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AN APPRAISAL OF NUCLEAR WASTE ISOLATION IN THE VADOSE ZONE IN ARID AND SEMIARID REGIONS
(with Emphasis on the Nevada Test Site)

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ABSTRACT

An appraisal was made of the concept of isolating high-level radioactive waste in the vadose zone of alluvial-filled valleys and tuffaceous rocks of the Basin and Range geomorphic province. Principal attributes of these terranes are: (1) low population density, (2) low moisture influx, (3) a deep water table, (4) the presence of sorptive rocks, and (5) relative ease of construction. Concerns about heat effects of waste on unsaturated rocks of relatively low thermal conductivity are considered. Calculations show that a "standard" 2000-acre repository with a thermal loading of 40 kW/acre in partially saturated alluvium or tuff would experience an average temperature rise of less than 100°C above the initial temperature. The actual maximum temperature would depend strongly on the emplacement geometry. Concerns about seismicity, volcanism, and future climatic change are also mitigated. The conclusion reached in this appraisal is that unsaturated zones in alluvium and tuff of arid regions should be investigated as comprehensively as other geologic settings considered to be potential repository sites.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The vadose zone, the unsaturated region between the surface and the water table, has been considered, principally by members of the U.S. Geological Survey, as an attractive setting for a nuclear waste repository. The arid regions of the Basin and Range geomorphic province may lend themselves to consideration for repository sites in the vadose zones of alluvial-filled valleys and of tuffaceous rocks occupying highland areas or underlying the valleys.

The unsaturated zone in alluvium-filled valleys of the Basin and Range province possesses several characteristics that would favor isolation of nuclear wastes--i.e., inhibit the migration of radionuclides from discrete sites into and through the hydrologic system: (1) the flux of moisture into and through the alluvium is extremely low; (2) the components of the alluvium at specific locations favor the sorption of radionuclides should they escape from waste canisters; (3) at some locations the alluvium is underlain by tuffaceous rock above the water table, which also provides a lower-permeability, sorptive barrier to downward migration of radionuclides; (4) the thickness of alluvium exceeds 1000 m at many localities, and the depth of the water table exceeds 500 m. These provide a substantial hydrologic flow path between a relatively shallow repository (depth of a few hundred m) and the saturated zone. A fifth important attribute is that the enclosed groundwater basins of the Basin and Range province are isolated; there is no ultimate discharge to the ocean.

Several of the advantages of waste isolation in the vadose zone of alluvium also pertain to isolation in tuffaceous rock: low moisture flux, high sorptive capacity, and substantial thickness of rock above the water table. Specific to tuff is the attribute of having competent rock units sandwiched between less competent but highly sorptive zeolitized units. The competent units are amenable to machine mining and require little ground support in underground workings.

It is emphasized that even though tuffs underlie highland areas, the depths at which a repository would be located should be determined primarily by the occurrence of a favorable stratigraphic setting. Whether the repository is in tuff situated within a topographic high (a mesa or range) or situated well below the local topographic relief is of less importance than its location above the water table in a competent tuff unit encompassed by zeolitized units. It is conceivable that a favorable setting might be a tuff unit overlain by alluvium beneath a Basin and Range valley (Winograd, 1981).

The costs of constructing a relatively shallow repository in alluvium, either by underground mining methods if the depth exceeds 100 m or by open pit methods at shallower depths, are comparable to those encountered in harder rock under saturated conditions. Experience at the Nevada Test Site (NTS) has shown that the strength characteristics of alluvium are such that extensive ground support for underground workings is not required to depths of 200 m.

Open pit construction would permit installation of barrier materials completely encompassing the repository, if necessary. In either case, a repository at a relatively shallow depth in alluvium, compared with a deep, hard-rock site, permits relative ease of emplacement and, if necessary, retrieval of the waste.

Only underground construction is considered applicable to a site in unsaturated tuff. This would take advantage of a highly competent unit, which could be mined by machine and which would require minimal support of the workings. The most desirable stratigraphic position for such a unit would be between zeolitized units.

The hydrological properties of densely welded, strongly fractured tuff units which contain lithophysal zones are of concern insofar as they influence drainage around a repository. In this case, considerations of rock mass permeability, in the context of waste isolation, would be similar to those for other hard rock types: principally, the effect of heating on the near- and mid-field fracture-controlled hydrologic systems. The coupled thermo-mechanical-hydrological effects of heating must also be carefully considered.

The principal concerns of waste isolation in the unsaturated zone in the Basin and Range province may be considered to be alleviated for the following reasons:

- Properly chosen sites in alluvium in tectonically active areas may take advantage of local tectonism: situating a repository on the basinward side of an active normal fault sufficiently removed from the fault zone as to be unaffected by major and associated faulting could ensure that an increasing thickness of material would accumulate above the repository with time, reducing the concern of future tectonic-erosive exhumation of the site. Unless a site in tuff is unfortunately located in or closely adjacent to a caldera which will have volcanic activity associated with it in the near geologic future (a possibility which should be laid to rest by appropriate geological and geophysical investigations in the course of site selection), the concerns about volcanism and seismicity are similar to those for the case of an alluvial repository. Obviously, the location of the repository astride an active Basin and Range fault must be avoided. The relatively high seismicity of the Basin and Range region requires that the response of surface and underground facilities to ground motion associated with earthquakes of given magnitude and epicentral distances be assessed for given site locations; these should be taken into account in the design of the facilities.

- Evidence of the climate in the Basin and Range province during Pleistocene pluvial periods indicates that future pluvial periods would result in increases in moisture infiltration rates, but the saturation conditions and water table elevations at alluvial sites (away from obvious locations of playa lakes and barring perched water near the repository horizon) would not differ significantly from those of today, insofar as affecting a repository in alluvium.

Climatological considerations for a site in tuff are essentially the same as those for alluvium: significantly increased moisture infiltration rates in a future pluvial period may affect the position of the water table. However, as with alluvial areas in arid regions, it is expected that the effect of even a doubling of the infiltration rate would be insignificant, because the rates are so low, and because precipitation did not exceed evapotranspiration at any time during the last pluvial.

- If 100°C is the maximum allowable temperature rise in the immediate vicinity of a repository due to the introduction of waste, the low thermal conductivity of dry alluvium would require that the repository occupy roughly twice the area of one in saturated hard rock. The average temperature rise in a "standard" 2000-acre repository with a thermal loading of 40 kW/acre in partially saturated alluvium would remain below 100°C. Thermal considerations are of less concern for tuff than for alluvium because of the significantly higher thermal conductivity of dry or partially saturated tuff units.

- The possible structural instability of zeolitized tuff units in response to heating can be alleviated by siting a repository in a competent nonzeolitized unit, sandwiched between zeolitized horizons that would serve as sorptive barriers.

- The Basin and Range province has a very low population density; most of the land is under federal jurisdiction. Large alluviated areas exist where there is no present mining activity and where the future mineral resource potential of these areas is not considered to be significant. At sites amenable to waste isolation, the depth of the water table is excessive for development of groundwater resources. Compared with alluvial sites, there is a greater potential for conflict over a waste repository location with mineral resource potential in the tuffaceous rocks. Precious metals are relatively common in ash-flow tuffs associated with magmatic-hydrothermal systems of Tertiary calderas. A resource assessment should therefore be an important part of the site investigations.

It is concluded that the unsaturated zones in alluvium or tuffaceous rocks of the Basin and Range province are strong candidate environments for consideration as sites for nuclear waste repositories, and as such should be investigated as comprehensively as the other geologic settings presently being considered.

1. INTRODUCTION

The vadose zone, or that subsurface region lying between the surface and the water table, is well developed in arid and semiarid regions. In arid regions the vadose zone may be several hundred meters thick, while in areas of higher precipitation it may be nonexistent or only a few meters thick. In the vadose zone, where the pore spaces between grains and where fractures in hard rock are not saturated with groundwater, there would be a long hydraulic flow path between a repository and the saturated regime beneath the water table, and thus a long, time-consuming pathway for radionuclides to be transported ultimately to the biosphere. Primarily in this respect the vadose zone in arid regions is considered as a possible environment for geologic isolation of nuclear waste.

There are several topographic and lithologic combinations in the vadose zone of arid regions that may lend themselves to waste isolation considerations. In some cases, topographic highs such as mesas and interbasin ranges made up of several rock types, may exhibit esentially dry or partially saturated conditions favorable for isolation. Adjacent basins, especially in the far western and southwestern U.S., may have no surface or subsurface hydrologic connections with systems ultimately leading to the ocean.

In the unsaturated zone, a host rock with high permeability would facilitate good drainage, so that if groundwater came in contact with the waste package the time of contact would be minimal. On the other hand, very low permeability may be considered a favorable characteristic of some host rocks. In either case, it is important that the host rock contain appropriate minerals for the chemical retardation of radionuclides. Environments exhibiting these attributes include areas in the Basin and Range geomorphic province underlain by relatively permeable alluvium and by tuffaceous rock of varying permeability. Valley areas, where tuffaceous debris makes up a significant component of valley fill alluvium, may contain thick zones of unsaturated material, and as such, also lend themselves to strong consideration as repository environments. This was recently pointed out in a comprehensive appraisal in Science by I. Winograd (1981), which brought to the attention of the scientific and engineering communities the attributes of alluvial environments. Partly for this reason, and also because of the current focus of waste repository investigations at the Nevada Test Site, this report covers the aspects of nuclear waste isolation in unsaturated regimes in alluvial-filled valleys and tuffaceous rocks of the Basin and Range province. Highland and alluvial areas in other arid regions underlain by other rock types may serve equally well or better than those described here. Such areas include ranges and hills of basaltic and other volcanic rock in the Columbia Plateau* and large mesas underlain by sandstone in the Colorado Plateau and Great Basin.

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*The National Academy of Sciences has recommended that a repository site be considered in the unsaturated basalt of the Rattlesnake Hills of the Hanford Reservation, Washington.

Section 2 briefly summarizes the requirements of a repository; Section 3 emphasizes the aspects of waste isolation in the vadose zone of alluvial-filled valleys; and Section 4 similarly discusses the aspects of tuffaceous rocks. The report culminates in a brief appraisal of the attributes of waste isolation in these environments, and recommends research topics to more thoroughly investigate this concept.

2. REQUIREMENTS FOR A WASTE REPOSITORY SITE

The principal requirement of a repository site is that it provide long-term (10^5 years or more) isolation of radionuclides. The engineering and demographic aspects of the site must also be suitable for waste repository construction, operation, and maintenance of long-term integrity.

The primary mechanism for radionuclide escape will be migration of contaminated groundwater. The requirement, at present, is that the groundwater travel time from the repository to the accessible environment, prior to waste emplacement, be at least 1000 years. In order to meet this requirement, hydraulic conditions in the unsaturated zone should provide that:

- The moisture content of the host rock be low and nearly constant.
- The water table be sufficiently below the repository horizon such that the capillary fringe does not encounter the host rock.
- There be essentially no potential for the water table to rise significantly so as to saturate the host rock in the vicinity of the repository.
- A hydrogeologic unit above the host rock be extensive enough to divert downward-infiltrating water beyond the limits of the underground facility.
- The saturated permeability and effective porosity of the host rock are sufficient to furnish a freely draining condition.
- The host rock be of sufficient thickness and extent to maximize groundwater transit time to other geologic units.
- The mineralogical and geochemical characteristics be such that they promote precipitation and sorption of radionuclides and do not increase, but possibly decrease, groundwater mobility. In response to thermal loading, these properties should remain unaltered or be enhanced.
- The response of the host rock to the repository excavation and to waste-induced heating should have minimal effect on the hydrological integrity of the repository.
- Any major geologic discontinuities should contribute to isolation (such as a fault zone acting as an aquitard).

Another possible source of radionculide escape is exhumation, either by natural processes--tectonism, volcanism, and erosion--or by man. Human intrusion could be deliberate or inadvertent. Therefore, the site should offer little resource value, be geologically stable, and be at sufficient depth to make exhumation by man difficult and by erosion highly improbable. Currently, a minimum depth of 300 m is required, but, as pointed out in this report, shallower depths in the unsaturated zone may be acceptable.

Demographically, the site should be in an area of low population density which has little probability of growth and where the probability for future land use changes which could jeopardize the integrity of the repository is small.

Engineering factors include mineability of the host rock and overburden, stability during construction, waste emplacement, and the 50-year retrievability period following, as well as long-term stability to insure isolation. The responses of the rock to thermal loading and seismic disturbances must be within acceptable limits to insure short-term stability and long-term integrity of the site.

A given site may be determined to meet the requirements as that site exists today, but, aside from the changes induced by construction and waste storage, the site is subject to long-term natural processes. It will be necessary to predict those processes for tens and possibly hundreds of thousands of years. For this purpose the assumption will be made that those processes which have been operating on the site during the Quaternary Period will continue to operate. Therefore, it will be necessary to evaluate the hydrogeologic, geochemical, geomorphic, structural, and tectonic stability since the start of the Quaternary Period.

It is not likely that an ideal rock type or an ideal site will be found. Each must be analyzed and evaluated with an open mind, and any conditions, natural or man-made, which detract from isolation must be judiciously weighed against those which favor the site.

3. WASTE ISOLATION IN THE VADOSE ZONE IN ALLUVIUM-FILLED VALLEYS

General characteristics of alluvium-filled valleys are described, emphasizing their geologic and hydrologic characteristics, material properties, and their bearings on considerations of repository construction. Most information available on these topics is from work performed at the Nevada Test Site (NTS), so this area is emphasized in the general discussion. The NTS is considered a type locality for the more specific discussion in Section 3.2.

In the context of this report, alluvium is considered to include rock and debris eroded from interbasin highland areas and transported by slope wash and stream action, to be eventually deposited in the basins and on the adjacent slopes. Prisms of alluvium, in some places up to 1 km thick, made up of material ranging in grain size from clay particles up to boulders, occupy most valleys of the Basin and Range province.

3.1. GENERAL CHARACTERISTICS OF ALLUVIUM-FILLED VALLEYS

3.1.1. Geographic Distribution

The Basin and Range geomorphic province occupies essentially the entire state of Nevada, a good portion of Utah, and portions of eastern California, southeastern Oregon, southern Idaho, western and southern Arizona, southern New Mexico, and western Texas. As described in detail in the following sections, alluvium-filled valleys best suited for nuclear waste isolation in the vadose zone are those where the water table is deep and where a large component of the alluvium is derived from adjacent tuffaceous highland areas.

Alluvial valleys most likely containing appreciable debris from tuffaceous highland areas, and which in some cases may be underlain by tuff beds, occur predominantly in southern and western Nevada (tuffaceous highland areas are shown in Fig. 1). The region is sparsely populated, and the valley areas between the highlands are almost entirely under federal control, primarily by the Bureau of Land Management.

3.1.2. Geologic and Hydrologic Characteristics

The factors which influence the flow path of water from a repository site in unsaturated alluvium include the geologic structures, the thickness of the alluvial prism, the depth of the water table, and the juxtaposition of aquifers and aquitards.

Structural Control of Groundwater Movement

The geologic structure exercises both local and regional control over groundwater movement in the Basin and Range province. Faulting may create paths for groundwater flow through resultant fractures, or hydraulic barriers may be created by fault gouge development along a shear zone. Also, structural juxtaposition of rocks with marked differences in hydraulic transmis-

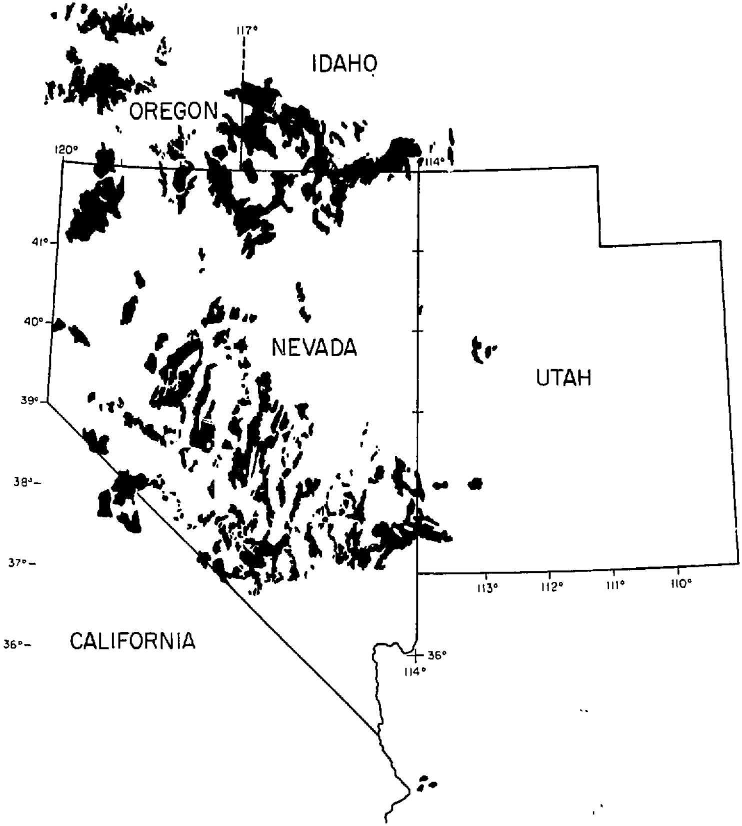

Figure 1. The northwestern portion of the Basin and Range province, showing highland areas underlain by felsic volcanic rocks that contain tuff. Valleys between these highlands may have components of tuffaceous alluvium. [XBL 8112-4898]

sibility results in prominent hydraulic discontinuities (Winograd and Thordarson, 1968).

Along with intergranular flow, groundwater flow through fractures associated with fault zones is an important hydrologic consideration. Brook et al. (1978), describing hydrothermal convection systems, stated: "Fault zones appear to be the most common conduits for movement of fluids in convection systems; locations of many systems seem to be controlled by intersecting structures." Near-surface groundwater moving through alluvium and alluvial fans may percolate into Basin and Range fault systems, especially in zones of fault intersections, become heated at depth in this region of relatively high crustal heat flow, and join in a circulating hydrothermal system (Hose and Taylor, 1974).

Folding and faulting can create barriers to groundwater flow, especially where different lithologic units have highly contrasting transmissibility. Winograd and Thordarson (1968) pointed out that "Deformation of the carbonate rocks" (in south-central Nevada) "results in regions of high transmissibility, but juxtaposition by faulting or folding of thick (relatively impermeable) clastic strata against carbonate aquifers results in prominent groundwater barriers, some of which are more than ten miles long. The apparent hydraulic gradients across the thick clastic aquitards vary from 150 to 1300 ft per mile; by contrast, gradients in the adjacent carbonate aquifers vary from 0.5 to 10 ft per mile. Barriers may also result from gouge developed along major fault zones."

Figure 2 shows the relationship between the hydrology and the geology in a north-south cross section, about 6 miles west of Indian Springs, Clark County, Nevada, southeast of the NTS. The two discontinuities in the potentiometric surface are believed to be due to fault-induced hydraulic barriers. The northern barrier may result from the juxtaposition of Lower Cambrian and older clastic rocks and Ordovician and Cambrian carbonate rocks. The location of the southern hydraulic barrier and the inferred position of the Las Vegas Valley shear zone roughly coincide. This barrier appears to be due to the presence of relatively impermeable gouge developed along the shear zone. It is doubtful that the prominent differences in water level altitude are due to steep gradients within the carbonate aquifer. First, water levels in two wells between the barriers indicate a gradient of 5 ft per mile to the west, and second, pumping tests of these wells indicate transmissibilities of 10,000 to 20,000 gpd/ft. It is doubtful that steep hydraulic gradients could develop in these rocks (Winograd and Thordarson, 1968).

