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THE VERY DEEP HOLE CONCEPT: EVALUATION OF AN ALTERNATIVE FOR NUCLEAR WASTE DISPOSAL

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July 1979

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Prepared for the U.S. Atomic Energy
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M. T. O'Brien, L. H. Cohen, T. N. Narasimhan,
T. L. Simkin, and H. A. Wollenberg

EARTH SCIENCES DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720

and

W. F. Brace, S. Green, and H. P. Pratt

TERRA TEK
420 WAKARA WAY
SALT LAKE CITY, UTAH 84108

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ABSTRACT

One proposal for disposing of radioactive waste is to put it in drill holes or mined cavities so deep that the waste would be effectively isolated from the surface. Even if radioisotopes escaped from the disposal canister, they would be removed from the circulating groundwater system by sorption and/or chemical reaction in their transit on very long paths to the surface. This report, originally a contribution to a comprehensive Generic Environmental Impact Statement (DOE, 1979), summarizes the feasibilities and costs of making deep holes and deep mine shafts; estimates probable technological advances by the year 2000; presents thermal history and thermally induced stress calculations based on several assumptions regarding age of waste and density of emplacement; and summarizes the geologic uncertainties and lack of knowledge that bear upon the isolation of waste at great depth.

"How deep is deep enough?" depends upon the geologic characteristics of the site, especially hydrologic conditions, rock strength, and rock-waste interactions. Thus comparatively shallow depths may suffice in domal salt because of its relatively low permeability, whereas in other areas, required depths would be greater and might exceed depths that could be mined or drilled in the forseeable future.

In strong rock, present technology would probably enable us to drill a hole 20 cm (7-7/8 in) in diameter to a depth of 11 km (35,000 ft) and sink a shaft 10 m (30 ft) in diameter to about 4.3 km (14,000 ft). By the year 2000, with advancement of technology, holes of 15 km (50,000 ft) depth and 20 cm (7-7/8 in) diameter could be drilled, and shafts of 6.4 km (21,000 ft) or deeper could be sunk.

The heat output of 5.5-year-old spent fuel and 6.5-year-old reprocessed waste is used to calculate temperature increases and stress buildups in the surrounding rocks. Some waste configurations may cause unacceptably high temperature increases; indeed, limitations on temperatures reached will in some cases limit the packing density of waste canisters and/or require longer cooling of the waste before emplacement.

Sealing boreholes and shafts for significant times, i.e. 1,000 to 100,000 years and beyond, presents additional problems. The casing or lining of the borehole or shaft would have to be removed in the region where seals are constructed, or the lining material would have to be designed to function as an integral part of the long-term seal. Sealing fractures in the rock around the borehole or shaft will be quite important.

Also addressed in this report are the problems of criticality, adequacy of the data bases for analysis, and research and development needs.

FOREWORD

This report was prepared at the request of the U. S. Department of Energy by the staffs of Lawrence Berkeley Laboratory and Terra Tek and several independent experts. Most of these scientists and engineers met in Salt Lake City in July 1978, to prepare this report and assess the feasibility of drilling a deep hole or mining a deep shaft. We were asked to perform two major tasks:

- Define the geotechnical and geophysical state of knowledge of the earth's crust at depths of 10 to 15 km. The characteristics to be reviewed included:

  lithology; depth vs. stress, temperature, mechanical properties, permeability, and hydrological conditions; and resource inventory.

- Identify the state of the art and estimate the probable technological advances, by the year 2000, to drill a very deep hole or sink a very deep shaft. Specifically, we were asked to:

  Establish depth vs. diameter capabilities of drilling and shaft-sinking equipment, their limitations, and time and cost estimates

  Document the deepest mines and drill holes

  Consider construction constraints such as number of stages, horizontal openings, and strengths of hoists and casing strings

  Recommend research and development needed for technological advances.

We wish to acknowledge the valuable information and assistance from these experts and the organizations they represent. The following individuals contributed to the evaluation of geotechnical constraints:

John A. Apps, LBL (geochemistry)
Larry V. Benson, LBL (geochemistry)
Robert S. Barneyback, Jr., Purdue University, Lafayette, Indiana (borehole sealing)
Neville G. W. Cook, University of California, Berkeley, California (rock mechanics)
John Handin, Texas A & M University, College Station, Texas (tectonophysics)
William Hustrulid, Colorado School of Mines, Golden, Colorado (mining)
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Robert C. Newton, University of Chicago (petrology)
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Chin-Fu Tsang, LBL (modeling)
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Carl Brechtel, Terra Tek, Salt Lake City, Utah (mining engineering)
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This report represents the ideas and recommendations of the many individuals listed above and does not reflect the views or opinions of any one person.

INTRODUCTION

The U. S. Department of Energy (DOE) is responsible for selecting an appropriate system for the ultimate disposal of commercial radioactive wastes in a way that is safe, permanent, and economical. As part of the selection process, DOE commissioned a Generic Environmental Impact Statement (GEIS) that would describe alternative processes, emplacement media, and waste management technologies. Further, GEIS provides data for decisions on candidate site selection, appropriate emplacement media, and appropriate disposal technology. The 10 alternative isolation concepts reviewed in GEIS include the concepts of conventional geologic disposal, chemical resynthesis, very deep hole, rock melting, island disposal, sub-seabed disposal, ice sheet disposal, reverse-well disposal, partitioning and transmutation, and space disposal. Lawrence Berkeley Laboratory was asked by DOE to review and assess the feasibility of the very deep hole concept. This report arises from LBL's contribution to that study, Section 3.3 of Draft Environmental Impact Statement: Management of Commercially Generated Radioactive Waste (DOE, 1979). In the DOE document, provisional levels of effort and cost estimates for developing the very deep hole concept were summarized; they are not included in this report.

The very deep hole concept relies on using great depths to delay the reentry of nuclear material into the biosphere. The concept assumes hydrologic isolation from the earth's surface. The answer to the question, "How deep is deep enough?" requires that the wastes be located below circulating groundwaters and that the time required to transport materials from the repository to the surface is long enough to ensure that little or no radioactive material reaches the biosphere. The concept assumes that disposal in very deep holes does not permit retrieval of wastes. The very deep hole concept provides for disposal of radioactive wastes at the greatest depth possible below the surface; it should, therefore, embody the ultimate that can be achieved in geologic isolation. It also provides assurance that no climatic or surface change will affect disposal.

The design of a satisfactory repository requires that the necessary depth, at a given site, be first defined. This requires determining site-specific limits on the transport of radioactive materials to the biosphere, the site-specific hydrologic regime, and the heat-source configuration (waste packing). Once the depth required has been determined, then the technology for making the hole to the required depth and the ability of the surroundings to accept the heat source become the limiting factors. It is clear that problems of making the hole, holding it open, emplacing the waste, and sealing the hole must be considered together.

Environmental considerations for the very deep hole concept are those associated with drilling a deep well or sinking a deep shaft, constructing the predisposal surface facilities, and possibly maintaining surface or near-surface long-term monitoring facilities.

This is a generic study and is not a substitute for the analysis of the very deep hole concept at a specific site. To write a specific statement, detailed site-specific data would be necessary. This report follows the format of an environmental impact statement. First, there is a general discussion of the concept, the geotechnical considerations, and the feasibility of making the very deep hole. Then the adequacy of the present data base is described and environmental impacts of developing a deep hole are estimated. Finally, research and development needs are identified.

WHAT IS VERY DEEP?

The utility of the deep hole concept is affected by the specific site characteristics and the size of the hole. In the past, "How deep is deep?" was not clearly defined. Past reports (Banister et al., 1978; Parsons et al., 1978; ERDA, 1976, p. 25.5; Schneider and Platt, 1974, section 4.1.8; American Physical Society, 1978, p. S118; U. S. Geodynamics Committee, 1979, p. 47) have mentioned or discussed holes of depths of several kilometers to 10 km or more. Whatever the depth, deep isolation requires disposal below circulating groundwaters. This depth must be determined based on the distribution of porosity (or free water content), permeability, and hydraulic potential as a function of depth.

Available data from the literature, primarily from the oil and gas industry, show that some sedimentary rocks are porous and permeable to depths in excess of 9 km (30,000 ft). Investigations of crystalline rock, although very limited, suggest that at much shallower depths some such rocks have relatively low porosities and permeabilities. Hence "very deep" for these crystalline rocks may mean a few kilometers instead of the 9 km or more required for sedimentary rocks.

In summary, "very deep" is dependent both upon rock type and geologic factors at a specific site. This generic study outlines the current state of knowledge and suggests the factors to be considered when evaluating a specific site.

GEOTECHNICAL CONSIDERATIONS

The critical geologic parameters for defining the feasibility and impact of nuclear waste disposal in a deep hole system are: lithology, tectonics and structural setting, hydrologic conditions, states of stress, mechanical properties of the rocks at depth, natural thermal regime, and geochemical reactions. The interactions of these parameters and the effect of heating by the waste (thermomechanical factors) are also significant. Geologic assumptions underlying the very deep hole concept are that the hole would be drilled or a shaft excavated in a regime of moderate to low geothermal gradient in rock of high strength and low permeability. Furthermore, the wastes would be deposited irretrievably -- not stored. In the following sections the individual criteria are discussed.

Lithology

The possible host rocks for waste isolation include crystalline and sedimentary rocks and mixed sections. Crystalline rock, defined here as any non-evaporite or non-carbonate rock with bulk porosity <1%, includes primarily intrusive igneous rocks and moderate- to high-grade metamorphic rocks. Crystalline rocks are perhaps the most qualified for the waste isolation sector of the very deep hole, based on considerations of rock strength, hole/shaft stability, and sealing the excavations. Potentially less desirable, but perhaps still acceptable, is a configuration penetrating several kilometers of sedimentary rock near the surface but with the predominant length of the hole, its lower portion, in crystalline rock.

Crystalline rock types considered most acceptable for nuclear waste isolation are evenly textured granitic rocks such as those occurring in Mesozoic and Tertiary batholiths and plutons of the western United States, and in Precambrian plutons of the Rocky Mountains, mid-continent, and eastern portions of the United States. Less isotropic, moderately to strongly foliated plutonic or high-grade metamorphic rocks such as amphibolite, schist, and gneiss, primarily of Precambrian age, are also acceptable. They are perhaps less desirable than more evenly textured crystalline rocks because the foliation may provide preferentially oriented zones of weakness. Larsson (1977), however, indicates that, because of their contorted nature, high-grade metamorphic rocks have fewer through-going fractures and are therefore less transmissive than more isotropic granitic rocks. Areas where crystalline rocks predominate at the surface are delineated in Figure 1.

Deep sedimentary basins may also be suitable (Hess, 1956), particularly if the sites are in hydrologically stable synclines. Locations are known where deep downward-circulating systems (closed, low fluid potential basins) occur (Tóth, 1978; Berry, 1959). Along with the search for crystalline rock sites, further study should be done to identify sections of sedimentary rocks where fluids migrate downward and that would be devoid of hydrocarbon, geothermal, ore, and other potential resources.

