.3 - 3
2.	Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix	0.3 - 3
3.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling	0.3 - 3
4.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling	0.3 - 3
5.	Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix	1 - 3
6.	Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix	1 - 6
7.	Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting	3 - 6
8.	Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix	9 - 16
9.	Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix	9 - 16
10.	Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid	1^+ - 3

4.3.9 Dimensions of Host Rock

The minimum acceptable horizontal dimensions of the host rock will depend on specific site analysis of several factors: 1) the total size and shape of the host rock formation; 2) the thickness and extent of any overlying rock formations; 3) the isotropy and homogeneity of the host rock; 4) thermal properties of the host rock formation; and 5) the hydraulic regime which will control any potential dissolutioning and waste transport. Therefore, minimum horizontal dimensions cannot be defined in simple terms. It is believed reasonable, however, for solid waste disposal to avoid areas where suitable host rock could not be demonstrated to extend to a radial distance of at least 500 meters from the boundary of the disposal cavity. One thousand meters horizontal distance is suggested for disposal of liquid waste. Factors affecting vertical dimensions are discussed in Section 4.3.8.

A rock exhibiting a high degree of isotropism, homogeneity and massive nature would need to be less extensive to confine the waste. However, a rock mass exhibiting these characteristics will by its very nature be more continuous and thicker than one deviating considerably from that optimum. Desirably the total configuration of the rock mass should be defined, including its thickness, lateral extent, the nature and extent of overlying and underlying formations, the chemical and physical nature of the rock mass, and the hydraulic regime within it.

4.4 TECHNICAL FEASIBILITY

The technical feasibility of the potential disposal concepts was determined in this study by responding to these primary questions: 1) Can the disposal concept be implemented using today's technology? That is, have we enough information to assess the overall development requirements? 2) Can the disposal concept be implemented with future technology based upon current theory? That is, is it theoretically possible? 3) Can the disposal concept provide the potential for confining or eliminating the waste over the time period of concern? Only qualitative indications were developed for this study. 4) Does the concept have a favorable energy balance? (Is the energy consumed in implementation of the concept less than the electrical energy obtained?)

This study's responses to these questions regarding all the geologic concepts are summarized in Table 4.35.

Each element of systems requirements for implementing waste disposal by geologic emplacement (see Figure 4.53) was examined for technical feasibility. The elements were examined from the standpoint of utilizing existing technology as well as technology which could be developed in the future. All geologic concepts, with the possible exception of the very deep hole, appear to be technically feasible.

Studies to date indicate that technology permitting the emplacement of solid or liquid waste either is, or can be, established and that rock

TABLE 4.35. Summary of Technical Feasibility for Alternative Geologic Waste Management Systems

	Can It Be Implemented?		General Characteristics Relative to Feasibility	
Concept	With Today's Technology	Theoretically in Future	Favorable	Unfavorable
"Reference" Concept (solid waste emplaced in mined cavity, no fluid cooling or melting.)	Yes	Yes	Fair distance from man's environment Safety from storms, most of man's activities	Some potential for penetration by man in future Poor retrievability and monitoring Possible groundwater transport
Differences from Above Information are Listed Below				
Geologic Concepts				
1. Solid waste emplaced in mined cavity; no fluid cooling or melting	--	--	Ion-exchange of rocks as back-up[a]	--
2. Solid waste emplaced in mined cavity; initial water cooling; melting	--		(a) --	Irreversible high temperature in rock
3. Solid waste emplaced in manmade structure in mined cavity; initial air cooling; no melting		--	(a) Provides ready interim retrievability	Requires interim operation by man
4. Solid waste emplaced in manmade structure in mined cavity; initial water cooling; no melting	--	--	(a) Provides ready interim retrievability	Requires interim operation by man
5. Liquid waste emplaced in mined cavity; initial reflux cooling; melting	--		(a) No waste transportation	Irreversible high temperature in rock Liquid waste temporarily in repository
6. Liquid waste emplaced in exploded cavity; initial reflux cooling; melting	--	--	(a) No waste transportation	Very poor retrievability and monitorability Irreversible high temperatures in rock Cracks in surrounding geology for waste transport Liquid waste temporarily in repository Explosive effects on surface activities
7. Solid waste emplaced in matrix of drill holes; no fluid cooling or melting	--	--	(a)	Very poor retrievability and monitorability Many penetrations to surface
8. Solid waste emplaced in deep holes; no fluid cooling; melting or nonmelting	No	--	(a) Large distance from man's environment	Very poor retrievability and monitorability Deep geology unknowns
9. Liquid waste emplaced in deep holes; initial reflux cooling, melting	No	--	(a) Large distance from man's environment No waste transportation	Very poor retrievability and monitorability Deep geology unknowns
10. Liquid waste emplaced by hydrofracture; in-place curing	--	--	(a) No waste transportation	Limited favorable geology Significant heat transfer limits

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a) Ion exchange of soil-rocks as back-up applies to all the geologic concepts.

formations exist in geologic environments which should have the potential to provide confinement for long-time periods. No significant breakthroughs in technology are required for concept designs and no uncommon construction, mining or operational problems are anticipated except for drilling of a deep hole and allowing in-place conversion of waste to a rock-waste matrix.

Key elements pertaining to the technical feasibility of the potential geologic concepts to dispose of waste include the ability to: 1) store and retrieve both liquid and solid waste; 2) convert liquid waste to an encapsulated solid; 3) transport the encapsulated solids; 4) form the repository in the various candidate geologic formations; and finally

5) emplace the waste in the repository.

The primary need in proving the feasibility of implementing the concepts involving in-place conversion is to assure the behavior of the waste and the molten rock from the time in-place conversion is started until the molten rock-containing waste is resolidified to its final form.

4.4.1 Retrievable Liquid Storage

Interim storage of the high-level aqueous waste, an option for all concepts has been used as a management technique in the U.S. since the 1940's. The technology for storing high-level radioactive waste in tanks has been demonstrated, and continued improvement in tank design has proceeded to the point where latest designs are complex, double wall, steel vessels.(145,146)

High-level waste has been retrieved from tanks for further processing. Supernates and solids (precipitates) have been pumped and sluiced from storage tanks for recovery of cesium and strontium.(147,148) Liquid waste has typically been stored from two to five years in stainless steel tanks prior to retrieval for fluidized bed calcination at the AEC's National Reactor Testing Station.(149)

4.4.2 Solidification and Encapsulation

Four solidification processes have been developed in the United States to the point of radioactive demonstration on an engineering scale: pot calcination, spray solidification, phosphate glass solidification, and fluidized bed calcination.(150,151) Over seven million liters of liquid waste have been calcined using the latter process.(149) Encapsulation and remote sealing of canister caps by welding is an established operation.(152) Solidification and encapsulation of the waste is described in Volume 1, Section 2.

4.4.3 Retrievable Solid Storage

Prior to emplacement of solid waste in the repository, the waste canisters may be stored in a retrievable manner in some type of a surface storage facility. This interim storage will be accomplished using state-of-the-art techniques, i.e., using modular concrete structures with either air or water cooling to remove the heat resulting from radioactive decay or using individual sealed casks for each canister, stored in the open. Such storage could be done at the reprocessing plant and/or at a central repository. A Central Federal Retrievable Surface Storage Facility is currently being designed by Atlantic Richfield Hanford Company.(153)

4.4.4 Transportation

Detailed mechanical designs have not been developed for casks for shipping of high-level waste canisters. However, the technology that has been developed for the transportation of irradiated fuel elements can be directly applied to waste canisters. Irradiated fuel shipping casks are designed to withstand severe transportation accidents, including the damaging effects of impact, puncture, and fire.(154,155) As stated in Reference 156 "...There is no reason to believe that the performance specifications during accident conditions required by the Department of Transportation and the AEC cannot be met [for casks for the shipment of waste canisters]."

4.4.5 Excavation, Operation and Sealing

Present equipment and technological capabilities meet or exceed needed requirements for mining and drilling except possibly in the deep hole concepts (8 and 9). Suitable sealing techniques for the time periods required by the geologic concepts considered in this study have not been demonstrated.

Cavities have been constructed in a variety of geologic materials and of the sizes required by the mined cavity concepts (1 through 5). Cavity sizes range from the estimated 100 kilometers of 4.5 meters high by 4.5 meters wide tunnel required in Concept 1 to the approximately twenty meters-diameter sphere described in Concept 2. For any given depth below the surface, rock structural strength and temperature can limit cavity size and structural capabilities but are not expected to adversely influence the mined cavity concepts considered in this study.

Except for the deep drilled hole, holes of the sizes required for shafts (waste emplacement, ventilation, personnel access, etc.) have been drilled to the depths under consideration.(157,105,158,79) The largest required is the 2.3 meters in diameter waste emplacement shaft for the 1.5 kilometers deep Concepts 2, 5 and 6. Concepts 1, 3 and 4 will utilize 600 meters deep ventilation and personnel access shafts 1.8 meters in diameter. Waste emplacement holes of 0.4 meters in diameter by 4.5 kilometers deep and about 0.2 meters in diameter by 1 kilometer deep are used for the reference cases of Concepts 7 and 10, respectively.

Drilling of a deep hole is beyond present equipment capabilities but should be achievable with extension of existing technology. It has been speculated that a deep hole such as required for Concepts 8 and 9 can be drilled unless unusual specific site conditions are encountered.(157,78) Needed technological developments have not been acquired to permit drilling of deep holes due to the lack of commercial need for such a hole and hence the commitment to drill it.

For hydraulic fracturing (Concept 10), Oak Ridge National Laboratories development program has established the ability to form horizontal fractures.

Operating experience has proven the feasibility of handling high-level liquid waste in piping and process equipment on a scale commensurate with those concepts disposing of waste in liquid form (5, 6, 9 and 10).(147,159) Also, technology for removing liquid high-level waste and sludge from storage tanks has been developed and demonstrated.(147,159) This technology can be directly applied if it is decided to exercise the option of retrievable liquid storage or if it becomes desirable to retrieve liquid waste contained in the repository (Concepts 5, 6 and 9).

Wide industrial application has proven the technical feasibility of anticipated cooling techniques and the operability of required equipment needed for Concepts 3 and 4. Additional study is required to prove the reliability, safety and maintainability of the cooling system in view of the possible disruption of cooling lines and ventilation shafts by rock movements.

Sealing techniques exist for drilling and mining procedures which are suitable at least for the short term,(118,157,105,79) but adequate sealing for the long time periods considered here remains to be demonstrated.

The disposal of intermediate-level radioactive waste by hydraulic fracturing has been studied and demonstrated by ORNL for more than 10 years.(134) Seven experimental injections involved a total volume of about 2.5 million liters of intermediate-level waste. ORNL's development program included: design and fabrication of a plant and equipment capable of safely handling the radioactive waste; chemical development of mix (waste-cement) formulas for maximum retention of radionuclides and for desirable slurry properties at minimum cost; and the development of techniques and instruments for monitoring the behavior of the fracture. With the technical feasibility of this concept generally established for disposal of low-level radioactive waste, significant technical breakthroughs are not needed for this concept to handle high-level waste.

4.4.6 Energy Requirements

Calculations indicate that the energy required for the drilling and excavating of repositories needed by the various concepts for burial of waste is at least five orders of magnitude lower than the electrical energy generated by the nuclear power plants that supply the irradiated fuel to the reference reprocessing plant. Calculated energy requirements for specific geologic disposal concepts are presented in Table 4.36.

The calculated energy requirements, using information from References 160 and 161, are based on procedures currently used in the drilling and mining industries. The factors considered for the drilling operation were chipping of the rock by drilling, friction losses in pumping the mud, raising the rock to the surface, and lifting the drill string. For cavity formation the energy associated with powder hole drilling, blasting and rock removal were included in the calculation. Energy requirements for auxiliary operations such as ventilation, lighting, materials and personnel transport, etc., are not included but are estimated to be smaller than those for cavity forming. For drilling and excavating requirements of specific concepts, see Appendix 4.F on cost bases for geologic concepts.

4.4.7 In-Place Conversion to a Solid

Whether the concepts involving in-place conversion start with emplacement of solid waste (as in Concepts 2 and 8) or liquid (Concepts 5, 6 and 9), it is necessary to assure the behavior

TABLE 4.36. Estimated Energy Requirements For Excavation[(a)]

	Concept	Calculated Excavation Energy Requirements kW-hr[(a)]
1.	Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting	2×10^7
2.	Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix	2×10^7
3.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling	3×10^7
4.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling	3×10^7
5.	Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix	2×10^7
6.	Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix	2×10^7
7.	Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting	3×10^8
8.	Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix	3×10^8
9.	Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix	1×10^8
10.	Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid	2×10^5

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a. Calculations are based on the excavation required for burial of waste from 25 years operation of a plant reprocessing 5 MT/day of fuel. This reference plant reprocesses fuel which represents 1×10^{13} kW-hr of generated electrical energy. For specific excavation requirements for each concept, on which these estimates are based, see tables in Appendix 4.F, Cost Bases.

of the waste in its geologic environment. Melting and cooling situations with waste, rocks, and related materials have been analyzed on a general basis.(68,162) General behavior of heat sources in underground rock formations has been studied.(68) However, at this time it is not possible to assess the behavior of the molten mass in sufficient detail to conclude that concepts using melting as a method for ultimate solidification of the waste are technically feasible. Laboratory studies have shown that simulated waste, when mixed with rock and melted, forms a rock-like material.(163) But a detailed study is needed to establish with certainty the behavior of the molten mass within a geologic formation.

For in-place conversion concepts, waste and rock go through a molten phase and back to the final solid form. Cooling to a solid proceeds by natural cooling for several hundred years. Waste from 45,600 metric tons of fuel from the reference reprocessing plant would be incorporated in a volume of rock approximately equivalent to a sphere with a diameter of about 100 meters for the cavity concepts. In the deep drilled hole concepts the shape will be approximately cylindrical with a diameter of 3 to 10 meters.(68,162) Such shapes will provide reasonably low perimeter surface-to-volume ratios.

Radionuclides will extend to the outer areas of the melted phase. For Concepts 2, 5 and 6, the resulting average concentrations of the fission product oxides are calculated to be in the order of 800 parts per million (ppm), and actinide oxides would be approximately 100 ppm.(164) Average radionuclide concentrations for Concepts 8 and 9 are expected to be about twice as high.(164) Variation of radionuclide concentrations will likely occur in the final solidified waste-rock product, with the tendency being for higher radionuclide concentrations in the center than at the perimeter. Some chemical separation of the radionuclides into zones of higher than average concentration could occur. It appears that most of the waste constituents would dissolve in most of the candidate rock types. Shale, clays, basalt, granite and feldspar usually melt to yield homogeneous silicate-based solutions and, when cooled relatively rapidly, form homogeneous glass-like solids.(165) Slow cooling will yield similar microcrystalline solids. The waste would generally be composed of oxides, and most of these oxides should be soluble in the melt.(165)

A specific example of molten rock-waste chemical conversion is found in the work reported by Isaacson, et al.(163) Simulated fission product nitrate salt cake was reacted with basalt at high temperatures to produce a "silicious rock-like material that is similar in gross chemical composition to basalt." It is concluded that the radionuclides should be tied up chemically within the rock matrix, although some concentration gradient may exist between the center of the melted volume and the outer areas.

The solid product remaining after cooling is expected to be a glass-like(163,165) or microcrystalline material. When the melt cools, it will solidify as a single mass, and thermal stresses developed will probably be relieved by cracking. The chemical similarity of the waste-containing rock to the natural surroundings should provide for minimized interaction with the adjacent rocks over long time periods.

4.4.8 Potential for Retrieval of Liquid Waste from a Mined Cavity

For the concept of liquid emplacement in a mined cavity, retrieval of aqueous waste from the cavity may be desired for reasons such as reprocessing to recover a product, to solidify and dispose of the waste by some other technique, or to accomodate an unforeseen failure or undesirable behavior. Retrieval of the aqueous waste could be accomplished using extensions of present techniques after start-up if it were determined that the aqueous waste must be recovered from the mined cavity. Full retrieval would require relatively complicated sludge removal and/or dissolving operations because of accumulation, settling, and "cementing" of solids in the aqueous waste. Complete decontamination of the liner and piping after removal of all the waste would require considerable additional operations.