Thickness of Alluvium

The thickness of alluvium is another important factor in the ability of radionuclides to reach underlying aquifers. For location of a waste repository, the alluvium should be thick enough so that burial can be sufficiently deep to: (1) prevent migration of radionuclides to the surface, (2) prevent pulses of water from easily percolating from the surface to the repository, (3) prevent exhumation by natural physical processes, and (4) protect against human intrusion.

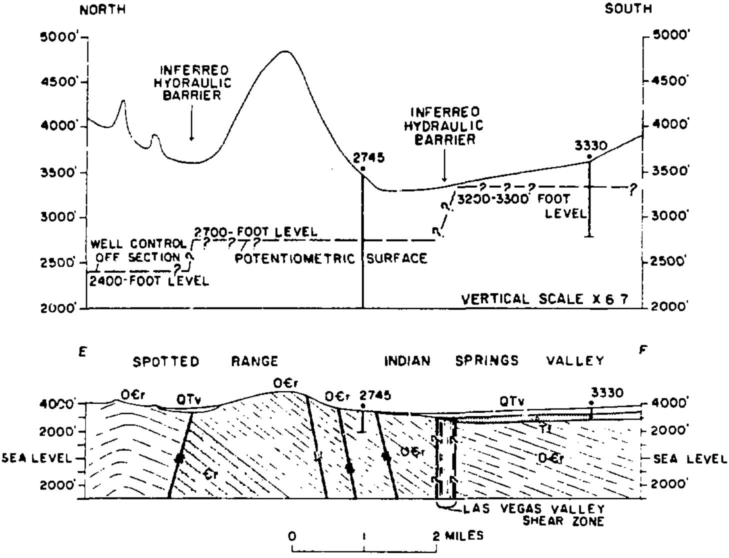

Figure 2. Geologic and hydrologic cross section, southern Indian Springs Valley. QTv, Quaternary and Tertiary valley fill; Tt, Tertiary tuff; O€r, Ordovician and Cambrian carbonate rocks; €r, Lower Cambrian clastic rocks (from Winograd and Thordarson (1968). [XBL 832-8119]

Winograd (1981) suggests burying transuranic radioactive wastes at relatively shallow depths of 15 to 100 m. Construction of a capillary barrier above the wastes at these relatively shallow depths, plus incorporation of other natural and engineered barriers, should circumvent the need for deep burial in alluvium. There should also be sufficient thickness below the repository to provide a long enough flow path to the accessible environment, thus allowing sufficient time for radioactive decay and insuring that there be sufficient surface area for adsorption. The alluvium should therefore be thick enough to isolate wastes from the biosphere above and, to some extent, from the water table below.

In the Basin and Range region, up to 300 m of alluvium occurs above the water table (Smyth et al., 1979) with total thicknesses in many cases exceeding 1000 m. These deposits have been derived from erosion of surrounding highland areas and are still agrading (Geotechnical Engineers, Inc., 1979). Ranges continue to rise, providing for a long-term increase in the thickness of unsaturated alluvium as well as for increasing aridity of adjacent basins. Figure 3 illustrates an idealized Basin and Range valley where approximately 300 m of alluvium overlies tuff, which in turn overlies Paleozoic carbonate rock.

The configuration of the basin is an important factor in determining the thickness of alluvium. Though the basins are generally shallow at their upper ends and deepen as the valley broadens, gravity and seismic surveys have indicated that cross faulting has caused deep sub-basins at several locations along the axes of valleys. Other factors influencing the thickness of alluvium include the climate, how easily the source rocks are eroded, and the rate that the valley subsides during deposition of alluvial material.

Depth to Water Table

In isolating wastes in the vadose zone, a deep water table is an asset. Areas in the Basin and Range have extremely thick vadose zones. The regional water table beneath Yucca and Frenchman Flats at the NTS lies from 150 m to 600 m below the surface (Geotechnical Engineers, Inc., 1979), while the depth to water under peripheral valleys, such as parts of Emigrant and Indian Springs Valley, is much less, as little as 0 to 70 m (Winograd and Thordarson, 1968).

Water transporting radionuclides from a breached canister may percolate to the water table; therefore, the amount of adsorption of radionuclides and time spent reaching the water table are prime concerns. The length of the flow path to the water table, as well as conditions above the water table, such as thickness of aquitards and amounts of clays and zeolites, all play important roles.

As is typical of arid regions, very little water reaches the water table vertically through the overlying vadose zone. Most often, water recharge is laterally from upland areas. Precipitation falling directly on porous alluvium of the valleys may not infiltrate more than a few meters, while precipitation falling on outcropping or thinly covered fractured rocks on the flanks of the valleys may eventually reach the water table by vertical and lateral percola-

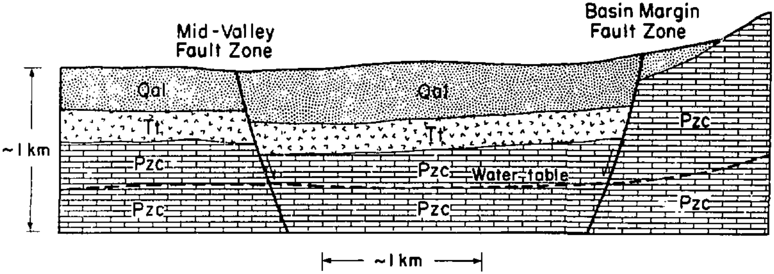

Figure 3. Schematic geologic cross section through an idealized Basin and Range valley, showing alluvium (Qal), overlying tuff (Tt), and Paleozoic carbonate rock (Pzc), with the water table at depth in the Paleozoic rock (based on Winograd, 1981). [XBL 821-1621]

tion over several kilometers (Geotechnical Engineers, Inc., 1979). Depth to the water table then is predominantly influenced by the stratigraphy and the transmissivities of the various units, the structure of the area, and the amount of precipitation and evaporation.

Aquifers and Aquitards

The nature and relative position of aquifers and aquitards determine the length of the flow path from the repository to the point of discharge and the flow rate of water percolating down and laterally through the alluvium. The flow path and permeability determine the transit time of the water, critical in allowing radionuclide decay. An ideal stratigraphic setting for a repository would be alluvium underlain by an aquitard, in turn underlain by an aquifer. A tuffaceous aquitard underlying the alluvium will adsorb radionuclides as well as increase the transit time of the contaminated water. Even though it may have relatively high porosity, a zeolitized nonwelded tuff will have low interstitial permeability and will be a good sorber of radionuclides. On the other hand, welded tuff, where permeability is controlled by fractures, may be considered an aquifer in a strict hydrologic sense, even though radionuclide sorption may be considerably less than in more permeable, but zeolitized nonwelded tuff. The slow passage of water through the interstices of nonwelded tuff, given the proper thermodynamic conditions, may allow the formation of clay minerals and zeolites, as would the alteration caused by water passing through the fractures in more strongly welded tuff (Surdam, 1979).

In the event of a future pluvial period, the aquifer should have a large enough capacity to handle the increased load so that there is not a marked rise in the water table, which would flood the repository.

3.1.3 Climatological Considerations

A major change in climate could have a significant effect on groundwater flow around a repository. Comparison of present and past climates may be used as an indicator of future climatological conditions.

A future pluvial climate will change the local and regional groundwater patterns with the accompanying effects on the isolation of waste: a rise in the water table might reduce the distance of groundwater flow from the repository to the discharge point, and an increase in recharge could result in increased groundwater velocity and therefore shorter residence times for dissolved radionuclides. An increase in groundwater recharge during a pluvial period might cause water to come into contact with the waste canisters more frequently, thereby increasing the probability of canister corrosion and subsequent leaching of the waste. (This problem could be partially mitigated by engineering measures; e.g., installation of drainage systems to conduct water around waste canister sites.) Also, a higher water table would increase the likelihood of future residents drilling for water. The effects of a rise in the water table on flow paths are illustrated in Figure 4.

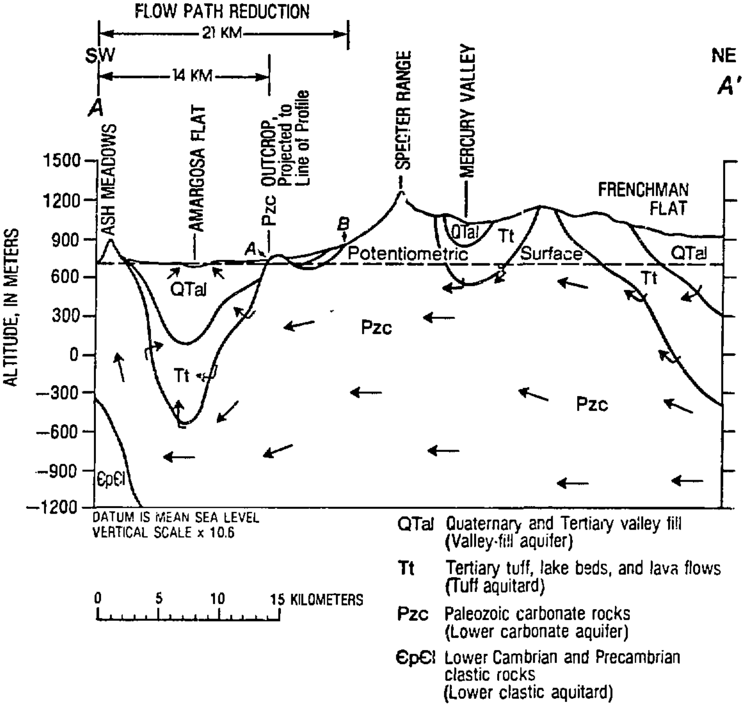

Figure 4. Diagrammatic section illustrating effects of possible past or future pluvial-related water table rise on length of groundwater flow path from Frenchman Flat to points of natural discharge at Ash Meadows in the Amargosa Desert, Nevada. Water level rises of 40 and 150 m would initiate discharge from the lower carbonate aquifer at points A and B, respectively 14 and 21 km northeast of modern spring lineament; arrows depict groundwater flow (from Winograd and Doty, 1980). [XBL 832-8110]

Evidence of past hydrologic conditions, such as tufa deposits, calcitic veins, strand lines marking former stillstands of lakes, clay mineralogy, and fossil seeds and spores in packrat middens are useful in estimating future conditions.* These factors indicate that the climate of the Great Basin was significantly wetter at times during the Pleistocene Epoch. During the middle late Wisconsin time (40,000 to 10,000 years ago) some topographically closed basins in the southern Basin and Range contained lakes. Juniper grew at elevations 600 m lower than at present.

These conditions of lake formation and growth of woodland plants were due to a combination of increased rainfall and reduced temperatures (Winograd and Doty, 1980). In a study of a pluvial lake in Spring Valley (east-central Nevada), Snyder and Langbein (1962) estimated that during the last pluvial period, the annual precipitation was 51 cm, compared to today's 31 cm, and evaporation was 79 cm, compared to the present 110 cm. Mifflin and Wheat (1979) state that in the northern two-thirds of Nevada (the area that had the most pluvial lakes), the mean annual temperature was 3°C lower and precipation 65% higher than at present.

Water infiltration rates were probably not more than twice those of today (a few mm per year) and, coupled with increased transpiration from a denser vegetation cover, would have resulted in vertical percolation not significantly greater than at present. Therefore, if future pluvial periods are similar to those of the Pleistocene, the wetter climate should have little effect on the suitability of these sites for waste isolation. Continuing uplift of the Sierra Nevada, which borders the Basin and Range province on the west, may result in increasing aridity of the climate as the Sierra more effectively blocks the easterly flow of moist air from the Pacific.

3.1.4 Geologic Hazards

The geologic hazards of predominant concern to the concept of a repository at relatively shallow depths in alluvium in the Basin and Range province are seismicity and volcanism. The tectonic setting of the region encompassing a repository site is the principal factor in determining its seismicity, as well as the long-term considerations of faulting and subsidence.

The frequency of volcanic events may be determined from the historical record and from age dating of volcanic rocks. The type and location of the most recent volcanic activity in the Basin and Range province are somewhat restricted. The most recent volcanism has occurred on the western margin of the province, exemplified by rhyolitic volcanic activity in the vicinity

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*As reported in the review meeting and quarterly reports of the Nevada Nuclear Waste Isolation Investigations, matrix fines of alluvium are being examined to see if a mineralogical signature can be identified that would indicate the position of the water table during past pluvial periods. Definitive water table positions have not yet been established by this procedure, nor is there yet definitive information on paleo water table positions based on studies underway of zeolites and clay minerals in presently unsaturated tuff (R. Spengler, private communication, April 1982).

of the Long Valley caldera and the Inyo-Mono Craters. Rhyolitic and basaltic volcanism are evident on both the eastern and western margins of the province, while the most recent activity away from the margins is predominantly basaltic. The most recent large explosive episode, associated with the Long Valley caldera, occurred approximately 0.7 m.y. ago (Bailey et al., 1976).

The effect of local and regional seismicity on underground workings in alluvium involves considerations similar to those for surface facilities: the magnitude of the earthquakes, the distance from the repository to the epicenter, the regional geologic setting, and the nature of the materials encompassing the repository. The Basin and Range province contains several seismically active zones, and the western portion of the region is characterized by relatively high seismic hazard (Fig. 5).

An assessment of earthquake damage to underground facilities by Pratt et al. (1978) suggests that in general the deeper the underground workings, the less their response to a given earthquake, compared to surface conditions. This is largely attributed to attenuation of the high-frequency ground motions with depth below the ground surface. Vertically oriented workings--shafts and wells--are less prone to damage than are horizontal workings. The primary concern, then, aside from the obvious one of not locating the site astride an active fault, is shaking, which might disrupt support facilities on the surface. However, surface structures are very short lived compared to the repository. The effects of earthquakes on these structures are of principal concern during the period of repository operations rather than during the period of long-term isolation.

Long-term subsidence of valleys due to faulting must be taken into account when considering the effects of tectonism on a prospective repository site. The Basin and Range region is undergoing crustal extension and is characterized by mountain blocks separated by high-angle normal faults, resulting in a horst-and-graben structural configuration (such a pattern of faulting is illustrated in the simplified geologic map, Fig. 6).

As most Basin and Range region faults remain active, the valleys (grabens) are sinking relative to the adjacent mountain blocks. This may be an advantage in considering a site in alluvium. Winograd (1981) proposed burying wastes in Sedan Crater, Yucca Flat, Nevada Test Site, which is 1200 m east of the north-south-trending Yucca Fault. The Sedan Crater occupies a tectonically induced depositional environment, since the east side of the Yucca Fault is downthrown. The valley fill just to the east of the fault is 75 to 380 m thicker than the fill west of the fault. Winograd proposed that as subsidence continues in response to east-side-downward movement along the Yucca Fault, wastes in the Sedan Crater would be buried deeper. Even if the fault is no longer active, material will continue to erode from surrounding uplands to add to the valley fill. Winograd (1981) also points out that if subsidence eventually lowers wastes to the water table at Yucca Flat, the time required would be great enough so that substantial decay of radionuclides would have occurred. Subsidence in the Sedan Crater-Yucca Flat area is a site-specific concern. Measurements and calculations of rates of subsidence, erosion, and sedimentation rates should be made for any candidate site in the Basin and Range region.

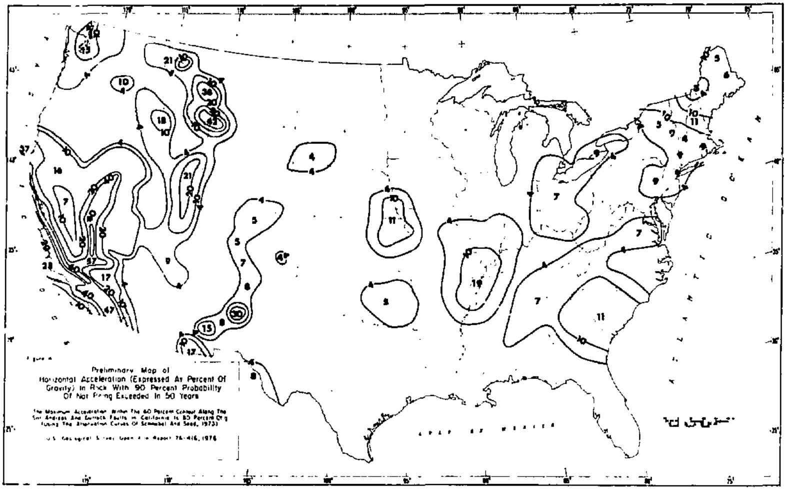

Figure 5. Relative seismic hazard in the conterminous U.S. as indicated by horizontal acceleration (expressed as percent of gravity) in rock with 90% probability of not being exceeded in 50 years (after Algermissen and Perkins, 1976).
[XBL 797-10475]

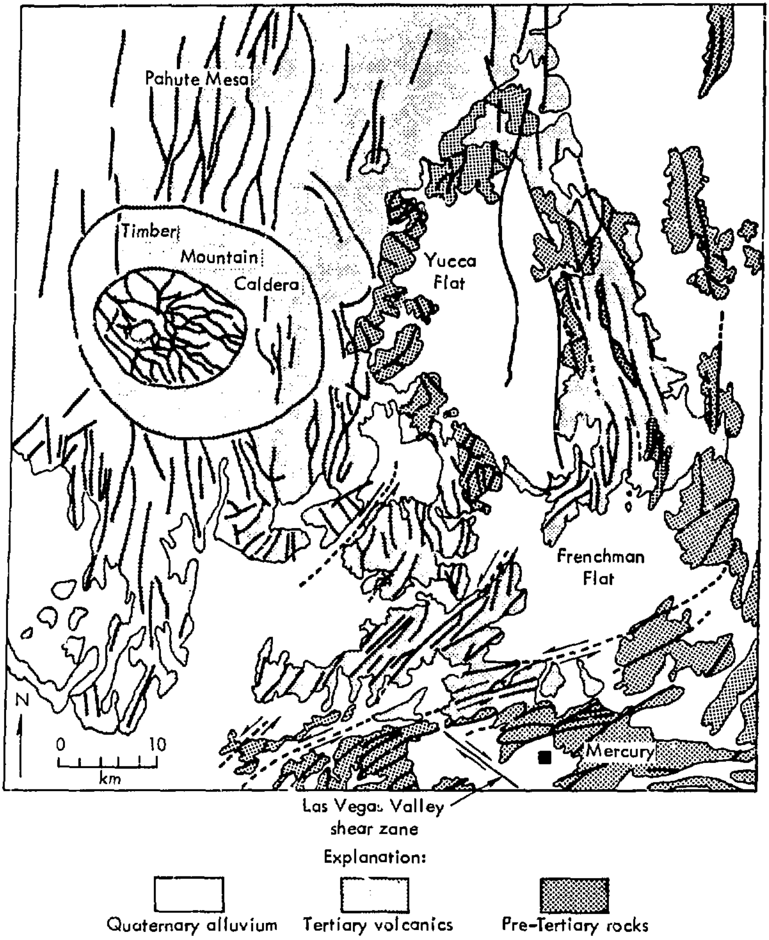

Figure 6. Map showing pattern of Basin and Range faults in Nevada Test Site and vicinity (after Ekren, 1968, from Borg et al., 1976). [XBL 832-8111]

3.1.5 Rock Properties

The hydrologic, chemical, and physical properties of the rocks and alluvium at a prospective repository site must be examined to understand future interactions between radioactive wastes and the geologic environment.