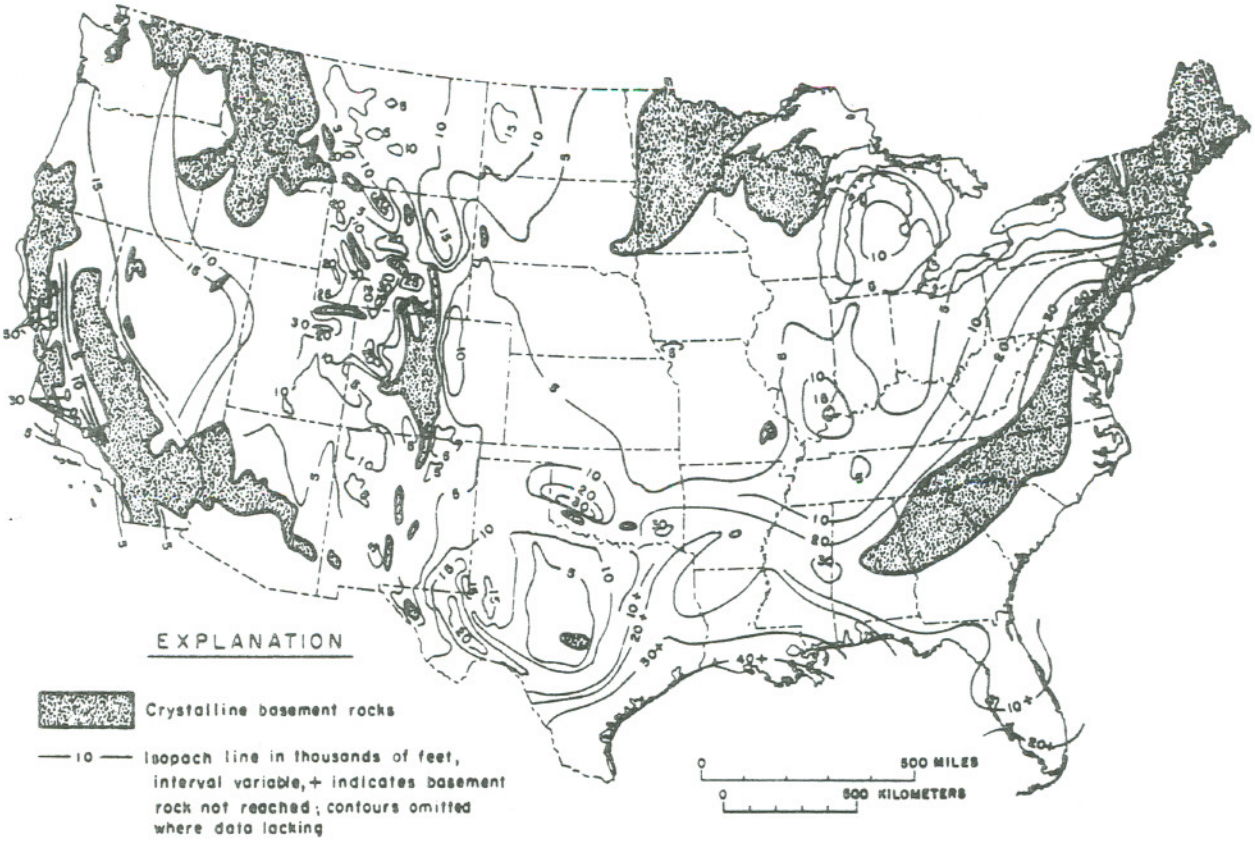

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Figure 1. Principal areas of intrusive igneous and metamorphic rocks and thickness of sedimentary rocks in the U. S. (Source: Ekren et al., 1974).

Relatively impermeable domal salt, bedded salt, and thick shale units may not support very deep holes. Although they may furnish adequate containment for nuclear waste in shallow holes, drilling is difficult in these rocks below depths of 3 to 4 km (10,000 to 13,000 ft) due to low rock strength. Plateau basalt flows, whose aggregate thickness may exceed several kilometers, may not be as acceptable as crystalline rocks for deep holes due to permeable sediments between flows and permeable zones within flows. Isolation would be jeopardized if a vertical column of waste intersected one or more of these permeable zones.

Tectonics and Structural Setting

Sites for very deep holes should be located in areas of tectonic and seismic stability. The geologic and structural setting should be relatively free of faults and shear zones, either presently active or inactive. Fault zones, though often forming impermeable barriers, may serve as permeable pathways for the circulation of groundwater in some cases, and thus may provide significant vertical pathways of hydrologic communication near surface. Faults, though presently inactive, may serve as loci for displacement in future earthquakes.

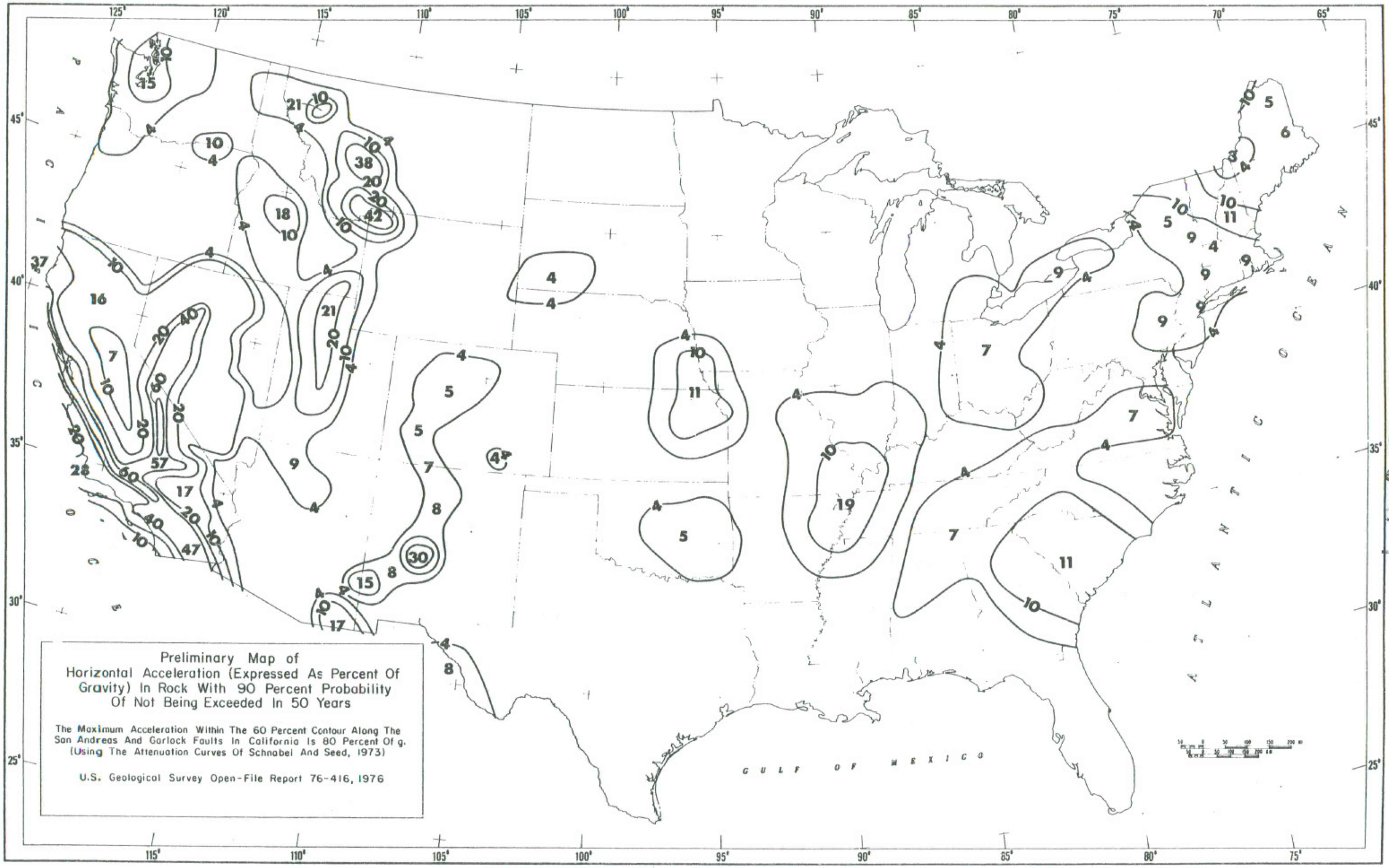
The relative seismic setting of the conterminous United States is illustrated in Figure 2. The numbers indicate potential horizontal acceleration of the ground surface and reflect relative seismic hazard and thus crustal stability. It is advisable that very deep holes not be located in areas of highest potential acceleration.

Hydrologic Factors

Isolation of the wastes from the hydrologic regime is critical to the very deep hole concept. The ratio of permeability to porosity determines the velocity with which fluids move past the wastes. Other factors are the source of the water, distribution of fluid potentials over the subsurface system, and the role of geochemical retardation. In sedimentary basins hydrologic data are available in varying detail to depths >7 km (>23,000 ft) whereas very few measurements have been made in crystalline rocks below a depth of 3 km (10,000 ft).

Existence and state of pore fluids. Oil and gas wells in Oklahoma and Texas produce from depths of 7 km (23,000 ft) and deeper. Water in the form of brine occurs in conjunction with gas and oil at such depths. The existence of water at great depths in crystalline rocks can probably be inferred from electrical resistivity measurements, since dry minerals have very high resistivity (10^{12} ohm-m). In the absence of metallic minerals and graphite, resistivity of rocks is considerably diminished by the presence of water in interconnected pores (Keller and Furgerson, 1977). Electrical surveys, which penetrate to depths of 10 to 15 km (33,000 to 50,000 ft), yield interpreted resistivities up to 10^5 ohm-m, a value which implies ionic conduction in aqueous solution (Brace, 1971). The data available from a few sites in New York, Germany, and Africa indicate that crystalline rocks probably contain interconnected water-filled pore space down to depths of 10 to 15 km (33,000 to 50,000 ft) (VanZigl, 1977).

Meteoric water may infiltrate to great depths in both crystalline rocks and sedimentary units, move laterally over long distances, and finally move up toward the land surface, creating deep circulating groundwater systems. Although direct evidence is not available, circulating meteoric waters may reach depths of several kilometers (Drescher, 1965). The existence of closed, low fluid potential basins indicates downward movement of groundwater; however, deep zones with water pressure under artesian or even lithostatic conditions may indicate upward movement of water. Apart from the discharge areas of deep circulating groundwater systems, upward hydraulic gradients may also exist in areas of high heat flow due to convective flow, or in areas of geopressured sediments due primarily to consolidation of clays.



Preliminary Map of
Horizontal Acceleration (Expressed As Percent Of Gravity) In Rock With 90 Percent Probability Of Not Being Exceeded In 50 Years

The Maximum Acceleration Within The 60 Percent Contour Along The San Andreas And Garlock Faults In California Is 80 Percent Of g. (Using The Attenuation Curves Of Schnabel And Seed, 1973)

U.S. Geological Survey Open-File Report 76-416, 1976

XBL 797-10475

Figure 2. Relative seismic hazard in the conterminous U.S. (Source: Algermissen and Perkins, 1976).

Based on measured geothermal gradients, and indirectly from deep resistivity soundings, we conclude that the effect of increasing hydrostatic pressure overrides that of increasing temperature with depth. As a result, interstitial fluid would have a density more like liquid than vapor nearly everywhere in the earth's crust.

Porosity. Although substantial data are available on the variation of porosity in sedimentary rocks to depths of 6 km (20,000 ft) or more, direct porosity measurements at significant depths in crystalline rocks are not available. Electrical soundings suggest a porosity of 0.1% to 0.5% in crystalline rocks at depths of 10 km (33,000 ft) (VanZigl, 1977). This range is consistent with laboratory measurements on many igneous and metamorphic rocks under pressures comparable with those found at 10 km depth. It is also consistent with the same rock samples having porosities as high as 1% at room temperature and pressure (Brace, 1979). Interestingly, joints and other larger fractures do not play a role here. Resistivity is dependent primarily on porosity, and fracture porosity even at depths as shallow as 0.1 km (330 ft) appears to be about 0.001% (Snow, 1968a). Thus fracture porosity is of no consequence when compared with that of the intergranular pores and microcracks (Brace, 1975).

Permeability. Permeability is a complex function of porosity, pore diameter, tortuosity, and interconnection of the pores in porous materials. In fractured rock, permeability depends on fracture spacing, aperture, roughness, and interconnections. Because of the difficulties inherent in direct measurement of these quantities, the only available means of obtaining permeability data are through in-situ measurements. The range of permeability of typical geologic materials may vary over 12 orders of magnitude (Table 1). Fracture permeability is probably the controlling factor in deep holes in crystalline rocks. Fortunately, fractures are seldom continuous for more than a few meters. Since hydrologic gradients are expected to vary considerably with time, travel times of fluid from deep hole depths to the surface may vary over several orders of magnitude.

Because fractures tend to close with depth due to overburden pressure, fracture permeability generally decreases with depth. The making of the hole or opening, however, tends to increase local fracturing and thus increase fracture permeability. To a depth of 50 m (165 ft) approximately 100 measurements in crystalline rock (Figure 3) show that permeability ranges from 10^{-3} to 10 darcies (Snow, 1968a). Below this depth a few measurements show very low permeability -- less than 1 nanodarcy (Ballou, 1979, p. 45) -- although at many sites, measurements show permeability similar to that of near-surface rocks. Only three sets of measurements are available from drill holes below 500 m (1,650 ft): the Rocky Mountain Arsenal well (Snow, 1968b), the Savannah River Plant (Marine, 1967), and Fenton Hill, Los Alamos (West et al., 1975). These permeability measurements range down to 10^{-6} darcy. Some sections of the drill holes are as permeable as near-surface rocks.