The liquid portion of the waste could be blown or pumped out at any time during the life of the plant(147) if retrieval were desired. At Hanford, high-level liquid waste is routinely pumped out of near-surface tanks and to and from processing plants and other tanks.(81,159) The liquid phase has been pumped out at rates on the order of 600 liters/min.(159) The primary limit on rate is pump and pipe size.(159)

Radioactive slurries have also been pumped out of waste tanks, using specially developed equipment and procedures.(159) Significantly less sludge is expected from acid waste which is boiling (the most likely option here) than for aged and nonboiling neutralized waste as handled at Hanford.(147,159,166) The sludge removal technology is well summarized by Larson(147) for the Hanford well-cooled alkaline waste sludges which range in age from 5 to 25 years old. Special oil well pumps exist in types which appear to be applicable for liquid waste and slurry pump-out, such as one with a capability for 60 liters/min of flow from depths of 3 kilometers.(81)

4.5 SAFETY

Safety is a major consideration in decisions on the use of any potential scheme for disposal of radioactive waste. An acceptable disposal option must provide protection during operational phases and provide the necessary isolation during the long time periods of the disposal phase.

A quantitative measure of safety has not yet been developed in this study. However, the methodology has been developed and preliminary evaluations are in progress. The methodology is described in Section 3, Volume 1 of this report. The methodology involves calculating probabilistic risk to man by estimating consequences of potential radionuclide releases to man and multiplying these times the estimated probability of radionuclide releases. Failure mode analysis using fault trees is used to identify mechanisms for failure of the waste disposal system. A preliminary generalized fault tree which can be applied to geologic disposal concepts was developed, and sample calculations of risk were made for one series of failure events to demonstrate the methodology for evaluating concept safety. The sample calculations, given in Section 3, indicate the potential risk to man from the one failure sequence for solid waste burial in a mine cavity to be in the order of 10^{-14} to 10^{-10} mrem/yr during the operational period, 10^{-10} to 10^{-6} mrem/yr at 1000 years after disposal, and 10^{-6} to 10^{-3} mrem/yr at 1,000,000 years after disposal. However, the calculations are only for a hypothetical case and cannot be used quantitatively.

In the fault tree developed for geologic disposal, a total of 77 basic failure events shown in Table 4.37 was identified as possibly contributing to release of waste from a geologic disposal site. Many of these events are common to all the geologic disposal concepts studied, as shown in Table 4.37 Those failure events which are not applicable to a given concept are identified by the letter N.

Information presented in the table is not indicative of the relative safety of the concepts since all failure elements do not have the same importance. In addition, it is expected to be shown through further study, that many more failure events are not applicable to a particular geologic disposal concept. Thus, the list shown in Table 4.37 cannot be used to judge various concepts. The information does, however, identify the potential failure elements which must be considered in order to evaluate the safety of each geologic disposal concept. Additional information on the fault tree study and on the various failure mechanisms is given in Section 3.

As the result of sorption of radionuclides by rocks, certain geologic formations will, in the unlikely event of ground-or surface-water intrusion, significantly reduce the consequences of such an event. Radiological consequences of a postulated release incident, with and without removal of waterborne nuclides by sorption, were discussed in Section 4.0.4.

4.6 RESEARCH AND DEVELOPMENT NEEDS

Although all geologic disposal concepts were found to be technically feasible, they all need Research and Development for their implementation. Research and Development needs (i.e., scope of studies, cost, and time requirements) were estimated for each of the 10 geologic concepts studied, assuming they would be selected for the ultimate disposal concept, and assuming no findings would be uncovered which would negate the concept. Research and Development needs are primarily associated with the analysis of past and future geological events, the definition of the effects resulting from the emplacement of the waste in an underground repository, development of specialized waste emplacement techniques, and cost optimization of concepts involving large amounts of drilling or excavating. Except for the deep drilled hole concepts, design and construction of a repository complex should not involve serious technological problems. Additional objectives of Research and Development studies are the quantitative definition of effects of heat and radiation on the geologic environment, the evaluation of events that could impair confinement integrity, and the behavior of the system if in-situ waste fixation by waste-rock melting is involved. The major consideration is the investigation of any mechanisms that could cause protective rock structures to fail to the extent that ground-or surface-water could enter the repository and

TABLE 4.37. Basic Geologic Disposal Failure Events Identified by Fault Tree Analysis

Failure Event	Description of Failure Event	Geologic Disposal Concept Numbers[a]									
		1	2	3	4	5	6	7	8	9	10
1	Barrier Ruptured by Aging										
2	Barrier Ruptured by Glacial Action										
3	Barrier Ruptured by Erosion of Ice, Wind, Weathering, Rivers, etc.										
4	Barrier Ruptured by Volcanic Activity										
5	Barrier Ruptured by War, Sabotage										
6	Barrier Ruptured by Waste Imposed Stresses										
7	Barrier Ruptured by Tectonic Action										
8	Barrier Ruptured by Meteor										
9	Water Finds Path into Burial Vault										
10	Tests Fail to Dectect Barrier Flaw										
11	Cavity Collapse from Aging										N[b]
12	Cavity Collapse from Glacial Action										N
13	Cavity Collapse from Erosion, Weathering, Wind, Water, Ice										N
14	Cavity Collapse from Volcanic Activity										N
15	Cavity Collapse from Monitoring Tests										N
16	Cavity Collapse from Stress Imposed by Waste										N
17	Cavity Collapse from Tectonic Action										N
18	Cavity Collapse from Meteorite Impact										N
19	Cavity Collapse from War or Sabotage										N
20	Cavity Enlarges and Collapse Occurs										N
21	Flaw in Barrier Develops from Tests to Show Barrier Integrity										
22	Cavity Migrates into Formation Which Cannot Support Cavity and Waste Forced to Surface	N									
23	Vent Formed to Surface from Cavity Collapse										N
24	Cavity Collapse for Radiation Damage										N
25	Waste in Mobile Form in Cavity	N						N			
26	Collapse Mechanics Permit Migration of Mobile Waste to Surface	N						N			
27	Pressurizes from Internal Energy Release										
28	Pressurizes from Entry of Lava or Magma										
29	Pressurizes from Water Entry and/or Steam Formation										
30	Pressurizes from Chemical Reaction of Waste or Heat Rock										
31	Pressurizes from Intrusion of Oil or Gas										
32	Pressurizes Upon Waste Melting	N						N			N
33	Pressurizes Upon Waste Solidification	N						N			
34	Shaft Seal Fails from Tectonic Events										
35	Shaft Seal Fails from Againg										
36	Shaft Seal Fails from Volcanic Activity										
37	Shaft Seal Fails from Water, Ice, Weathering, Wind, Rivers, etc.										
38	Shaft Seal Fails from Tests, Monitoring										
39	Shaft Seal Fails from War or Sabotage										
40	Shaft Seal Fails from Stresses Imposed by Waste										
41	Shaft Seal Ruptured by Meteors										
42	Shaft Seal Not Correctly Made										
43	Surface Flooded										
44	Climatic Change Caused Region Aquifer										
45	Water Flow Induced										
46	Volcano in Storage Region										
47	Lava Contacts Waste										
48	Flow Induced Through Barriers										
49	Barrier Mined for Mineral Content										
50	Barriers Removed by Meteor										
51	River Located in Region for Periods Sufficient to Remove Barriers										
52	Weathering, Erosion Remove Barriers										
53	Barriers Removed by Tectonic Activity										
54	Duration of Glacial Periods Sufficient to Remove Barrier										
55	Region Strata Suspected of Containing Valuable Resource										
56	Waste Contacted by Exploration										
57	Waste Contacted During Mining										
58	Waste Contacted During Testing										
59	Waste Contacted Purposely										
60	Waste Contacted During Geothermal or Other Future Use of Region										
61	Pressure Required to Displace Waste to Surface Exceeded	N						N			
62	Pressure Required to Rupture Shaft Exceeded										
63	Insufficient Heat Transfer Melts Solid Waste										
64	Oil or Gas in Region										
65	Oil or Gas Transfer Waste Through Barrier										
66	Cavity Shape Unstable Through Waste Pressurization	N									
67	Waste Normally Molten	N		N	N			N			N
68	Pressure Exceeds Barrier Strength										
69	Technology to Detect Rupture No Longer Exists										
70	Shaft Seal Improperly Repaired										
71	Technology to Repair Rupture No Longer Exists										
72	Barrier Fails or Deteriorated from Design Uncertainity										
73	Cavity Dissolves Barrier Between Waste and Surface										
74	No Monitoring of Disposal Site										
75	War or Sabotage Occurs Before Decommissioning										
76	Natural Disaster Occurs Before Decommissioning										
77	Efforts to Control Aquifer Fail										

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a. Descriptions of the concepts are:

1 Solid Waste Emplaced in Mined Cavity - No Liquid Cooling or Melting

2 Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix

3 Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling

4 Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling

5 Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix

6 Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix

7 Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting

8 Solid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix

9 Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix

10 Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid

b. **Those failure events which are not applicable to a given concept are identified by the letter N.**

transport waste constituents into man's environment. Substantial experimental and evaluative efforts are currently under way concerning the development of a mined cavity repository in bedded salt.(124) There has been much less effort associated with other potential geological environments, and considerably less is known about their suitability for waste disposal.

Total estimated Research and Development time and funding requirements for individual disposal concepts are summarized in Table 4.38.

Estimated Research and Development costs range from 50 to 180 million dollars. Concepts 1, 3, 4, 7 and 10 are at the low end of the range because extensive Research and Development efforts performed to date on similar disposal methods (e.g. mined cavities in salt formation and emplacement of intermediate level radioactive waste by hydraulic fracturing) have produced information

TABLE 4.38. Estimated Research and Development Needs and Timing to Routine Operations for Geologic Disposal Concepts

	Concept	Research and Development		
		Total Cost, Millions of Dollars	Total Time, Years	Total Time for Operation, Years[a]
1.	Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting	50	15	20-25
2.	Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix	90	20	25
3.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling	50	15	20-25
4.	Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling	50	15	20-25
5.	Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix	160	20	25
6.	Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix	170	20	25
7.	Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting	70	20	30
8.	Solid Waste Emplacement in a Deep Hole In-Place Conversion to a Rock-Waste Matrix	160	25	30-35
9.	Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix	180	25	30-35
10.	Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid	50	10	15-20

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a. Includes Research and Development time which can be directly applied to them. Because Concept 2 involves investigation of in-place conversion to a solid and a more extensive demonstration plant than the mined cavity concepts without melting, the total Research and Development funding required is estimated to be on the order of 90 million dollars. The remaining concepts require Research and Development funding of about three times the mined cavity nonmelting concept as a result of additional studies to establish procedures and techniques for disposing of liquid waste, allowing in-place conversion and/or drilling deep holes. The total time required to complete Research and Development studies for individual disposal concepts ranges from 10 to 25 years. Details of estimated time schedules for the Research and Development efforts associated with specific concepts are presented in Appendix G. Information concerning the scope of the Research and Development studies on a generalized basis for the geologic disposal concepts is presented in the following sections.

4.6.1 Thermal and Radiation Effects

Laboratory and field experimental work, and developmental work on a pilot-plant scale is believed to be required for each of the concepts to assure that geologic confinement of waste is not impaired by thermal and radiative effects. This is the basic approach being taken in the development studies of bedded salt as a host geologic environment, and as stated in Reference 123, "...extrapolation of...laboratory data to the gross effects of large quantities of waste on actual rock formations is difficult; construction and operation of an in-situ pilot facility to bridge the gap between laboratory and operations seem to be indicated." Key elements of studies to investigate thermal and radiation effects would include those discussed below:

Heat Dissipation. Thermal properties of the geologic environment (primarily thermal conductivity and heat capacity versus temperature) must be defined to the point where it can be assured that the long-term temperature transients resulting from emplaced waste will not exceed those desired for the waste or the canisters, the geologic formations, any nearby water-bearing formations and/or the surface.

Repository Stability. The effect of temperature and temperature transients on the horizontal and vertical stresses and rock properties must be defined. In addition to causing expansion and flow or slip, it is conceivable that temperature effects could cause phase or chemical changes in the surrounding rock. Heating of formations that contain bound water could result in special problems related to release of that water. Depending on formational plasticity, concepts involving direct placement of waste canisters in a geologic formation should have investigated the possibility of canister movement along with repository stability. Radiation could result in energy storage in the formation (by displacement of atoms or formation of defects within the crystalline lattice of the host rock) and later sudden release.

The possibility of subsidence initiated by a release of this energy should also be investigated. Long term mechanics of host environments should be investigated for concepts which entail long-term access and operation.

Thermal/Radiation Decomposition. A variety of new chemical forms could be formed in-situ by either radiation or thermal decomposition. Again these decompositions are of special concern when bound water is present. The possibility of the formation of products corrosive to canisters and to liners, heat transfer equipment and connecting piping must be investigated. Also the possibility of formation of explosive and/or noxious products must be considered.

A variety of geological events could conceivably impair containment integrity under abnormal, catastrophic situations or perhaps under normal long-term occurrences. Such events would be the subject of Research and Development programs. An obvious geologic event to be considered is seismic activity. Any movement, folding, or faulting of the geologic environment must be considered. The possibility of exposure of waste by erosion and denudation and the possibility of leaching of waste by groundwater must be considered for all formations.

The extent of migration of radionuclides should be investigated. Potential transport mechanisms for these radionuclides include primarily, liquid and gas phase transport but also include solid state diffusion and migration along free surfaces. If bound water can be released, radionuclide mobility could be increased beyond that normally expected. The determination of formation permeability becomes important if bound water can be released and especially when considering concepts based upon emplacing liquid waste.

4.6.2 In-Place Conversion

All aspects of in-situ waste fixation must be analyzed and understood to permit accurate prediction of results. Four areas can be specifically noted: 1) heat and mass transfer; 2) rock-waste chemistry in the molten and high temperature solid phases; 3) system stability; and 4) the stress-force field. Heat and mass transfer models and studies must be developed to accurately predict behavior in all extremities of the affected geologic environment. Rock-waste chemistry must be studied under the temperature-pressure conditions to be encountered in a repository. The potential movement of the molten rock-waste mixture must be thoroughly defined. Rock mechanics studies must be performed to permit accurate prediction of forces, stresses, and rock physical reactions. Construction and operation of a pilot facility can be used to bridge the gap between laboratory studies and actual in-place conversion to a solid.

4.6.3 Deep Hole Drilling

Studies indicate that the formation of a deep hole is feasible with current technology in areas with low geothermal gradients. Unpredictable conditions at depths below those explored (about 9 kilometers) could stop an attempt at reaching full depth and/or desired diameter at full depth (see Section 4.0.5. Therefore, additional deep hole drilling development work is needed. Potential areas of investigation for conventional drilling techniques include developments in drilling and drilling mud technology to overcome the high temperatures at great depth, higher rotating table capacity, greater drill pipe strength, greater bit strength, higher casing strength and overcoming downhole stress conditions (temperature, pressure, rock mechanics). In addition, certain nonconventional drilling techniques may offer advantages for drilling of deep holes and should be investigated for deep hole concepts.

4.6.4 Cost Optimization

Although cost optimization is not necessarily critical for the sucessful application of a geologic disposal concept, it is important to assure cost-effective implementation of a concept.

Total tunnel volume required by Concept 1 to contain the United States waste inventory projected through the year 2000 could approach ten million cubic meters. Because of the total cost involved, advances that can be used to reduce tunnel volume requirements only a few percent can save millions of dollars. For example, the development of machines that can form burial holes and emplace waste from a minimum of working space could significantly reduce tunnel volume requirements and costs. Slight changes in the temperature limits associated with emplaced waste, the host geologic formation, any nearby water-bearing formations, and/or the surface could result in significant changes in excavation requirements. The above investigation of thermal properties can lead to sound temperature limits and the ability to optimize waste form and cavity dimensions to meet these limits.