Hydrologic Properties

The hydrologic properties of unsaturated media are not entirely dependent on porosity and permeability. Hydraulic conductivity in unsaturated alluvium generally decreases significantly with decreasing water content and increasing negative pressure potential (Borg et al., 1976; Geotechnical Engineers, Inc. 1979). This situation can be even more complex in a medium with varied particle size, as in a mixture of sand and clay.

Moisture content of unsaturated sand is controlled chiefly by capillarity (a function of soil structure), while the moisture content of clay is controlled by adsorption (a function predominantly of the types of clay minerals present and groundwater chemistry). These factors make it difficult to predict the soil-water retention characteristics of a mixture of sand and clay (Geotechnical Engineers, Inc., 1979); however, experiments are presently being conducted in alluvium by the U.S. Geological Survey to better understand these characteristics (these experiments are described briefly below).

It is difficult to generalize the hydrologic properties of alluvium because the grain size and depositional characteristics are so variable. The porosity and permeability of alluvium vary with particle size. Shape, packing, size distribution, and cementation of particles also are important factors in determining porosity and permeability. Depositional mode largely controls these features, especially size characteristics and particle packing.

The hydrologic properties of unsaturated alluvium are extremely variable. From laboratory measurements of desert soils, Mehuys et al. (1975) point out that hydraulic conductivity of alluvium, containing a wide range of particle sizes, may vary over seven orders of magnitude, from 10^{-8} to 10^{-1} cm/h, as volumetric water content (the volume of water divided by the bulk volume) varies from 0.05 to 0.3.

The relation between hydraulic conductivity, water content, and pressure potential must then be determined experimentally for each medium. While laboratory experiments can provide general information on hydraulic processes in unsaturated rocks, in situ experiments are necessary for a detailed evaluation to avoid the inevitable disturbances that occur during sampling and during transport to the laboratory.

As reported recently at the review meeting of the Nevada Nuclear Waste Storage project (Las Vegas, August 1981), active research in the hydrological properties of the alluvium of the Nevada Test Site is being conducted by the Water Resources Division of the U.S. Geological Survey. Topics under study include the moisture flux in the alluvium, its permeability, and the effect of the tortuosity of flow paths on the permeability. A 12-m-deep caisson has been installed in Jackass Flat in which the alluvium's moisture content and moisture flux are being measured. The air permeability of alluvium and tuff is measured by recording the change in pressure in pore air in response to atmospheric pressure changes. The effect of the tortuosity of flow paths in alluvium on gas permeability is being determined by measurements employing tracers. Mapping is planned to discern the thickness and lithology of the alluvial unsaturated zone.

Chemical Properties

The chemical properties of the alluvium and the groundwater will affect interactions between isolated wastes and material near the waste canisters, as well as between radionuclides moving from the repository and material in the far-field environment. Adsorption of radionuclides by clay minerals, predominantly montmorillonite and illite, and zeolites (predominantly clinoptilolite) is a principal retardant to radionuclide migration. The sorptive capability of alluvium then depends on the presence of these minerals and the Eh and pH of the groundwater. The capability of a material to adsorb radionuclides is generally expressed by its distribution coefficient, K_d, defined as:

$$\frac{\text{Amount of radionuclide in solid phase/weight of solid}}{\text{Amount of radionuclide in liquid phase/volume of liquid}} .$$

Borg et al. (1976) compiled a list of distribution coefficients for NTS rocks for strontium and cesium. Alluvium from central Nevada had K_d's for Sr from 48 to 2454; for Cs from 121 to 3165. Tuff from the NTS exhibited K_d's for Sr from 260 to 4300 and for Cs from 1020 to 17,800. Variations reflect differences in rock samples and differences in solutions. (The sorptive properties of tuff and the effect of heating on some zeolite minerals are discussed in Section 4.1.3.)

Laboratory measurements do not always successfully predict the sorbtive behavior of radionuclides in the alluvial environment. For example, Coles and Ramspott (1982), in a field study of the migration of radionuclides in groundwater in tuffaceous alluvium at the NTS, observed that ^{106}Ru migrated at about the same velocity as ^{3}H from the site of an underground explosion to a pumped well 91 m away. Batch sorption tests predicted that Ru would move only 0.03 to ~3 m during the 15 years of observations. Coles and Ramspott (1982) concluded that batch sorption K_d values may be valid for single-valence elements if sorption isotherms are known, but the chemical speciation of multivalent elements like Ru must be known to predict their behavior in a groundwater environment.

However, whatever the variations, the presence of sorbing minerals in alluvium with a large component of tuffaceous material provides a good environment for chemical retardation of radionuclides.

Thermal Properties

The ability of alluvium to dissipate the heat generated by the waste package is one of the primary concerns in the design of a repository. Maximum temperature and induced thermal stresses for a given areal thermal loading depend on the thermal properties. For systems where heat conduction is dominant, the properties of specific heat capacity, thermal conductivity, and thermal expansion are important for calculation of induced thermomechanical stresses. These properties are summarized in Tables 1 and 2.

Compared with other rock types, alluvium has a low thermal conductivity, especially under partially saturated conditions. As indicated in Table 1, under saturated or nearly saturated conditions, the range is 0.9 to 2.0 W/m°C. The higher value compares with hard rocks such as granite, 2.5 W/m°C, and basalt, 1.5 W/m°C. In a partially saturated or dry state, however, the thermal conductivity can be considerably reduced. As a lower bound, 0.2 W/m°C has been measured for dry alluvium, 0.5 to 0.8 W/m°C for unsaturated unconsolidated alluvium, and 1.0 to 1.2 W/m°C for indurated unsaturated alluvium (Smyth et al., 1979).

The marked change in thermal conductivity with degree of saturation is due to the relatively large volume of water or pore space present in most alluviums, particularly alluvium that is poorly indurated (or unconsolidated). Pore volume or porosity can range to 30% or more. If the rock is dry, the pore space is filled with air, a poor thermal conductor in comparison to water (ratio of thermal conductivities, $K_{water}/K_{air} = 25$; Carslaw and Jaeger, 1959).

Dependence of thermal conductivity on degree of saturation is rock specific and site specific. Many models have been prepared for estimating the effective conductivity of a rock/water mixture. These models are briefly discussed in the Appendix. The effects on thermal conductivity of the drying of saturated or partially saturated alluvium because of heating by the repository (and the ramifications of drying on the allowable thermal loading) are discussed in Section 3.1.6.

Specific heat is also dependent on the degree of saturation and porosity. Although very little information on the specific heat of alluvium was found, values on the order of 1000 J/kg°C (similar to felsic rocks) are used in thermal calculations (Smyth et al., 1979).

Data on thermal expansion are also equally scarce, and actual measurements were not found. Considering the high porosity and significant fraction of hydrous minerals contained in many alluviums derived from tuffaceous environments, it is reasonable to expect a negative thermal expansion or contraction with drying and mineralogical phase changes on heating above 100°C. Relations between porosity and thermal expansion would probably be similar to those for tuff (see Fig. 19, Thermal Properties, Section 4.1.3).

Table 1. Thermal conductivities of alluvium.

Location	Number of holes	Method of measurement	Range of mean value[a] (W/m°C)	References
Black Rock Desert[b]	12	Downhole probes	0.91-1.14	Sass et al. (1979b)
Black Rock Desert[b]	4	Chips[c]	1.19-1.41	Mase and Sass (1980)
Buffalo Valley[b]	2	Cores[c]	0.98-1.42	Sass et al. (1976a)
Grass Valley[b]	7	Cores or chips[c]	1.21-1.81	Sass et al. (1976a)
Saline Valley[b]	8	Cores or chips[c]	1.51-2.00	Mase et al. (1979)

[a] Harmonic mean value of thermal conductivity for each hole.

[b] In situ measurements in the Black Rock Desert were in holes drilled in fine-grained unconsolidated lake sediments, containing abundant clay and some sandy layers a few centimeters thick (Sass et al, 1979a). Cores and chips measured from the western arm of the Black Rock Desert and from Buffalo, Grass, and Saline Valleys consisted predominantly of silty alluvium with varying amounts of sand and clay.

[c] The thermal conductivity of the rock is deduced from those of solid rock and water phases by the geometric mean model:

$$K = K_{\text{rock}}^{(1-\phi)}\, K_{\text{water}}^{\phi} ,$$

where the porosity ϕ is assumed to be 0.3. The measurements on cores and chips are made at saturated conditions (J. Sass, private communication, 1981).

Table 2. Thermal and mechanical properties of alluvium.

Specific heat: 1000 J/kg°C (estimated)[a]

Thermal conductivity: 0.2-2.0 W/m°C[b] (depending on degree of induration and saturation)

Thermal expansion: no data

Unconfined compressive strength:[c]
Average 2.2 MPa below 60 m depth,
varies with depth from 0.5 to 2 MPa over the upper 60 m

Moisture content (estimated range): 5-15%

Average dry unit weight: 1.6 g/cm[c]

Internal friction angle: ~ 45°[d]

Mean seismic velocity (above water table): 1789 m/sec[e]

Young's modulus (estimated range): 5-10 GPa

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[a] Smyth et al. (1979).

[c] Smyth et al. and Table 1.

[c] Pack and Skinner (1976) (boulder gravel comprised of fragments ranging from 30 cm diameter to sand, silt, and clay).

[d] Strohm et al. (1964) (Sedan Crater alluvium, northern Yucca Flats).

[e] Ramspott and Howard (1975) (mean value of NTS alluvium).

Mechanical Properties

A knowledge of mechanical properties is important for the design of the repository, evaluating construction methods and costs, and determining the long-term integrity of the underground openings. In particular, it is necessary to know the modulus of elasticity or of deformation to estimate the thermally induced stresses. The strength properties and the characteristics of the rock mass (i.e., including discontinuities) must be known to evaluate allowable thermal loading, depth of the repository, and stability of the underground openings. With respect to underground construction considerations, very useful information is often obtained from people with experience in constructing openings in similar environments.

Mechanical properties of alluvium, such as modulus, cohesion, friction, grain size distribution, and uniformity in extent can be extremely variable. They depend on the mineralogical composition, the geologic environment at the time of deposition, and the influence of subsequent processes such as consolidation, compaction, and cementation. It is important to note that alluvium is often classified as soil, e.g., cohesionless sands or gravels and cohesive clays, or weak rock when poorly indurated or cemented.

The construction procedures and design of stable underground openings and cut slopes strongly depend on the mechanical properties of the material encountered. To restrict the scope of the following discussions, only the properties of the alluvial fill at the NTS will be considered. They are summarized in Table 2.

From the numerous test wells or boreholes, shafts, and tunnels constructed in the NTS valley fill, it is possible to describe the properties of the Quaternary alluvium in general terms. Major clastic constituents include fragments of welded and nonwelded tuff as well as Paleozoic carbonate rocks. Fragment sizes range from boulders more than one foot in diameter to sand, silt, and clay. The size gradation is variable. At the site of a 550-ft-deep shaft in northern Yucca Flat, the material was classified as a boulder gravel according to the Unified Soil Classifiction (Pack and Skinner, 1976). At other locations a predominance of silty sands and gravelly sands has been reported (Strohm et al., 1964).

Matrix materials influence the degree of induration or cementation. These include calcite (often as secondary cement caliche), clays, zeolites, cristobalite, and authigenic feldspars (Symth et al., 1979). It appears that a large proportion of the alluvial material at the NTS is cemented.

Drill cuttings and borehole logs from the 750-ft-deep exploratory hole for the shaft in northern Yucca Flat revealed few if any cohesionless zones, except possibly small interbedded zones near the surface to a depth of 125 ft (Pack and Skinner, 1976). Cores were found to be extremely fragile, easily disturbed by the process of drilling and by the drilling fluid, especially water, which destroyed the cementation. In general, it is very difficult to obtain undisturbed samples of weak rock, particularly when the average grain size is a significant proportion of the diameter of the core barrel. Consequently, the cores do not properly represent the ground conditions.

From the intact cores that were obtained at the shaft site, a total of 42 unconfined compressive strength tests were performed. The results revealed an average strength of 315 psi (2.2 MPa), evidence of significant cementation. Strengths were reasonably consistent (standard deviation of 80 psi) except for the first 200 ft, along which the strength increased with depth from 75 to 300 psi. Average moisture content of all cores was 10.2%, and average dry unit weight was 120.6 pcf (1.93 g/cm^3).

Triaxial tests were not performed on the cores obtained from the site; however, tests on alluvium from the general area indicated an internal friction angle of nearly 45° or less (Strohm et al., 1964).

Indirect evidence from numerous vibroseis seismic surveys and downhole seismic logs tends to substantiate the relative competence of valley fill at the NTS as compared with cohesionless sediments. A statistical treatment of these data (Ramspott and Howard, 1975) indicates a mean seismic velocity of 1789 m/sec (5870 ft/sec) for alluvium above the groundwater table in Yucca Flat, measured in the vicinity of the working point (the center of explosive energy of the nuclear device). An average velocity between the working point and ground surface is 1340 m/sec (5395 ft/sec). These velocities are fairly high compared with cohesionless materials. For example, the velocity in clean sand above the water table typically ranges between 300 and 800 m/sec depending on density and moisture content. It is reasonable to assume that a significant degree of induration is necesary to achieve the higher velocities recorded. It appears that the alluvium is similar to a weak conglomerate as suggested by the velocity range for typical sandstones, 1400 to 4200 m/sec.

Other soil mechanics property tests have been performed on Diagonal Line alluvium (Heard and Stephens, 1970) and Merlin alluvium (Bonner et al., 1972); however, most of these tests were carried out at high confining pressures far in excess of the stresses anticipated in the vicinity of a repository.

Tests on the Merlin alluvium indicate a strong influence of water content on strength (Bonner et al., 1972) as was demonstrated in drill holes employing water for drilling fluid (Pack and Skinner, 1976). This large loss of strength with increasing water content, as shown in Figure 7, is possibly the result of loss of cementation by solution, a reduction of interparticle friction, and the effect of increasing pore pressure. With respect to this last point, not enough information on the test procedure was given to determine if the samples were fully drained or undrained, although the latter appears to be the case. It should be noted that the triaxial tests whose results are illustrated in Figure 7 were conducted under relatively high confining pressures compared to pressures considered for a typical repository environment.

No data on the elastic modulus of NTS alluvium was found. It is reasonable, however, to assume that it is strongly dependent on porosity in

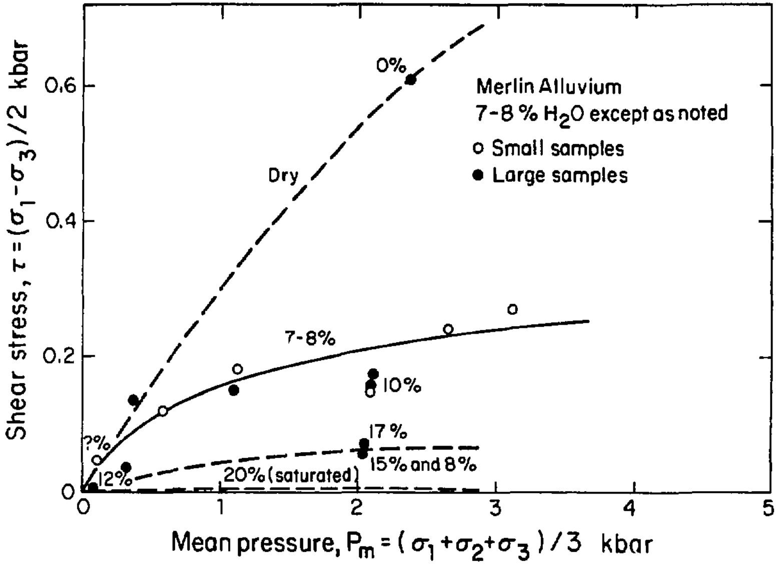

Figure 7. Failure envelopes for alluvium with varying water content (after Bonner et al., 1972). [XBL 826-2299]

much the same manner as tuff (see Fig. 21, Mechanial Properties, Section 4.1.3). Similarly, no information was found on the effect of temperature on mechanical properties. Trends expected in tuff are discussed in Section 4.1.3.

3.1.6. Design and Construction Considerations

Preliminary design considerations include investigations of thermal response for a given areal loading. The dependence of repository temperature on a range of thermal conductivites, as well as on different waste forms, repository depths, and repository sizes, are discussed in the Appendix and are briefly summarized in this section.

A repository located above the water table in alluvium can be constructed by one of two possible methods. If a relatively shallow depth of canister burial is deemed permissible, involving the arguments presented by Winograd (1981), an open excavation from the surface is possible. If cover in excess of 100 m is required, the economics strongly favor a mined underground repository. Both construction methods will be explored in this section, and the advantages and disadvantages of each method will be compared.

Thermal Response

As previously discussed, the thermal conductivity of alluvium has a large range, depending on degree of saturation and the specific characteristics of the material. The influence of thermal conductivity on the repository temperature increase is clearly illustrated in Figure 8. Calculations were based on a repository depth of 150 m, an area of 2000 acres (radius 1605 m), and a thermal loading of 40 kW/acre with 10-year-old spent fuel. The range of thermal conductivities shown is that which could be expected for dry poorly indurated alluvium (0.5 W/m°C) to saturated indurated alluvium (1.5 W/m°C). Peak repository temperature increases are 130°C and 75°C, respectively, and occur 58 years after emplacement of the waste package. It is emphasized that these maximum temperatures are an average for the whole repository; the maximum local temperatures will strongly depend on the emplacement geometry and thermal loading per canister.

Repository temperatures in excess of 100°C can result in accelerated drying of saturated or partially saturated alluvium and a corresponding decrease in thermal conductivity. Given a material with 30% porosity, a saturated thermal conductivity of 1 W/m°C, and a geometric mean model for the dependence of conductivity on water saturation (see Appendix for details), the increase in repository temperature with reduced water content was determined. Figure 9 presents the temperature rise, ΔT, normalized with respect to the temperature increase for a fully saturated (wet) or dry alluvium. As indicated, the repository in dry alluvium can have a temperature increase of 1.6 times that of a repository in saturated material.