Table 1. Degrees of permeability of various rock types

Conductivity (cm/sec)*	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}
Darcies	10^{5}	10^{4}	10^{3}	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Degree of permeability	Very high		High		Moderate			Low			Very low	
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	rocks	———	———	———|

* To obtain Darcies, multiply by 1.04 x 10^{3}

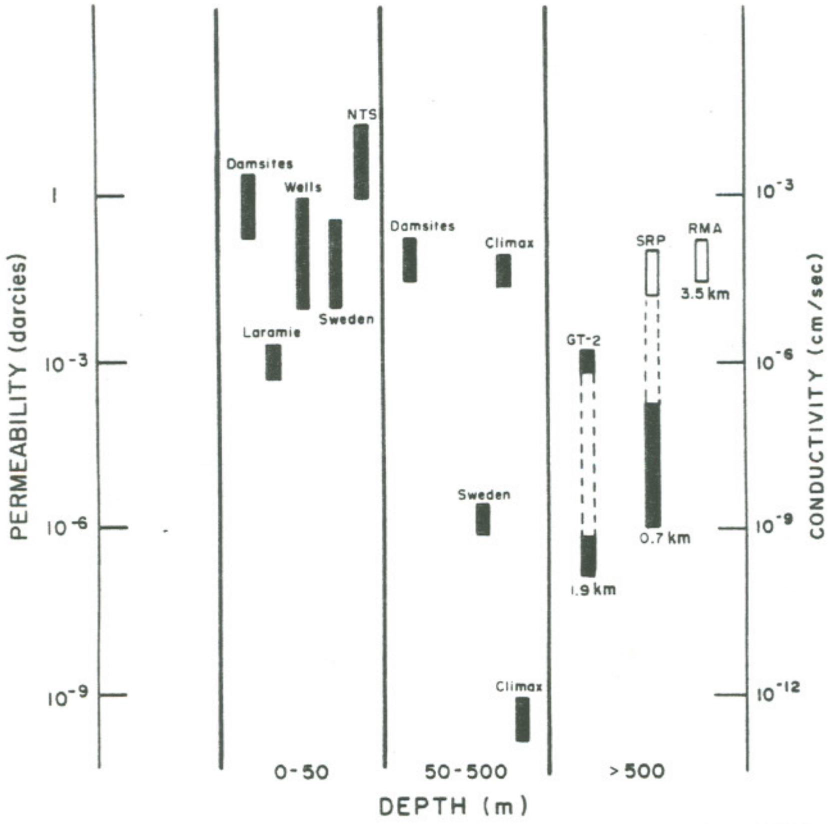


Figure 3. Measurements of in-situ permeability of crystalline rocks as a function of depth.

Bar for each site shows the range of measured values. Maximum depth is given under the bar for the three deep sites: Savannah River Plant (SRP), Rocky Mountain Arsenal (RMA), and Fenton Hill, Los Alamos (GT-2). NTS = Nevada Test Site.

We conclude that permeability of crystalline rock may vary over 4 to 6 orders of magnitude. This suggests that isolated natural fractures in crystalline rock play an important role as fluid conduits at depths of several kilometers. In-situ permeability is usually higher than laboratory measurements in cores (Witherspoon et al., 1979); thus laboratory measurements may give a useful lower bound.

We must also consider the relationship between permeability and temperature. As the emplaced waste heats up, the permeability of the fractures in the vicinity of the deep hole will change. Depending on their state of stress and fracture orientation, some fractures may open and others may close. The nature of these and other changes is complex and depends on factors such as the formation of thermal cracks in the host rock, the chemistry and the phase characteristics of the interstitial fluid, and the solubility of minerals of the rock in the interstitial fluid. The effects of temperature on permeability could be significant, yet at present they are poorly understood.

State of Stress

To design a very deep hole, either drilled or excavated, we must have a knowledge of the in-situ state of stress. For a given rock, the stability of the borehole or the shaft during excavation will depend on the initial states of stress. The in-situ stress state is also the baseline upon which the thermomechanical loading caused by the nuclear waste is superimposed. The resulting perturbation in both the mechanical rock mass properties and hydrologic conditions may be critical. A knowledge of all the components of the state of stress -- the vertical stress, and the maximum and minimum horizontal stresses -- are required over the depth of interest, 0 to 15 km (0 to 50,000 ft). Stress has been measured by hydraulic fracturing from the surface to depths as great as 5 km (Haimson, 1977; see also Cook, 1977). The general trend of Haimson's (1977) data is shown in Figure 4; the data are extrapolated to 15 km (50,000 ft). The plots indicate the following:

> A wide scatter in the ratio of horizontal to vertical stress exists at shallow depths (1 km or less).
>
> The vertical stress, which is calculated from the density of the overburden, is approximately 270 bars/km (1.2 psi/ft) for crystalline rocks and 226 bars/km (1.0 psi/ft) for sedimentary rocks.
>
> The ratio of the minimum horizontal stress to the vertical stress is 0.6 - 0.7 for crystalline rocks and 0.8 for sedimentary rocks at depth.

The temporal change in stress due to tectonic loading/unloading is expected to be insignificant when compared with the stress change induced by the thermal loading of the nuclear waste (see page 22). No data presently exist on long-term changes in stress with time.

Geothermal Gradient

Thermal gradients in regions of low, moderate, and high heat flow are given in Figure 5 and Table 2. The temperatures at depth estimated from the profiles in Figure 5 may vary by 20% for a given region.

The slight curvature to the profiles reflects concentration of radioelement heat producers in the upper portions of the crust. The temperature profiles for the stable mid-continent and eastern regions are probably representative of most of the United States. Few regions have as low heat flow and thermal gradients as the Sierra Nevada, or as high as those measured in the Basin and Range province and the Columbia River Plateau. The profiles indicate that in most areas in the United States, temperatures would approach 200°C (392°F) at 10 km (33,000 ft) and 250°C (482°F) at 15 km (50,000 ft).

Rock Strength

High rock strength is critical for hole stability during both the drilling and operation of a deep isolation facility. The important

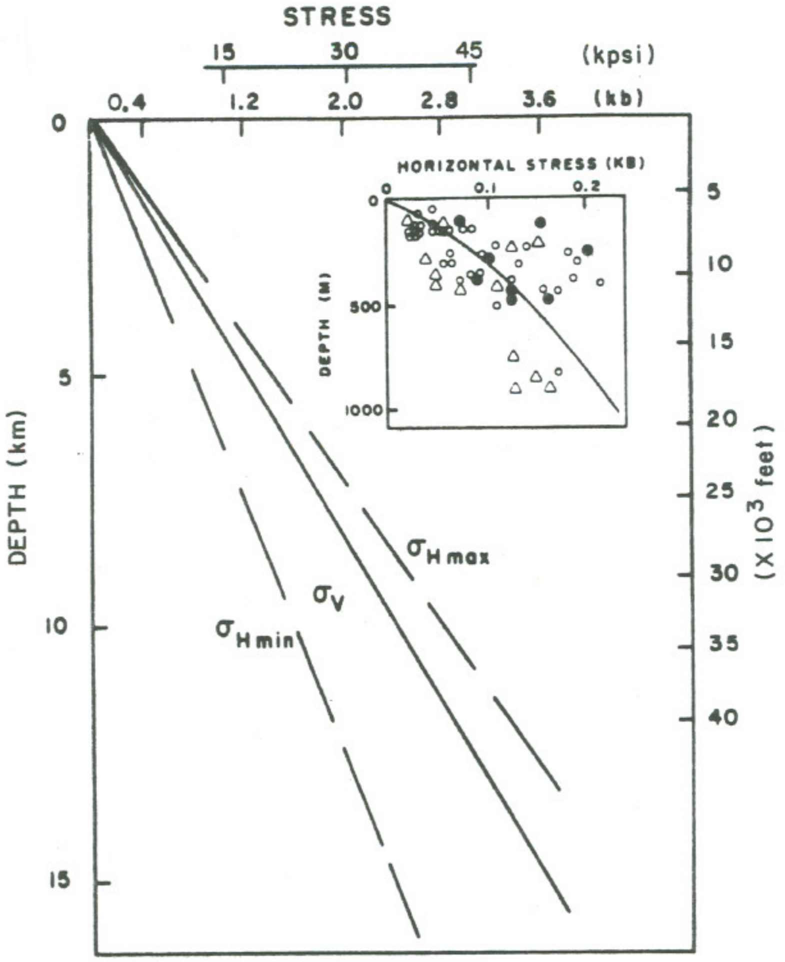


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Figure 4. In situ-stress as a function of depth based on hydrofracturing data (σ_V = vertical stress; $\sigma_{H\ min}$ = minimum horizontal stress; $\sigma_{H\ max}$ = maximum horizontal stress).

The inset shows the actual measurements of horizontal stress as a function of depth to 1 km (3,300 ft). o = overcoring borehole measurements for σ_H; Δ = hydrofracture data for $\sigma_{H\ min}$; ● = hydrofracture data for $\sigma_{H\ max}$. The line shown in the inset ($\sigma_H = 2.50 \times 10^{-3} D^{0.65}$) is a least squares fit of the data with correlation coefficient, r = 0.84 (σ_H = average horizontal stress in kbar; D = depth in meters).

considerations are the strength of the rock and how strength is affected by joints, elevated temperature, and the presence of fluids.

Unconfined compressive strength of hard crystalline rocks at ambient temperature ranges from about 1.3 to perhaps as high as 2.5 kbar (20,000 to 38,000 psi). The influence of confining pressure, pore pressure, and

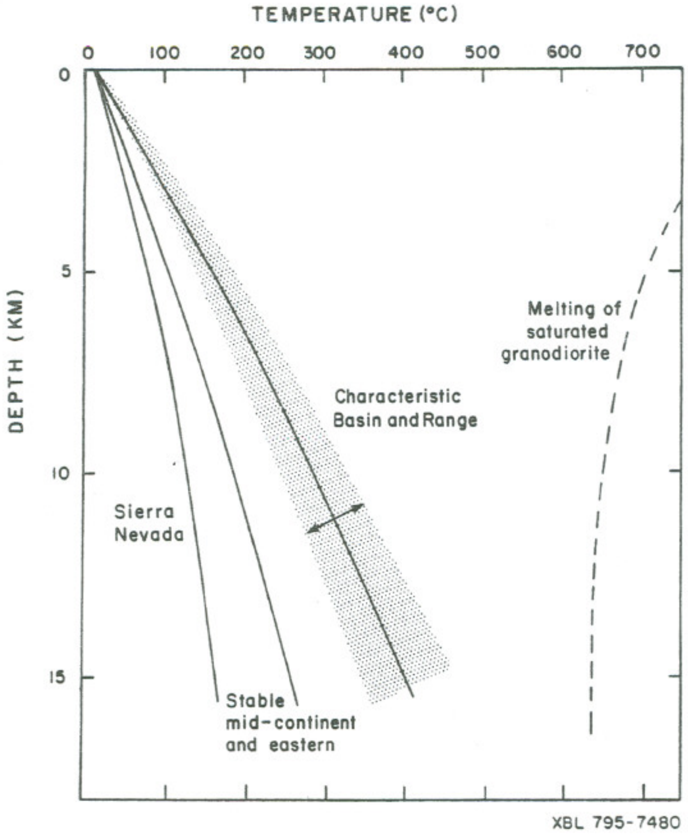

Figure 5. Temperature profiles for low, normal, and high heat flow regions of the United States.

The dashed curve is the lower bound of the zone of melting of water-saturated granodiorite. (Source: adapted by permission from Lachenbruch and Sass, 1977.)

fractures on strength is illustrated in Figure 6 for granodiorite, a typical plutonic rock. Additional, new fractures reduce the strength of both fractured and previously unfractured rock as long as pore pressure is low; for example, if the rock under stress were drained. If pore pressure remains close to confining pressure, the strength remains close to the unconfined values; this is illustrated in the two lower curves (Heard, 1970). The shear strength of jointed rock may be significantly reduced by pore pressure. Due to the interlocking of asperities on joint surfaces, however, the failure envelope for unfilled joints will merge with that of intact rock at high confining pressure or under conditions of zero normal displacement (Goodman, 1976, p. 165). The latter condition is likely to hold except in the immediate vicinity of the borehole wall.