For the matrix of drilled holes assuming 3000 meters of overburden and a 1500-meter thick host formation, over 1000 kilometers of drilled hole length would be required for the waste inventory projected through the year 2000. Advances that can be used to reduce drilling costs could save great sums of money.

Optimization of waste form from a physical (ease of burial) as well as thermal standpoint should also be considered as a means for reducing drilling and mining requirements. Finally, continued investigation of drilling alternatives (see Section 4.0.5) that appear to be economically competitive with conventional mining/drilling methods is obviously warranted.

4.6.5 Fluid Cooling Systems and Containment Structures

Containment structures enhance the retrievability of the waste while interim fluid cooling minimizes the area requirements for storage disposal.

Laboratory corrosion studies are needed to obtain corrosion rates for the important materials of construction when exposed to the environment of the disposal facility. Consequently,the chemical and physical environment in the cavities and shafts of an actual pilot facility should be characterized so that realistic laboratory corrosion tests can be carried out. The most definitive information will be obtained from actual observations made in a pilot facility during its useful life time. Other potential areas of Research and Development may be associated with techniques to monitor and evaluate the integrity of containment structures such as repository liners in addition to connection(s) between the repository and the surface facilities.

4.6.6 Special Studies for Hydraulic Fracturing

To develop a suitable mix formulation for hydraulic fracturing injection into a geologic formation, specifications for the mix are needed including characteristics and durability of the final waste-grout solid, viscosity, thickening time, setting time, compressive strength, phase separation and fluid loss. Pumpable mixes (slurries) whose viscosity remains low and consistency remains stable during injection need to be developed. Retention of radionuclides by the final solid must be evaluated and studies must be undertaken to develop solids with improved characteristics. Several materials such as cements, clays, etc., should be evaluated. Also, further work is needed to develop laboratory test procedures that will more closely simulate the mixing and pumping operations in the fracturing plant.

The measurement of surface uplifts is needed to indicate if a vertical fracture has occurred when emplacing waste by hydraulic fracturing. Improved techniques are needed to determine reliably the beneficial extent of waste-grout sheets. Theoretical derivation of surface uplift should be compared to experimental data to develop a workable model for determining how to prevent vertical fractures.

4.6.7 Pilot-Scale Demonstration

A pilot-scale demonstration to extend information obtained in laboratory studies relative to certain key items is expected to be required for the geologic concepts. The pilot-scale demonstration is expected to require at least 10 years of design, construction, and actual operation for most of the concepts. The deep-drilled hole concepts are believed to require at least 20 years for demonstration because of problems anticipated in routine drilling to great depth. The major purpose of the demonstration is to supplement and confirm the results of laboratory investigations on thermal, chemical, mechanical, and radiation damage resistance properties of the geologic environment. Confirmation that handling and disposal of waste can be accomplished safely and that acceptable drilling and excavation techniques exist will also be done here.

4.6.8 Other Research and Development Needs

The development of materials and techniques for the final sealing of openings that were once used for repository operation is needed.

To maintain the integrity of a geologic formation potentially suitable for disposal of radioactive waste, development of techniques other than core boring to assure that the formation is not penetrated by cracks or faults that could conceivably connect the cavity or tunnels to surrounding water bearing formations might be warranted.

Continued development of techniques to monitor tunnel movement would be desirable; such movement could signal the onset of formational cracking.

4.7 TIME REQUIREMENTS FOR COMMERCIAL OPERATION

Estimates of the total time required to place disposal facilities for each of the geologic concepts in operation are shown in Table 4.38. Total time requirements range from 15 years to 35 years, depending upon the concept under consideration, with the time necessary to complete needed Research and Development work being the controlling factor in the time required to implement the concepts. Beyond Research and Development studies, other activities needed to implement a disposal concept are design, licensing, and construction of the repository. These elements are estimated to require 5 to 10 years beyond that for research and development. Estimated time requirements of the key elements for each of the geologic concepts are presented in Figures 4.G.1 through 4.G.10 contained in Appendix 4.G.

The objective of the site evaluation is to examine alternative sites on a national scale and select specific sites (formations) for further detailed evaluation.

When candidate sites have been identified, site evaluation studies will confirm that the potential sites selected have the characteristics and properties that will permit long-term isolation of radioactivity from man's environment. The specific geology and rock mechanics of the host rock formation and the geology and hydrology of the related nearby geologic environment will be defined in detail and evaluated.

For each of the concepts, a 5 to 8 year effort is estimated to be involved for site evaluation activities.

It is believed that, in general, a total of about 10 years will be required for licensing, designing and constructing the commercial facility. Five years are estimated to be required to obtain a construction permit and 5 years are allotted for completion of design and construction, portions of which are conducted concurrently.

4.8 CAPITAL AND OPERATING COSTS

Preliminary capital and operating costs and levelized total system disposal costs (those charged at the time of reprocessing to cover waste management costs) were derived for each of the concepts and are presented in Table 4.39. All of the necessary

TABLE 4.39. Capital and Operating Costs for Geologic Disposal Concepts

Concept	Reference Plant Cost[(b)] (million dollars)		Total Waste Management Unit Charges[(a)]		Comments
	Capital Cost	Annual Operating Cost	$/MT	mills/kW-hr	
1 Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting	230	2.8	12,000	0.046	Almost 70% of the capital costs attributed to tunneling. Operating costs based on staff of 34.[(c)]
2 Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix	29	1.4	9,000	0.034	Of the capital cost, hole drilling requires about 22%, the cavity liner about 30%, and all other equipment and facilities about 48%. Operating costs based on staff of 34.
3 Solid Waste Emplaced In Manmade Structures in Geologic Formations - Interim Air Cooling	550	4	17,000	0.064	About 75% of the capital costs due to drilling of ventilation and access holes. Operating costs based on staff of 47.
4 Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling	240	3.6	12,000	0.047	Major capital cost items are excavation 38%, pressure vessel 23%, rate sensitive anchors 8%, and containment shell 4%. Operating costs based on staff of 47.
5 Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix	22	1.4	6,400	0.024	About 30% of capital costs due to drilling and excavating, and 65% to steam condensers. Operating costs based on staff of 19.
6 Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix	23	1.4	6,300	0.024	About 25% of capital costs due to drilling and excavating, and 60% to steam condensers. Operating costs based on staff of 19.
7 Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting	140	1.5	10,000	0.039	About 95% of capital costs due to drilling holes. Operating costs based on staff of 34.
8 Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix	160	1.6	11,000	0.041	About 95% of capital costs due to drilling holes. Operating costs based on staff of 36.
9 Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to Rock-Waste Matrix	80	1.1	8,000	0.030	About 95% of capital costs due to drilling holes. Operating costs based on staff of 19.
10 Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid	15	1.0	11,000	0.042	About 20% capital costs due to drilling wells. Operating costs based on staff of 19.

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a. Assessed at time of reprocessing.
b. Based upon managing waste from a plant which reprocesses 5 metric tons/day (1825 MT/yr) of spent nuclear fuel for an assumed 25-year plant life.
c. Size of staff based upon operating a single reference repository.

components of a complete waste management system are included in the total system disposal costs. The system cost includes, for example, any added spent fuel transport for cases where the fuel reprocessing plant and the disposal site must be the same location, interim liquid waste storage, waste solidification, interim solid waste storage, transport of solid waste canisters to the disposal site, and final disposal. The disposal costs do not include the Research and Development studies costs developed in section 4.6. Volume 1, Section 3 of this study contains a detailed discussion of the procedures used to develop the levelized cost information and presents costs associated with variations in the type of rock used for a disposal site and in the depth at which the repository is located.

For each concept, disposal system costs were developed for a reference facility sized to handle the high-level waste from a 5 metric ton/day (1825 MT/yr) LWR fuel reprocessing plant. Costs for this reference facility were then scaled as described in Volume 1, Section 3, to accommodate the total requirements for a 25-year period starting in 1980.

The highest total disposal cost corresponds to a value of $17,000 per metric ton of fuel. This cost is equivalent to about 0.064 mills per kilowatt-hour of electricity, or less than 1 percent of current nuclear electric power generating costs. Consequently, none of the geologic disposal concepts would significantly increase the cost of nuclear electric power, and thus cost will probably not be of great initial importance when ranking the various geologic concepts.

Appendix 4.F presents the reference bases used for estimating the systems costs.

4.9 PUBLIC RESPONSE

This section discusses some considerations of public response to various characteristics of geologic concepts for disposal of radioactive waste. It should be noted that public reaction to a certain characteristic will not always be uniform. For example, public reaction to the fact that the waste is isolated from man's environment by hundreds of meters of "rock" can be favorable. On the other hand, there will be those who question the concept simply because the isolation is required in the first place or, more importantly, because the isolation could conceivably make the waste irretrievable, especially in case of a major geologic event. It should also be noted that it may be possible to counter certain negative or unfavorable reactions with information and educational programs once details are available concerning a specific site. This expectation is borne out to some extent by the results of a preliminary pilot survey test conducted with a small sample of people, as described in Volume 1, Section 3 of this study. The test described in Section 3 discusses in detail the respondents' perception of waste management factors and characteristics of a number of geologic types of waste management systems.

In addition to isolation of the waste by geologic distance, public acceptance could be enhanced by the possibility of locating the repository far from population centers. However, in the pilot test referred to above, the "average" respondent felt that distance from our immediate environment and nearby population density were two relatively unimportant criteria for waste management. The fact that geologic emplacement will isolate the waste from surface storms and accidents and reduce the possibility for sabotage and other malicious acts of man appear to be perceived as important characteristics.

Unfavorable public reaction could arise from the fact that surface transportation of waste canisters will probably be involved in concepts based on emplacement of solid waste. Assurance of the suitability of geologic disposal is based in part on seismic and tectonic stability, and demonstrated past stability may be questioned as an adequate indicator of the future. Finally, geologic isolation leads to difficulties in monitoring of the system and the detection of releases of radioactivity, if any. In the above referenced test results, the subjects ranked protective reaction (countermeasures in the event of release of radioactivity), retrievability, emplacement operations (including surface transportation), and long-term stability as important risk characteristics for geologic concepts.

4.10 POLICY CONSIDERATIONS

An examination of written national and international policies that might apply to the disposal of high-level nuclear waste was presented in Volume 1, Section 3.

Those solid waste disposal concepts which do not involve melting are compatible with existing policies and programs. Specifically, they could fulfill the requirements of a Federal Repository (facility for permanent custody) discussed in 10 CFR Part 50, Appendix F.(167) In addition they are compatible with the current plans for a Federal Retrievable Surface Storage Facility(168) for interim storage of solidified waste prior to ultimate disposal.

The national rules and regulations as established by the Atomic Energy Commission in 10 CFR 50 (Appendix F) state specifically that all high-level nuclear waste must be disposed of in solid form on federally owned and controlled land. This clearly affects the liquid waste disposal concepts and those concepts which permit waste-rock melting. If the facility for permanent custody were based on liquid emplacement and/or melting, the existing AEC rules and regulations would be in conflict. In addition, liquid emplacement and melting are not compatible with the current plans for a retrievable storage facility.(168)

Internationally, the Nonproliferation Treaty could conceivably affect all of the concepts since it provides for the safeguarding of all source and special fissionable materials. The treaty specifies that the International Atomic Energy Agency safeguard standards must be observed in all peaceful nuclear activities whether within a state or under its control anywhere.

4.11 ENVIRONMENTAL IMPACT

The nonradiological environmental impact of geologic concepts were presented in Volume 1, Section 3 of this study, and are reviewed briefly here. Major environmental impacts resulting from geologic disposal concepts are expected to be the commitment of land, the transportations needs, the associated potential loss of resources, and the potential effects of heat dissipation.

For the total U.S. waste inventories projected to need disposal through the year 2000, there is the commitment of typically 130 square kilometers (50 square miles) of land, including a 3.2 kilometer buffer zone surrounding the disposal area. Larger areas must in general be committed for the liquid disposal concepts, up to 1600 square kilometers for Concept 10, because a multiplicity of sites is necessary to allow locating the reprocessing plant at the disposal area. Assuming a 10-year holdup time at the reprocessing plant, up to 200 megawatts of thermal power might be dissipated to the surrounding formation for eventual transfer to the atmosphere. Up to 600 megawatts might be dissipated without the holdup period as would be the case for concepts utilizing liquid waste emplacement. This amount of heat is less than 30% of that rejected from one 1000 MWe thermal electrical generating plant. Although it is conceivable that the biological environment could be affected by this chronic heat source,(116) no major consequences are expected, but detailed analyses of specific sites will be required.

As much as ten million cubic meters of mine tailings might result from excavation operations associated with mined cavity concepts which do not involve waste-rock melting. Esthetic impact can be minimized by the onsite "environmental" treatment of mine tailings. If salt and perhaps other evaporites are removed from the repository, ocean disposal or disposal in nearby abandoned mines may be required for the tailings. During the mining operation and disposal of mine waste, some dust contamination of the air could also be expected.

Nominal demographic impact and water and electrical consumption are expected. Finally, for concepts employing disposal of solid waste, there will be the impact of rail or truck shipments. For the waste to be disposed of in the year 2000, the annual shipping rate of canisters could exceed 3000. Assuming each shipment contains six canisters, over 500 trips into and out of the complex could be expected.

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APPENDIX

SECTION 4: GEOLOGIC DISPOSAL

APPENDIX 4.A

GLOSSARY OF GEOHYDROLOGIC TERMS

GLOSSARY OF GEOHYDROLOGIC TERMS

Technical terms, particularly those with somewhat obscure meanings, are defined in this glossary. For terms not defined in this glossary the reader is referred to the "Glossary of Geology and Related Sciences," compiled by the American Geological Institute, and Webster's New World Dictionary, College Edition.

In some instances, definitions have been enlarged beyond the standard textbook definitions. No attempt has been made to cite the source of definitions, and those definitions that have been enlarged may deviate slightly from the standard definitions.

Alluvial fan. A sloping, fan-shaped mass of loose rock material deposited by a stream at the place where it emerges from an upland into a broad valley or a plain.

Alluvium. All detrital material deposited permanently or in transit by streams.

Amphibole. A group of dark, rock-forming, ferromagnesian silicate minerals which are closely related in crystal form and composition and which have abundant and wide distribution in igneous and metamorphic rocks.

Anorthosite. A granular plutonic igneous rock composed almost exclusively of soda-lime feldspar.

Anion. An ion that is negatively charged.

Anticline. A fold, the core of which contains stratigraphically older rocks, and which in simplest form, is elongate and convex upward with the two limbs dipping away from each other.

Aquifer. A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs.

Aquitard. A natural rock or fine-grained, unconsolidated unit of low permeability which is stratigraphically adjacent to one or more aquifers and through which water movement is markedly retarded or impeded.

Argillite. A compact rock, derived from claystone, siltstone, or shale, which has undergone a somewhat higher degree of induration than is present in these sedimentary rock types but which is less clearly laminated than shale, does not have the fissibility of shale, and lacks the cleavage distinctive of slate.

Artesian. Pertaining to an aquifer is one that is confined so that its hydraulic head rises above the top of the aquifer unit; thus an artesian water body is one confined and under hydraulic pressure.

Basement. A complex of undifferentiated rocks that underlies the oldest identifiable rocks in the area.

Basin. A depressed area generally having no surface outlet; a segment of the earth's crust that has been downwarped by the accumulation of sediments on it; a synclinal tract or area in which the rocks dip toward a central point, and in which folding occurred subsequent to deposition; an elongate, fault-bordered intermountain area.

Batholith. An igneous intrusion greater than 40 square miles in surface exposure, composed predominantly of granitic rocks.

Bauxite. A rock composed of an impure mixture of earthy hydrous aluminum oxides and hydroxides and is the principal commercial source of aluminum.

Bentonitic. Pertaining to a rock containing bentonite, a clay formed from the decomposition of volcanic ash.

Biotite. A complex silicate of aluminum, potassium, magnesium, and iron with hydroxyl that is a widely distributed and important rock-forming mineral of the mica group.

Block-faulting. A type of vertical faulting in which the crust is divided into structural or fault blocks of different elevations and orientations.