The ramifications of drying saturated or partially saturated alluvium have led to a consideration of the areal thermal loading needed to keep the

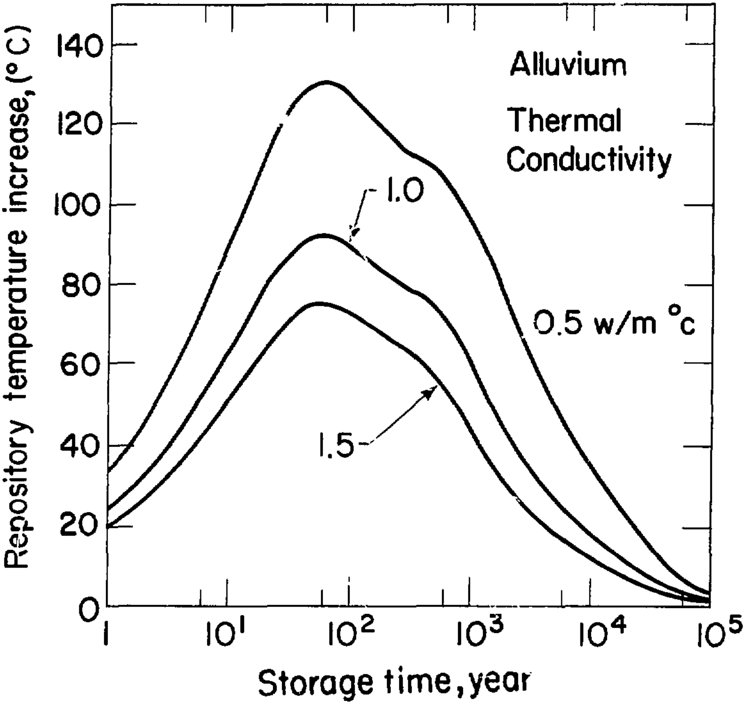

Figure 8. Effects of thermal conductivity on alluvial repository temperature. [XBL 825-1391]

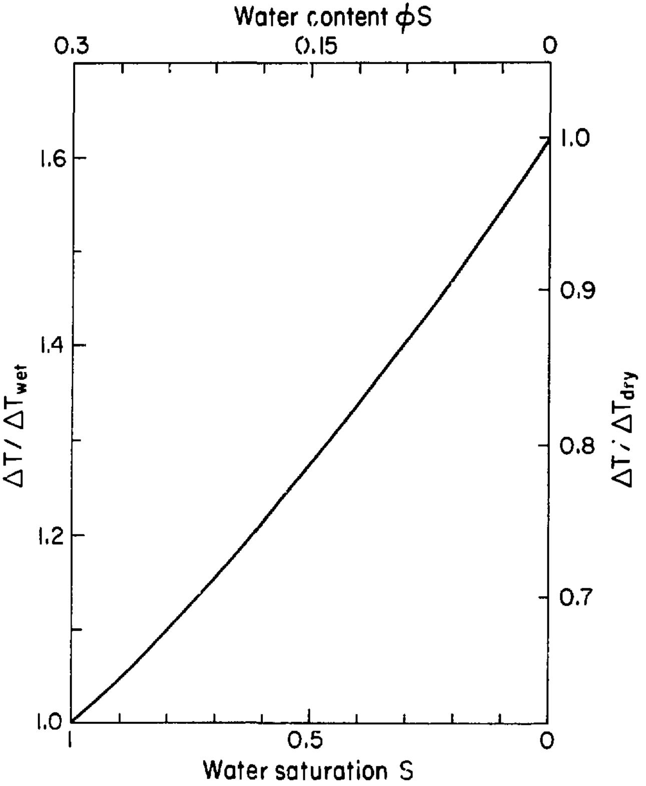

Figure 9. Variation of temperature rise with water saturation. [XBL 8111-4883]

maximum repository temperature at or below 100°C. For a thermal conductivity of 1 W/m°C, this is 33 kW/acre, and for a dry alluvium of conductivity 0.38 W/m°C, loading would be limited to 20 kW/acre, assuming an ambient temperature of 25°C.

Results presented above and in Figure 9 are conservative, as they are based on constant material properties for all the material surrounding the repository and do not consider the beneficial effect of heat transport by vapor diffusion. In reality, the properties will vary with distance from the repository heat source, and only the ground nearest the repository openings will experience a large decrease in thermal conductivity due to drying. To establish a realistic areal thermal loading for alluvium it is necessary to be site and material specific and to employ improved predictive models with variable thermal properties.

Other factors affecting repository temperature are waste form and repository depth, while repository area has little effect on temperature. Disposal of reprocessed waste results in a maximum temperature increase of 75°C 35 years after emplacement, compared with 93°C for spent fuel, assuming a thermal conductivity of 1 W/m°C and a thermal loading of 40 kW/acre. Varying the repository depth from 150 to 600 m has a negligible effect on the maximum temperature, but results in a reduction in temperature for repositories at shallower depths after 300 years of storage (see Fig. A5 in the Appendix).

Surface Excavation

Considering the size of a typical repository, on the order of 2000 acres, the surface excavation would have to be implemented on a massive scale, similar to large open pit mining operations. Although open pits have been excavated to depths of 1000 m and more, the ore body is relatively localized compared to the lateral extent of a typical repository. Furthermore, a deep pit requires a large capital investment and a 20- to 30-year development period.

Equipment employed in large-scale operations often consists of 23-cubic-yard shovels and a fleet of 170-ton trucks. A large operation can remove 400 thousand tons of material per day at a cost of $0.50 to $1.25 per ton. From the strength data, it appears that it would be necesssary to lightly blast the alluvium prior to excavation. This would decrease the wear on machinery and increase production.

Slope angles of the open excavation depend on the material properties and depth. On the basis of a friction angle of 45° or less, slopes on the order of 30° to 40° are deemed reasonable, with decreasing angle for increased depth.

The required area for the repository should be similar to that of an underground mined repository if the thermal loading per acre is limited by the adverse influence of heat on the sorptive properties of the alluvium. This appears to be the situation, and a 250°C maximum temperature is suggested (Smyth et al., 1979; Smyth and Sykes, 1980). If higher temperatures are tolerable or a lower-power waste form is involved, it should be possible to reduce the area of the repository and stack or layer the rows of canisters at several horizontal levels within the excavation. This would significantly improve the economics of an open excavation compared to a mined repository.

Major advantages of a repository in a surface excavation are the relative ease of canister placement and the installation of engineered barriers and backfill. Standard earth-moving equipment can be used to install sorptive barriers and large-scale filters near the canisters to retard the infiltration of soil moisture toward the repository (Winograd, 1981). Methods for quality control assurance are also well developed.

Underground Excavation

Two of the major factors influencing the stability of underground openings in alluvium are the cementation or degree of induration that can be assumed and the depth of the repository openings. In general, cohesionless soils tend to run or ravel into the excavated opening if the tunnel or shaft is left unsupported. Consequently, the headings of tunnels often employ a shield to provide immediate temporary ground support; a continuous permanent support system is installed prior to advancing the tunnel face.

The loads which develop on the support system are usually not very large, particularly if the soil is dense and has a significant angle of friction (in excess of 40°). For shafts, the pressure on the support tends to increase until a depth equal to about five times the shaft diameter is reached, after which the load remains essentially constant due to the development of a significant ground arch which carries the majority of the external ground pressure. The maximum support pressure, Ph, is about

$$Ph = 0.4\gamma r,$$

where γ is the unit weight of the soil and r is the radius of the shaft (Proctor and White, 1977). For a typical 20-ft-diameter (6.1-m) shaft, this is only 1 KSF (0.05 MPa).

For tunnels constructed in dry, dense sand, model studies have shown that the support loads are related to the amount of ground yield associated with the tunneling operation, or how quickly and effectively the support can be installed. Loads were also shown to be a function of the size of the opening, but largely independent of the depth. The range of vertical support pressure, Pv, depending on the amount of yield, is:

$$Pv = (0.27 \text{ to } 0.60)\times(B + H),$$

where B is the tunnel width and H the height (Terzaghi, 1946). Again, this pressure is not large and ranges between 1.2 and 2.7 KSF (0.06 and 0.13 MPa) for a typical-sized repository room opening.

It should be emphasized that the cohesionless soils discussed above are not typical of the alluvium at the NTS, but their behavior illustrates an upper bound or worst condition for support pressures and construction procedures. Shaft and tunnel experience in the alluvium reveals the stabilizing influence of the cementing materials present in the alluvium. Even relatively small amounts of cohesion can eliminate the need for immediate support provided by a shield and significantly reduce required permanent support pressures.

A most revealing case history is that of a 168-m-deep (550-ft) shaft with rectangular cross section 2.7 x 4.3 m (9 x 14 ft) serving lateral drifts excavated in the alluvium of northern Yucca Flat (Pack and Skinner, 1976). Although the shaft was designed for light- to medium-support loads, with steel sets spaced on 6-ft centers and continuous timber lagging of the sidewalls, very little, if any, ground pressure was observed. Strain measurements on the steel sets indicated maximum ground pressures of less than 0.07 KSF. At no time during or after construction was the timber lagging observed to be under load. No loose or running ground or significant spalling or sloughing of the shaft walls was encountered during construction. In fact, the 2.4 x 3.0 m (8 x 10 ft) horizontal drift, excavated for several hundred feet from the base of the shaft, was left unsupported and presented no stability problems.

It is interesting to note that those areas with potential problems, as suggested by the weak cores and borehole logs, presented no problems. To the contrary, it was necessary to use light blasting to maintain satisfactory progress.

There are other examples of tunnels and shafts in the alluvium suggesting similar good tunneling conditions. In another site, the opening was described as behaving like excavations in tuff with mining costs similar to those typical of that material (Smyth et al., 1979).

If the repository were to be situated at a depth much in excess of 200 m (650 ft), the question arises as to the stability of the openings and the amount of support required. Again, as an upper bound, the support pressures given for a cohesionless soil can be used as ~ough estimate for openings at large depths (up to 500 m).

The depth at which stability problems will require the systematic use of support and/or reinforcement can be estimated from the compressive strength of the alluvium, about 315 psi. Model studies in similar type materials have found that significant stability problems do not occur until the overburden pressure exceeds twice the compressive strength (Korbin and Brekke, 1975). This is equivalent to roughly 210 m (700 ft) for the alluvium. The influence of the thermal load has not been considered and may necessitate the use of support at shallower depths.

Appropriate types of support systems for the control of moderate stability problems and ground pressures include combined systems employing shotcrete, rock bolts, and wire mesh. At large depths or in regions with little cohesion, probably the most economical method is to employ steel sets with continuous lagging, although other approaches are possible.

Methods of excavation include drill and blast or mechanical means. To preserve the integrity of the weakly cemented alluvium, only mechanical methods should be used. Excavation would be by roadheaders employing picks or, more likely, a large digger arm or spade with or without a surrounding shield. Excavation costs should be relatively low and rates of advance relatively high, provided that excessive ground support is not required or can be placed after excavation.

Comparison: Surface and Underground Excavations

To estimate the practical depths for a repository placed in a surface excavation or open pit requires a consideration of the economics. The cost of an open excavation with depth is given in Figure 10; it is assumed that a mined repository and open pit have the same area requirements (2000 acres) due to thermal loading restrictions of 40 kW/acre. The range of costs is based on \$1.50 to \$2.50 per m^3 excavated and a slope angle of 31°. Two times the volume of the pit is used in the calculations, as it is necessary to backfill the excavation.

Cost for the mined repository is based on the same area, a 6% extraction ratio, a thermal loading of 40 kW/acre from 10-year-old waste, 1.75 kW per waste package (the same as the Hanford repository waste package design), and a typical room size of 4.3 m wide by 6.0 m high. The result is about 113 km of tunnel at a cost between \$4600 and \$9200 per meter of tunnel. The cost per meter of tunnel was derived from experience at G Tunnel (NTS) in tuff, using a McAlpine roadheader for excavation and a light pattern of rock bolts with wire mesh for support. Cost figures were scaled proportional to the cross-sectional area of the excavated openings, and the upper bound numbers include a 100% contingency for additional support, materials handling, and ground problems. (The NTS tunneling contractor, Fenix and Scission, Inc., reports that tunnel construction costs in alluvium are similar to those in granite and 20% more than in tuff; Smyth and Sykes. 1980.)

Figure 10 suggests that the economic limit of pit depth is about 40 m; at greater depth a mined repository may be more economically feasible. It should be emphasized that this is a rough estimate and can change considerably with the assumptions; however, it is difficult to envision an economic surface excavation deeper than 100 m. Other factors not considered which would improve the economics of a surface operation include the cost of the mined repository shafts, the additional cost of handling the waste package, and the more expensive procedure for backfilling and sealing the underground repository.

In summary, it is apparent that construction of a mined repository in alluvium above the water table is feasible, and depending on several factors, may not be significantly more costly or difficult than other proposed underground repositories in hard rock or salt.

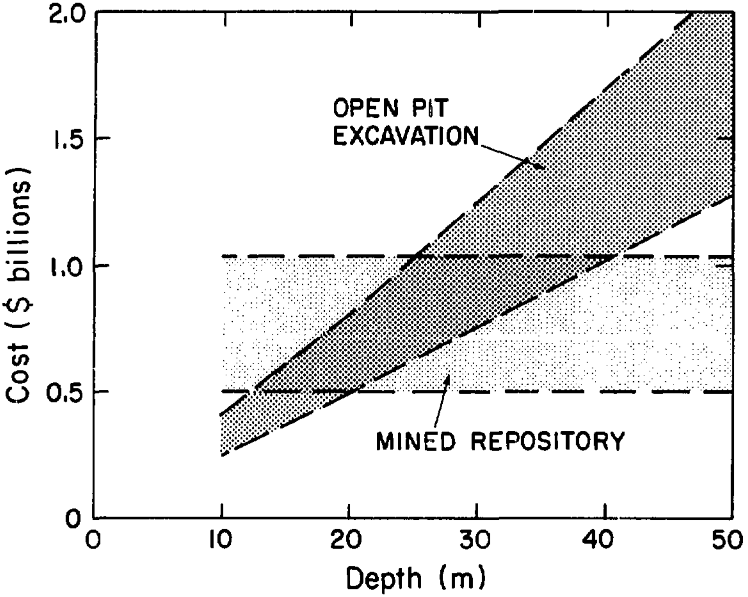

Figure 10. Cost of mined repository compared with open pit excavation as a function of depth. [XBL 821-1747]

3.1.7 Mineral and Water Resources Considerations

The mineral resource potential of alluvial basins of the Basin and Range province is dominated by evaporite deposits. In the southern Basin and Range and Mojave Desert regions, predominantly in Calfornia, a number of minerals are being extracted from lakebed playas. The principal commodity presently being produced is boron, from borate minerals mined at evaporite deposits in southeastern California. Other minerals from saline deposits, mined by conventional methods or, in some cases, by brine extraction, include trona (sodium carbonate), calcium chloride, clays, potash, and zeolites. A commodity of considerable future interest is lithium, which also occurs in potentially economic concentrations in evaporite deposits and their associated brines (Vine, 1976). However, for engineering and hydrological reasons, evaporite areas in the Basin and Range and Mojave Desert regions are considered poor locations for repositories.

Somewhat in contrast to the relatively high-grade concentrations of evaporite minerals, a low-grade but important resource of alluvial valleys is their sand and gravel, occurring in greatest abundance on the sides of the valleys and in the valleyward ends of alluvial fans. This resource is most important when it is located near large construction projects and/or near population centers.

Present-day conflict between repository siting and mineral resource potential on the NTS, either in alluvial valleys or in tuffaceous rocks, is essentially nonexistent, since by regulation mining is forbidden. Away from the NTS the possibility of conflict with evaporite mineral resources is slight because playas are poor repository locations.

Conflict with future groundwater resource development is essentially avoided because of the nature of potential sites. A principal criterion for a promising site would be the great depth to the water table in or below the alluvium. Such a depth would probably exceed the economic threshold for pumping. Protection of aquifers in rocks underlying the alluvium is of principal concern, and in this respect reliance on the sorptive properties and low hydraulic transmissivity of aquitards (discussed in Section 3.2.2) is paramount.

3.2 ALLUVIUM-FILLED VALLEYS AT THE NEVADA TEST SITE AS TYPE LOCALITIES

The NTS is an ideal type locality for studying the concept of isolating radioactive wastes in alluvial-filled valleys. A significant amount of hydrogeologic information on the NTS is available as exemplified by papers by Winograd and Thordarson (1968), Borg et al. (1976), Winograd and Doty (1980), and Winograd (1981).

3.2.1 Geologic Setting

The NTS lies north and east of the Las Vegas Valley-Walker Lane shear zone and east of an area characterized by large Mesozoic plutons (Fig. 11). Alluvium-filled basins occupy about 30% of the area, with Paleozoic and late

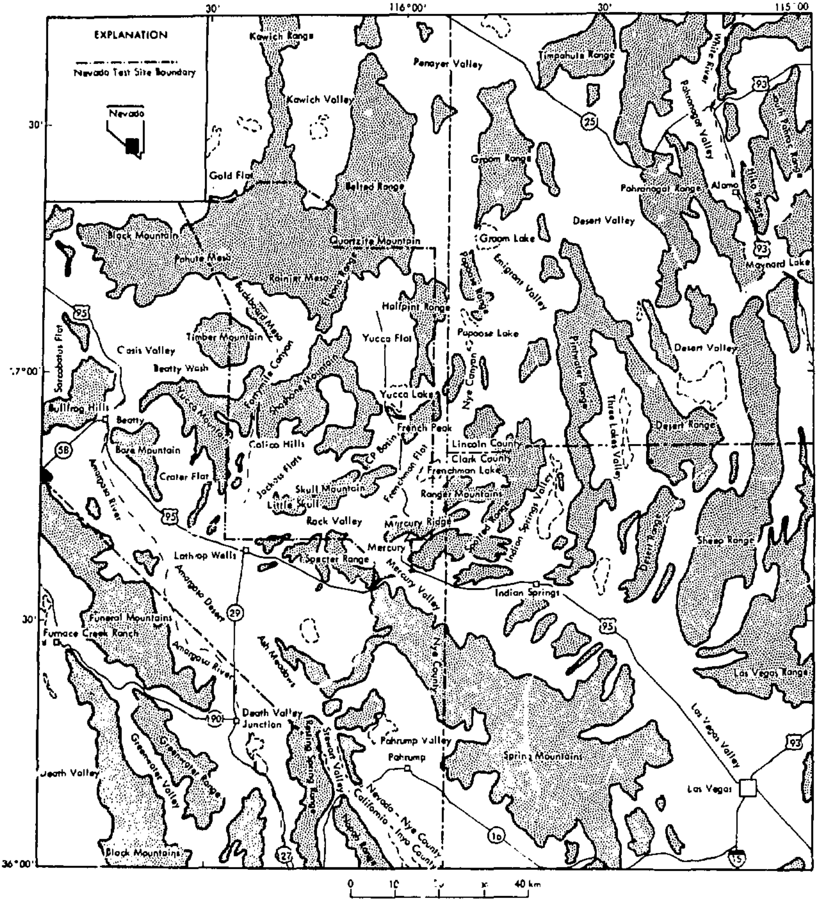

Figure 11. Index map of Nevada Test Site and vicinity (after Winograd and Thordarson, 1975). [XBL 832-8116]

Precambrian sedimentary rocks forming roughly 30% of the outcrops. The remainder of the area is underlain primarily by volcanic rocks and related Tertiary intrusions (Ekren, 1968).

The NTS area has experienced regional thrust faulting with horizontal movement of material over individual thrust surfaces up to 40 km or more (Fig. 12). Thrust faulting in southern Nevada began approximately 300 million years (m.y.) ago and ended approximately 75 m.y. ago. Thrust faulting in the area of the NTS was most prevalent approximately 180 m.y. ago (Smith et al., 1981).

Basin and Range faulting began in the Tertiary at least 30 m.y. ago, and major normal faulting over most of the Basin and Range province commenced 13 to 18 m.y. ago (Carr, 1974; Smith et al., 1981). Normal faults are abundant throughout the area of the NTS; their general distribution is shown in Figure 6. Normal faults flanking major basins may have throws ranging from several hundred meters to over 1 km (Ekren, 1968).