High temperatures lower the strength of rocks; the degree of weakening depends on the temperature compared with the solidus of the rock.

Table 2. Thermal gradients measured in crystalline, plutonic, and basaltic rocks in relatively stable tectonic areas

Area	Number of measurements	Mean gradient ($^oC/km$)	Range	Standard deviation	References
Lake Superior and Precambrian shield	6	17.1	14.1-18.9	1.6	Roy et al. (1968, 1972); Judge and Beck (1973)
New England plutons*	17	21.4	13.5-29.9	4.4	Roy et al. (1968)
New England plutons**	14	19.1	13.5-23	3.3	Roy et al. (1968)
Piedmont-Appalachians	3	16.2	15-18	1.6	Diment et al. (1965a,b); Diment and Werre (1964)
Adirondacks	4	17.7	15.9-18.5	1.2	Roy et al. (1968)
Black Hills	3	19	9.1-25.6	8.5	Sass et al. (1971)
Sierra Nevada	10	11.9	6.4-18.3	3.9	Sass et al. (1971)
Columbia Plateau	4	38.3	37.2-42	3.0	Blackwell (1974) Sass et al. (1971)
Southeast Missouri	4	16.5	14.8-18.5	1.5	Roy et al. (1968)

* Including the Conway granite

** Excluding the Conway granite

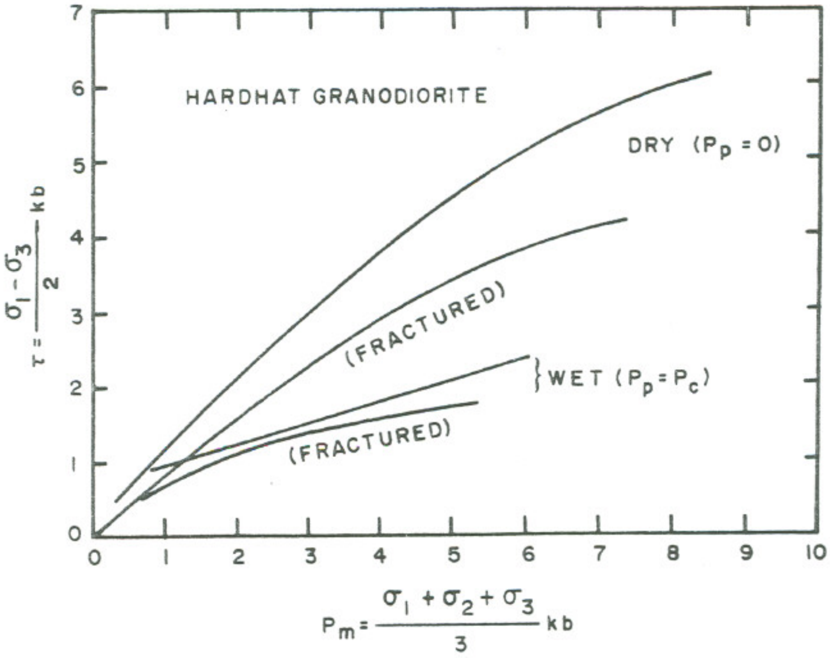

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Figure 6. Failure envelopes for Hardhat granodiorite tested in compression at 25°C (77°F) at a strain rate of 10^{-4}/sec.

"Fractured" curves show strength of dry ($P_p = 0$) and wet ($P_p = P_c$) rock after first fracture. P_p = pore pressure; P_c = confining pressure; P_m = mean pressure; τ = shear stress; σ_1, σ_2, and σ_3 = principal effective stresses.

For crystalline rocks such as granite, diabase, and gabbro, creep in the laboratory is first detected around 500°C (900°F). Below this temperature brittle fracture and frictional resistance are virtually unaffected.

One special effect that may have to be considered in the deep hole concept is stress corrosion. Brittle strength of silicate rocks is seriously degraded by water, particularly at elevated temperatures (Griggs and Blacic, 1965).

Geochemistry

The rocks considered here consist of silicate minerals, and the repository encompasses the rocks, waste, and hydrologic regime. The form of the waste may have a significant effect on this system. In this section we discuss the interaction between liquid or solid waste forms and the geologic environment and the general aspects of radionuclide transport from a deep hole.

Reaction between liquid wastes and rock. Spent fuel from commercial sources has not yet been reprocessed in the United States; hence military liquid wastes are used as a model of potential commercial wastes. The composition of such wastes can be extremely variable depending upon the processing techniques used; undoubtedly their composition could be formulated to make wastes somewhat geochemically compatible with site-specific geologic requirements.

Reliable predictions of reactions between liquid wastes and rocks require a knowledge of: (a) waste composition; (b) rock composition; (c) temperature; (d) pressure; (e) availability of water; (f) fluid flow regime; (g) rate of injection; and (h) a data base that contains both equilibrium and kinetic data for sorption phenomena, reactions, and equilibria for major species and radionuclides. A major consideration in injecting liquid wastes into rocks at great depth is that water lowers the temperature of the solidus of crystalline rocks and also lowers rock strength (see p. 13).

Reactions between solid wastes and rock. As with liquid waste disposal, predicting reactions between solid waste and rock requires much site-specific information in addition to the necessary data base. We have considered reactions in hydrous and anhydrous environments. Actually, water should be avoided since its presence hastens radionuclide transport, independent of both the waste form and rock type. A limited amount of locally present water that is not connected to a reservoir (i.e. water that cannot be replenished once it is removed by reaction in the neighborhood of the canister) can be accommodated in the design. Under anhydrous conditions, we assumed that no water is available to react with the canister and contents, and that no water will be available over the life of the repository.

The various forms of solid nuclear waste and their interactions with host rock are briefly described here; waste compositions are listed in DOE (1979, v. 2, Appendix A).

1. Salt cake: Anhydrous salt cake has essentially the same physical characteristics as pure $NaNO_3$, the most important being its one-atmosphere melting point of 308°C (590°F). At higher temperatures, we expect reaction of the salt cake with wall rock to form refractory silicate-nitrate minerals which should immobilize the major components of the waste.

2. Calcine: McCarthy and Scheetz (1977) state that the composition of calcine varies, depending upon the processing procedures, and that its phase composition is unknown. In the absence of mineralogical information, therefore, we cannot predict the ultimate fate of this material in the hole.

3. Supercalcine, synthetic minerals: Because these waste forms consist of geologically refractory phases, we do not expect them to be mobile in an anhydrous environment.

4. Glass: In a nearly or completely anhydrous environment, the principal reaction, given time, will be devitrification of the glass. With elevated temperature there would probably be limited reaction of

glass and wall rock. The viscosity of the glass as a function of pressure and temperature is unknown. Such information, along with the rate of devitrification, would be necessary to predict whether the glass would be mobile or would first devitrify.

5. Spent fuel elements: The metallic components of spent fuel elements would remain stable at the reducing conditions expected at great depth in crystalline rocks. McCarthy et al. (1978) expect reducing conditions within the contents of the fuel rods, indicating that the spent fuel material would also remain stable. Spent, unreprocessed fuel rods would thus probably be stable in an anhydrous deep environment over geologic time.

Radionuclide transport from the deep hole. If hole integrity is breached, radionuclides will migrate in a fluid phase -- if such a phase exists. This fluid may be water or, if the temperature is high enough, it may be a silicate melt. If a melt forms it will migrate until a low enough temperature causes it to solidify or, if hydrous, until water escapes. Sorption processes and reactions will, however, retard the rate of waste transport relative to the fluid flow rate. During transport the radionuclides will contact some combination of country rock, casing, and sealing materials. As adsorption of a substance from solution is generally exothermic, the relative adsorption of the radionuclides should be small near the canister and become significant only in cooler regions. Sorption selectivity should also be small near the canister and increase in the lower temperature regions. The above is speculative; in fact, the dependence of electrolyte adsorption on pressure and temperature has not yet been systematically studied for a waste-rock system of interest. In high temperature regimes associated with the bottom-hole environment, radionuclides may be incorporated in the existing mineralogical assemblage due to reaction and thus may hinder the migration of the waste materials.

In the disposal of nuclear wastes, the radioactive gaseous components such as ^{85}Kr and ^{129}I must be considered. These gases are lost from the solid waste when processed. Spent fuel rods, however, contain significant quantities of ^{85}Kr (half life of 10.7 yr), but secure storage before disposal for relatively a short time (100 years) would reduce the ^{85}Kr concentration to 0.2%. ^{129}I has a very long half life and could become a significant problem.

Thermomechanical Factors

Temperature distribution. Under a normal geothermal gradient of 20° to 30°C/km (60° to 85°F/mile), temperatures in excess of 200° to 300°C (390° to 570°F) should occur at a depth of 10 km (33,000 ft) (Figure 5). The heat released by radioactive decay of the emplaced waste will further increase the temperature of the surrounding rocks. The magnitude of this induced temperature increase is determined by the thermal properties of the surrounding rocks and the power output of the waste, and the latter depends upon waste density, composition, and age.

For the very deep hole concept, thermal considerations at the earth's surface are relatively unimportant. For example, it takes 200,000 years for thermal effects generated at 5 km depth to reach the surface. On the other hand, the thermally induced effects at depth are important and could have significant effects both on mechanical integrity of the rocks and on driving groundwater convection.

As a result of radioactive decay, the heat output of the nuclear waste decreases with time. At any point in the system, the waste reaches a peak temperature at some time after emplacement, which depends upon the characteristics of the waste and the thermal properties of each material. The order of magnitude of the temperature increase can be estimated from simple heat conduction using thermal properties typical of a crystalline rock. Two waste forms are considered here -- reprocessed high-level wastes in which the activity decays rapidly with time, and spent fuel in which the activity decays much more slowly with time.

Consider first the case of storing solid spent fuel in a very deep hole. We assume the spent fuel is enclosed within cylindrical canisters of diameter 0.3 m (1 ft) and height 4.9 m (16 ft). Each canister contains one fuel assembly from the pressured water reactor (PWR) (Kisner et al., 1978, p. 23). A hole 0.31 m (12-1/4 in) in diameter can thus contain a single column of waste canisters.

Because of the very large height-to-diameter ratio of the column of radioactive waste, the heat flux from the waste is mainly in the radial direction, i.e. as if it were from a long cylinder. The temperature within the heat source itself is very nearly uniform and drops abruptly at the ends of the column.

If the spent fuel is cooled on the surface for 5.5 years before being emplaced in the hole, the power density at loading will be 174 W/m (Kibbe and Boch, 1978a, p. II-71; Kisner et al., 1978, p. 41). Figure 7 shows the temperature increase at the wall of the hole as a function of time. For comparison, the figure presents the temperature-time relationship for reprocessed high-level waste (HLW) and spent PWR fuel (SF) at different power densities and surface cooling periods. The HLW is in a more concentrated heat-producing form. Each high-level waste canister with diameter 0.3 m (1 ft) and height 3 m (10 ft) contains reprocessed waste of 6.6 PWR fuel assemblies. If the HLW is cooled on the surface for 6.5 years, the power density at loading is 1,420 W/m (Kibbe and Boch, 1978a, p. II-71; Kisner et al., 1978, p. 45-46). This level of power density is higher than the heat generation rate allowed (DOE, 1979, v. 2, section A) for HLW in the host rock -- from 400 W/m for argillaceous rocks to 1,000 W/m for granites, depending on rock type. A more diluted form of HLW should therefore be considered for emplacement in a very deep hole. The temperature generated is proportional to the power density at loading and will be lower for a more diluted form of HLW.

The temperature field is very sensitive to the duration of surface cooling period (Figure 8). Thus, surface storage for several years allows the short-term large heat output from fission products to dissipate. The effect of rock type is shown for granite, shale, and basalt (Figure 9).