Brackish. A somewhat general term applied to mineralized water of concentrations intermediate between those of brine and fresh water.

Breccia. A coarse-grained clastic rock composed of large, angular, and broken rock fragments cemented together in a fine-grained matrix.

Caliche. Calcareous material that forms on or near the surface of stony soils of arid and semiarid regions; thought to be genetically associated locally with capillary fringe of the water table; and is inferred to form when evaporation exceeds precipitation.

Cap rock. A low-permeability body of anhydrite and gypsum which overlies a salt body, or plug in a salt dome.

Cation. An ion that is positively charged.

Chimneying. The process of progressive collapse of rock overlying an explosion-produced cavity resulting in a tall underground cylinder (chimney) of broken rock.

Chlorite. A group of green hydrous silicate minerals containing magnesium and iron, with or without aluminum; that these minerals are widely distributed, especially in metamorphic rocks.

Clastic. Pertaining to or being a rock or sediment composed principally of broken fragments derived from preexisting rocks or minerals.

Cleavage. The property or tendency of a rock to split along secondary, aligned fractures or other closely spaced, planar surfaces, produced by deformation or metamorphism.

Coal measures. A succession of sedimentary rocks (or measures) consisting of clays or shales, sandstones, limestones, and conglomerates with interstratified beds of coal; a group of coal seams interbedded with the above strata.

Conglomerate. A coarse-grained clastic sedimentary rock composed of rounded to subangular fragments larger than 2 mm in diameter, such as granules, pebbles, cobbles, and boulders, set in a fine-grained matrix of sand, silt, or cementing materials, such as calcium carbonate, iron oxide, and silica. The consolidated equivalent of gravel.

Consolidated (material). In geology, natural materials that have been made firm, cohesive, and hard.

Crystalline rock. An inexact but convenient term designating an igneous or metamorphic rock, as opposed to a sedimentary rock.

Depositional environment (sedimentary environment). A geographically restricted environment where sediment accumulates under similar physical, chemical, and biological conditions.

Diagenesis. Process involving physical and chemical changes in sediment after deposition that converts the sediment to consolidated rock.

Diamond pipe. Term used for an occurrence of kimberlite (periodotite that has been converted to a hydrous magnesian silicate) in volcanic pipes large enough and sufficiently diamond bearing to be minable.

Diapirism. The piercing of overlying rocks by a mobile core, such as a salt body or an igneous intrusion.

Discharge. In groundwater hydrology, water that issues naturally or is withdrawn from an aquifer.

Dome. A dome-shaped landform or rock mass; a large igneous intrusion whose surface is convex upward with sides sloping away at low but gradually increasing angles; an uplift or an anticlinaltype structure, either circular or elliptical in outline, in which the rock dips gently away in all directions, for example, a salt dome.

Dunite. A coarse-grained plutonic igneous rock composed almost entirely of olivine.

Ephemeral stream. A water course carrying surface water part of the time but dry or having only underflow in the streambed materials part of the time.

Epidote. A basic orthosilicate mineral containing calcium, aluminum, and varying amounts of iron, and commonly occurring in metamorphic rocks.

Fault. A fracture or fracture zone along which there has been displacement of the sides relative to one another parallel to the fracture.

Fault block. A crustal unit bounded by faults, either completely or partly.

Fault system. A system of parallel faults that are related to a particular deformational episode.

Feldspar. Any of an important group of rock-forming minerals that are essentially silicates of alumina and some other base, such as potash, soda, or lime.

Flood-plain deposit. Sandy and clayey sediment deposited by river water that spread out over a flood plain.

Foliation. A general term for a planar arrangement of textural or structural features in any rock type, but most commonly applied to metamorphic rocks, such as cleavage in slate or schistosity in a metamorphic rock.

Garnet. An important group of silicate minerals rich in alumina, iron, lime, and magnesia that occur chiefly as accessory constituents of metamorphic rocks and less commonly of igneous rocks.

Geohydrologic. Of or pertaining to the geology and hydrology. An abbreviation combining the adjectives geologic and hydrologic.

Geoid. The figure of the earth considered as a mean sea-level surface extended continuously through the continents.

Geothermal. Pertaining to the heat of the interior of the earth.

Glacial outwash gravel. Gravel removed or "washed out" from a glacier by meltwater streams and deposited in front or beyond the margin of an active glacier.

Graben. An elongate, relatively depressed crustal unit or block bounded by faults on its long sides.

Granitic. Of or pertaining to granite. Granite-like.

Granitoid. A textural term indicating grain size and mineral distribution typical of granite.

Hornblende. A common member of the amphibole group of minerals.

Hydraulic gradient. The change in static head per unit of lateral distance in a given direction.

Hydrostatic pressure. The pressure exerted by the water at any given point in a body of water at rest.

Hydrothermal. A term applied to heated or hot magmatic emanations rich in water and applied to the rocks, ore deposits, alteration products, and springs produced by hydrothermal processes.

Ion exchange. Replacement of ions adsorbed on a solid--such as a clay particle--or exposed at the surface of a solid by ions from solution, usually in natural water. The phenomenon is known to occur when natural water moves through clays, zeolitic rocks, and other materials of the earth's crust.

Interfluve. The area between adjacent streams flowing in the same general direction.

Interstices. In geology, small openings between solid particles in a rock or unconsolidated material; may be a void or pore and often contains groundwater. Interstitial permeability is used to differentiate interconnected pore permeability from fracture permeability.

Iron formation. A chemical sedimentary rock, typically thin-bedded and (or) finely laminated, containing at least 15 percent iron of sedimentary origin.

Isopach. A line drawn on a map through points of equal thickness of a designated stratigraphic unit or group of stratigraphic units.

Joint. A fracture or parting in a rock, without displacement.

Kaolinite. The mineral characteristic of kaolin, a group of minerals consisting essentially of hydrous luminum silicate and which are closely related in chemical composition and crystal structure.

Laccolith. A concordant igneous intrusion with a known or assumed flat floor and a postulated dikelike feeder somewhere beneath its thickest point.

Lithification. The conversion of unconsolidated sediment into solid rock by processes such as compaction, cementation, and crystallization.

Lithology. The character of a rock (described in terms of) its structure, color, mineral composition, grain-size, and arrangement of its component parts.

Loess. An unconsolidated or weakly consolidated sedimentary deposit which is composed dominantly of silt-sized rock and mineral particles and which is deposited by wind.

Low-angle fault. A fault, the dip of which is no more than 45° (or less).

Mafic. Pertaining to or composed dominantly of magnesium rock-forming silicates.

Magmatism. The development, movement, and solidification to igneous rock, of magma, a naturally occurring mobile rock material, generated within the earth and capable of intrusion and extrusion.

Matrix-hole concept. A type of radioactive water repository consisting of several drill holes spaced moderately close together.

Mesa. An isolated, nearly level landmass standing distinctly above the surrounding country, bounded by steeply sloping erosion scarps on all sides, and capped by layers of resistant, nearly horizontal rocks.

Metallic. Of or belonging to metals, containing metals, more particularly, valuable metals that are the object of mining ore.

Mica. A group of silicate minerals of aluminum and other bases, especially potassium, magnesium, and iron, and characterized by a great perfection of cleavage in one direction that produces thin, though, elastic plates or laminae.

Monocline. A unit of strata that dips from the horizontal in one direction only, and is not part of an anticline or syncline.

Nepheline syenite. A plutonic rock composed almost entirely of alkali-feldspar and nepheline which is a silicate mineral containing appreciable amounts of potash, soda, and alumina.

Olivine. An olive-green, common rock-forming ferromagnesian silicate mineral of mafic, ultramafic, and low-silica igneous rocks.

Outcrop. A part of a body of rock that appears, bare and exposed, at the surface of the ground.

Permeability (permeable). The relative ease with which a porous medium can transmit a liquid under a hydraulic gradient.

Plagioclase. The group of common rock-forming feldspar minerals that contain varying mixtures of sodium and calcium.

Playa. A flat-floored area composed of thin, evenly stratified sheets of fine clay, silt, or sand, and representing the lowermost or central part of a shallow completely closed or undrained, desert lake basin in which water accumulates after a rain and is evaporated, usually leaving deposits of soluble salts.

Peridotite. A coarse-grained plutonic igneous rock composed chiefly of the mineral olivine but also containing considerable amounts of other ferromagnesian minerals.

Pluton. A body of intrusive igneous rock of any shape or size.

Pluvial (period). Pertaining to a period of time or a climate in which rainfall or precipitation is abundant.

Porosity. That property of a rock or soil which enables the rock or soil to contain water in voids or interstices, usually expressed in percentage or a decimal fraction of void volume as compared to total volume.

Pyroxene. A group of dark, rock-forming silicate minerals closely related in crystal form and analogous in chemical composition to the amphiboles, and found chiefly in igneous rocks.

Pyroxenite. An ultramafic plutonic igneous rock chiefly composed of pyroxene.

Quartz monzonite. A coarse-grained igneous rock, intermediate in composition between granite and granodiorite, which contains quartz and about equal amounts of the alkali and soda-lime feldspars.

Recharge. In hydrology, a source or means for replenishment of water withdrawn or discharged from an aquifer. An aquifer in hydraulic equilibrium will discharge a quantity of water about equal to the amount of recharge.

Rift. A long fairly relative narrow depression formed along lines of multiple fracture.

Rift valley. An elongate narrow trough or valley formed by the sinking of a strip of the earth's crust between two more or less parallel nearly vertical faults.

Rift zone. A system of crustal fractures.

Rise (marine). A broad, elongate, and smooth elevation of the ocean floor.

Sedimentary basin. Geologically depressed area with thick sediments in the interior and thinner sediments at the edges.

Seismicity. The phenomenon of earth movements as manifested by earthquakes.

Shield. A continental segment of the earth's crust which has been relatively stable over a long period of time and which has exposed crystalline rocks mostly of Precambrian age; in general, representing the oldest rocks of the continent.

Sill. A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

Sink hole. A funnel-shaped depression in the land surface generally in a limestone region often connected to a subterranean passage developed by solution.

Static head. The height above a standard datum of the surface of a column of water (or other liquid) that can be supported by the static pressure at a given point.

Stock. An igneous intrustion less than 40 square miles in surface exposure.

Strain. Deformation resulting from applied stress; proportional to stress.

Stratum. A single layer of homogeneous or gradational lithology, deposited parallel to the original dip of the formation.

Strike-slip fault. A fault, the actual movement of which is parallel to the strike of the fault.

Syncline. A fold, the core of which contains stratigraphically younger rocks, and which in simplest form, is elongate and concave upward with the two limbs dipping toward each other.

<u>Tectonic</u>. Pertaining to the forces involved in, or the rock structures and external forms resulting from the deformation of the earth's crust.

<u>Tectonism (diastrophism)</u>. Crustal movement produced by earth forces, such as the formation of plateaus and mountain ranges; the structural behavior of an element of the earth's crust during, or between, major cycles of sedimentation.

<u>Terrace</u>. A long, narrow, relatively level or gently inclined surface, generally less broad than a plain, bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope, and containing unconsolidated material.

<u>Thrust fault</u>. A fault with a dip of 45° or less in which the upper rock mass appears to have moved upward relative to the lower rock mass.

<u>Transmissivity</u>. Volume of water flowing through a one-foot width of aquifer of given thickness under a unit gradient (one foot vertically for each foot laterally) and at the viscosity prevailing in the field. Mathematically, it is the product of permeability and aquifer thickness.

<u>Ultramafic</u>. Pertaining to igneous rocks composed chiefly of ferromagnesian, dark minerals.

<u>Underthrust</u>. A type of thrust fault in which the lower rock mass has been actively moved under the upper, passive rock mass.

<u>Uplift</u>. A structurally high area in the crust, produced by positive movements that raise or upthrust the rocks, as in a dome or arch.

<u>Upwarping</u>. Uplift of a regional area of the earth's crust.

<u>Water table</u>. That surface of an unconfined water body at which the pressure is atmospheric.

<u>Zeolite</u>. Any of a large group of minerals that are hydrous silicates of aluminum with sodium and calcium, or rarely, with barium and strontium.

<u>Zeolitization</u>. The process by which feldspars and other alumino silicates of a rock are altered to zeolites.

APPENDIX 4.B

MAJOR STRATIGRAPHIC AND TIME DIVISIONS

Major Stratigraphic and Time Divisions

[By Geol. Names Committee, U.S. Geol. Survey, 1972]

Subdivisions in Use by the U.S. Geological Survey			Age estimates commonly used for boundaries (in million years)	
Era or Erathem	System or Period	Series or Epoch	(A)	(B)
	Quaternary	Holocene		
		Pleistocene	1.5-2	1.8
	Tertiary	Pliocene	ca. 7	5.0
		Miocene	26	22.5
		Oligocene	37-38	37.5
		Eocene	53-54	53.5
		Paleocene	65	65
Mesozoic	Cretaceous	Upper (Late) Lower (Early)	136	
	Jurassic	Upper (Late) Middle (Middle) Lower (Early)	190-195	
	Triassic	Upper (Late) Middle (Middle) Lower (Early)	225	
Paleozoic	Permian	Upper (Late) Lower (Early)	280	
	Pennsylvanian	Upper (Late) Middle (Middle) Lower (Early)	320	
	Mississippian	Upper (Late) Lower (Early)	345	
	Devonian	Upper (Late) Middle (Middle) Lower (Early)	395	
	Silurian	Upper (Late) Middle (Middle) Lower (Early)	430-440	
	Ordovician	Upper (Late) Middle (Middle) Lower (Early)	ca. 500	
	Cambrian	Upper (Late) Middle (Middle) Lower (Early)	570	
Precambrian	Time subdivisions of the Precambrian: Precambrian Z--base of Cambrian to 800 m.y. Precambrian Y--800 m.y. to 1,600 m.y. Precambrian X--1,600 m.y. to 2,500 m.y. Precambrian W--older than 2,500 m.y. A--Geological Soc. of London, 1964 B--Berggren, 1972			

APPENDIX 4.C

CHEMICAL COMPOSITIONS (IN PERCENT) AND PHYSICAL AND HYDROLOGIC PROPERTIES OF PRINCIPAL ROCK TYPES

Chemical compositions (in percent) and physical and hydrologic properties of principal rock types