The general distribution of rock types at the NTS is shown in Figure 13. The NTS lies within the miogeosynclinal belt of the Cordilleran Geosyncline, where marine carbonate and clastic rocks were deposited during the late Precambrian and Paleozoic. The NTS also occupies a Tertiary volcanic province. Accumulations of rhyolitic and quartz-latitic ash-flow tuffs and ash rhyolites range from a few hundred to more than 4000 m thick. Quaternary and Tertiary clastic deposits of alluvial and lacustrine origin occur in most valleys of the Basin and Range province. They are usually only a few hundred meters thick, but in places accumulations of greater than 1000 m of tuffaceous alluvium occur above the water table, commonly containing significant amounts of clay and zeolite materials with large specific surface areas and large sorption ratios for fission-product radionuclides (Smith et al., 1981).

In Yucca Flat at the NTS, about 300 to 600 m of tuff and clay occur between the alluvium and the underlying Palezoic carbonate rock (Fig. 3). This aquitard is composed predominantly of zeolitized tuffs and also contains montmorillonitic and illitic clays. In western Jackass Flats, the aquitard thickness may exceed 1370 m. In the stratigraphic sequence, this tuff aquitard effectively separates the alluvium from the underlying Paleozoic carbonates in major NTS basins (Reynolds Electrical, 1978).

3.2.2 Hydrologic Setting

The eastern two-thirds of the NTS, including Yucca Flat, Frenchman Flat, Mercury Valley, Rock Valley, and part of eastern Jackass Flat and the range bordering and separating these valleys, lies within the Ash Meadows groundwater basin (Borg et al., 1976). Most water flowing beneath the NTS is considered to discharge from a line of springs in Ash Meadows, approximately 40 km southwest of Mercury (Fig. 12).

Winograd (1961) described a study of 8 wells drilled in Yucca, Frenchman, and Jackass Flats; each flat occupies a distinct topographic basin. The

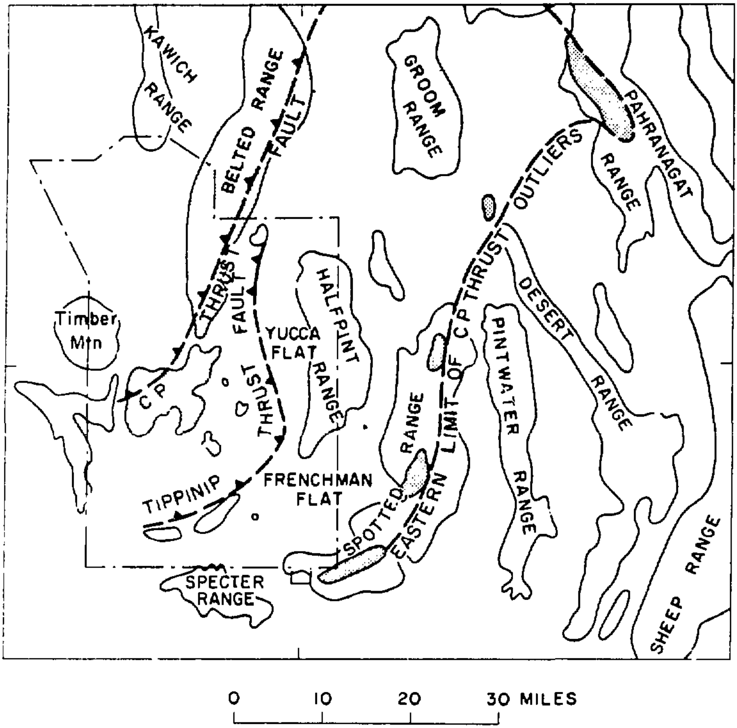

Figure 12. Map showing thrust faults in Nevada Test Site and vicinity (from Ekren et al., 1968). [XBL 832-8115]

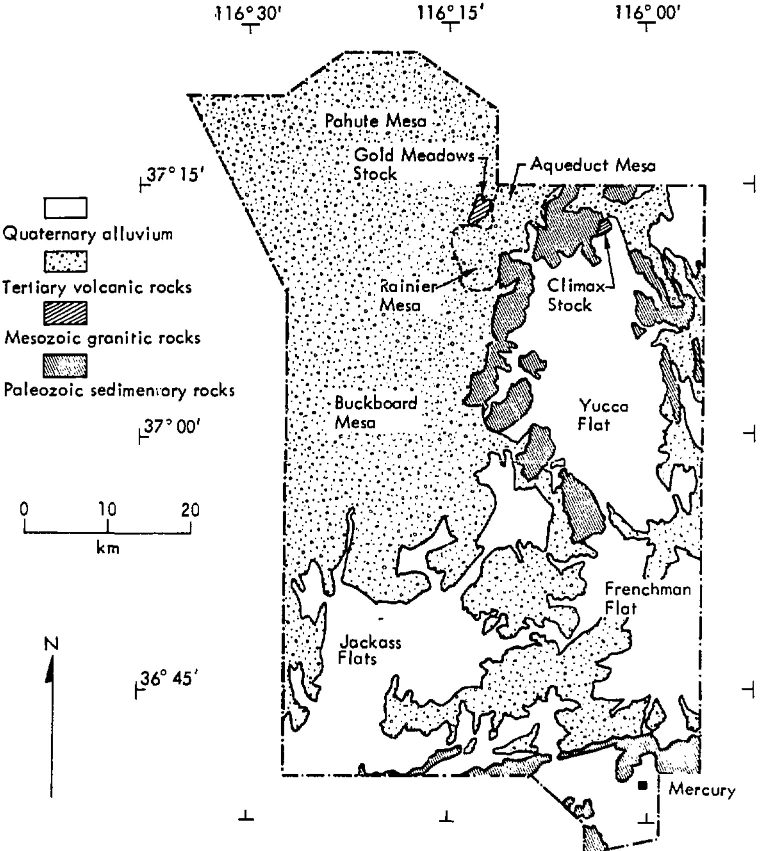

Figure 13. Principal rock types at Nevada Test Site (from Ramspott and Howard, 1975). [XBL 832-8112]

altitudes of static water level in the three basins were similar, ranging between 2390 and 2440 ft. This similarity in water levels and the large diversity in piezometric surfaces in other nearby basins suggested hydraulic connection between the three basins. The connection is provided by a sequence of highly fractured paleozoic carbonate rocks, ranging from several hundred to a few thousand meters thick, termed the lower carbonate aquifer by Winograd and Thordarson (1975). The carbonate aquifer is continuous beneath ridges and valleys and permits groundwater flow beneath at least 10 intermontane valleys, integrating them into a single groundwater basin, the Ash Meadows Basin (Fig. 14).

Between Frenchman Flat and Ash Meadows, the hydraulic gradient in the regional carbonate aquifer is very low, 0.11 m/km (0.6 m drop in water level over 58 km), reflecting the high fracture transmissibility of this aquifer. Estimates of transmissivities of this unit are in the range of 5 x 10^4 m^2/day (4 x 10^6 to 6 x 10^6 gallons per day per foot) (Winograd and Thordarson, 1975; Winograd and Doty, 1980). As with most of the Basin and Range, the NTS is in a closed drainage system. Groundwater from the NTS does not drain southeastward to the Colorado River.

Extent of Vadose Zone

The regional water table under Yucca and Frenchman Flats lies from 150 to 600 m below the surface (Geotechnical Engineers, 1979; Winograd, 1980), while the depth to water under peripheral valleys, such as parts of Emigrant Valley and Indian Springs Valley, is much less, as little as 0 to 70 m (Winograd and Thordarson, 1968).

Transit Time of Water

Estimates of groundwater velocities in the tuff aquitard and in the underlying carbonate aquifer have been made by Winograd and Thordarson (1975). Depending upon interstitial permeability, porosity, and hydraulic gradient, average vertical velocities in the aquitard may range from 1.5 x 10^{-4} to 6 x 10^{-2} m/year. The transit time of water through the ~300-m-thick aquitard would be at least several thousand years, and perhaps one to two orders of magnitude longer. In contrast, estimated velocities in the carbonate aquifer range from 2 to 200 m/year beneath Yucca Flat, to nearly 20 km/year beneath the Specter Range. Winograd and Pearson (1976) point out that the anomalous ^{14}C contents of water from an orifice in the Ash Meadows spring line suggest the presence of a major longitudinal heterogeneity in the carbonate aquifer; this feature would have a strong influence on the transit time of water in that aquifer. However, the long residence time of water in the suballuvial tuff aquitard is the more significant consideration in the movement of radionuclides from an alluvial repository at the NTS.

The possibility that water moves from the surface of non-playa portions of Yucca and Frenchman Flats to the Paleozoic carbonate aquifer seems remote because of the presence of caliche (secondary calcium carbonate) at shallow

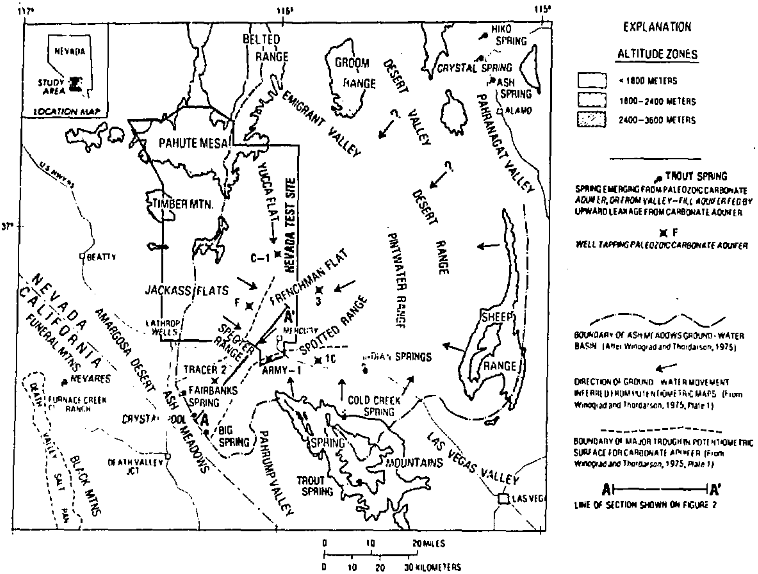

Figure 14. Index map of the Nevada Test Site and vicinity, showing generalized hydrogeology and boundary of the Ash Meadows groundwater basin, Nevada (from Winograd and Doty, 1980) . [XBL 832-8117]

depths, the great depth to the saturated zone, and the arid climate of these two valleys (Borg et al., 1976). (Caliche forms where soluble elements in downward-percolating water are precipitated in the zone of shallow groundwater evaporation and transpiration. The presence of caliche in the vadose zone then indicates the limited depths to which percolating water moves before it is halted by near-surface evaporation.) These hydrologic conditions are most favorable for the retention of nuclear wastes in the alluvium.

3.2.3. Climatological Considerations

Considerations general to the southern Basin and Range province were discussed in Section 3.1.3. The present climatological setting and hydrologic ramifications of a future pluvial episode at the NTS are discussed briefly here.

In the area of the NTS, the mean annual precipitation in the valleys ranges from about 8 to 16 cm, and mean annual precipitation in most upland areas is 30 cm or less. In the Sheep Range and Spring Mountains southeast and south of the NTS, respectively, annual precipitation is much greater (56 to 71 cm) (Winograd and Thordarson, 1975). It should be kept in mind that the NTS lies in the most arid part of Nevada, which is the driest state in the union (Borg et al., 1976). Precipitation is considerably higher in the more northerly areas of the Basin and Range province.

At no time during the last pluvial did precipitation exceed evapotranspiration in the region of the NTS (Geotechnical Engineers Inc., 1979). In the event of a pluvial, little if any rise is expected in the water table because of the low gradient and relatively high transmissivity of the regional carbonate aquifer. Even if flow increased to the point at which the discharge capacity of the Ash Meadows fault zone were exceeded, there are many other Paleozoic carbonate rock outcrops northeast of Ash Meadows through which discharge could occur at somewhat higher altitudes (Winograd and Doty, 1980).

Despite the fact that strong evidence exists for semiarid climates on the valley floors of the NTS during the late Pleistocene, Winograd (1981) acknowledges the possibility of deep percolation of precipitation to the water table during past and future pluvial climates, and Winograd and Thordarson (1975) estimate that 25 to 65 acre-feet per year leaks from semi-perched groundwater in Cenozoic rocks underlying Yucca and Frenchman Flats. Such downward leakage probably also occurs from Cenozoic rocks beneath other similar valleys. This percolation should not disqualify these unsaturated zones for burial of radioactive waste, as natural and man-made systems may be relied upon to increase travel time and reduce concentrations of radionuclides. These include: (1) sorptive properties of unsaturated valley fill and underlying zeolitic tuffs, (2) dilution (by several orders of magnitude) of radionuclide content of vadose water moving through the Paleozoic carbonate aquifer, (3) construction of a capillary barrier (wick effect), and (4) low solubility of the waste form (Winograd, 1981).

3.2.4. Geologic Hazards

The setting of the Basin and Range province with respect to seismicity and volcanism is discussed in general in Section 3.1.4. More specifically, in the region encompassing the NTS, explosive silicic volcanism ended 6 to 7 m.y. ago, and the youngest basalt in the region (in Crater Flat, approximately 20 km west of Yucca Mountain) is about 300,000 years old. The probability of volcanic disruption for a potential repository in the southwest corner of the NTS has been estimated to be 10^{-8} to 10^{-9}/year (Winograd, 1981).

The locations of epicenters in a region encompassing the NTS were illustrated in Rogers et al. (1977). Apart from the intense clusters on the NTS, associated with nuclear explosions, and another cluster east of Las Vegas, probably associated with Lake Mead, earthquakes of magnitude 6 or greater appear to be rare within the region encompassing the NTS; earthquakes of magnitude 3 to 5 are much more common. An assessment of the seismic hazard of the NTS region by Rogers et al. (1977) suggests that peak accelerations at the surface would range from 0.2 to 0.7 g for an earthquake of magnitude 7; accelerations of this size would recur within 1500 to 15,000 years. This range of accelerations can be readily incorporated in the design of the surface and underground facilities. Furthermore, as expressed in Section 3.1.4, maximum ground motions should be significantly lower underground.

3.2.5. Demographics

The Nevada Test Site occupies an area of 3711 km^2 in south-central Nevada with a low population density (a location map is shown in Fig. 15). The NTS is bounded on three sides by Nellis Air Force Range, which occupies 9039 km^2. The Tonopah Test Range to the north occupies an additional 1616 km^2. These two facilities provide a buffer of 24 to 105 km between the NTS and public land on three sides. The base camp of Mercury at the south entrance to the NTS and the area between Yucca Flat and Mercury provide a buffer of 20 to 30 km between public land and the nearest testing area (Reynolds Electrical, 1978).

Most of south-central Nevada has a low population density and a low percentage of privately owned land. This is due to the arid climate, lack of industrialization, the exclusion of the public from the NTS and Nellis Air Force Range, and Federal ownership of a large part of the land. The NTS is relatively isolated, with the nearest permanent communities of Lathrop Wells approximately 5 km from its border, and Cactus Springs approximately 13 km away. The major city of Las Vegas is 120 km southeast of the NTS, and several villages with populations of 2000 or less are situated to the northwest of Las Vegas along Highway 95. Las Vegas depends on recreation for its livelihood, while Henderson, farther southeast, is industrialized, with a few chemical and metal refining plants. Scattered communities to the southwest and northeast of the NTS depend on agriculture and cattle ranching. There are a few scattered mining operations to the west, northwest, and north of the NTS. A large increase in the population around the NTS in the next few decades is unlikely because of the low annual precipitation, limited available groundwater, and sparse vegetation (Reynolds Electrical, 1978).

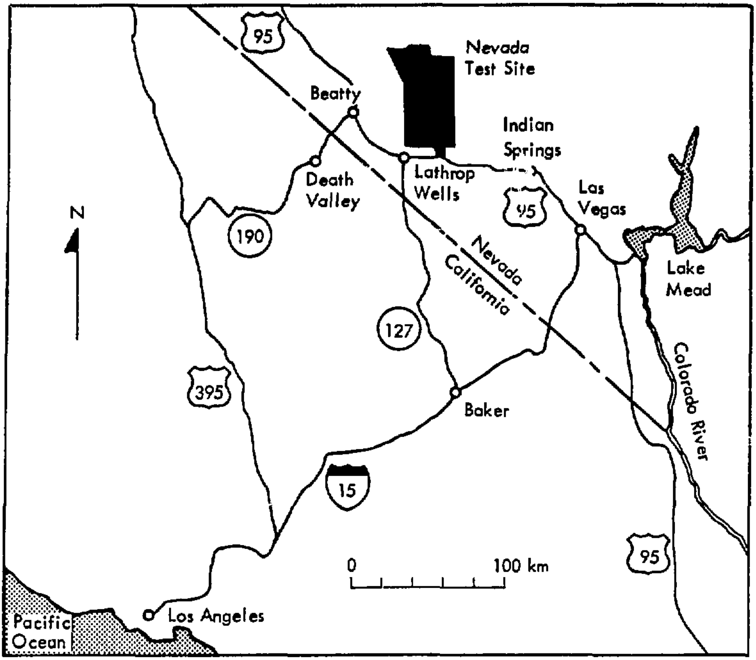

Figure 15. Location of Nevada Test Site (from Borg et al., 1976).
[XBL 832-8107]

3.3 ADVANTAGES AND CONCERNS OF WASTE ISOLATION IN THE VADOSE ZONE OF ALLUVIUM-FILLED VALLEYS

The unsaturated zone in alluvial-filled valleys of the Basin and Range province offers several attributes for nuclear waste isolation. Principal advantages as well as the concerns are listed in Table 3 and are discussed below.

Several factors inhibit the migration of radionuclides from discrete sites into and through the hydrologic system: (1) the flux of moisture into and through the alluvium is extremely low; (2) the components of the alluvium at specific locations favor the sorption of radionuclides should they escape from waste canisters; (3) at some locations the alluvium is underlain by tuffaceous rock above the water table, which also provides a less-permeable sorptive barrier to downward migration of radionuclides; (4) the thickness of alluvium exceeds 1000 m at many localities, and the depth of the water table exceeds 500 m. These, together with the tuff aquitard beneath the alluvium, provide a substantial hydrologic flow path between a relatively shallow repository (depth of a few hundred m) and the saturated zone. The enclosed groundwater basins of the Basin and Range province are hydrologically isolated; there is no discharge ultimately to the ocean.

The costs of construction of a relatively shallow repository in alluvium, either by underground mining methods if the depth exceeds approximately 100 m or by open pit methods at shallower depths, are comparable to construction costs in harder rock under saturated conditions. Experience at the Nevada Test Site has shown that the strength characteristics of alluvium are such that extensive ground support for underground workings is not required to depths of 200 m. Open pit construction would permit installation of barrier materials completely encompassing the repository, if necessary. In either case, a repository at a relatively shallow depth in alluvium, compared with a deep, hard rock site, permits relatively comparable ease of emplacement and, if necessary, retrieval of the waste.

The Basin and Range province has a very low population density, the vast majority of the land being under federal jurisdiction; large alluviated areas exist where there is no present mining activity or pumping of groundwater. The future mineral resource potential of these areas is not considered to be significant, and at selected locations the depth to the water table would be excessive for development of groundwater resources.

There are several factors which will alleviate or mitigate the principal problems of waste isolation in unsaturated alluvium:

- Properly chosen sites in tectonically active areas may take advantage of local tectonism: situating a repository on the basinward side of an active normal fault would insure that an increasing thickness of material would accumulate above the repository with time, reducing the possibility of future tectonic-erosive exhumation of the site. However, it would be necessary to take into consideration

Table 3. Principal advantages and concerns of waste isolation in the unsaturated zone of Basin and Range alluvial-filled valleys.