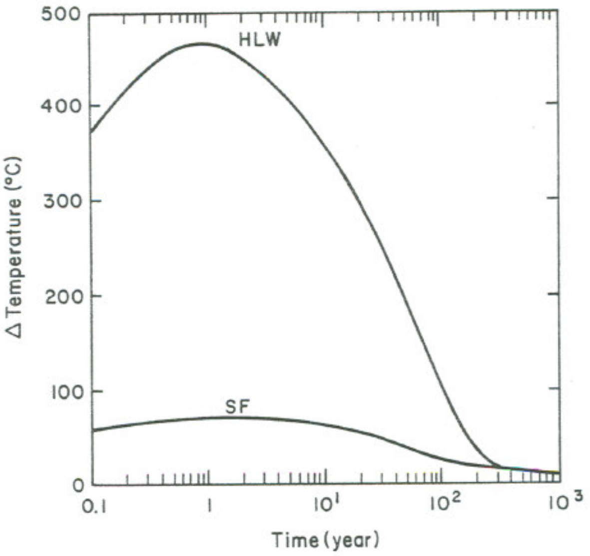

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Figure 7. Wall temperature of 0.31 m (12 1/4 in) diameter hole as a function of time for single column of PWR spent fuel (SF) and reprocessed high-level waste (HLW) canisters emplaced in granite.

The SF corresponds to 5.5 yr surface cooling, with power at emplacement being 174 W/m or equivalent to 0.0945 metric ton of heavy metal per meter (MTHM/m). The HLW corresponds to 6.5 yr surface cooling, with power at emplacement being 1,420 W/m or equivalent to 0.997 MTHM/m (Kibbe and Boch, 1978a; Kisner et al., 1978). The temperature rise is proportional to the power at emplacement and will be lower for more diluted forms of HLW.

Granite, with its relatively high value of thermal conductivity, has a lower temperature build-up.

If a shaft 10 m (33 ft) in diameter is used instead of the small hole, multiple columns of canisters can be stored. The temperature at the wall of the hole is not very sensitive to the detailed distribution of the waste within the shaft. Figure 10 shows the wall temperature, where there are multiple columns of canisters, as a function of time. Under maximum packing, in a single layer, the 10 m (33 ft) diameter hole can accommodate 950 cylindrical canisters of diameter 0.3 m (1 ft), or 1,300 square canisters with side dimensions of 0.24 m (9-1/2 in). A shaft 5 km deep could be packed with a million canisters, and the temperature increase would be in excess of 2,000°C for SF and 100,000°C for HLW. This is definitely unacceptable. If the temperature increase is limited to 100°C (212°F) above the ambient temperature, only 5,000 spent-fuel canisters or 1,200 HLW canisters could be stored in the 5 km column of a 10 m diameter shaft. Bourke and Hodgkinson (1977) also calculated large temperature rises caused by waste canisters emplaced in cubic and planar arrays. It is clear that unacceptably high temperatures could occur from relatively fresh waste unless very low packing densities are employed.

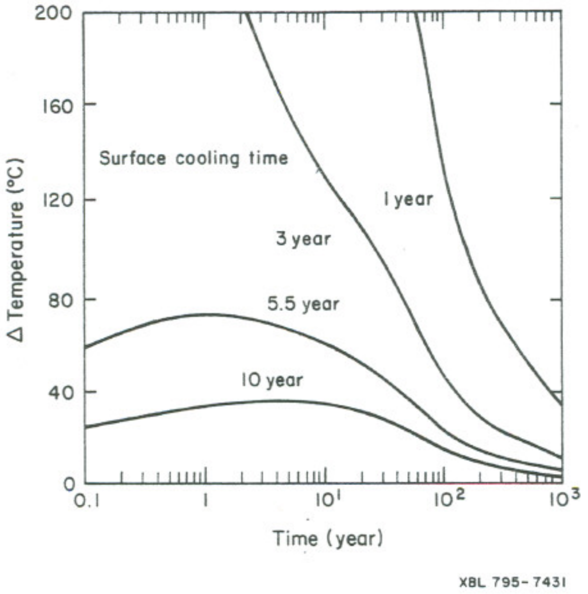

Figure 8. Effect of surface cooling period on wall temperature as a function of time after emplacement.

The case is for PWR spent fuel canisters placed in a 0.31 m (12-1/4 in) diameter hole in granite.

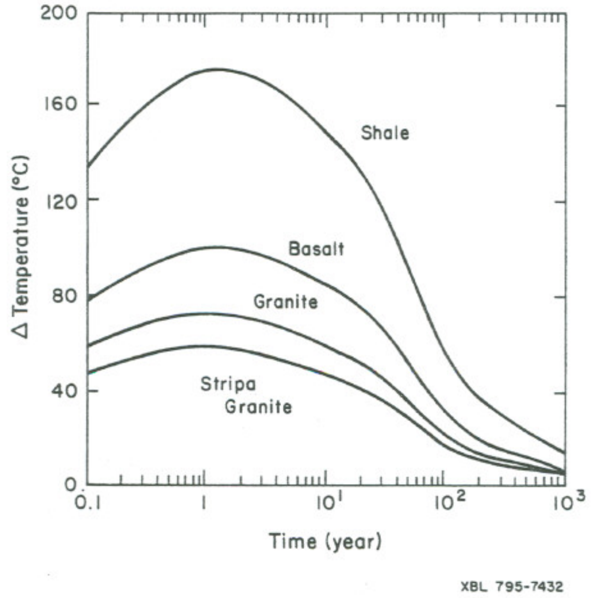

Figure 9. Effect of rock types on wall temperatures as a function of time after emplacement.

The case is for PWR spent fuel canisters placed in a 0.31 m (12-1/4 in) diameter hole after surface cooling period of 5.5 years.

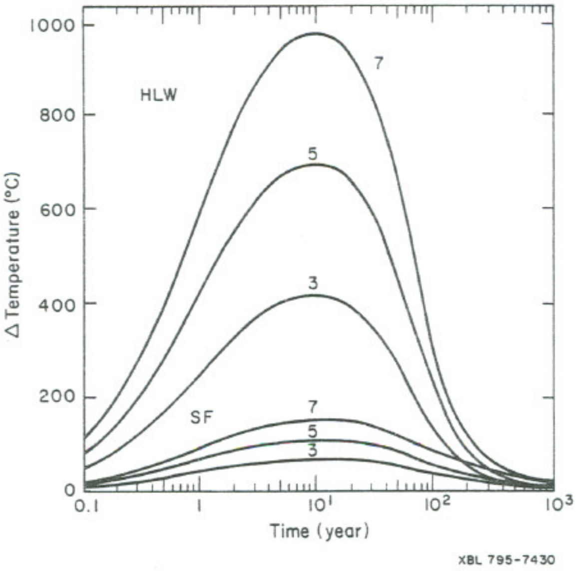

Figure 10. Wall temperature of a 10 m (33 ft) diameter shaft as a function of time for 3, 5, and 7 vertical layers of PWR spent fuel and reprocessed high-level waste canisters emplaced in granite.

In summary, for a nominal amount of thermal loading, we have calculated the temperatures at the rock surface of the hole for both high-level wastes and spent fuel at all times. For the case of a 0.31 m (12-1/4 in) diameter hole, only one column of canisters can be accommodated. The peak temperature rise is about 470°C (878°F) for high-level waste and 72°C (162°F) for spent fuel emplaced after surface cooling for 6.5 years and 5.5 years, respectively. For the case of a 10 m (33 ft) diameter hole, the temperature rise that can be tolerated by the host rock strongly limits the number of columns of canisters that can be emplaced.

Increases in temperature may cause a variety of physical and chemical effects in a rock mass such as phase changes, partial melting, thermally induced stresses, excitation of convection in the overlying hydrologic system, and generation of fluid pressures. The literature of experimental petrology will yield predictions on equilibrium chemical effects; other potential effects can be modeled. In future research on the very deep hole concept, all expected effects of increase in temperature would have to be investigated in detail.

Fluid pressure buildup. A potentially severe problem could occur if the fluid in the rock near the repository became heated. The critical point for pure water is 374°C at 221 bars; above that pressure or temperature there is no distinction between liquid and vapor. The critical pressure corresponds to a hydrostatic head of 2 km (6,600 ft) of water or 1 km (3,300 ft) of rock. If perturbed by the waste, an increase in temperature of the pore fluid in the surrounding rock could affect the pressure and potentially rupture the system. If the rock has low permeability, the volume of the fluid system remains nearly constant and thus the pressure rises. Clearly an assessment of this pressure increase depends on initial conditions, availability of water, porosity, permeability, heating rate, and dissolved solids in the water. If the pore pressure reaches the level of the rock stress, then fracturing and rupture of the waste containment system will occur.

Thermomechanical stresses. We calculated thermal stresses for the geometry of a long cylindrical heat source using classical theory of thermoelasticity. The tensile stresses are higher at the end of a heated long cylinder than they are outside the mid-section and will be treated first. For the end problem it is an excellent approximation to use the theory for a uniformly heated elongated ellipsoid. Calculations indicate the following tensile tangential stresses at given distances above the waste column for a 100°C (212°F) temperature rise:

Top of waste column	910 bars	(13,400 psi)
2.5 km (8,200 ft) above top	114 bars	(1,675 psi)
5 km (16,400 ft) above top	34 bars	(500 psi)

For illustration, a 10 km (33,000 ft) deep hole with a modest temperature rise caused by the waste induces large tensile stresses, which are comparable with the uniaxial tensile strength of hard rock determined in the laboratory. Our calculations show that stresses outside the curved surface of the section of the hole containing the waste are inconsequential compared with stresses above the top of the waste.

Linear thermoelastic continuum theory was used in the above calculations, as it is in most other models of thermal effects on rocks. If the rock is jointed, the joints may be able to "absorb" the thermal expansion without transmitting the high stresses. Other in-situ properties, such as permeability, may be affected by joints "absorbing" thermal expansion. Hence in-situ rock properties studies and numerical modeling of the behavior of jointed rock masses must be pursued.

MAKING THE VERY DEEP HOLE

A primary consideration in establishing the feasibility of the very deep hole concept is the technology available to excavate a deep hole. We review four methods of excavation here, including the present capabilities and potential advancements of each. Finally, we make some comments on technological developments needed to make deeper holes.

Methods

To excavate a very deep hole, four methods could be used. These are oil-field rotary drilling, big-hole drilling, drill-and-blast shaft sinking, and blind-hole shaft boring.

For oil-field rotary drilling, standard oil-field drill equipment would be used. A drill bit attached to a drill pipe is rotated from the surface and drilling mud is circulated through the pipe to carry cuttings to the surface. The drilling mud is a critical element in providing borehole stability, lubrication, and cooling; helping prevent corrosion; and minimizing pipe sticking. Current drilling muds are either water-base or oil-base with bentonite clay added to increase viscosity, barite added for weight, and various additives used to improve selected properties. Substantial rotary drilling experience exists; however, most of the drilling has been in sedimentary rocks. At least the upper portions of deep rotary drilled holes will be cased; in fact, the entire hole may need to be cased for borehole stability. Cement grouts are pumped from the bottom of the hole up around the high-strength steel casing to grout the casing tightly against the borehole. If the entire borehole is cased, then the hole could be bailed dry and left standing open for long periods of time. If the bottom portion of the hole is not cased, it is unlikely that the borehole would stay open if the hole were bailed dry; therefore fluid of density greater than fresh water would probably be required in the open hole at all times.

Big-hole drilling would use oil-field equipment with a large cutter head attached to drill pipe; the assembly is rotated from the surface. Reverse circulation would be used, whereby the drilling fluid would be brought up through the hollow drill pipe using air-lift and high fluid flows. The hole would be drilled to some depth and then, if required, casing would be run from the surface to the bottom of the hole. The casing would be grouted in place with care to ensure that the grouting does not create such high pressures that the casing would collapse during the operation. Big-hole drilling would not require men in the hole, and a smooth wall with no damaged zone around the borehole would result.

Shaft-sinking refers to drill-and-blast construction techniques using mucking methods that rely on a cable lift. The drill-and-blast operation is a cyclic process; i.e. first blast holes are drilled, then they are loaded with explosives, then blasting occurs, then the blasted rock (muck) is removed. The blasting operation leaves a damaged zone around the shaft, since it creates fractures one or more shaft diameters into the rock. The shaft must be bailed; that is, water must be pumped out since workers would be in the shaft during construction. Removing the muck after the rock has been blasted will generally be the most time consuming operation for deep shafts. The shaft must be lined, and because lining cannot be done simultaneously with the drill-and-blast excavation, this causes another cyclic operation. The lining is required to prevent loose rock from falling down the shaft and to keep groundwater from entering the shaft. At great depths the lining also helps provide shaft stability. Near the surface, the lining might be a grout-gunite shot on a wire mesh bolted to the shaft wall. A cement lining could be cast in place using slip forms as the shaft progresses deeper. High-strength steel segments that are lowered and bolted into place might be required at great depth.