	Sandstone[1]	Shale[2]	Limestone[3]	Dolomite[4]	Granite[5]	Granodiorite[6]	Diorite[7]	Gabbro[8]	Rhyolite[9]	Quartz latite[10]	Dacite[11]	Andesite[12]	Basalt[13]	Quartzite[14]	Amphibolite[15]	Gneiss[16]	Schist[17]	Phyllite[18]	Slate[19]	Salt	Marble	Tuff
SiO_2	78.66	58.10	5.19	4.08	70.18	65.01	56.77	48.24	72.80	62.43	65.68	59.59	49.06	83.30	50.39	64.17	65.74	61.78	61.90			
TiO_2	.25	.65	.06	---	.39	.57	.84	.97	.33	.85	.57	.77	1.36	.49	1.88	1.03	.55	.73	.82			
Al_2O_3	4.78	15.40	.81	.83	14.47	15.94	16.67	17.88	13.49	16.15	16.25	17.31	15.70	7.44	14.67	15.90	17.35	16.54	16.54			
Fe_2O_3	1.08	4.02	.54	.13	1.57	1.74	3.16	3.16	1.45	4.04	2.38	3.33	5.38	3.69	4.02	2.31	1.90	2.43	2.73			
FeO	.30	2.45	---	.95	1.78	2.65	4.40	3.95	.88	1.20	1.90	3.13	6.37	.62	8.34	4.56	3.35	5.45	3.63			
MnO	Trace	Trace	.05	.14	.12	.07	.13	.13	.08	.09	.06	.18	.31	<Trace	<.28	<.15	.03	.07	Trace			
MgO	1.17	2.44	7.90	19.28	.88	1.91	4.17	7.51	.38	1.74	1.41	2.75	6.17	.92	5.85	2.63	1.90	2.35	2.99			
CaO	5.52	3.11	42.61	29.48	1.99	4.42	6.74	10.99	1.20	4.24	3.46	5.80	8.95	.33	9.12	3.40	1.25	1.94	1.07			
Na_2O	.45	1.30	.05	---	3.48	3.70	3.39	2.55	3.38	3.34	3.97	3.58	3.11	1.58	2.84	2.62	1.78	1.89	2.57			
K_2O	1.32	3.24	.33	---	4.11	2.75	2.12	.89	4.46	3.73	2.67	2.04	1.52	1.62	.96	1.87	3.28	4.14	3.15			
P_2O_5	.08	.17	.04	---	.19	.20	.25	.28	.08	.27	.15	.26	.45	.21	.24	.15	.12	.27	.04			
H_2O	1.64	5.00	.77	.41	.84	1.04	1.36	1.45	1.47	1.90	1.50	1.26	1.62	1.16	1.54	1.15	2.01	2.32	3.84			
CO_2	5.04	2.63	41.58	44.42	---	---	---	---	---	---	---	---	---	---	Trace	<.03	None	---	.59			
Grain size (mm)[20]	0.05-0.8	<0.01	0.001-0.85	3.5-4.0	0.1-12.0	---	0.2-10.0	<1.0-3.0	---	---	---	0.3-1.6	0.01-20.0	<0.3	0.1-2.0	0.1-18.0	0.04->6.0	0.01-3.0	>0.03-0.2	10-40	<1-8.5	0.12-0.25
Mohs' hardness[20]	2.42-6.13	3.16-5.68	2.79-4.84	5.26	5.83-6.5	---	4.68-6.37	5.68-6.14	---	---	---	6.17-6.25	3.95-6.21	5.75	4.74-6.37	5.26-6.58	5.2-5.68	3.47-5.11	3.79-4.32	---	3.7-4.32	---
Specific gravity (avg)[20]	2.06-3.26	2.4-2.92	2.44-2.83	2.72-2.84	2.61-2.65	[21]2.68-2.98	1.0-3.03	2.81-2.93	[21]2.26-2.50	---	---	2.57	2.04-3.01	2.75	3.01-3.12	2.65-3.36	2.68-2.75	2.18-3.24	2.74-2.93	2.5	2.72-3.2	[21]2.42-2.55
Compressive strength (psi)[20]	2,270-34,100	4,970-34,800	9,700-29,500	46,700	8,250-35,400	---	9,310-48,300	18,300-40,200	[21]17,200-42,000	---	---	18,710-19,150	2,470-52,000	91,200	30,400-74,900	22,200-36,400	1,160-23,500	970-18,300	22,500-30,400	1,080-5,000	18,400-33,000	[21]40,000
Modulus of elasticity (10^6 psi)[20]	0.87-7.02	6.73-9.87	4.1-10.73	12.3	3.85-6.41	---	4.4-12.2	12.3	---	---	---	---	0.91-13.9	12.3	6.74-15.1	3.48-15.0	2.6-8.7	2.7-11.1	11.0-13.66	---	7.15-11.9	---
Interstitial porosity (percent)	[22]0-51	[23]0.7-[22]45	[22]0-32		Granitic and other plutonic rocks: [24]0.05-[25]3.0				Volcanic rocks excluding basalt: [26]<1-[23]48				[27]0.9-[28]37	Metamorphic rocks: [24]/[27]0.02-2.4						[26]<1	[21]0.9-2.3	[21]29.1-42.5
Interstitial permeability (gpd/sq ft)	[29]$2X10^{-3}$-[30]220	[23]$7X10^{-7}$-4	[23]$2X10^{-5}$-[26]6		Granitic and other plutonic rocks: [31]$9X10^{-7}$-$5X10^{-6}$				Volcanic rocks excluding basalt: [23]$2X10^{-6}$-18				[30]$4X10^{-5}$-0.9	Metamorphic rocks: [31]$1X10^{-6}$-0.05						[26]$1.3X10^{-4}$-0.07	---	---
Production rates from wells (gpm)	[32]<0.1-[26]870	[29]<0.1-[33]64	[32]<0.1-[33]2,950		Granitic and other plutonic rocks: [26]0-63				Volcanic rocks excluding basalt: [23]<1-700				[27]10-5,300	Metamorphic rocks: [34]<1-[26]56						---	---	---
Types of principal permeability[23]/[26]/[27]	Interstitial, fracture	Fracture	Interstitial, fracture, solution		Granitic and other plutonic rocks: Fractures				Volcanic rocks excluding basalt: Fractures, interstitial				Fractures, interstitial	Metamorphic rocks: Fractures						---	---	---
Solubility[27]	Low	Low	Moderate		Granitic and other plutonic rocks: Low				Volcanic rocks excluding basalt: Low				Low	Metamorphic rocks: Low						High	---	---
Cation-exchange capacity[35] (milliequivalents/100 g)	---	10.0-41.0	---	---	---	---	---	---	---	---	---	---	0.5-2.8	0.6-5.3	---	---	---	---	---	---	---	32-49
Thermal conductivity[36] (10^{-3} cal/cm sec °C)	3.5-10.2	2.8-6.9	4.7-8.0	9.6-12	6.2-9.0	6.2-8.3	[37]5.53	[37]4.16	7.4-8.8	---	---	[37]3.06	[37]3.45-4.09	8.7-19.2	6.1-9.1	4.6-11.4	4.1-8.9	6.5-14.0	---	[36]12.75-17.2	[37]5.2-7.14	---
Thermal expansion, 20°-100°C[38] (avg linear expansion coefficient 1ΔL/LΔT)	$10±2X10^{-6}$	---	$8±4X10^{-6}$	---	$8±3X10^{-6}$	---	$7±2X10^{-6}$	$5.4±1X10^{-6}$	$8±3X10^{-6}$	---	---	$7±2X10^{-6}$	$5.4±1X10^{-6}$	$11X10^{-6}$	---	---	---	---	$9±1X10^{-6}$	---	$7±2X10^{-6}$	---
Incipient melting (°C)[39]	---	---	---	---	Below 700	---	---	---	---	---	---	1095-1098	1040-1072	---	---	---	---	---	---	---	---	---

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1/ Composite analysis of 253 samples (Clarke, 1924, p. 547) (includes 0.07 percent SO_3, trace Cl).

2/ Average of 78 analyses (Pettijohn, 1957, p. 344) (includes 0.64 percent SO_3).

3/ Composite analysis of 345 samples (Clarke, 1924, p. 564) (includes 0.05 percent SO_3, 0.02 percent Cl).

4/ Average of 5 analyses (Clarke, 1924, p. 579).

5/ Average of 546 analyses (Daly, 1933, p. 9).

6/ Average of 40 analyses (Daly, 1933, p. 15).

7/ Average of 70 analyses (Daly, 1933, p. 16).

8/ Average of 41 analyses (Daly, 1933, p. 17).

9/ Average of 126 analyses (Daly, 1933, p. 9).

10/ Average of 12 analyses (Daly, 1933, p. 13).

11/ Average of 90 analyses (Daly, 1933, p. 15).

12/ Average of 87 analyses (Daly, 1933, p. 16).

13/ Average of 198 analyses (Daly, 1933, p. 17).

14/ Average of 3 analyses (Clarke, 1924, p. 619).

15/ Average of 3 analyses (Clarke, 1924, p. 603).

16/ Average of 7 analyses (Clarke, 1924, p. 630) (includes 0.03 percent S).

17/ Average of 5 analyses (Clarke, 1924, p. 631) (includes 0.03 percent SO_3, 0.58 percent C).

18/ Average of 4 analyses (Mehnert, 1969, p. 278) (includes 0.01 percent S).

19/ Average of 22 analyses (Clarke, 1924, p. 631) (includes 0.11 percent FeS_2)

20/ Wuerker, 1969, tables 1-5.

21/ Judd, 1969, Appendix E.

22/ Manger, 1963.

23/ Winograd and others, 1971.

24/ Talobre, 1957.

25/ Izett, 1960.

26/ Davis and DeWiest, 1966.

27/ Meinzer, 1923.

28/ Mundorff and others, 1964.

29/ Levorsen, 1954.

30/ Morris and Johnson, 1967.

31/ Johnson, 1963.

32/ O'Connor, 1971.

33/ Cederstrom, 1972.

34/ McConaghy and others, 1964.

35/ Carroll, 1959, table 3.

36/ Clark, 1966, tables 21-1 and 21-2.

37/ Daly, 1933, table 12.

38/ Clark, 1966, table 6-10.

39/ Daly, 1933, table 16a.

APPENDIX 4.D

MODIFIED MERCALLI INTENSITY SCALE

Table 7. Abridged Version of Modified Mercalli Intensity Scale of 1931 (Coffman and von Hake, 1972, p. 4-7)

I. Not felt except by a very few under specially favorable circumstances. (I)

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II)

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motorcars may rock slightly. Vibration like passing of truck. Duration estimated. (III)

IV. During the day, felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls made creaking sound. Sensation like heavy truck striking building. Standing motorcars rocked noticeably. (IV to V)

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI)

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII)

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars. (VIII-)

TABLE 7. (contd)

VIII.	Damage slight in specially designed structures; considerable in ordinary, substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving motorcars disturbed. (VIII+ to IX)
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+)
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with their foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X)
XI.	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.
XII.	Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into air.

APPENDIX 4.E

PROMINENT EARTHQUAKES IN THE UNITED STATES THROUGH 1970

APPENDIX 4.E

Prominent earthquakes in the United States through 1970

(Coffman and von Hake, 1972, p. 6)

Date	Locality	N. Lat degrees	W. Long degrees	Area sq. mi.	Modified Mercalli Intensity Scale
1663 Feb. 5	St. Lawrence River region	47.6	70.1	750,000	X
1755 Nov. 18	East of Cape Ann, Mass	42.5	70.0	300,000	VIII
1811 Dec. 16 1812 Jan. 23 1812 Feb. 7	Near New Madrid, Mo	36.6	89.6	2,000,000	XII
1812 Dec. 21	Off coast of southern California	34	120	....	X
1836 June 10	San Francisco Bay	38	122	....	IX-X
1838 June	San Francisco region	37 1/2	122 1/2	....	X
1853 Nov. 9	Near Fort Yuma, Ariz	33	114 1/2	....	VIII-IX
1857 Jan. 9	Near Fort Tejon, Calif	35	119	....	X-XI
1865 Oct. 1	Fort Humboldt and Eureka, Calif	41	124 1/2	....	VIII-IX
1865 Oct. 8	Santa Cruz Mts., Calif	37	122	....	VIII-IX
1868 Apr. 2	Near south coast of Hawaii	19	155 1/2	....	X
1868 Oct. 21	Hayward, Calif	37 1/2	122	....	IX-X
1872 Mar. 26	Owens Valley, Calif	36 1/2	118	125,000	X-XI
1886 Aug. 31	Northwest of Charleston, S.C	32.9	80.0	2,000,000	IX-X
1892 Feb. 23	Northern Baja California	31 1/2	116 1/2	....	VIII-IX (U.S.)
1892 Apr. 19	Vacaville, Calif	38 1/2	122 1/2	....	IX
1892 Apr. 21	Winters, Calif	38 1/2	122	....	IX
1893 Apr. 4	Northwest of Los Angeles, Calif	34 1/2	118 1/2	....	VIII-IX
1895 Oct. 31	Charleston, Mo	37.0	89.4	1,000,000	VIII
1898 Apr. 14	Mendocino County, Calif	39	124	....	VIII-IX
1899 Sept. 3	Yakutat Bay, Alaska	60	142	....	XI
1899 Sept. 10	....do	60	140	....	XI
1899 Dec. 25	San Jacinto and Hemet, Calif	33 1/2	116 1/2	100,000	IX
1906 Apr. 18	Northwest of San Francisco, Calif	38	123	375,000	XI
1915 Oct. 2	Pleasant Valley, Nev	40 1/2	117 1/2	500,000	X
1918 Apr. 21	Riverside County, Calif	33 3/4	117	150,000	IX
1921 Sept. 29 1921 Oct. 1	Elsinore, Utah	38.8	112.2	....	VIII
1922 Mar. 10	Cholame Valley, Calif	35 3/4	120 1/4	100,000	IX

APPENDIX 4.E (contd)

Prominent earthquakes in the United States through 1970--Continued

Date	Locality	N. Lat degrees	W. Long degrees	Area sq. mi.	Modified Mercalli Intensity Scale
1925 Feb. 28	St. Lawrence River region	47.6	70.1	2,000,000	VIII
1925 June 27	Helena, Mont	46.0	111.2	310,000	VIII
1925 June 29	Santa Barbara, Calif	34.3	119.8	....	VIII-IX
1927 Nov. 4	West of Point Arguello, Calif	34 1/2	121 1/2	....	IX-X
1931 Aug. 16	Western Texas	30.6	104.1	450,000	VIII
1932 Dec. 20	Western Nevada	38.7	117.8	500,000	X
1933 Mar. 10	Long Beach, Calif	33.6	118.0	100,000	IX
1934 Jan. 30	Southeast of Hawthorne, Nev	38.3	118.4	110,000	VIII-IX
1934 Mar. 12	Near Kosmo, Utah	41.7	112.8	170,000	VIII
1935 Oct. 18	Northeast of Helena, Mont	46.6	112.0	230,000	VIII
1935 Oct. 31	....do	46.6	112.00	140,000	VIII
1940 May 18	Southeast of El Centro, Calif	32.7	115.5	60,000	X
1949 Apr. 13	Western Washington	47.1	122.7	150,000	VIII
1952 July 21	Kern County, Calif	35.0	119.0	160,000	XI
1954 July 6	East of Fallon, Nev	39.4	118.5	130,000	IX
1954 Aug. 23	....do	39.6	118.5	150,000	IX
1954 Dec. 16	Dixie Valley, Nev	39.3	118.2	200,000	X
1958 July 9	Southeastern Alaska	58.6	137.1	100,000	XI
1959 Aug. 17	Near Hebgen Lake, Mont	44.8	111.1	600,000	X
1964 Mar. 27	Southern Alaska	61.0	147.8	700,000	IX-X
1965 Apr. 29	Northwestern Washington	47.4	122.3	130,000	VIII

APPENDIX 4.F

DESCRIPTION OF SYSTEMS FOR COST BASES

APPENDIX 4.F

DESCRIPTION OF SYSTEMS FOR COST BASES

Listings of conceptual facility, major equipment, and operating requirements for each of the geologic disposal concepts are contained in this appendix. The listings were prepared to provide bases for preliminary estimates of capital and operating costs associated with individual concepts. Costing of the various concepts was not intended to be exact because of the lack of definition of a specific site and detailed repository design. Thus the cost bases developed here provide sufficient information for approximate cost estimates and for estimating relative costs among various concepts. Section 3.2.3.1 of Section 3 in Volume 1 of this report enumerates in more detail the cost bases for various depths and types of rock.

It is assumed that 14,500 canisters (30 centimeters outside diameter by 3 meters long), resulting from 25 years of operation of the reference 5 MT/day fuel reprocessing plant (45,625 metric tons of fuel equivalent) will be handled and buried. Maximum burial activity will be 20 canisters per week. Waste volume and maximum heat generation per canister are 0.18 m^3 and 3.39 kilowatts, respectively.

For the liquid disposal concepts, the waste, piped from the reference on-site fuel reprocessing plant, will be available at an average rate of 1900 liters per day.

A standard buffer zone of 3.2 kilometers is expected to surround the disposal site.

Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting (Concept 1)

Capital cost estimates are based on a reference wherein waste canisters would be buried in the floor of a tunnel complex located inside a thick granite formation. The top of the granite formation is located at or near ground level while the working level of the mine is assumed to be located 600 meters below grade. Dimensions of major facilities and buildings and major equipment are summarized in Table 4.41. Additional details are presented below:

Surface Facilities. Surface facilities include surge "tailing" storage, two hot cells, and the following concrete block/steel roof buildings: The receiving facility, hoist house, protection for ventilation fans and filters, and offices and laboratories (see Table 4.41). The receiving facility is equipped with a 100-ton-capacity bridge crane for cask handling. Canisters and cell cover blocks are manipulated with the aid of a 15-ton in-cell crane. In the cell, the cask is transferred through the transfer gallery to beneath the hatch (cover block) of the transfer cell with a remotely operated transfer cart (the unit can also be used to raise the cask to form a seal against the underside of the cell during canister removal). The two surface hot cells are equipped with six viewing windows and six pairs of slave manipulators.