Advantages	Concerns
Low downward water flux	Tectonically active region, history of seismicity and volcanism
Sorptive components in alluvium	Future climatic changes
Tuffaceous layer underlies alluvium	Low thermal conductivity of dry or unsaturated alluvium may require a reduced thermal loading to limit repository temperature
Long groundwater transit time through tuffaceous aquitard	
Up to 500 m depth to water table	Enhancement of movement of radionuclide gases if a vapor phase is formed by heating of partially saturated alluvium
Enclosed groundwater basins with no discharge ultimately to the ocean	
Engineering properties of alluvium permit construction of repository by open pit methods at depths < 100 m or by conventional underground methods to greater depths	

the relatively high seismicity of the Basin and Range region in the design of the workings.

- Evidence of the climate in the Basin and Range province during Pleistocene pluvial periods indicates that future pluvial periods would result in increases in moisture infiltration rates, but the saturation conditions and water table elevations at sites away from obvious locations of playa lakes would not differ significantly from those of today insofar as affecting a repository in alluvium.

- If 100°C is the maximum allowable temperature rise in the immediate vicinity of a repository due to the introduction of waste, the low thermal conductivity of dry alluvium would require that the repository occupy roughly twice the area of one in saturated hard rock. The temperature rise in a "standard" 2000-acre repository with a thermal loading of 40 kW/acre in partially-saturated alluvium would remain within the allowable 100°C limit.

- The formation of a vapor phase in respnse to heating of unsaturated alluvium (and other rock types) and the ramifications of its effect on radionuclide transport are well understood. The magnitude of this problem should be determined by appropriate calculations and experiments.

4. *WASTE ISOLATION IN THE VADOSE ZONE IN TUFFACEOUS* ROCKS OF THE BASIN AND RANGE PROVINCE

General characteristics of tuffaceous rocks are described, with emphasis on their geologic and hydrologic characteristics, chemical and mechanical properties, and their bearing on design and construction of a repository in tuffaceous rock. As with alluvium, most information on these topics is from work performed at the Nevada Test Site. Consequently this area is emphasized in the general discussion, and the Yucca Mountain site at the NTS is considered the type locality for the more specific discussions in Section 4.2.

4.1. GENERAL CHARACTERISTICS OF TUFFACEOUS ROCKS

4.1.1. Geographic Distribution

Tuffaceous rocks are relatively common in parts of the Basin and Range geomorphic province. Figure 1 (in Section 3.1) shows the areal distribution of volcanic rocks containing welded and nonwelded silicic ash-flow tuffs in the western portion of the province.

Prominent occurrences outside the map area are the Chiricahua Mountains of southeastern Arizona, the Mogollon-Datil volcanic province of southwestern New Mexico, the Superstition Mountains of central Arizona, the Oatman District of western Arizona, and the Chocolate Mountains of southeastern California (Smyth et al., 1978). Mackin (1960) estimated the volume of silicic volcanic rocks in the Great Basin to be about 50,000 mi^3 (204,800 km^3). This estimate is probably conservative; more recent geophysical studies suggest that additional volumes of tuff are concealed beneath alluvium (Snyder, 1981).

Geologic settings that appear appropriate for exploration targets for siting radioactive waste repositories in tuff are within collapsed calderas and within thick ash-flow sheets flanking large volcanic centers (Lappin and Crowe, 1979). Of these terranes old (>1 m.y.) volcanic centers may have advantages for waste isolation: (1) in the older volcanic centers there is a relatively lower risk of future volcanic activity, (2) the tuff is more likely to be zeolitized, and (3) younger centers are more likely to be in areas of high heat flow.

4.1.2. Geologic and Hydrologic Characteristics

Tuffaceous rocks are made up of ash-fall deposits, generally of relatively low density, and denser, more competent ash-flow deposits. Ash-flow tuff may contain welded zones which are generally more intensely fractured than unwelded and ash-fall tuff.

Ash-flow tuff can consist of a single emplacement, multiple emplacements deposited within a short time and cooled as a unit, or multiple emplacements that were not deposited in rapid succession. A flow consisting of a single emplacement or multiple emplacements that cooled together is termed a cooling unit (Fig. 16). The variability of fracturing within cooling units plays a major role in groundwater movement in tuffs. In a simple cooling unit there will be at most one densely welded and fractured zone, while in a composite cooling unit two or three of these zones may be present (Winograd, 1971).

Many characteristics of tuffs are related to degree of welding, the process of compaction and cohesion of glassy fragments by viscous deformation (Smyth et al., 1978). Tuffs deposited at temperatures above 550°C (minimum welding temperature) in the presence of water vapor will weld (Smith, 1960). Compaction of ash flows during welding commonly results in a 50% reduction of porosity (Winograd, 1971). The degree of welding of a tuff unit is affected by (1) temperature of emplacement, (2) amount and composition of volatiles, (3) composition of ash, (4) lithostatic load, (5) rate of cooling, and (6) rate of crystallization; the emplacement temperature and thickness of the unit are the most important considerations (Smith, 1960; Winograd, 1971). Welding within a single ash flow is variable. In some hot flows, the entire deposit may be welded, while in others welding may be entirely absent. Generally, the degree of welding is variable within a flow (Winograd, 1971). Smith (1960) distinguishes three zones in most ash flows: the zone of dense welding, commonly underlain and overlain by the zone of partial welding, which in turn is underlain and overlain by a zone of no welding (Fig. 16).Zones of dense and partial welding are often characterized by columnar jointing, formed in response to tensional forces during cooling (Winograd, 1971). As discussed in detail in Section 4.1.3, many of the mechanical properties of tuff vary greatly with degree of welding (Olsson and Jones, 1980).

Groundwater movement in welded tuff aquifers is controlled by their permeabilities, which in turn are influenced by joint density, presence of lithophysal zones, variation in degrees of welding and compaction, and vertical variations in interstitial porosity. The permeability of welded tuff is generally related to porosity, but partially welded and unwelded tuffs with high porosities may have low interstitial permeability, due to large amounts of fine-grained ash within the matrix, alteration minerals, and a low fracture density. Conversely, densely welded tuff has a high fracture density resulting from columnar cooling joints, and groundwater flow in these units is primarily controlled by the fracture system (Smyth et al., 1978).

In many instances, predominant flow paths may coincide with boundaries between welding zones, where contrasting porosities and permeabilites are juxtaposed (Crowe et al., 1978). Tuff aquifers may not be continuous over long distances because of lateral variability of ash-flow cooling units. Ash-flow units thin laterally due to progressive loss of material during transport, and normal faults may displace ash-flow sheets, bringing units of differing permeabilities into contact (Smyth et al., 1978).

Alteration of glassy tuffs can occur by (1) devitrification of hot flows, (2) vapor phase crystallization, and (3) interaction of groundwater (Sykes et al., 1979). A large portion of ash flows undergo devitrification after emplacement (Winograd, 1971). As the glass adsorbs groundwater, it may

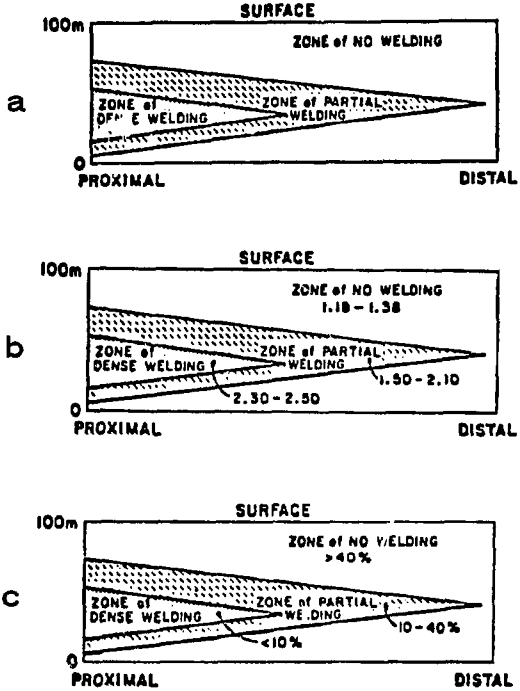

Figure 16. A schematic illustration (a) of welding zones of a simple cooling unit consisting of the deposits of an ash flow or sequence of ash flows which cooled as a single unit (after Smith, 1960b). Representative values of (b) bulk dry density (g/cm) and (c) percent porosity by volume with respect to the welding zones of a cooling unit are indicated (from Smyth et al., 1978).
[XBL 832-8126]

crystallize, forming quartz and alkali feldspar, although more commonly the alteration products will be cristobalite, various zeolites (particularly clinoptilolite, mordenite, and analcime), and clay minerals. Since zeolites result, in part, from groundwater action, they are better developed below present and paleo water tables and in less densely welded (more porous) tuffs. They also fill and line fractures in welded tuffs (Smyth et al., 1978). If a tuff has a high porosity and water of suitable composition is present, glass can alter completely to zeolites in as little as 10,000 years, even at temperatures below 100°C. Otherwise, the material may remain glassy for millions of years (Smyth and Sykes, 1980). Zeolite minerals may constitute up to 70% of some tuffs (Smyth et al., 1978).

4.1.3. Rock Properties

Hydrologic Properties

The hydrologic properties of tuff strongly depend on the degree of welding and, in densely welded tuff, on the intensity of fracturing, as illustrated in Figure 17. The coefficient of interstitial permeability is less than 1 microdarcy, and interstitial porosity is less than 5% in the densely welded zone. However, in some cases densely welded tuffs may be significant aquifers because of their high fracture transmissivity. Interstitial permeabilities may be several orders of magnitude higher and porosities several times greater in the adjacent partially welded zone, and higher still in the overlying and underlying unwelded zones.

In general, the porosity of tuff is inversely related to the degree of welding (Smith, 1960; Crowe et al., 1978; Smyth et al., 1978). It may vary by as much as an order of magnitude within a cooling unit, ranging from as little as 5% in the densely welded zone to 50% in the zone of no welding (Smith, 1960; Crowe et al., 1978; Smyth et al., 1978). Vapor phase crystallization reduces porosity and may have important effects on permeability (Crowe et al., 1978).

Bulk porosity of a tuffaceous rock mass may be influenced by the presence of lithophysal cavities, resulting from the expulsion of entrapped gases during cooling of the tuff unit. However, unless these cavities are interconnected or influence the connectivity of the fracture system, they have little effect on the overall rock mass permeability.

Permeability of tuffaceous rocks varies with the character of the tuff. Zeolitized tuffs from the NTS exhibit permeabilities as high as 6×10^{-2} darcies while welded tuffs have very low interstitial permeabilities. Mean values of interstitial permeabilities of tuffs (in darcies) are: bedded tuff, Rainier Mesa, NTS, 10^{-4}; zeolitized tuff, NTS, 6×10^{-4}; clayey tuffs, NTS, 6×10^{-6}; welded tuffs, NTS, 5×10^{-5}. It is emphasized that these measurements are for intact rock samples and do not take into account fracture permeability (Smyth et al., 1978).

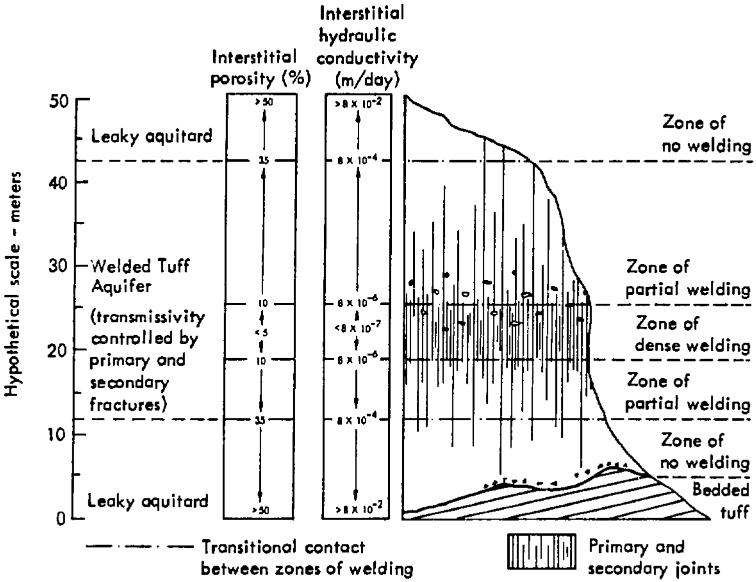

Figure 17. Idealized section of ash-flow tuff, showing relation of joint density, interstitial porosity, and interstitial hydraulic conductivity to the degree of welding. The simple cooling unit is illustrated; in a multiple flow compound cooling unit, two or more zones of dense welding may be present (from Winograd and Thordarson, 1975). [XBL 832-8108]

The water content of tuffs is an important consideration in the isolation of heat-producing radioactive wastes, because of the influence on chemical and thermomechanical properties. Water content of tuff ranges from less than 3% in welded, devitrified tuff to more than 20% by weight in zeolitized bedded tuff. This water can occur as (1) interstitial liquid, (2) water adsorbed on zeolites and clays, and (3) water found in the crystal structure of zeolites, clays, micas, and amphibole minerals (Smyth et al., 1978). Since the constituent phases of devitrifed, welded tuffs are anhydrous, they are stable to high temperatures. Nonwelded tuffs may contain more than 80% zeolites and 18% structural water plus several percent adsorbed water; therefore, they are thermodynamically stable only at relatively low temperatures.

Chemical Properties

Sorption of radionuclides by zeolites and clays in tuffs is the chemical property of principal interest in relation to isolation of radioactive wastes. The sorption of fission-product and actinide elements on minerals depends to a large degree on the Eh and pH of the groundwater and the presence of zeolites and clay minerals. Sorption ratios for tuff were examined in detail by Vine et al. (1980) and are summarized in Table 4. The altered, poorly welded tuffs have considerably higher sorption ratios than their devitrified, welded counterparts, though there are broad ranges in each category.

In batch sorption-desorption measurements of tuff from Nevada, Vine et al. (1980) found that sorption ratios vary with the site of the sample: zeolitized tuff samples from Yucca Mountain have higher sorption ratios for Cs, Sr, and Ba than does a zeolitized tuff sample from Jackass Flats. Samples of microgranite-like devitrified tuff from both sites have considerably lower ratios for these elements, but sorption of Ce and Eu appears to be less dependent on the rocks' zeolite content (Table 4). Groundwater appears to be a major factor in sorption. Sr, Cs, and Ba ratios are higher in less concentrated solutions than in more concentrated solutions, while the opposite holds for sorption ratios of Ce and Eu.

A chemical-mineralogical property of tuff also of concern is the structural stability of various minerals in response to heating. An assessment by Lappin ([illegible]) indicates that, with the exception of the minerals heulandite and phillipsite, zeolites are structurally stable to temperatures > 600°C. Heulandite and phillipsite, which comprise small portions of some tuff units at the NTS, have crystal lattice structures which begin to transform at temperatures as low as 180°C; the resulting contraction may affect the overall expansion of tuff in response to heating in a repository environment.

Thermal Properties

Thermal properties of tuff are dependent on the porosity, water content, density, and mineralogical composition in a manner similar to that previously

Table 4. Ranges of sorption ratios in tuff from Yucca Mountain and Jackass Flats (data from Vine et al., 1980).

	Devitrified, welded tuff	Altered (zeolitized) nonwelded to slightly welded tuff
Sr	53-300	1800-12000
Cs	250-530	8600-29000
Ba	440-1200	1500-66000
Eu	500-1600	1200-2500
Ce	40-1400	550-1900

described for alluvium (properties are summarized in Table 5). In general, the properties of tuff are amenable to greater areal thermal loading than are those of alluvium, although the limitations associated with dehydration of the materials exist, particularly for the nonwelded units. Conversely, the properties of welded tuffs are in many aspects more similar to other hard rocks, such as granite and basalt, than alluvium.

Dependence of thermal conductivity on grain density and mineralogical composition is illustrated in Figure 18. A total of 12 samples with widely ranging properties has been included. To eliminate the porosity variable the measured conductivities are extrapolated and plotted for values of zero porosity. When the predictive relations indicated in Figure 18 are combined with the appropriate porosity and saturation data in a geometric means formulation, the results are within 15% of the measured natural state thermal conductivities (Lappin, 1980).

Measurements of the natural state and fully dehydrated thermal conductivities were obtained for samples of partially welded Bullfrog tuff at Yucca Mountain, NTS. The magnitude ranges from 2.2 to 2.7 W/m°C for samples at natural water contents and 1.4 to 1.7 W/m°C for dry samples (Lappin, 1980).

Very little information on the influence of porosity and degree of saturation on heat capacity is available. Measurements on samples of dry devitrified and glassy tuffs above 100°C indicate a heat capacity, Cp, of 0.20 cal/g°C. To account for porosity, ϕ, and saturation, S, the relation $Cp = 0.20\ (1-\phi) \times 1.0\ (\phi S)$ is used, assuming a heat capacity of 1.0 cal/g°C for water (Lappin, 1980). From this formulation it is evident that for a tuff with 18% porosity, the heat capacity can change by more than a factor of two from fully saturated to dry conditions.

Thermal expansion of tuff is markedly dependent on porosity and rock type. As indicated in Figure 19, the loss of water from the hydrated fraction results in the negative thermal expansion or contraction of nonwelded tuffs on heating to 200°C. The average thermal expansion for intact samples of welded tuffs was found to range between 7 and 11 x $10^{-6}{}^{\circ}C^{-1}$, largely independent of mineralogy. It is important to realize, however, that a welded tuff rock mass may be susceptible to contraction upon heating if the discontinuities contain significant amounts of expandable clays or zeolites, in particular heulandite or phillipsite (Lappin, 1980). Significant volumetric expansion due to phase inversion when heated to temperatures of 150 to 200°C is also possible for devitrified welded tuff containing cristobalite.

Mechanical Properties

Tuff is a highly variable material in terms of the physical properties which influence the design and construction of a mined repository (see Table 5 for summary). In one extreme, ash-fall tuff of relatively low density, the material is friable or poorly indurated, similar in character to the NTS alluvium. Often the cementing material is weak and/or present in minor amounts, as in the case of incomplete conversion of glass to zeolite. Sampling and

Table 5. Thermal and mechanical properties of Tuff.[a]

Specific heat: avg. ~ 850 J/kg°C

Thermal conductivity : 1.4 to 1.7 W/m°C (dry samples); 2.2 to 2.7 W/m°C at natural water contents

Thermal expansion : -9 to $11 \times 10^{-6}\,°\mathrm{C}^{-1}$

Unconfined compressive strength : 30 to 300 MPa

Moisture content : 3 to 20%

Dry unit weight : avg. ~ 2.3 $\mathrm{g/cm^3}$

Internal friction angle[b]: 40 to 50°

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[a] Data from Lappin (1980).

[b] Strohm et al. (1964).