For a deep shaft, the lining will not be able to fully resist the horizontal stresses even if thick high-strength steel segments are used. To prevent collapse of the lining as the rock yields around the shaft, an unfilled or loosely filled annulus between the rock and the lining might be desirable as the best mining technique; however, a porous filling around the annulus could be a potential pathway to circulating groundwater and would thus be quite undesirable. Ventilation and humidity control are critical for the workers in the shaft, and refrigerated ventilation will certainly be required at depths below 2.1 to 2.5 km (7,000 to 8,000 ft). The maximum allowable depth for a wire rope cable lift is 2.5 km (8,000 ft), but a more practical limit for current wire rope is about 2.1 km (7,000 ft). Shafts smaller than 3 to 4 m (10 to 12 ft) in diameter are impractical to sink, whereas shafts up to 9 to 10 m (30 to 35 ft) diameter would be practical.

Blind-hole boring refers to boring a shaft. A rotating head with disk or tungsten-carbide button cutters would be turned by electric motors downhole. The entire boring machine would be held fixed in the shaft by a hydraulic gripping arrangement. Planned muck removal would be with cable lift, just as for drill-and-blast shaft sinking. No deep, large diameter blind-hole shafts have yet been bored. However, two systems are currently in the construction stage, and field demonstration for a 6.1 m (20 ft) diameter shaft to about 0.6 km (2,000 ft) depth will be accomplished within the next few years. Present plans call for men in the shaft to operate and maintain the boring machine; hence the shaft would have to be lined.

Present Capabilities

There is little experience at drilling to great depths in hard, crystalline rocks, although such rocks may pose no more problems than drilling ultra-deep wells in sedimentary rocks. A limited number of oil-field rigs are capable of drilling to 7 1/2 km (25,000 ft) depths and beyond. Presently there are four rigs in the United States that could drill to a depth of 9 km (30,000 ft) or somewhat deeper. There are three wells drilled in sedimentary rocks in the United States that are slightly deeper

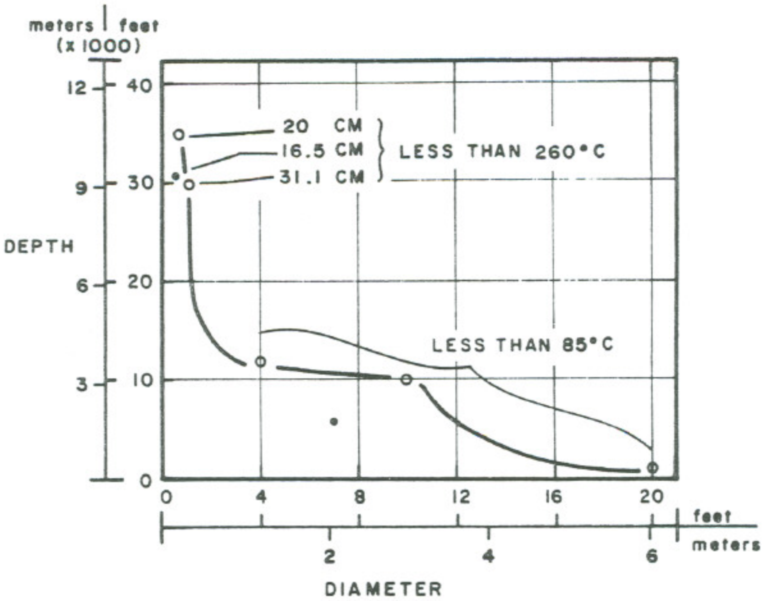

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Figure 11. Present (1978) capability to rotary-drill deep holes.

Solid points represent actual experience and open points represent limits currently believed to be possible.

than 9 km (30,000 ft). The bottom portion of the holes were drilled with a 16.5 cm (6-1/2 in) diameter bit, and the holes were cased to the bottom. There is some experience at drilling geothermal wells where formation temperatures approach 300°C (600°F); however, these wells have not been drilled much below 3 km (10,000 ft). Big-hole rotary-drilled holes up to about 2.1 m (7 ft) in diameter have been drilled to depths of nearly 2.1 km (7,000 ft). Reverse circulation using water and air lift was used for removing the cuttings.

We believe that somewhat deeper and larger diameter holes could be drilled. Figure 11 shows a plot of depth versus diameter actually attained and currently believed to be possible. Banister et al. (1978) reach more optimistic conclusions about possible depths attainable.

A maximum well depth of about 11 km (35,000 ft) in rocks where borehole stability is not a problem is believed possible, provided the bottom hole were drilled with a 20 cm (7-7/8 in) diameter bit. Nine-kilometer (30,000 ft) depths could be achieved with 31 cm (12-1/4 in) diameter bits in crystalline rocks where no gas pressure exists. For very strong rocks, the bottom part of the hole might be left open; and in fact for the 31 cm (12-1/4 in) diameter hole, current rigs (with current casing) would not be able to set casing to the bottom of the 9.1 km (30,000 ft) hole. Salt has been drilled successfully to about 4.6 km (15,000 ft); below this, borehole closure prohibits further drilling.

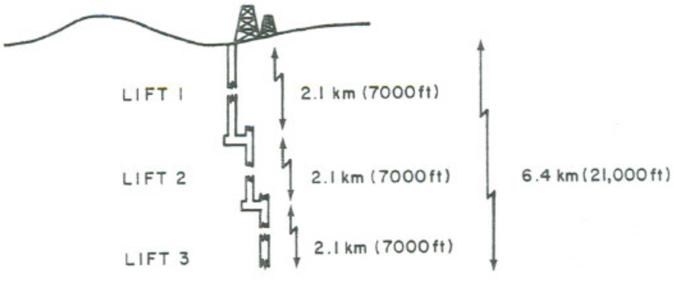

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Figure 12. Schematic of multiple-lift very deep shafts.

We also believe that a ~3 m (~10 ft) diameter hole could be rotary drilled to a depth of about 3 km (10,000 ft), in strong rocks where borehole stability and rock fractures are not problems. Big-hole drilling of a smaller diameter hole, 1.2 m (4 ft) diameter, is believed possible to only slightly greater depths, 3.7 to 4 km (12,000 to 13,000 ft). At present, temperatures for rotary drilling must be limited to about 260°C (500°F) for very deep holes and to about 93°C (200°F) for big-hole drilling.

Presently (1978) all large rotary drill rigs are in use and are contracted well into the future; this condition will probably continue for at least the next 10 years.

Many shafts have been sunk to depths of 1 to 1.8 km (3,300 to 6,000 ft) and a few shafts have gone to greater depths. The practical limit of about 2.1 km (7,000 ft) for a single lift with current wire-rope available [20 kbar (300,000 psi) tensile strength] requires that for deeper shafts, multiple lifts must be used -- as shown schematically in Figure 12.

Pertinent information on deep shafts throughout the world is summarized on Table 3. The deepest excavation is to 4.6 km (15,200 ft) in the South African gold mines. It was accomplished by sinking two vertical lifts to a depth of 3 km (10,000 ft), followed by an inclined shaft to about 4.6 km (15,200 ft).

Shaft diameters vary from about 3 to 10 m (10 to 30 ft) with ease of construction relatively the same over this diameter range. Circular and elliptical shafts have both been constructed; however, the deeper shafts are usually circular to facilitate lining support. We believe that with current technology, shafts to about 4.3 km (14,000 ft), with two lifts, could be constructed, assuming reasonable rock conditions. No shafts have yet been blind-hole bored.

Table 4 gives estimated costs and times for making holes by rotary drilling, big-hole drilling, and drill-and-blast shaft sinking. In all we assume that the rocks drilled are strong or moderately strong. Encountering very weak or highly fractured rocks in rotary drilling would

Table 3. Significant vertical shafts (single lifts)

Name of shaft or company	Location	Depth m (ft)	Diameter m (ft)	Rock type	Time to completion (months)	Method of excavation
Creighton No. 9	Sudbury, Canada	2,176 (7,100)	6.1 (20)	Norite	64.3	Drill and blast
Anglo-American Mine Co.	South Africa					
President Steyn No. 4		2,317 (7,600)	10.2 x 11.0 (33 x 37)	Sandstone, volcanics, quartzite	31	Drill and blast
deepest single shaft**		2,500 (8,300)	*		*	Drill and blast
Elsburg	South Africa	1,982 (6,500)	11.0 (37)	Sandstone, quartzite	70 (fully operational)	Drill and blast
Henderson Shaft	Colorado	610 (2,000)	7.3 (24)	Metamorphics	*	Drill and blast
Welkom Shafts (several)	South Africa	2,200 (7,000)	6 to 8.5 (20 to 28)	Quartzite	*	Drill and blast
U. S. Department of Defense	Amchitka, Alaska	1,906 (6,250)	2.0 (7)	Andesite	*	Drilled
Kerr McGee	New Mexico	450 (1,200)	2.0 to 2.5 (7 to 8)	Sandstone	*	Drilled
U. S. Department of Energy	Nevada	600 (2,000)	2.0 to 2.5 (7 to 8)	Alluvium, tuff	*	Drilled

* Information not available

** Ore only; not personnel

Table 4. Estimated costs and time of construction of deep holes.

Technique and depth km (ft)	Cost* (in millions of dollars)	Time to completion (years)	Remarks
Rotary drilled			
4.6 (15,000)	1.5	<0.5	31 cm (12-1/4 in)**
6.1 (20,000)	3	1.0	31 cm (12-1/4 in)**
9.2 (30,000)	15	2.5	31 cm (12-1/4 in)**
10.7 (35,000)	30-35	3.5	20 cm (7-7/8 in)**
Big-hole drilled			
3.0 (10,000)	25	2.5	Drilling cost alone
	10		Cutters for drilling
	10		Casing cost, if required
Drill-and-blast shaft sinking			
2.1 (7,000)	16-26	3.0	Single lift
4.3 (14,000)	50-70	6.0	Two lifts

* In 1978 dollars

** Maximum diameter at bottom of hole

add substantial cost and possibly require more time. Bad ground (bad water conditions, unstable rock, or very high in-situ stresses) would increase the time and cost of the shaft sinking.

Combination Systems

Drilling and shaft sinking could be combined to make the very deep hole configurations shown on Figure 13. Rotary drilling a small-diameter hole from a deep shaft (Figure 13a), underreaming a deep hole (Figure 13b), and side tracking from a rotary-drilled hole (Figure 13c) are combinations that might be considered. Drilling deep holes from a shaft -- or a shaft and tunnel complex -- poses major problems. Stresses in the rock at the shaft depth would make it more difficult to drill from a shaft than to drill from the surface. It is therefore not possible to expect that a 4.3 km (14,000 ft) shaft and a 10.7 km (35,000 ft) well could be combined to achieve a total bottom-hole depth of nearly 15 km (50,000 ft). It is likely that from a cost and time point of view, it would be more practical to drill directly from the surface.

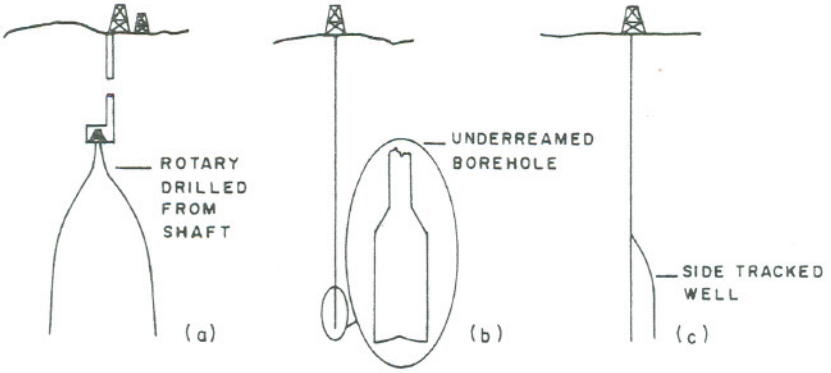

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Figure 13. Combinations of drilling and excavation methods.

Underreaming a deep drill hole to obtain more volume for storage may be possible but would require improved technology. Such underreaming of deep holes [below 6 km (20,000 ft)] has not been accomplished, and at best the hole diameter could be increased by a factor of about 2. Underreaming would require rocks with high strength, since the hole would be left uncased.