TABLE 4.41. Facility Details for Cost Estimating - Solid Waste Emplaced in Mined Cavity - No Fluid Cooling or Melting

Overall Facility Description

Concrete block/steel roof construction

- Rail car air lock: (45 x 6) x 14 meters high
- Hoist house: (9 x 9) x 6 meters high
- Ventilation building: (12 x 12) x 5 meters high
- Offices, laboratories, etc.: (30 x 12) x 5 meters high
- Total area: 880 square meters

Hot cells

- Shielding is 1.2 m thick high-density concrete
- Transfer gallery: (15 x 8) x 8 meters high
- Transfer cell: (15 x 15) x 6 meters high
- Mine-level receiving station: (15 x 15) x 6 meters high
- Total area: 580 square meters

Shafts (all concrete and steel lined)

- Transfer shaft: 0.6 m I.D.
- Ventilation shaft: 1.8 m I.D.
- Auxiliary shaft: 1.5 m I.D.
- Personnel shaft: 1.8 m I.D.

Tunnels

- Approximately 2.4 km^2 square tunnel complex with a 3.2 km buffer zone surrounding the complex, or approximately 65 km^2 of area
- Lattice spacing of canisters: 30 m (triangular)
- Burial tunnels: approximately 90 kilometers, 4.6 meters high x 4.6 meters
- Access tunnels: approximately 11 kilometers
- Ventilation tunnels: 0.6 m I.D.

Major Equipment

100 and 15 ton bridge cranes at surface

23,600 liters/sec mine ventilation system with fans, high efficiency (HEPA) filters, and prefilters

Transfer shaft hoist (elevator) - 150 m/min lift speed, cable tension 11,000 kg

Underground transporter; rubber tired, diesel power unit; shielded 35-ton movable cask 22.9 cm lead shielding; 38.1 cm bore; 3.7 m long; 5-ton hoist

6 viewing windows and pairs of manipulators

In-cell transfer carts - two required, remotely controlled, electric/hydraulic units

Mining rig including belt conveyors, shuttle cars, hole drilling rig, etc.

One bulkhead per individual burial tunnel

Operating Data

Staff: 11 supervisory, 23 nonsupervisory

- Administration: 4 supervisory, 10 nonsupervisory (including 5 security guards)
- Engineering: 5 supervisory, 5 nonsupervisory
- Operations: 2 supervisory, 8 nonsupervisory

Operation: 5 day week, 1 shift

Subsurface Facilities. In addition to the tunnel complex and mining equipment, subsurface facilities and components include the transfer shaft and associated hoist; ventilation shaft; personnel and auxiliary shafts; the working (mine) level receiving station; and the shielded underground transporter. The transfer shaft hoist is an "elevator" designed to assure safe lowering of canisters. The working-level receiving station is a hot cell equipped with an in-cell transfer cart operated from four viewing window/manipulator stations. The underground transporter removes canisters from the receiving station and transports them to the disposal tunnels where the canisters are lowered into holes in the tunnel floor.

The mine-level receiving station is located at the center of an approximately square tunnel complex. A buffer zone 3.2 kilometers wide is established around the complex including the acquisition of mineral rights. As shown in Table 4.41, individual burial sites are spaced on a 30-meter triangular lattice. Burial tunnels (drifts) are parallel to the 30-meter dimension, and five canisters are buried at each lattice position. There is one row of lattice positions in a burial tunnel. Preliminary calculations indicate that this triangular distribution limits granite and glass-ceramic waste temperatures to about 250°C and 400°C, respectively. Both values are believed to be conservative but, as suggested in Section 4.6, are subject to change as the result of the Research and Development findings. Burial depth is 2.4 meters to the top of the top canister, and "pillar" width between burial tunnels is about 20 meters (based on mine heat loading considerations). During burial, tunnels are lined with "wire-mesh" for personnel protection from rock spalls. Burial tunnels are backfilled with crushed rock and sealed with a bulkhead when emplacement activities are completed in each tunnel. It is assumed that mining and burial can proceed simultaneously in separate main access tunnels.

Facility Operations. The estimated operating staff requirements (except for security guards) are 11 supervisory and 23 nonsupervisory personnel on a 5-day week, one shift operation. The staff includes 4 supervisory and 10 nonsupervisory administrative personnel (including 5 security guards), 5 supervisory and 5 nonsupervisory engineering personnel, and 2 supervisory and 8 nonsupervisory operations personnel (cask/canister handling, burial, and mining crews).

Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix (Concept 2)

This concept is based on the random placement of waste canisters into a lined cavity located in any of several different geologic formations. For costing purposes, the cavity is located at a depth of 1,500 meters in a granite formation whose top extends to or near the surface. Structures and equipment are needed to receive and handle canisters shipped by rail in shielded shipping casks. The canisters are unloaded one at a time in hot cells and moved to the canister insertion room via crane. The crane cable will be used to lower the canisters into the mined cavity.

Surface components will include the receiving facility, the canister insertion room, a well-head room for piping, and the condensers and water recycle equipment.

Water-bearing surface formations will be sealed by setting and cementing a 1.4-meter inside diameter (nominal) casing in a 2.3 meter drilled hole. The volume of the concrete and steel lined cavity will be 13,000 cubic meters.

Other information for capital and operating cost estimating is detailed in Table 4.42.

Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling (Concept 3)

The economic incentive for artificial heat removal from buried waste lies in the reduced amount of mining required compared to a disposal concept which relies solely on conduction through the surrounding rock for removal of radioactive decay heat. The criterion used for sizing the facility is simply that the heat generation rate of the waste, at the end of the design lifetime of the cooling system, should be no greater than the rate at which heat can be conducted away from the waste through the surrounding rock without the waste containers or the surrounding rock reaching excessive temperatures. Therefore, at that time, the penetrations to the disposal area can be sealed.

To estimate the amount of mining required to hold the reference inventory of 14,500 canisters, it was assumed that: 1) The design lifetime of the cooling system is 100 years. 2) The permissible gross heat loading based on the surface area of the disposal site is 18.5 W/m^2 for the waste when it is 110 years old. This is roughly one-half the permissible heat loading of 33.6 W/m^2 est - mated for 100-year-old waste from heat conduction calculations for the Lyons, Kansas, disposal site.(169) 3) The waste is 10 years old when buried so that the initial gross heat loading is 184.1 W/m^2. 4) All of the decay heat is to be removed by the cooling system. 5) The heat generation rate per canister is 3.39 kilowatts at burial and decays to about 0.32 kilowatts 100 years after burial. 6) The burial depth is 600 meters.

The natural convection cooling systems are sized to remove the initial heat generation rate of 3.39 kilowatts per container. The cooling equipment reliability decreases with time, but so does the heat generation rate of the waste, so that a cooling unit can service more canisters in case some cooling units fail as they age. The facility requirements for this concept are listed in Table 4.43.

Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling (Concept 4)

The economic incentive for artificial heat removal from buried waste lies in the reduced amount of mining required compared to a disposal concept which relies solely on conduction through the surrounding rock for removal of radioactive decay heat. The criterion used for sizing the facility is simply that

TABLE 4.42. Facility Details for Cost Estimating Solid Waste Emplaced in Mined Cavities - Interim Liquid Cooling and Conversion to Rock-Waste Matrix

Overall Facility Description

Concrete block/steel room construction

- Rail car airlock: (45 x 6) x 14 meters high
- Offices, laboratories: (30 x 12) x 4.5 meters high
- Maintenance/storage facility: (30 x 15) x 14 meters high
- Cask transfer gallery: (15 x 9) x 7.5 meters high
- Total area: 1250 m^2

Hot Cells

- Shielding is 1.2 meters thick high-density concrete
- Transfer cell: (15 x 15) x 12 meters high
- Condenser cell: (15 x 6) x 12 meters high
- Cable drum cell: (6 x 15) x 6 meters high
- Total area: 420 m^2

Drilled Holes

- Drill a 2.3 meter diameter hole 1520 meters deep
- Casing OD: 1.4 m (nominal) x 1.9 cm wall by 1520 meters
  Three 0.6 m (nominal) x 1.3 cm wall by 1520 meters
- Mined Cavity: 13,000 m^3 lined with concrete and steel
- Gross area: 16,000 m^2 plus 3.2 km wide buffer zone around site, or approximately 40 km^2

Major Equipment

100/15 ton bridge crane

One remotely controlled in-cell crane for in-cell transfer

One large cable drum

Eight viewing windows and pairs of manipulators

Two condensers of 20 megawatts capacity each (includes 100% redundancy)

40 megawatts of secondary air or water cooling capability (includes 100% redundancy)

Operating Data

Staff: 1 supervisory, 23 nonsupervisory

- Administration: 4 supervisory, 10 nonsupervisory (including 5 security guards)
- Engineering: 5 supervisory, 5 nonsupervisory
- Operations: 2 supervisory, 8 nonsupervisory
- 7 day week, 3 shifts

TABLE 4.43. Facility Details for Cost Estimating - Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Air Cooling

Overall Facility Description

Incoming Waste Handling Facilities

- Rail car air lock: 45 x 6 x 14 meters
- Hoist House: 9 x 9 x 6 meters
- Ventilation equipment: 12 x 12 x 5 meters
- Offices and laboratories: 30 x 12 x 5 meters
- Hot cell transfer gallery: 15 x 7.6 x 7.6 meters
- Transfer cell: 15 x 15 x 6 meters
- Working level cell: 15 x 15 x 6 meters
- Shielding for hot cells: 1.2 meters of high-density concrete
- Underground transporter

Shafts

- Waste transfer shaft: 0.6 meter diameter (concrete and steel lined)
- Personnel ventilation shaft: 1.8 meter diameter (concrete and steel lined)
- Personnel shaft: 1.8 meter diameter (steel and concrete lined)

Disposal Tunnels

- Tunnel diameter: 9 meters
- Rock bolts: 2.5 cm-diameter bolts, 3 meters long on 2.1 meter by 2.1 meter pattern
- Lining: 18 cm.-thick shotcrete
- Tunnel arrangement: Parallel spacing 45.7 meters center to center
- Canister spacing: 1 canister per 0.387 linear meter of storage tunnel
- Total length of storage tunnel: 5.5 kilometers
- Disposal area exclusive of safety zone: 0.25 km^2
- Safety zone: 3.2 kilometer minimum distance from storage area to site boundary
- Total site area: Approximately 50 km^2

Cooling Facilities

- Total number of individual systems: 20
- Total number of cooling shafts: 40
- Shaft diameter: 2.1 meters (the shaft will be cased, rock bolted and/or shotcreted, depending on rock properties.)
- Total high efficiency filter area: 370 square meters
- Total medium efficiency filter area: 370 square meters
- Total heat removal duty for 20 systems: 50 megawatts
- Total cooling air flow for 20 systems: 3,000,000 kg/hr
- Cooling air exit temperature: 90°C

Operating Data

Staff: 14 supervisory, 33 nonsupervisory

- Administration: 4 supervisory plus 8 nonsupervisory (including 5 security guards)
- Engineering: 5 supervisory, 5 nonsupervisory
- Operations and maintenance: 5 supervisory, 20 nonsupervisory

Operation: 5 day week, 1 shift except for security guards the heat generation rate of the waste, at the end of the design lifetime of the cooling system, should be no greater than the rate at which heat can be conducted away from the waste through the surrounding rock without the waste containers or the surrounding rock reaching excessive temperatures. Therefore, at that time, the penetrations to the disposal area can be sealed.

To estimate the amount of mining required to hold the reference inventory of 14,500 canisters, it was assumed that (1) the design lifetime of the cooling system is 100 years, (2) the permissible gross heating load based on the surface area of the disposal site is 18.5 W/m^2 for the waste when it is 110 years old. (This is roughly one-half the permissible heat loading of 33.6 W/m^2 estimated for 100-year-old waste from heat conduction calculations for the Lyons, Kansas site),(169) (3) the waste is 10 years old when buried so that the initial gross heat load is 184.1 W/m^2. (4) All of the decay heat is to be removed by the cooling system. (5) The heat generation rate per canister is 3.39 kilowatts at burial and decays to about 0.32 kilowatts one hundred years after burial. (6) The burial depth is 600 meters.

The amount, size and kind of additional equipment and labor required are shown in Table 4.44 for the boiling water cooling. The cooling systems are sized to remove the initial heat generation rate of 3.39 kilowatts per container. The heat generation rate of the waste decreases with time thus reducing the cooling system heat removal load. A reduction in the heat load permits placing certain of the cooling units in a standby status for use in case failure of some of the operating units is experienced.

Boiling Water Cooled Storage. Waste canisters remain within the repository after water cooling is terminated. They are initially spaced to produce an allowable heat loading of 18.5 W/m^2 after 100 years which should allow heat to be dissipated through the host rock without canister wall temperatures exceeding 300°C. Heat is transferred to the surface by steam.

Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix (Concept 5)

The concept is based on the placement of liquid waste into a mined cavity which is lined and located in any of several different geologic formations. For costing purposes, the cavity depth is taken to be 1500 meters in a granite formation whose top extends to or near the surface. The waste is piped from an on-site fuel processing plant.

Surface components include the hot cell where the condensers are located, the condenser operating area, and equipment for gas treatment before the gas is returned to the reprocessing plant.

Water-bearing surface formations are sealed by setting and cementing a 1.4 meter inside diameter (nominal) casing in a 2.3 meter drilled hole. The cavity has a volume of about 4000 cubic meters and has a concrete and stainless-steel liner.

Other information for capital and operating cost estimating is detailed in Table 4.45.

TABLE 4.44. Facility Details for Cost Estimating - Solid Waste Emplaced in Manmade Structures in Geologic Formations - Interim Water Cooling

Incoming Waste Handling Facilities

Rail car air lock: (45 x 6) x 14 meters
Hoist house: (9 x 9) x 6 meters
Ventilation equipment: (12 x 12) x 5 meters
Offices and laboratories: (30 x 12) x 5 meters
Hot cell transfer gallery: (15 x 7.6) x 7.6 meters
Transfer cell: (15 x 15) x 6 meters
Working level cell: (15 x 15) x 6 meters
Shielding for hot cells: 1.2 meters of high density concrete
Underground transporter

Shafts

Waste transfer shaft: 0.6 meter diameter (concrete and steel lined)
Personnel ventilation shaft: 1.8 meter diameter (concrete and steel lined)
Personnel shaft: 1.8 meter diameter (steel and concrete lined)

Tunnels

Tunnel diameter: 9 meters
Rock bolts: 3.5 cm diameter bolts, 3 meters long on a 2.1 meter by 2.1 meter pattern
Lining: 18 cm thick shotcrete
Tunnel arrangement: parallel spacing 45.7 meters center to center
Canister spacing: 1 canister per 0.39 linear meter of storage tunnel
Total length of storage tunnel: 5.5 kilometers
Disposal area exclusive of safety zone: 0.25 km^2
Safety zone: 3.2 kilometer minimum distance from storage area to site boundary
Total site area: approximately 50 km^2

Containment Shell

Diameter: 4.6 meters
Shell wall: 0.3 meter thick reinforced concrete
Shielding: 1.5 meter thick high density concrete
Rate sensitive anchors: spaced on 1.8 meter by 1.8 meter pattern

Cooling Facilities

Total number of individual systems: 20
Total number of cooling shafts: 40
Shaft diameter (cased): 0.45-0.51 meters
Pressure vessel dimensions: elliptical 2.3 x 3.1 meters with 1 cm thick wall of low alloy steel
Total dry cooling tower heat transfer area: 14,100 square meters (20 towers)
Total condensate tank volumes: 6,000,000 liters (20 tanks)
Total noncondensible gas bleed filter area: 46.5 square meters with 58 kilowatts gas pre-heaters (20 units)

Total cooling water ion exchange bed volume: 2,000,000 liters (20 units)

Labor (assume day shift only except for security guards)

Administration: 4 supervisory plus 8 nonsupervisory (including 5 security guards)
Engineering: 5 supervisory, 5 nonsupervisory
Operations and maintenance: 5 supervisory, 20 nonsupervisory

TABLE 4.45. Facility Details for Cost Estimating - Liquid Waste Emplaced in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix

Overall Facility Description

Concrete block/steel room construction

- Offices, Laboratories: (30 x 12) x 4.6 m high
- Maintenance/storage facility: (30 x 15) x 6 m high
- Total area: 84 m^2

Hot Cells

- Shielding is 1.2 m thick high-density concrete
- Condenser and well-head room (6 x 6) by 6 m high
- Partial cell for feed tank (3 x 3) by 6 m high
- Total area: 50 m^2

Drilled Hole

- Drill a 2.3 m diameter hole 1500 meters deep
- Stainless-steel lined casing: one 1.4 m OD (nominal) x 1.9 cm wall by 1525 m
  three 0.6 m OD (nominal) x 1.3 cm wall by 1525 m
- Mined cavity, 4300 m^3 lined with concrete and stainless steel
  Gross area: 16,000 m^2 plus 3.2 km wide buffer zone around site or approximately 40 square kilometers

Major Equipment

Two condensers of 80 megawatt capacity each

Process gas and liquid piping to reprocess plant

3800 liter temporary waste holdup tank

Operating Data

Staff: (Incremental above that of reprocessing plant needs)
5 supervisory, 14 nonsupervisory

- Administration: 2 supervisory, 7 nonsupervisory (including 5 security guards)

- Engineering: 2 supervisory, 2 nonsupervisory
- Operations: 1 supervisory, 5 nonsupervisory

Operation: 7 day week, 3 shifts

Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix (Concept 6)

The concept is based on the placement of liquid waste into an exploded cavity located in any of several different geologic formations. For costing purposes, the cavity is formed at a depth of 1500 meters in a granite formation whose top extends to or near the surface. The waste is piped from an on-site fuel processing plant.