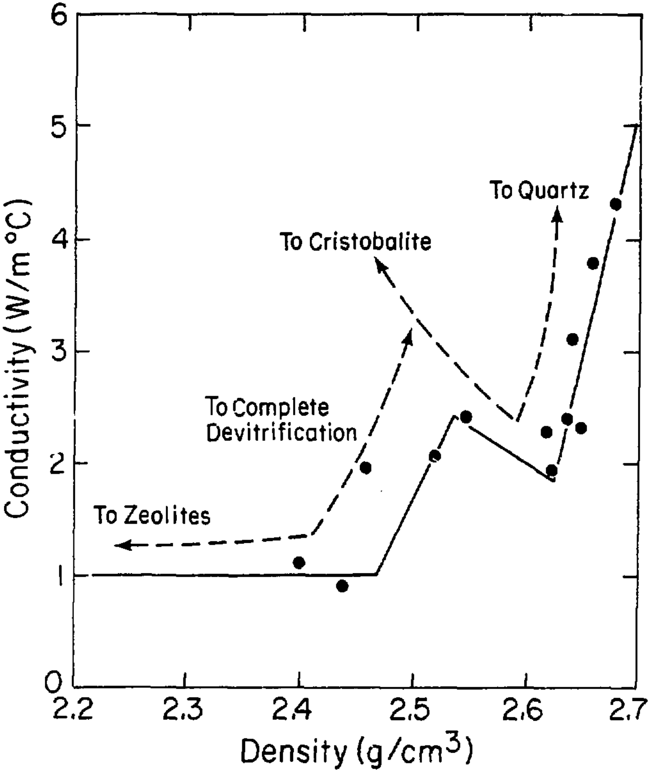


Figure 18. Extrapolated zero-porosity thermal conductivity of measured tuffs versus grain density. Lower bounding curve (solid line) based on experimental data (after Lappin, 1980). [XBL 825-2210]

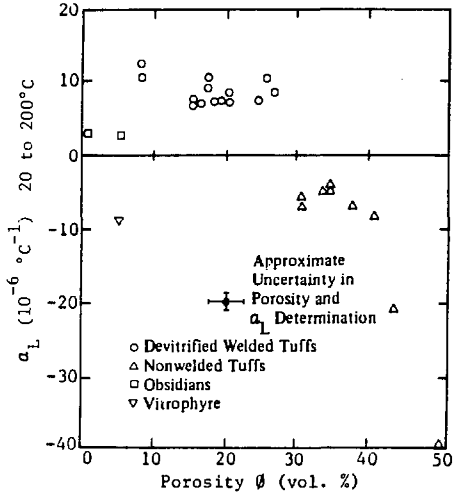


Figure 19. Average linear expansion coefficient of tuffs between ambient temperature and 200°C as a function of porosity (after Lappin, 1980). [XBL 832-8123]

testing of friable tuffs presents problems similar to those encountered with alluvium, and consequently it is difficult to obtain representative material-property data. Compressive strengths probably range from several MPa (several hundred psi) up to 7 MPa (1000 psi).

The ash-fall tuff grades to a more competent indurated rock of increased density, occasionally identified as a bedded tuff (Keller, 1960). Compressive strengths of bedded tuff range between 7 and 60 MPa with an average of about 25 to 35 MPa (Keller, 1960; Tyler, 1979). In comparison with the low to medium compressive strength, the tensile strength is exceptionally low. The ratio of compressive to tensile strength is between 30 and 40.

In the other extreme, the welded tuffs are relatively dense and strong. Average compressive strengths range between 100 and 150 MPa. Compressive to tensile strength ratios are also very high. Despite the good compressive strength characteristics, the rock mass in situ can be highly fractured or jointed due to cooling and/or tectonic forces. This fracturing and jointing is compatible with the relatively high stiffness of welded units, compared with nonwelded tuffs of very low tensile strength. Densely welded tuffs occasionally contain lithophysal (or vuggy) zones which may also influence bulk material properties.

Evidence for extensive fracturing in situ is suggested by downhole geophysical logs of the Oak Spring Formation at the NTS. The contrast between the compressional wave seismic velocity obtained from intact samples in the laboratory (average of 3 km/sec (9750 ft/sec)) with the in situ velocity of approximately 1.7 km/sec (5500 ft/sec) at a depth of 335 m (1100 ft) probably indicates extensive open fractures. Conversely, units of ash-fall tuff, directly above and below the welded unit, reveal considerably higher in situ velocities than laboratory values, suggesting a lower intensity of fracturing than in the welded unit.

In general, the mechanical properties of intact tuff, both strength and stiffness, vary with the degree of welding, which is reflected in the porosity of the rock, as shown in Figures 20 and 21. Furthermore, Young's modulus is basically independent of confining pressure, as indicated in Figure 21. From the data presented in Figures 20 and 21 (Olsson and Jones, 1980), it was also observed that a rough correlation exists between porosity and angle of internal friction: about 25° at 33% porosity, and 68° at 8.8 %.

Temperature and degree of saturation also influence strength. Preliminary indications suggest that up to a 30% decrease in strength occurs when rock temperature is increased to 200°C; a similar decrease occurs when rock conditions are changed from dry to fully saturated (Olsson and Jones, 1980). The effect of water on strength is primarily chemical. At temperatures above 250°C, the breakdown of analcime to nepheline may result in further loss of strength, particularly in highly zeolitized tuff (Smyth and Sykes, 1980).

In contrast to zeolitized nonwelded or poorly welded tuff, welded tuffs are less sensitive to strength loss with temperature (Tyler, 1979) and moisture content because of their lower porosity and lower content of hydrous

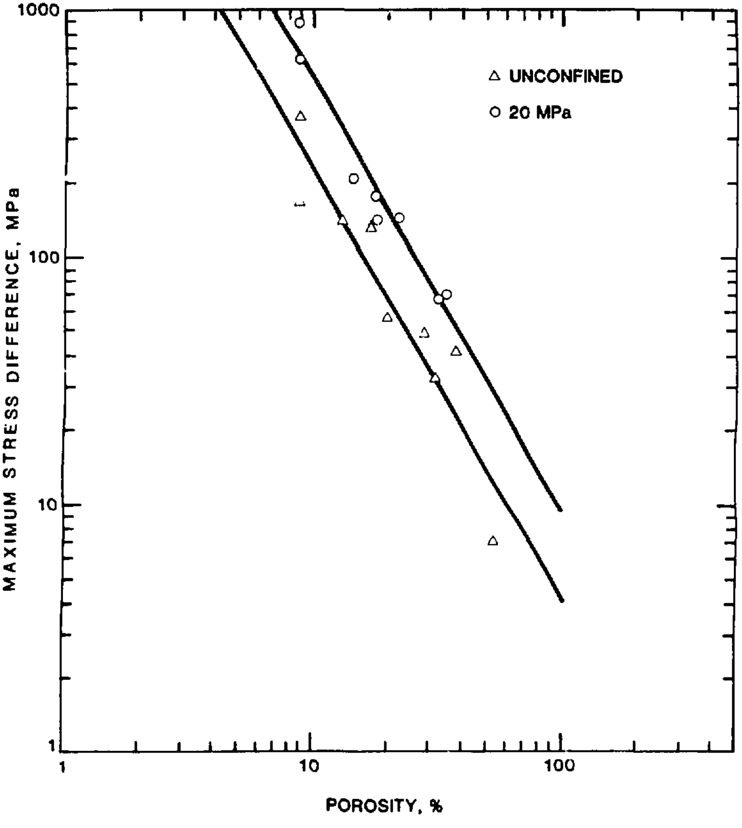


Figure 20. Compressive strength (maximum stress difference) as a function of porosity of tuff for confining pressures of 0 and 20 MPa (after Olsson and Jones, 1980). [XBL 832-8109]

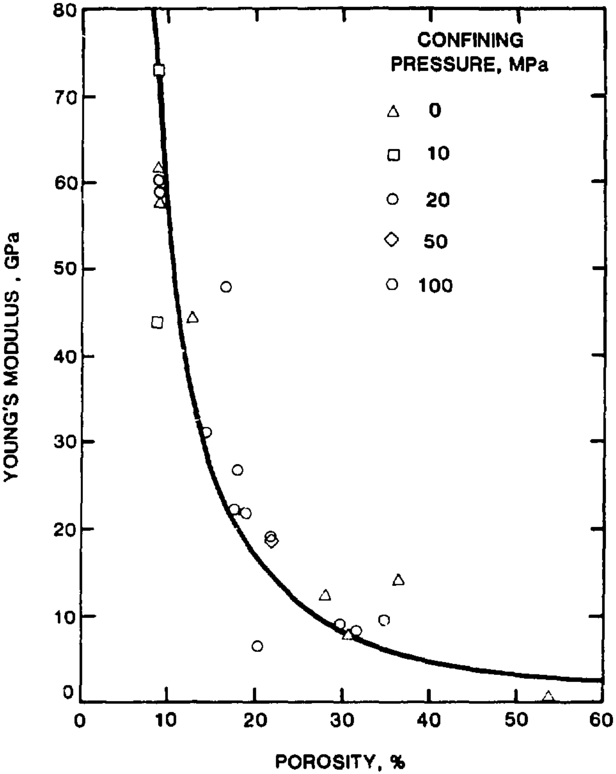


Figure 21. Young's modulus as a function of porosity of tuff for various confining pressures (after Olsson and Jones, 1980). [XBL 832-8124]

minerals (Smyth and Sykes, 1980). Accordingly, the siting of a repository in devitrified welded tuff may mitigate several of the problems associated with temperature, allowing for a larger thermal loading per acre than in nonwelded units. The higher strength and thermal conductivity of welded units are also favorable. The degree of favorability of fracturing or jointing in welded tuff depends on the site-specific character of these discontinuities (e.g., joint spacing, continuity, roughness, aperture, and presence of joint-filling and/or cementing materials).

In general, the thermomechanical properties of welded tuffs are in many aspects similar to those properties of other hard igneous rocks, such as basalt and granite. One of the major difficulties, however, in siting a repository in welded tuff may be in identifying a sufficiently thick continuous unit. The individual units are highly variable in vertical and lateral extent and, furthermore, are commonly displaced by faults (Tyler, 1979).

4.1.4. Design and Construction Considerations

The simple thermal response of a repository as a function of thermal loading, thermal conductivity, repository depth, and repository size are reviewed, as was done with alluvium in Section 3.1.6. The major construction considerations related to an underground excavation are then presented and illustrated with case histories. Surface excavations in tuff are not considered; however, the discussion relative to alluvium (Section 3.1.6) is also applicable to surface excavation in poorly indurated tuff.

Thermal Response

The influence of thermal conductivity on repository temperature increase has been calculated on the basis of a repository depth of 800 m, an area of 2000 acres (radius of 1605 m), and a thermal loading of 40 kW/acre with 10-year-old spent fuel; the curves are shown in Figure 22. For a range of conductivities between 0.9 W/m°C, representative of a dry nonwelded tuff, and 2.[illegible] W/m°C, for a saturated welded tuff, the increases in temperatures are 87 and 51°C, respectively. These maximum temperatures occur 58 years after emplacement of the waste and are average temperatures for the repository. Actual maximum local temperatures will depend strongly on emplacement geometry and thermal loading per canister.

Comparison of Figures 22 and 8 reveals the significant difference in predicted repository thermal responses for underground waste disposal in tuff and alluvium. This difference is related not only to the relatively higher thermal conductivity of tuff as compared to alluvium, but also to the higher density of tuff. In both cases the maximum temperature occurs at approximately the same time.

The accelerated increase in temperature due to dehydration of tuff (especially nonwelded units) is, as for alluvium, a factor limiting the maximum repository temperature, and hence, areal thermal loading. For a

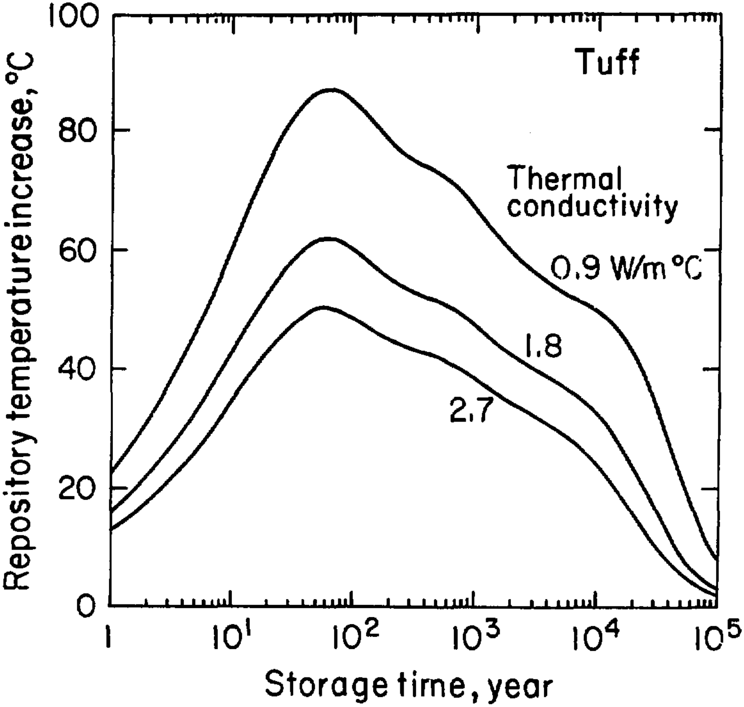


Figure 22. Effects of thermal conductivities on tuff repository temperature. [XBL 8112-4888]

100°C maximum repository temperature, the permissible thermal loading in dry tuff (thermal conductivity of 1.0 W/m°C) is 27 kW/acre; for saturated or partly saturated tuff (1.8 W/m°C), the loading is 36 kW/acre. This assumes a 44°C ambient temperature, based on a 20°C surface temperature and a 30°C/km geothermal gradient with the repository horizon at 800 m depth. Similar limitations apply to the calculated results, as discussed in Section 3.1.6. To more accurately define the allowable areal thermal loading for a prescribed maximum temperature requires detailed modeling of the dehydration process, including the fluid/vapor pressure, heating rate, and pressure release path length.

Other factors influencing repository temperature are waste form, repository depth, and repository area. Disposal of reprocessed waste results in a maximum temperature increase of 51°C 35 years after emplacement, as compared to 62°C for spent fuel, assuming a thermal conductivity of 1.8 W/m°C and 40 kW/acre thermal loading. Altering repository depth from 400 m to 1600 m, and area from 500 to 8000 acres, has negligible effect on the thermal response up to 2000 years after waste emplacement. For longer storage time, the influence is relatively minor, with a greater depth and larger area resulting in slightly increased temperatures (see Appendix for details).

Because of the important consequences resultant from water loss in tuff upon heating, several laboratory and field experiments have been carried out to investigate the processes involved. Water transport in porous rocks can occur as flow of liquid vapor, as well as by diffusion of water vapor through air.

Laboratory experiments on cores of saturated tuff were performed to measure the rate of water loss on heating from 25 to 150°C, and two models were formulated to predict the measured results (Hadley, 1980). In one model, the transport of vapor was treated as Darcy flow driven by the higher partial pressure of water vapor at the liquid-vapor front. The other model assumes that molecular diffusion is the dominant mode of water vapor transport. A comparison of the two predicted results with the measured result clearly indicates the dominance of the diffusion mechanism. Furthermore, an in situ heater experiment at G tunnel, in the Grouse Canyon tuff, basically confirms the results of the laboratory experiment presented above (Johnstone and Wolfsberg, 1980).

Besides the influence of temperature and dehydration on changing thermal properties and response, the effect of temperature on mechanical response is equally important. In general, if the tuff contains sufficient amounts of a contracting or expanding mineral or phase, the stability of the repository rooms could be adversely affected. Excessive contraction would result in loss of confining stress in the rock surrounding the opening, and depending on the character of the rock mass, fallouts of loosened material could occur. Thus the use of additional support may be required. Excessive expansion would cause overstressing of the rock nearest the opening and failure or slabbing of the material. Again, the use of additional support may be required.

Underground Excavations

One of the major factors influencing the stability of underground openings is the in situ stress state. Several stress measurements from within the openings under Rainier Mesa (depth of cover approximately 360 to 380 m) indicate a relatively low horizontal stress field. The maximum horizontal stress was shown to range between full and one-half overburden pressure (Carr, 1974). Ideally, the in situ stress state should be close to uniform to minimize the concentration of stress within the rock nearest the opening.

As previously described, the strength of tuff is extremely variable. Openings situated within poorly indurated ash-fall tuff could be expected to perform much the same as openings in alluvium at similar depths. The upper bound support pressures given for excavations in dense, cohensionless alluvium (Section 3.1.6) are also applicable for openings in the weakest of tuffs.

Tunnels and shafts constructed in the more competent bedded tuff (average compressive strength in excess of 25 MPa) should be reasonably stable with little or no support required to depths of up to 600 m. Depending on the thermal load, a light rock mass reinforcement system would most likely be required to assure retrievability over a period of 25 to 50 years.

Ground support and construction procedures in welded tuff would largely depend on the intensity of jointing and the character of these discontinuites. If the rock mass was very blocky, with numerous clay seams and/or open joints, the support pressures could be expected to approach that of a cohesionless sand. In the more likely event that the tuff is relatively fractured, but the joints are clean and rough or lightly cemented, a light to medium support system is reasonable. This could include shotcrete and/or rock bolts with wire mesh.

There are numerous examples of tunnels constructed in tuff at the NTS to illustrate the feasibility of a mined repository. Many of these openings are 3 x 3 m (10 x 10 ft) to 4 x 4 m (13 x 13 ft) in size, driven to a depth on the order of 400 m below Rainier Mesa. The rock mass encountered is bedded tuff containing both welded and nonwelded units. These openings, subjected to large dynamic forces from underground nuclear explosions, have performed exceptionally well (Smyth and Sykes, 1980).

In the vicinity of G Tunnel, the welded tuff is very blocky (near-vertical joint set spacing 5 to 30 cm; joints are tight, planar, and coated with alteration products). Rock support, consisting of rock bolts and wire mesh, is very effective in controlling minor raveling and fallouts. The nonwelded unit is less jointed (blocky to massive), although its lower strength results in minor stress-induced spalling or slabbing. This is also easily controlled with rock reinforcement and wire mesh. Use of mechanical methods of excavation (i.e., a McAlpine roadheader) results in a minimum of disturbance to the rock mass, thereby minimizing stability problems.

Occasionally, specific ground conditions have been encountered which make tunneling difficult and costly. Drift U12n.03, approximately 1100 ft below the surface in Rainier Mesa, crosses the Aqueduct Syncline and was driven nearly parallel to several faults (Ege et al., 1980). Near the base of the syncline several of the tuff units were altered to swelling (calcium montmorillonite) clay. Because of their exposure in the tunnel and the presence of water, up to 5 gpm, the swelling pressures in these clayey units resulted in distortion of the support sets and yield of the rock bolts. Furthermore, the low strength of the clay also resulted in ground squeeze in addition to swelling. Additional problems and overbreak were also caused by the unfavorable geometry of several intersected faults striking nearly parallel to the tunnel axis.

Another surprise in drift U12n.03 was the relatively large groundwater inflow encountered in more competent rock near the end of the tunnel (at the working point). Groundwater from fractures was initially recorded in September 1966 at 55 gpm; 16 months later the flow was ~8 gpm and reduced to 0.35 gpm by 1979. The source of this groundwater was most likely a perched zone.

Costs for tunnel excavation in competent nonwelded and welded tuff as reported by the NTS tunneling contractor, Fenix and Scisson, Inc., are about 20% less than those in granite (Smyth and Sykes, 1980). This apparent cost savings is probably the result of the use of mechanical excavators in the tuff and more expensive drill-and-blast methods in granite which are not amenable to roadheader-type mechanical excavators.