Side tracking from a deep hole is currently possible and appears very attractive. A series of 9 to 11 km (30,000 to 35,000 ft) holes could be side-track drilled from a depth of 6 to 7-1/2 km (20,000 to 25,000 ft) in a single well; hence, the drilling time and costs for drilling the first 6 to 7-1/2 km (20,000 to 25,000 ft) would be saved. Since the shallow drilling is the easy part of boring the well, side-track drilling may not be attractive when borehole plugging and environmental uncertainties are considered.

Expected Advancements

Increasing our capability to rotary drill deep wells beyond about 11 km (35,000 ft) by the year 2000 will require significant development of new technology. Currently there is no industrial demand to produce the technological advancement necessary. If sufficient resources were used to further technology, by the year 2000 we could probably drill to about 15 km (50,000 ft) deep. The improvements in technology required to reach this depth include:

- New drilling muds capable of withstanding 370 to 430°C (700 to 800°F) formation temperatures
- Development of high-temperature drill bits, either roller cone or diamond
- New drill pipe and casing, including improved designs and high-temperature steels

- Improved downhole support equipment such as high-temperature logging and surveying tools and fishing tools
- High-temperature cements and surface pumps for pumping these cements

With the above improvements in technology, a 15 km (50,000 ft) well could be drilled, where the formation temperatures do not exceed 370° to 430°C (700 to 800°F). The bottom hole would be drilled with either a 15.9 cm (6-1/2 in) bit, or in the best case, a 20 cm (7-7/8 in) bit. Most of the hole would be cased; however, in high-strength rocks without gas pressure, the bottom part of the hole might be left open.

Big-hole drilling is currently believed to be at its limit in terms of the depths attainable using current concepts, materials, and technology. No significant increase in the depth that could be drilled is expected, even if large sums were spent on technology. Specifically, the ability to drill about a 6 m (20 ft) diameter hole 0.3 to 0.6 km (1,000 to 2,000 ft) deep, a 3 m (10 ft) diameter hole to about 3 km (10,000 ft) deep, or a 1.2 m (4 ft) diameter hole to 3.7 to 4 km (12,000 to 13,000 ft) deep in ideal rocks is the limit that can reasonably be expected from big-hole drilling.

To increase the depth that a shaft can be sunk with a single lift requires increasing wire rope capabilities. Because current wire rope has a tensile strength of about 20 kbar (300,000 psi), we do not expect a large improvement. The maximum depth that shafts can be sunk even with multiple lifts depends on the equipment used, the rock strength, and the in-situ stresses. Ventilation and humidity control become critical below 2.1 to 2.4 km (7,000 to 8,000 ft) and would be very difficult below 4.3 to 4.9 km (14,000 to 16,000 ft). Ground control and the prevention of liner collapse as the shaft is sunk becomes more difficult below the first lift, and little experience exists for design. Based on simple analysis and assuming that the maximum horizontal stress is equal to the vertical stress (approximately 0.226 bars/m, or 1 psi/ft), the hoop stress around the shaft would be twice the vertical stress. Therefore, for a rock with an unconfined compressive strength of 2 kbar (30,000 psi), a critical depth where yield and failure around the shaft wall would occur -- due to the in-situ stress alone, not due to blasting -- is around 4.6 km (15,000 ft).

We believe that shafts deeper than presently exist could be sunk; however, major unknown problems would be encountered primarily because of the yielding and failure of rock around the shaft wall. Only very approximate cost and time estimates can be made for shafts deeper than about 4.3 km (14,000 ft). To sink a shaft to 4.3 km (14,000 ft), or somewhat deeper might require six years and $50 to $70 million (Table 4); to sink another lift to 6.4 km (21,000 ft) might require an additional six to eight years and an additional $70 to $100 million (all in 1978 dollars). We did not estimate the cost and time required for sinking shafts deeper than 6.4 km (21,000 ft).

Table 5. Reasonable advancements possible in ability to make a very deep hole by the year 2000 (if technology and experience are advanced).

Depth km (ft)	Diameter	Temperature ^{o}C (^{o}F)	Cased/lined	Fluid in hole	Method
15.2 (50,000)	20 cm (7-7/8 in)	370-430 (700-800)	At least to 9.2 km (30,000 ft)	Mud	Rotary drilling
10.7 (35,000)	31 cm (12-1/4 in)	370-430 (700-800)	At least to 7.7 km (25,000 ft)	Mud	Rotary drilling
6.1 (20,000)	6-9 m (20-30 ft)	93 (200)	Lined	No	Drill and blast shaft
4.3 (14,000)	1.2 m (4 ft)	150 (300)	Not necessarily	Probably	Big-hole drilling
3 (10,000)	3 m (10 ft)	150 (300)	Not necessarily	Probably	Big-hole drilling
3 (10,000)	3-6 m (10-20 ft)	93 (200)	No	No	Blind-hole boring

Blind-hole boring may offer promise in the future, after reliable equipment has been built and operated. This construction technique would be more attractive for waste disposal if the following innovations could be made:

- Remote control operation to avoid having men in the shaft
- Remote operation with fluid in the hole at all times
- Automated muck removing system using slurry instead of cable lifts
- Some means to emplace waste material without requiring men in the shaft or bailing the shaft dry

Table 5 shows the best estimate of advancements that could reasonably be expected up to the year 2000, if the limitations enumerated here are removed.

Sealing and Containment

Sealing a borehole or a shaft, and the long-term containment capabilities of either, are addressed on page 35. The design of seals should begin, however, with the drilling or shaft sinking technique. For holes filled with fluid, the seal must be emplaced in that medium; the rock at the immediate edge of the excavation, where the sealing material must firmly adhere, must be cleaned of drilling mud or loose rock; and damage and fracturing in the rock immediately surrounding the opening must be considered. Hence the drilling or blasting techniques chosen must be integrated with the design for closure.

EMPLACEMENT

In the disposal of radioactive waste in a very deep drill hole, we assume that the material is placed in a canister or container of some kind to be lowered into the hole. If relatively small-diameter rotary-drilled holes were used, canisters must fit inside holes drilled with a 31 cm (12-1/4 in) bit; that is, the canisters would have a 20.3 to 22.9 cm (8 to 9 in) maximum diameter. Canister lengths up to 9.1 m (30 ft) would be relatively convenient since this is the length of standard drill pipe. It is likely that canisters would be lowered into the hole by wire line while the hole was full of liquid.

If the hole were drilled with a 31 cm (12-1/4 in) bit and cased, the spent fuel elements probably would not fit inside the casing. Special drill bits and casing could be produced that would allow a slightly larger diameter hole so that the spent fuel elements could be emplaced directly in the cased hole.

For large-diameter shafts, cable lifts would be used to lower radioactive material to the bottom. The waste would be contained in canisters, which would be packed in the shaft. We do not envision any other special treatment, except that filling of interstices with a preselected material would be required. This backfill material might be chosen for mechanical stability, sorption of or reaction with waste products, sealing against water penetration, slight swelling to fill voids and exert some back pressure on the surrounding rocks, or some combination of these properties.

CRITICALITY

Criticality could become an important issue in isolating nuclear wastes in a very deep hole. A critical mass for a fission reaction could occur if plutonium were allowed to segregate, if the conditions were hydrous, and/or if the geometry of the container(s) or hole focused the segregation of the nuclides. Kibbe and Boch (1978b) estimate that given a concentration of 2 g/cm^3 of ^{239}Pu in a pure PuO_2-H_2O slurry from 5-year-old uranium recycle waste, the spherical critical mass in granite is 20.6 kg (45 lb) of ^{239}Pu and the critical radius is 13.5 cm (5-1/2 in). Critical masses as low as about 1 kg (2.2 lb) ^{239}Pu, with 17.1 cm (6-3/4 in) critical radius, occur for PuO_2-H_2O slurries with ^{239}Pu concentrations as low as 0.05 g/cm^3 (Kibbe and Boch, 1978b). Larger critical masses and smaller critical radii would occur for a segregated PuO_2-H_2O slurry in a cylindrical hole in granite. There is potentially more than this amount of ^{239}Pu in a spent fuel assembly canister or in a high-level waste canister, and the amount of ^{239}Pu available for segregation and criticality increases when additional waste canisters are added to a given hole.

A series of criticality calculations and criticality pulse analyses should be performed in order to quantitatively assess this issue.

For holes of large enough diameter, several adjacent spent fuel canisters can become critical with water intrusion, even without fuel deterioration and segregation of ^{239}Pu. In the short term this criticality can be avoided by using neutron-absorbing canisters. If the canister later deteriorated, removing the neutron absorber, critical thermomechanical pulses could occur.

The amount of ^{239}Pu and other fissionable daughter products that contribute to criticality increases considerably with time, particularly in high-level unreprocessed wastes, because of the decay of ^{243}Am. This radionuclide has a half-life of 7,930 years. Therefore, increase in the potential for criticality with time must be considered. The effect of actinides of greater atomic mass number on criticality also needs to be considered. For spent fuel without segregation, criticality may be due more to the ^{235}U than to the plutonium (Allen, 1978).

SEALING

After emplacing nuclear waste in deep boreholes, the holes must be sealed to isolate the waste from the biosphere. The time required to sustain isolation may be tens to hundreds of thousands of years for high-level nuclear wastes. Not only is it necessary to seal the borehole itself, but consideration must be given to plugging a possibly damaged zone around the opening.

The components of an adequate sealing system must have sufficiently low permeability to prevent contamination of the biosphere over the life of the seal. For integrity to be maintained the following requirements must be met by the sealing material:

> Chemical composition: The material must neither deteriorate nor its permeability increase with time. Chemical stability is essential to prevent reactions of sealing material with both the surrounding rocks and with waste or containment material.
>
> Strength and stress-strain properties: The seal must be compatible with the surrounding rocks. Mechanical stability must also be assured under the thermal regimes anticipated near the waste.
>
> Volumetric behavior: Shrinkage should be mimimized to prevent formation of conduits past the seal. If the material expands, pressures developed must be less than would cause fracturing of the rock.

Possible plugging materials include inorganic cements, clays, and/or rock. Whatever the plugging material, it must satisfy the requirements of mechanical and chemical stability in the environment of the hole for the required life of the repository.

Because the waste-containment section of the very deep hole probably will be cased and fluid-filled, any sealing scheme must take into account the casing and fluid. If the casing is removed, the methodology for constructing the plug must include positive assurance that the host rock is stable during construction. If the casing material is left in place, it must be designed to serve as a constituent of the seal system. This alternative introduces an additional component of the plug and an additional interface, thus complicating all adequacy considerations. If short low-permeability plugs are used as the primary seal, casing removal may only be required at the depths of these plugs.

Since the holes to be plugged will probably be filled with drilling fluid, emplacement will have to include working in an aqueous environment or removal of the fluid from the areas to be sealed. The standard oil-field practice of cementing the annulus around casing satisfies this requirement and routinely seals off gas at high pressure. The successful containment of gas for decades in an oil and gas well is evidenced by the lack of gas leaks to shallower formations or even to the surface.

The seal system consists not only of a plug or plugs placed within the borehole, but of the adjacent rocks and the interface between the two materials. Any seal must adequately restrict flow in all three zones. The required flow impedance may be achieved in a variety of ways: by a homogeneous plug placed the full length of the hole or by a series of low-permeability plugs placed in contact with the lowest-permeability units intersected by the hole. This would require backfill material between the low-permeability plugs.

For a rotary-drilled hole where drilling mud is used, borehole damage and possibly formation damage some distance away from the borehole can exist due to residual mud remaining in the formation. Techniques for cleaning the borehole surface, including water washing, acid treatment, and wire brushing, are all accomplished with the borehole full of fluid. Such techniques would undoubtedly be included in the design for sealing a borehole.

Sealing a shaft, particularly a very deep shaft with multiple lifts, is very likely to pose more difficult problems. A shaft sunk by drill-and-blast techniques will have a damaged zone around it caused by the blasting operations; at depth, the problem is compounded by rock yielding and failure. Assuming low-permeability host rock, this damaged zone will have a permeability greater than the host rock by one or two orders of magnitude. At present we are uncertain how to seal the damaged zone so that it has the same low permeability as the intact rock. Even for a bored shaft where blasting is not used, at great depths the fractured and hence permeable zone around the shaft caused by excavation could pose a serious sealing problem. Expansive plug materials (cements or clays) appear to be promising solutions to providing both continuity of the plug-formation interface and closure of fractures and microcracks around the hole. However, plug materials must not induce such high stresses at the hole wall that additional fracturing of the host rock occurs.