Surface components include the hot cell where the condensers are located, the condenser operating area, and equipment for gas treatment before it is returned to the reprocessing plant.

Water-bearing surface formations are sealed off by setting and cementing a 1.4 meter inside diameter (nominal) casing in a 2.3 m drilled hole. The cavity is generated by a 5 kiloton nuclear explosion at hole bottom and is not lined.

Other information for capital and operating cost estimating is detailed in Table 4.46.

Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting (Concept 7)

This concept is based on the placement of waste canisters in drilled holes in a thick granite formation, the top of which is located at a depth of approximately 3000 meters. It is overlain by medium-hard sedimentary rocks. Structures and equipment are needed to receive and handle canisters shipped in shielded casks. Canisters are unloaded one at a time in hot cells and then placed in a shielded, self-propelled charging vehicle. The vehicle transports the canisters to the disposal area (via a rail network) and lowers the canister into a previously drilled hole.

Surface components include the receiving facility, a storage and maintenance facility for the charging vehicle and drill rigs, and surge "mud" storage space.

Water bearing surface formations are sealed by setting and cementing a 38 centimeter inside diameter (nominal) casing in a drilled hole that accepts the casing. The casing extends the full length of each hole which is 4500 meters deep. Each hole contains 300 canisters in the bottom 1200 meters of the drill hole. After 300 canisters have been added to a hole, the top 3300 meters of the hole is sealed with alternating plugs of clay and cement sealants. One hole is drilled for each 4 hectares of land, and a total of 49 holes is needed.

Other information for capital and operating cost estimating is detailed in Table 4.47.

Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix (Concept 8)

The concept is based on the placement of waste canisters into deep holes drilled into any of several different geologic formations. For costing purposes, the reference stratigraphy used is 3 kilo meters of sedimentary rock overlaying a very thick (greater than 13 kilometers) granite formation. The hole depth is to be 16 kilometers. Structures and equipment are needed to

TABLE 4.46. Facility Details for Cost Estimating - Liquid Waste Emplaced in Exploded Cavities - In-Place Drying and Conversion to Rock-Waste Matrix

Overall Facility Description

Concrete block/steel room construction

- Office, laboratories: (30 x 12) x 4.6 m high
- Maintenance/storage facility: (30 x 15) x 6 m high
- Total area: 1,000 m^2

Hot Cells

- Shielding is 1.2 m thick high-density concrete
- Condenser room: (30 x 6) x 6 m high
- Total area: 185 m^2

Drilled Holes

- Drill a 2.3 m diameter hole 1500 m deep
- Stainless-steel lined casing:
  One 1.4 m OD (nominal) x 1.9 cm wall by 1525 m
  Three 0.6 m OD (nominal) x 1.3 cm wall by 1525 m
- Exploded cavity free volume 4,300 m^3
  Gross area: 16,000 m^2 plus 3.2 km wide buffer zone around site or approximately 40 square kilometers

Major Equipment

Two condensers of 80 MW capacity each
Process gas and liquid piping to reprocessing plant
3800 liter temporary waste holdup tank

Operating Data

Staff: (incremental above that of reprocessing plant needs)
5 supervisory, 14 nonsupervisory

- Administration: 2 supervisory, 7 nonsupervisory (including equivalent of 5 security guards)

- Engineering: 2 supervisory, 2 nonsupervisory

- Operations: 1 supervisory, 5 nonsupervisory

Operation: 7 day week, 3 shifts

TABLE 4.47. Facility Details for Cost Estimating - Solid Waste Emplaced in a Matrix of Drilled Holes - No Melting

Overall Facility Description

Concrete block/steel roof construction

- Rail car air lock: (46 x 6) x 14 m high
- Offices, laboratories: (30 x 12) x 4.6 m high
- Maintenance/storage facility: (30 x 15) x 14 m high
- Total area: 1,100 m^2

Hot Cells

- Shielding is 1.2 m thick high-density concrete
- Transfer gallery: (23 x 9) x 7.6 m high
- Total area: 210 m^2

Drilled Holes

- Hole depth: 4,500 meters
- Casing OD: 40.5 cm (nominal) x 1.3 cm wall
- Number required: 49
- Drilling and casing rate: 195 m per week, average
- "Lattice" spacing: square, 200 m on center
- Gross area: 2 km^2 plus a 0.8 km wide buffer around site, or approximately 10 km^2
- Equipped with sealed removable covers

Major Equipment

100/15 ton bridge crane

Drill rig

Charging vehicle and track layout; with shielded, 35 ton movable cask (23 cm shielding, 38 cm bore, 3.7 m long), self powered unit that travels on rails, equipped with run and jog speeds, and lowering hoist. Instrumentation/power console to indicate vehicle position and cable tension and evaluation, capable of cooling canister if required and sealing drill hole when cover is open.

One rig to add clay and cement sealants to each hole when hole is filled. Rig must keep hole sealed while operating.

One remotely controlled in-cell crane for in-cell transfer

Eight viewing windows and pairs of manipulators

Operating Data

Staff: 11 supervisory, 23 nonsupervisory

- Administration: 4 supervisory, 10 nonsupervisory (including 5 security guards)
- Engineering: 5 supervisory, 5 nonsupervisory
- Operating: 2 supervisory, 8 nonsupervisory

Operation: 5 day week, 1 shift except for security guards receive and handle canisters shipped by rail in shielded shipping casks. The canisters are unloaded one at a time in hot cells and transported to the hole in a shielded transporter. The vehicle is used to lower the canister into the previously drilled hole.

Surface components include the receiving facility, a storage and maintenance facility for the charging vehicle, a very large drill rig, and surge "mud" storage space.

The reference hole geometry and drilling steps are described as follows: Drill a 2.2 meter diameter hole to approximately 100 meters and set 1.5 meter inside diameter casing. Cement the casing to the surface. Drill a 0.8 meter hole to a depth of about 7.6 kilometers and set and cement a 0.5 meter outside diameter casing. Drill below the 0.5 meter casing with a 0.4 meter bit to the desired 16 kilometer total depth.

Each hole contains 2500 canisters in the bottom 7500 meters. One hole is drilled for each 0.4 square kilometer of land, and a total of six holes are needed. The top 8500 meters of each hole is sealed with alternating plugs of clay and cement sealants when the hole is full.

Other information for capital and operating cost estimating is detailed in Table 4.48.

Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix (Concept 9)

This concept is based on placement of liquid waste into deep holes drilled into any of several different geologic formations. For costing purposes, the reference stratigraphy used here is 3000 meters of sedimentary rock overlying very thick (greater than 13,000 meters) granite formation. The hole depth is 16,000 meters. The waste is piped into the hole from an on-site fuel processing plant.

Surface components include the hot cell where the condensers are located, the condenser operating area, equipment for gas treatment before it is returned to the reprocessing plant, a storage and maintenance facility for the drill rigs, and surge "mud" storage space. One hot cell and associated equipment is used for each drill hole.

The reference hole geometry and drilling steps are described as follows: Drill a 2.2 meter diameter hole to approximately 110 meters and set 1.5 meter inside diameter casing. Cement the casing to the surface. Drill a 0.8 meter hole to a depth of about 7600 meters and set and cement a 0.5 meter outside diameter casing. The casing is lined with 3 millimeter thick stainless steel. Drill below the 0.5 meter casing with a 0.4 meter bit to the desired 16,000 meter total depth.

For the reference 5 MT/day disposal site, each hole contains waste from 15,400 MT or 3100 days of operation in the bottom 7500 meters of the drilled hole. One hole is drilled for each 40,000 square meters of land and a total of three holes is needed.

TABLE 4.48. Facility Details for Cost Estimating - Solid Waste Emplaced in a Deep Hole - In-Place Conversion to a Rock-Waste Matrix

Overall Facility Description

Concrete block-steel room construction (same as for drilled matrix holes)

- Rail car airlock: (45 x 6 x 14 meters
- Offices, labs: (30 x 12) x 4.6 meters
- Maintenance/storage facility: (30 x 15) x 14 meters
- Total area: 1100 m^2

Hot Cells

- Shielding is 1.2 meter thick high-density concrete
- Can manipulating cells: (23 x 9) x 7.6 meters high
- Total area: 210 m^2

Drilled Holes

- Casing OD: 1.5 meter (nominal) x 1.3 cm wall to 107 meters depth
  0.5 meter (nominal) x 2.5 cm wall to 7600 meters depth
- Drill hole: 0.4 meter diameter by 7600 meter at bottom
- Drilling rate: 69 m per week average
  casing rate: 34 m per week average
- "Lattice" spacing: 637 m square pattern
- Gross area: 2.4 km^2 plus 3.2 kilometer wide buffer zone around the site, or approximately 65 square kilometers
- Equipped with sealed removable covers (the same as for drilled matrix holes)

Major Equipment

100/15 ton bridge cranes

One drill rig - biggest yet built

Charging vehicle and track layout; with shielded, 35 ton movable cask (23 cm of shielding, 28 cm bore, 2.6 cm long), self-powered unit that travels on rails, equipped with run and jog speeds, and lowering hoist. Instrumentation/power console to indicate vehicle position and cable tension and elevation, capable of cooling canister if required and sealing drill hole when cover is open.

One rig to add clay and cement sealants to each hole when hole is filled. Rig must keep hole sealed while operating.

One remotely controlled in-cell crane for in-cell transfer

Eight viewing windows and pairs of manipulators

Operating Data

Staff: 11 supervisory, 25 nonsupervisory

- Administration: 4 supervisory, 10 nonsupervisory (including 5 security guards)
- Engineering: 5 supervisory, 5 nonsupervisory
- Operations: 2 supervisory, 10 nonsupervisory

Operation: 5 day week, 1 shift except for security quards

After filling, the top 8500 meters of each hole is sealed with alternating plugs of clay and cement sealants.

Other information for capital and operating cost estimating is detailed in Table 4.49.

Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid (Concept 10)

Cost estimates are based on a reference system where the liquid high-level waste is mixed with dry solids such as cement to form a slurry which is subsequently injected into a well which has been fractured previously with water. The slurry is forced under pressure into the fracture and the pressure maintained until the slurry solidifies. The system consists of the surface facility, thirty injection wells, and sixty monitoring wells cased to 1000 meters. The remainder of the system consists of plant equipment such as storage tanks, mixer, pumps, well head, etc.

The waste is piped from an on-site fuel reprocessing plant to waste storage tanks, at an average rate of 1900 liters/day for 25 years for the reference five MT/day reprocessing rate. The waste is held for about five years of interim storage before injection. It is assumed that each injection will consist of 300,000 liters of a waste-cement slurry and that one well will receive about 18 million liters of waste.

The surface facility includes hot cells for mixing of dry solids and waste, an injection well head, equipment for offgas treatment waste and cement storage facility, and miscellaneous plant equipment.

The reference well is a 15 centimeter diameter cased and cemented hole by 1000 meters deep. The casing is 1.3 centimeter thick stainless steel. After the well is filled completely, it is sealed with mixtures of cements and sealants.

Other information for capital and operating cost estimating is presented in Table 4.50.

TABLE 4.49. Facility Details for Cost Estimating - Liquid Waste Emplaced in a Deep Hole - In-Place Drying and Conversion to a Rock-Waste Matrix

Overall Facility Description

Concrete block/steel room construction

- Office, labs: (30 x 12) x 4.6 m high
- Maintenance/storage facility: (30 x 15) x 14 m high
- Total area: 870 m^2

Hot Cells

- Shielding is 1.2 m thick high-density concrete
- Condenser and well-head room: (6 x 6) x 6 m high
- Partial cell for feed tank: (3 x 3) x 6 m high
- Total area: 46 m^2

Drilled Holes

- Stainless-steel lined casing:
  1.5 m OD (nominal) x 1.3 cm wall by 107 m
  0.5 m OD (nominal) x 2.5 cm wall by 7600 m
- Drill hole: 0.4 m diameter x 2600 m at bottom
- Number required: three
- Drilling rate: 34 m per week average
- Casing rate: 19 m per week average
- "Lattice" spacing: 200 m square pattern
- Gross area: 0.1 km^2 plus 3.2 kilometers wide buffer zone around site, or approximately 45 km^2

Major Equipment

Two condensers of 10 megawatt cooling capacity each

Drill rig - biggest yet built

Process gas and liquid piping to reprocessing plant

4000 liter temporary waste hold-up tank

One rig to add clay and cement sealants to each hole when hole is filled. Rig must keep hole sealed while operating

Operating Data

Staff: (incremental above that of reprocessing plant needs)
5 supervisory, 14 nonsupervisory

- Administration: 2 supervisory, 7 nonsupervisory (including 5 security guards)
- Engineering: 2 supervisory, 2 nonsupervisory
- Operations: 1 supervisory, 5 nonsupervisory

Operation: 7 day week, 3 shift

TABLE 4.50. Facility Details for Cost Estimating - Liquid Waste Emplaced by Hydraulic Fracturing - In-Place Conversion to a Solid

Overall Facility Description

Concrete block/steel room construction

- Office, labs: (30 x 12) x 5 m high
- Maintenance/storage facility: (30 x 15) x 6 m high
- Total area: 810 square meters

Hot Cells

- Shielding is 1.2-m thick high-density concrete
- Mixer cell, injection cell (6 x 6) by 6-m high
- Feed Tank and Waste Pump Cell (6 x 6) by 6-m high
- Total area: 108 m^2

Drilled Holes

- Stainless-steel lined casing:
  1-15 cm OD (nominal) x 1.3 cm wall by 1000 m
  4-5 cm OD (nominal) x 1.3 cm wall by 1000 m
- Drill hole: 1-15 cm diameter x 1000 m at bottom
  4-5 cm diameter x 1000 m at bottom
- Gross Area: 65 km^2 plus a 3.2 km wide buffer zone around the site, or approximately 200 km^2

Operating Data

Staff: (incremental above that of reprocessing plant needs)
5 supervisory, 14 nonsupervisory

- Administration: 2 supervisory, 7 nonsupervisory (including 5 security guards)
- Engineering: 2 supervisory, 2 nonsupervisory
- Operations: 1 supervisory, 5 nonsupervisory