The consequences of an inadequately sealed hole dictate a rigorous quality assurance program for the borehole seal. Such a program should include information on quality control during seal construction and quality assurance instrumentation during the life of the repository. Both of these tasks would be facilitated by placing several high-quality seals at critical sections along the borehole. Any instruments placed within or behind the plug should not compromise the integrity of the sealed hole.

ADEQUACY OF THE DATA BASES FOR ANALYSIS

The adequacy of the data for assessing the very deep hole concept is based on four elements:

- geotechnical considerations
- making the very deep hole
- heat source
- sealing

Uncertainties or inadequacies of the data will be discussed for each of the four sections separately.

Geotechnical Feasibility

To assess hydrological conditions expected at depth, the number of measurements of porosity and permeability in crystalline rocks needs to be greatly increased. Only about 100 measurements to a depth 50 m (165 ft) are known to have been made. Only three sets of measurements have apparently been made in crystalline rock at depths below 500 m (1,650 ft) (Brace, 1979). Many tests have been made of hydrological conditions in sedimentary environments, but hydrologic data are sparse with regard to crystalline rocks at great depths. Parameters that should be considered are the nature of groundwater, circulation, chemistry, and isotopic composition of waters at great depths in crystalline rocks.

Although there apparently are no measurements of in-situ stress in crystalline rocks below about 3 km (10,000 ft), many measurements have been made in sedimentary rocks at depths from 1 to 5 km (3,300 to 16,000 ft). Few measurements have been made in sedimentary rocks, however, below 5 km (16,000 ft). We do not know the in-situ thermomechanical characteristics of a rock mass at depth, and strength data appear to be particularly sparse for foliated rock. This is particularly true for temperatures at depth augmented by the heating due to the waste material. Even less data are available about the properties of jointed rock.

Geochemical information is scarce with regard to: the mineralogy of waste products; the stability of phases resulting from the interaction of various waste products and the surrounding host rock; and the impact of waste components on the oxidation state and subsequent effects on the stability of host rock minerals containing iron. We know too little about the kinetics of reaction between the waste products and the host rock; the kinetics of leaching of the waste forms by an aqueous phase; sorption (and thus migration behavior of fission products and trans-uranic elements at elevated temperature); and the viscosity and anhydrous devitrification products of proposed waste forms of glass.

Making the Very Deep Hole

Data and experience on making deep holes and shafts by various techniques provide a sound base for establishing current feasibilities. The pool of expertise available to ascertain the data base is extensive, and experts in given fields generally concur on current and expected capabilities to the year 2000. Costs could be substantially underestimated, particularly if the expansion of activities in oil-well drilling continues and if an increase in underground excavation were to monopolize equipment and talent to the year 2000.

Heat Source

Underground experiments in salt (OWI, 1976) and granite (Cook and Hood, 1979) have shown that, in these two quite different rock types, the thermal field around heaters can be adequately calculated with existing computer programs. Further confirmation will be necessary. At the great depths proposed for the deep hole concept, we expect that fractures will tend to close; thus thermal properties measured in the laboratory may be even more directly applicable than to nearer-surface experiments.

Sealing

The data base for sealing deep bore holes primarily consists of analytical evaluation of extensive oilfield practice; however, procedures for satisfactory containment of natural gas or hydrocarbons in deep formations may not be adequate for isolating radioactive materials for periods of 1,000 to 100,000 years. Uncertainties in the data base result from the buildup of water pressures if high subsurface temperatures are generated, the behavior of cements at prolonged high temperature, and the behavior of cements over extended time. The extensive experimental and field data of petrology may be applied to the design of seals.

Few data exist on sealing the damaged zones around large-diameter shafts. The largest uncertainty in the data base is directly and indirectly connected with unknown geotechnical conditions at depth. The deep-hole concept relies on isolating the wastes from circulating groundwater systems, or at least isolation in low-porosity and ultra-low permeability rocks existing at great depths. Thus sealing a large shaft would also require the same conditions. Yet of the physical properties of deep rock units, the least is known about porosity and permeability.

ENVIRONMENTAL ANALYSIS

Construction and Operation

During construction and operation, the environmental impacts of a very deep hole are expected to be those which are common to other drilling and excavation activities. Drilling or shaft-sinking a very deep hole would require the same environmental precautions that are required for drilling deep holes for oil, gas, and geothermal wells, or for mineral exploration and production. Constructing the deep hole via shaft-sinking techniques would receive the same environmental, ventilation, and safety considerations as for sinking mine shafts. The impacts are: the conversion of several square kilometers of land from their present use to drilling/mining and waste repository activities; disturbance and removal of vegetation; temporary impoundments of water for drilling or shaft sinking; accumulation of tailings; alteration of topography at and adjacent to the site; and socioeconomic impacts on housing, schools, and other community services. No special environmental precautions beyond those required for normal drilling or shaft sinking would be required.

An area of impact that should be weighed is the possibility of extending the waste cooling time at the surface before disposal. Several countries are presently considering interim cooling. Cooling facilities away from the disposal site would not affect environmental analysis of the deep hole itself.

The environmental impact and risk of radioactive waste leakage from the very deep hole is similar to that of conventional geologic disposal, with the exception of the great depth at which the wastes would be emplaced. Location of wastes in holes as deep as 10 to 12 km (33,000 to 40,000 ft) increases the transport path to several kilometers more than other geologic waste options, should leakage occur.

Microfractures and other openings may develop in the vicinity of the hole due to the stress relief created by drilling or excavation. In addition, small openings may develop within the cement plug and between the plug and the hole wall if the bonding between the two is not ideal. It is conceivable that such channels may develop and provide pathways for contaminated waters to migrate to the biosphere. If the hole is sited below circulating groundwater, the primary driving force for migration is likely to come from the thermal energy released by the radioactive waste. The travel time to the biosphere will therefore depend on the availability of water, the continuity and apertures of the existing and induced fractures, the time and magnitude of the energy released, geochemical reactions, and the volume and geometry over which the energy release persists. The lack of data on the presence of water and the properties of fractures in deep rock environments prevents us from making an estimate of the hazard.

Post-Operation and Long-Term Impacts

The long-term impact of the repository on the groundwater regime will be essentially governed by the nature of the deep groundwater system and the location of the site within that system. Due to the great depth of emplacement and the larger volumes of rock available to absorb the energy released by the waste, the deep groundwater system probably will not be appreciably perturbed by the waste itself. If the deep hole is located within a recharge zone or in a zone of lateral movement, the distance to the biosphere along the path of flow may be so long and the velocities so low that isolation may be effectively achieved. Furthermore, the transport of contaminants by the flowing water will also be greatly retarded by the increased residence times and the increased time for interaction of the contaminants with the host rock.

Heating, rock alteration, or thermomechanical pulsing caused by wastes reaching critical mass are common to other geologic disposal options and are potentially significant impacts. They are dependent on the specific rock and site characteristics, waste form, quantity, and spacing and can only be assessed when these parameters are defined.

Another concern for the very deep hole concept in the long term is the susceptibility of the groundwater system to tectonic changes and volcanism. The very concept of the deep hole is aimed at minimizing such effects by increasing the distance to the biosphere as much as is technically feasible. Additionally, by selecting the site in a tectonically stable region, the probability of such catastrophic events is very low.

Monitoring

A long-term monitoring system would most likely accompany a deep-hole repository. The configuration of such a system is beyond the scope of this document.

RESEARCH AND DEVELOPMENT NEEDS

The preceding sections address the feasibility of drilling or sinking a hole or shaft deep into the earth's crust to permanently isolate radioactive wastes, and the problems associated with the long-term interaction of the waste, the hole and the surrounding rock. The material to be isolated could either be high level liquid or solid radioactive wastes.

The adequacy of the data base is discussed on page 37. In general, the data base on conditions at great depths is insufficient to characterize:

- Hydrologic regimes in either crystalline or sedimentary rock
- In-situ rock mass properties, including permeability, strength, deformation, and stress state
- Geochemical interaction between the existing fluids, host rock, and radioactive wastes
- Sealing materials and methodologies

Geotechnical Considerations

To validate the concept of the very deep hole, research is required in the topics outlined immediately above and in the areas of site selection and site evaluation.

Site selection. It will be necessary to locate sites in strong, unfractured rock with low water content in tectonically stable areas. Strength and fracture density are difficult to assess on a regional basis, but electrical surveys give a good indication of water content. Only a few deep electrical soundings have been made in this country; a number of surveys should be made in stable tectonic regions of low heat flow and appropriate lithology.

Site evaluation. The in-situ state of stress, permeability, and the thermomechanical response of the rock near the hole are of major importance, yet methods of obtaining these characteristics are relatively underdeveloped, particularly for depths considered here.

Permeability. Permeability may be less than a microdarcy and therefore close to the lower limits of the present measurement capability. Improvement of downhole techniques is needed to measure sub-microdarcy permeability. The time required for measurement needs to be shortened.

In-situ stress. In-situ stress measurements downhole need considerable improvement. Assessment of stress direction is uncertain, as is determination of the maximum stress magnitude. The relation of surface stresses to downhole stresses is so poorly understood that the surface observations presently have little value.

Thermomechanical behavior of rocks. Thermomechanical behavior of rocks around a deep hole is not predictable at present. Because controlling factors are the jointing, fracturing and fluid content, this behavior needs to be studied in situ. Heater tests in a variety of rocks at design depths are probably necessary to understand the complex response of water-saturated, stressed, and fractured rock to local high temperature.

Some aspects of thermomechanical behavior of rocks can be studied in the laboratory. Because fractured rock is in question and since characterization of natural fractures has not yet been achieved, laboratory studies should involve large samples of rock containing one or more joints. The dimensions of the samples may have to be of the order of several meters, therefore requiring extension of present laboratory techniques and equipment to test at conditions simulating the in-situ environment. The areas where study is particularly needed include thermal cracking and other forms of degradation of rock; thermoelastic response of intact and jointed rock over long times; changes in permeability caused by heating a rock mass; two-phase transport of fluid in fractured rock; hydraulic fracturing in thermally stressed rock; thermal conductivity of hot, saturated thermally stressed rock; and stress corrosion due to heated groundwater in thermally stressed rock.

Geochemistry. Research should be conducted to better characterize the interactions between the radioactive waste and the host rock, and to resolve the uncertainties regarding the fate of waste products when emplaced in a deep hole and the effect such emplacement might have on the long-term isolation of wastes from the biosphere. The principal subjects should include:

- Characterization of the expected range of chemical compositions of waste products and of potential host rocks
- Investigation of the kinetics and thermodynamics of chemical reactions between waste products and the host rocks under the temperatures expected in deep holes
- Determination of radionuclide migration mechanisms and rates in host rocks under the pressures and temperatures expected in deep-hole environments.

Making the Very Deep Hole

The most significant advancement in shaft sinking to reduce cost and time would be the development of blind-hole boring techniques, particularly remote-controlled machines, so that men would not have to work in the shafts. This would allow the shaft to be sunk without lining in some cases; and it would allow the shaft to be kept full of fluid, which would substantially improve the stability of the shaft and significantly simplify slurry and muck removal.

Sealing Research and Development Needs

Research and development is needed in two major areas: materials development and placement methodology. Materials development includes investigating plugging materials, special cements, and casing materials and drilling fluids which might be incorporated into the sealing system. Because the seal includes the host rock, these investigations should include matching plug materials with the possible rock types. It is conceivable that different plug materials would be required at different points in the same hole.

Thermomechanical Data and Instrumentation

It will be necessary to develop the capability to mathematically model the transport of radioactive waste, combining the effects of heat, stress, fluid flow, and dispersion over geologic time. The aspects of stress and hydrology have been discsussed in the section on geotechnical considerations. In addition, methods and instruments should be developed to measure thermal properties in situ -- conductivity, heat capacity, and particularly expansivity. It will be necessary to operate the instrumentation in the high-temperature and high-pressure environments of the deep hole. This research and development program is incorporated into the geotechnical program.

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