Operation: 7 day week, 3 shift

APPENDIX 4.G

TIMING REQUIREMENTS FOR RESEARCH AND DEVELOPMENT NEEDS AND BENEFICIAL OCCUPANCY OF A COMMERCIAL REPOSITORY

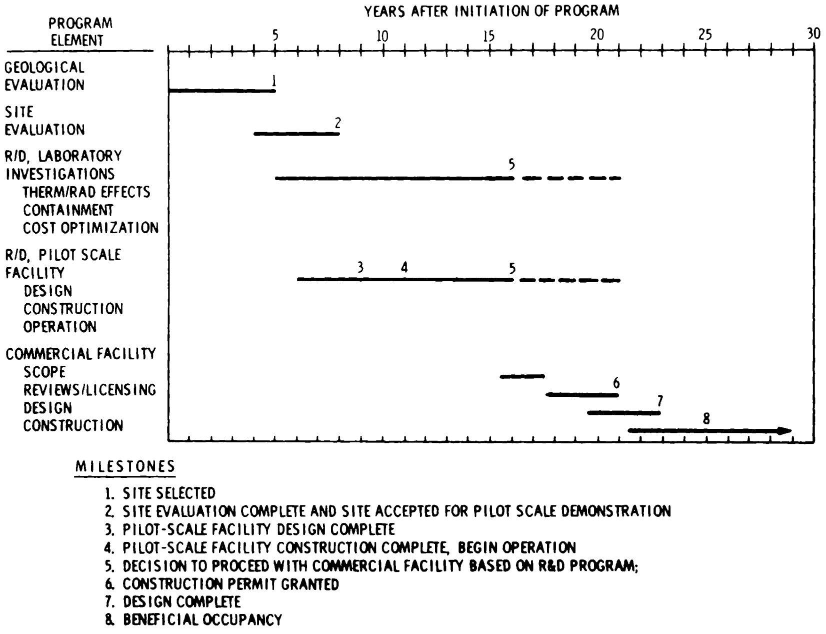


FIGURE 4.G.1. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplacement in a Mined Cavity - No Fluid Cooling or Melting

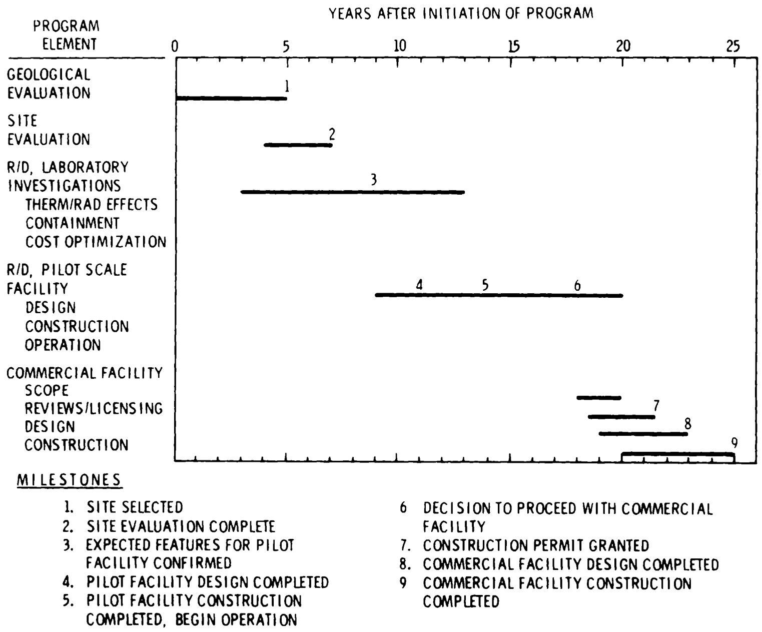
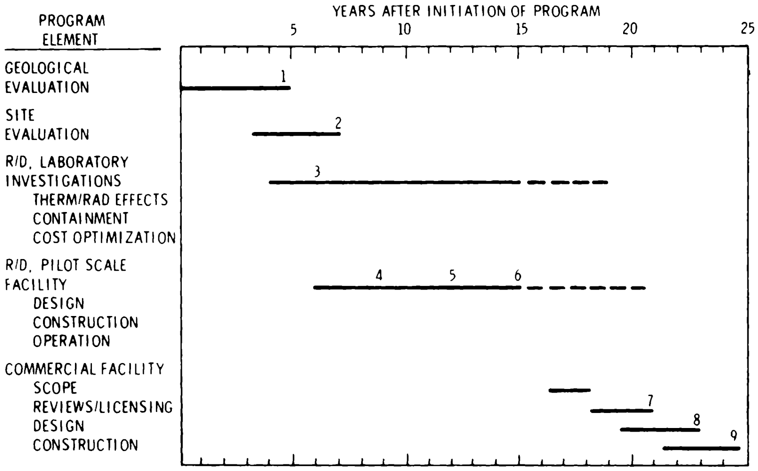


FIGURE 4.G.2. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplacement in a Mined Cavity - Interim Liquid Cooling and Waste-Rock Melting



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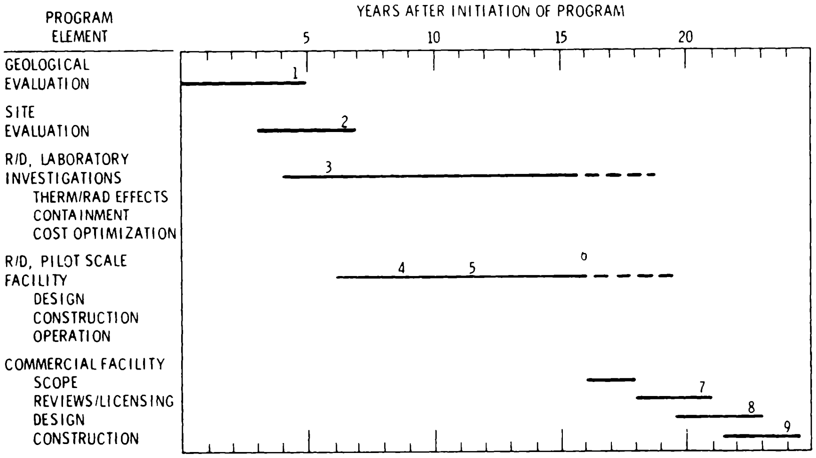
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

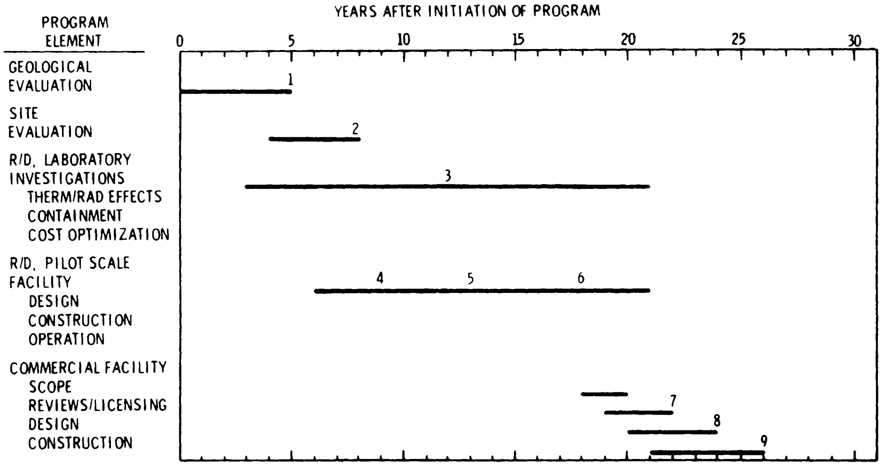
FIGURE 4.G.3. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplacement in a Mined Tunnel - Interim Natural Convection Air Cooling, No Melting



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

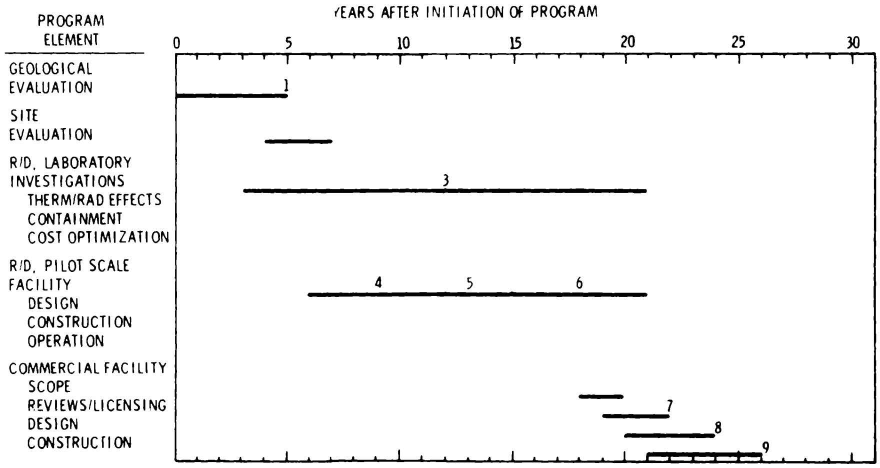
FIGURE 4.G.4. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplaced in Geologic Formations - Boiling Water Cooling, No Melting



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

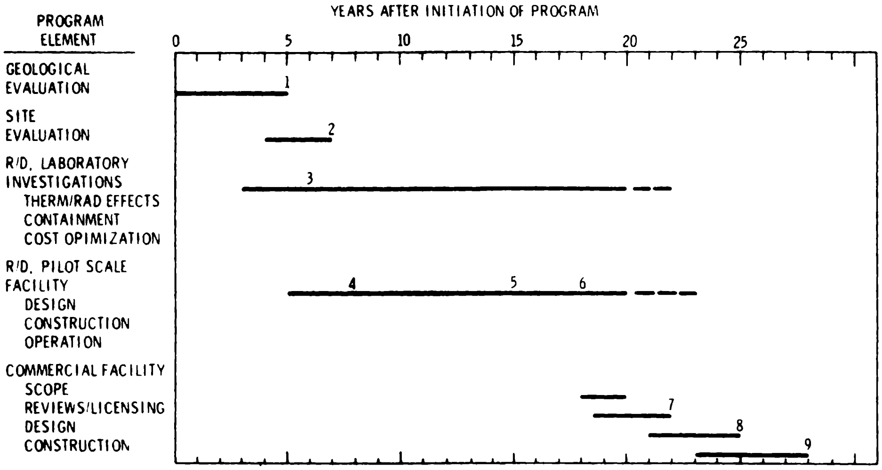
FIGURE 4.G.5. R&D Program Leading to Establishment of a Commercial Facility, Liquid Waste Emplacement in a Mined Cavity - In-Place Drying and Conversion to Rock-Waste Matrix.



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

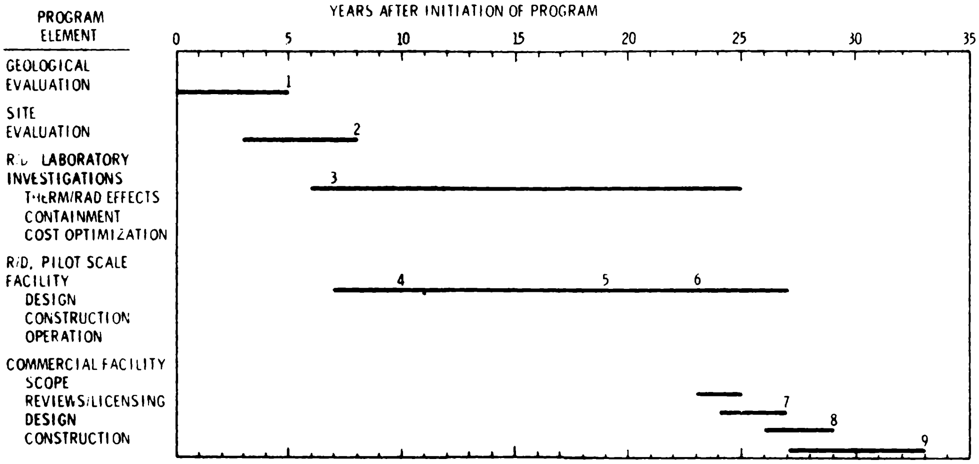
FIGURE 4.G.6. R&D Program Leading to Establishment of a Commercial Facility, Liquid Waste Emplacement in an Exploded Cavity - In-Place Drying and Conversion to Rock-Waste Matrix



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

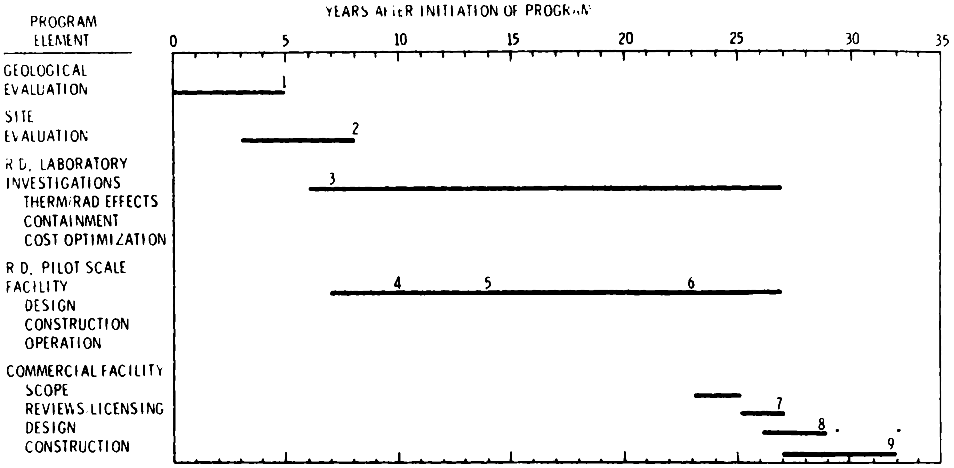
FIGURE 4.G.7. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplacement in a Matrix of Drilled Holes - No Melting



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

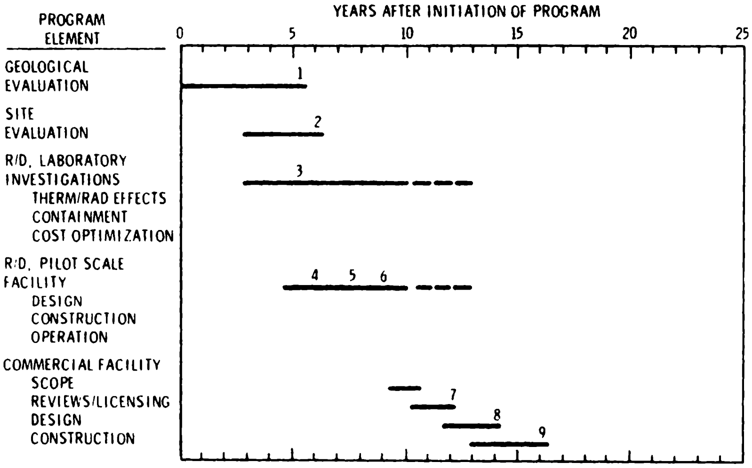
FIGURE 4.G.8. R&D Program Leading to Establishment of a Commercial Facility, Solid Waste Emplacement in a Deep Hole with In-Place Conversion to a Rock Waste Matrix



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

FIGURE 4.G.9. R&D Program Leading to Establishment of a Commercial Facility, Liquid Waste Emplacement in a Deep Hole - In-Place Drying and Conversion to Rock-Waste Matrix



MILESTONES

1. SITE SELECTED
2. SITE EVALUATION COMPLETE
3. EXPECTED FEATURES FOR PILOT FACILITY CONFIRMED
4. PILOT FACILITY DESIGN COMPLETED
5. PILOT FACILITY CONSTRUCTION COMPLETED, BEGIN OPERATION
6. DECISION TO PROCEED WITH COMMERCIAL FACILITY
7. CONSTRUCTION PERMIT GRANTED
8. COMMERCIAL FACILITY DESIGN COMPLETED
9. COMMERCIAL FACILITY CONSTRUCTION COMPLETED

FIGURE 4.G.10. R&D Program Leading to Establishment of a Commercial Facility, Liquid Waste Emplacement by Hydraulic Fracturing - In-Place Conversion to a Solid

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