4.1.5 Mineral Resource Considerations

Several important metallic elements have significant deposits associated with Tertiary tuffaceous rocks of the western United States. Most prominent are gold and silver deposits, while uranium and mercury are to some extent also associated with tuffs. These mineralizations were localized by hydrothermal systems where meteoric waters circulated in the tuffs in response to heating caused by the intrusion of magmatic rocks. In some cases, the ore minerals are disseminated within the tuff, while in others the mineralization is in veins localized along faults at contacts between the intrusive and tuffaceous rocks.

In western Utah and eastern and central Nevada, by 1970, 15.5% of the gold produced and 7% of the combined gold-silver production had come from Tertiary volcanic rocks (Hewitt, 1970). Prominent Basin and Range districts associated with Tertiary volcanic rocks include Bodie, California; Goldfield, Tonopah (gold-silver), and McDermitt (mercury, uranium), Nevada; and Marysvale (uranium) and Spor Mountain (beryllium), Utah. Outside of the Basin and Range province, important gold and silver districts, most prominently at Silverton and Creede, occur in the tuffaceous rocks of the San Juan Mountains of southern Colorado.

4.2 YUCCA MOUNTAIN, NEVADA TEST SITE, AS A TYPE LOCALITY

Yucca Mountain, one of the major highland areas along the western boundary of the NTS (Figs. 23 and 24), has been the subject of increasingly detailed geologic, geophysical, and hydrologic studies associated with the Nevada Nuclear Waste Storage Investigations program (NNWSI) (the detailed study area is outlined in Fig. 25). At the August 1981 meeting sponsored by the Nevada Operations Office, new information was disclosed by a number of investigators representing the Los Alamos National Laboratory, Sandia National Laboratory, and the U.S. Geological Survey. A good portion of the information presented in this report is extracted from verbal presentations of that meeting.

4.2.1. Geologic Setting

The western and northern portions of the NTS are part of a region of intense late Miocene and early Pliocene volcanism. The Silent Canyon and Timber Mountain-Oasis Valley calderas, shown in Figure 26, are the principal volcanic features. Yucca Mountain is a roughly north-south-trending ridge underlain by tuffaceous rocks most likely derived from these calderas to the north. Yucca Mountain consists of a series of north-trending structural blocks, most of which are tilted 2 to 10° eastward (Fig. 25). This dip may limit the lateral extent of a horizontal repository in a given tuff unit.

The eastern flanks of Yucca Mountain have been separated into a series of horsts and grabens delineated by normal faults. Yucca Mountain, along with most of the NTS, lies north of but close to the projected trend of the Walker Lane-Las Vegas Valley shear zone (Spengler et al., 1979). Recent gravity modeling indicates that Yucca Mountain is underlain by at least 3500 m of tuff which filled a large depression in pre-volcanic rocks (Snyder, 1981).

Stratigraphy of the tuff units beneath Yucca Mountain was first revealed by two holes drilled east of the present study area. As shown in Figure 27, hole UE25a-1 was drilled into the tuff sequence adjacent to the east side of Yucca Mountain. The hole was drilled to a depth of 762 m between north-south-trending faults, penetrating the Paintbrush Tuff and tuffaceous beds of the Calico Hills and Crater Flat (Sykes et al., 1979). Hole J-13 was drilled to a depth of approximately 1000 m in tuff underlying Jackass Flat, and more recently hole G-1 was drilled to approximately 2 km in the Yucca Mountain study area. The general stratigraphy of the Yucca Mountain area is given in Table 6, and the locations of these holes, stratigraphic sections, and a geologic cross section make up the sequence of Figures 28 through 30.

The lithology of the tuff sequence in UE25a-1 was described by Sykes et al. (1979) beginning with the lowermost units:

Crater Flat Tuff

Bullfrog Member. The oldest unit encountered, it is densely welded and crystal rich (approximately 20%), with crystals composed of sanidine, oligo-

Table 6. General stratigraphy of Yucca Mountain in the vicinity of drill hole UE25a-1.

Era	System	Series	Formation	Member or unit
Cenozoic	Quaternary	Holocene and Pleistocene	Alluvium and colluvium[b]	
	Tertiary	Pliocene	Timber Mountain Tuff	Rainier Mesa Member
		Miocene	Paintbrush Tuff	Tiva Canyon Member[b]
				Yucca Mountain Member
				Bedded tuff[b]
				Pah Canyon Member
				Topopah Springs Member
			Tuffaceous beds of Calico Hills[b,c]	
			Crater Flat Tuff	Prow Pass Member [b,c]
				Bullfrog Member[b,c]

[a] From Spengler et al. (1979).

[b] Encountered in drill hole.

[c] Not exposed in the immediate vicinity of drill hole.

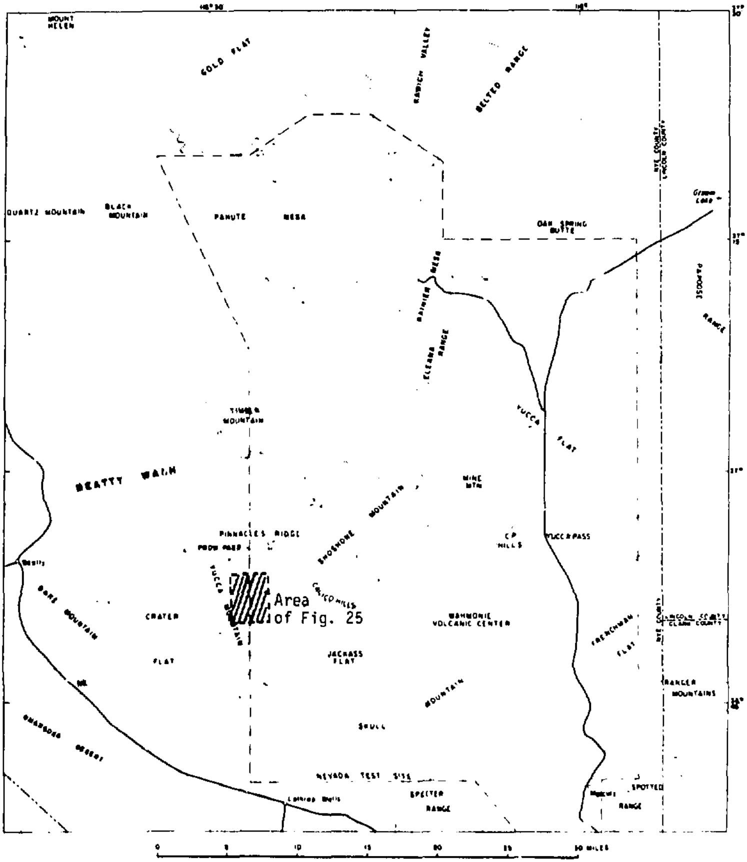


Figure 23. Index map of the Nevada Test Site and vicinity, showing the location of Yucca Mountain (from Spengler et al., 1981). [XBL 832-8114]

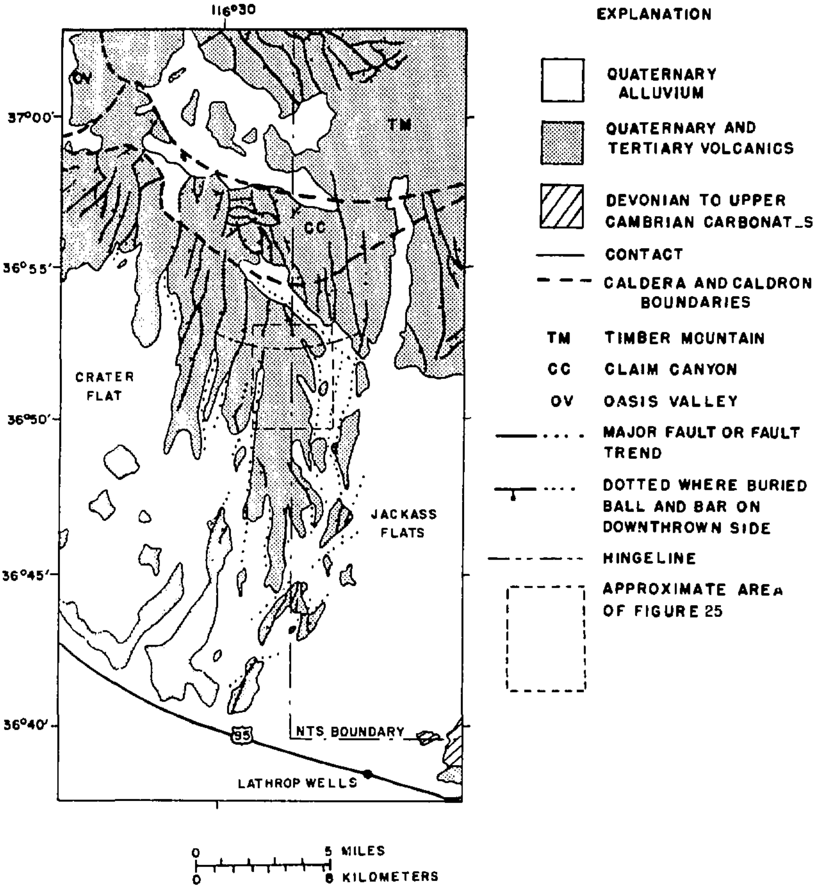


Figure 24. Generalized structural map of Yucca Mountain (from Spengler et al., 1979). [XBL 832-1706]

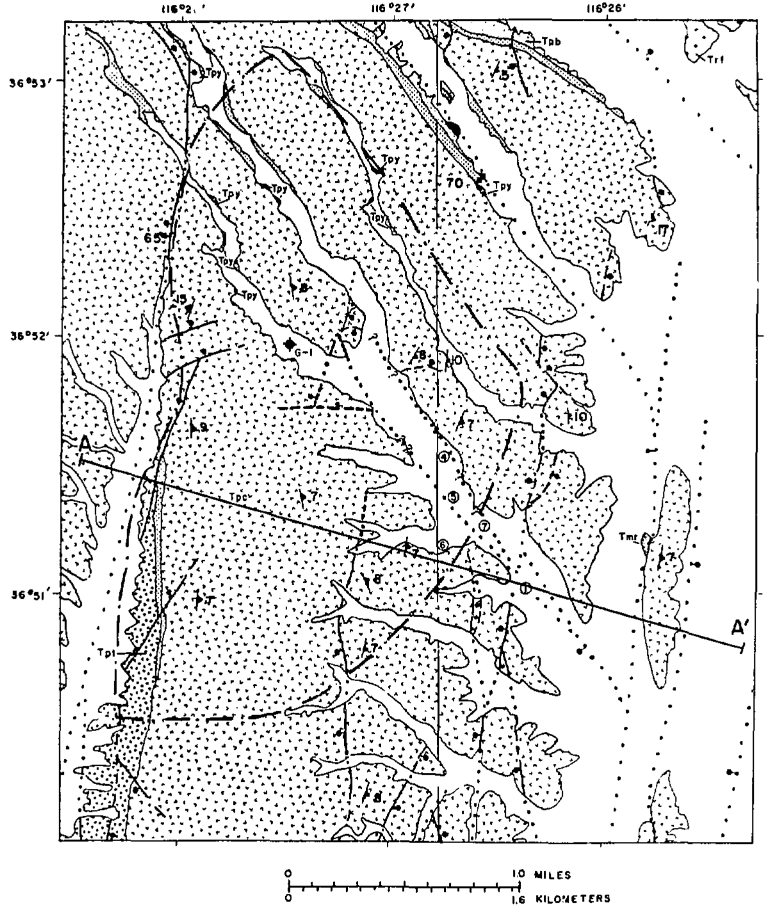


Figure 25 (above and facing page). Generalized geologic map and cross section of Yucca Mountain in the vicinity of drill hole UE25a-1 (from Spengler et al., 1979, 1981).
[map, XBL 832-8113; section, XBL 832-8118]

EXPLANATION

□ ALLUVIUM AND COLLUVIUM (QUATERNARY) (Qac)

▨ RHYOLITES OF FORTYMILE CANYON (Trf)

TIMBER MOUNTAIN TUFF
▨ RAINIER MESA MEMBER (PLIOCENE) (Tmr)

PAINTBRUSH TUFF
▨ TIVA CANYON MEMBER (MIOCENE) (Tpc)
▨ BEDDED TUFF
▨ YUCCA MOUNTAIN MEMBER (MIOCENE) (Tpy)
▨ PAH CANYON MEMBER (MIOCENE) (Tpp)
▨ TOPOPAH SPRING MEMBER (MIOCENE) (Tpt)

□ TUFFACEOUS BEDS OF CALICO HILLS (MIOCENE) (Tcb) (IN CROSS SECTION ONLY)

▨ CRATER FLAT AND OLDER TUFFS (MIOCENE) (Tcf) (IN CROSS SECTION ONLY)

⊸7 STRIKE AND DIP OF FOLIATION

70 ┴ ┴ ____.... FAULT- BALL AND BAR ON DOWNTHROWN SIDE, DASHED WHERE INFERRED, DOTTED WHERE CONCEALED, ARROW INDICATES MEASURED DIP OF FAULT, QUERIED WHERE UNCERTAIN

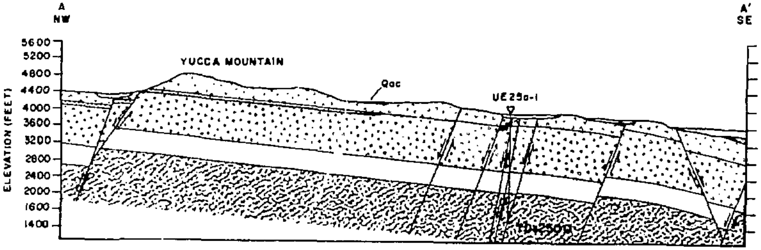
—·—·— AREA OF INTEREST

——— CONTACT

—— —— NTS BOUNDARY

① APPROXIMATE LOCATION OF DRILL HOLES UE25a-1, -4, -5, -6, -7

◆ APPROXIMATE LOCATION OF USW-G1



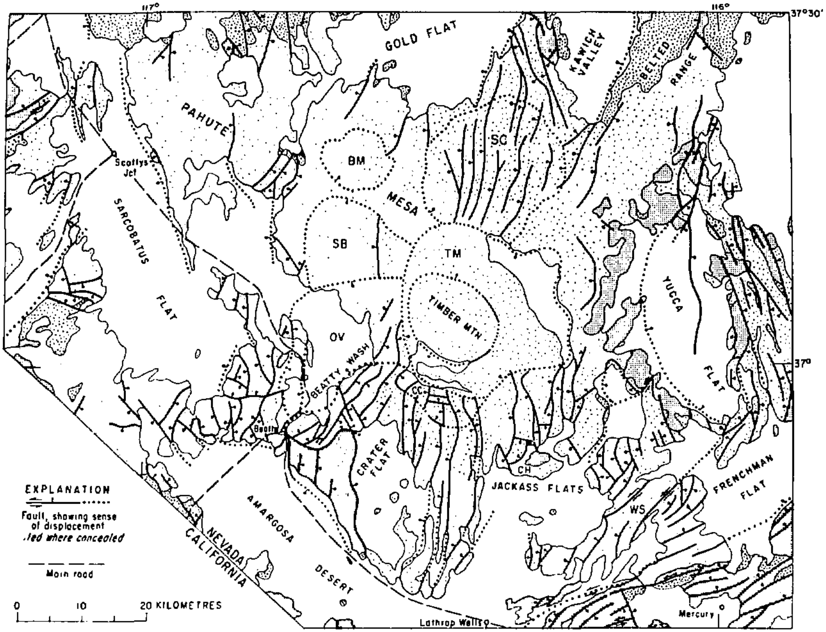


Figure 26. Structural setting of southwestern Nevada, showing normal faults (from Christiansen et al., 1977). Calderas abbreviated are Timber Mountain (TM), Black Mountain (BM), Oasis Valley (OV), Sleeping Butte (SB), and Silent Canyon (SC). [XBL 832-1705]

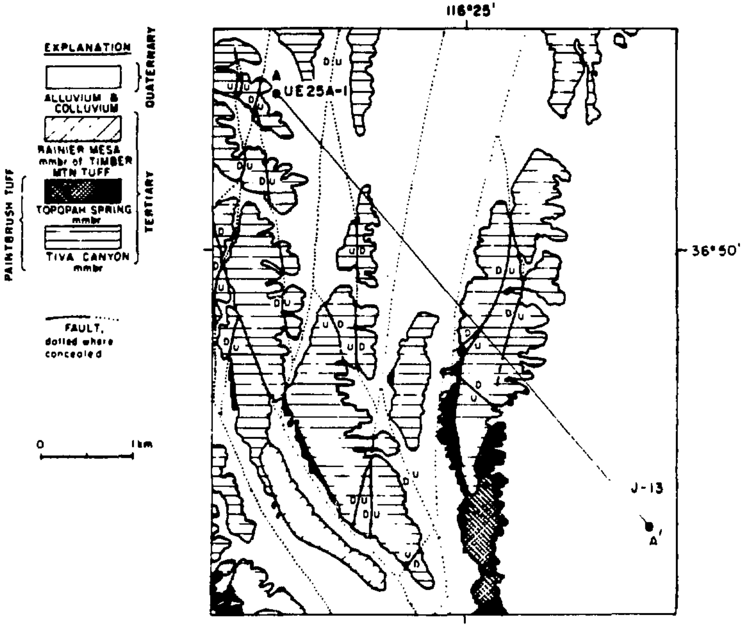


Figure 27. Generalized geologic map of the Yucca Mountain area, NTS, showing positions of drill sites UE25a-1 and J-13 (from Smyth and Sykes, 1980). [XBL 832-8125]

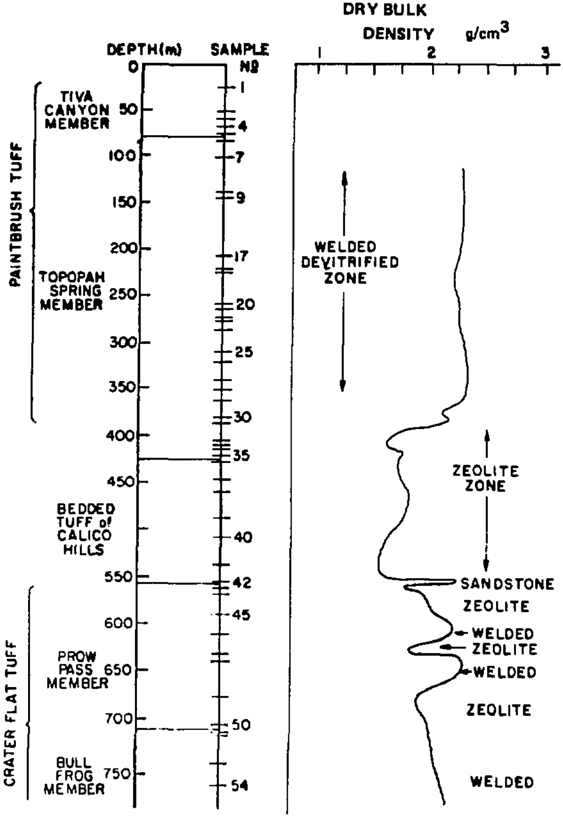


Figure 28. Stratigraphic section of drill hole UE25a-1, showing major authigenic phases (from Smyth and Sykes, 1980).
[XBL 832-8122]

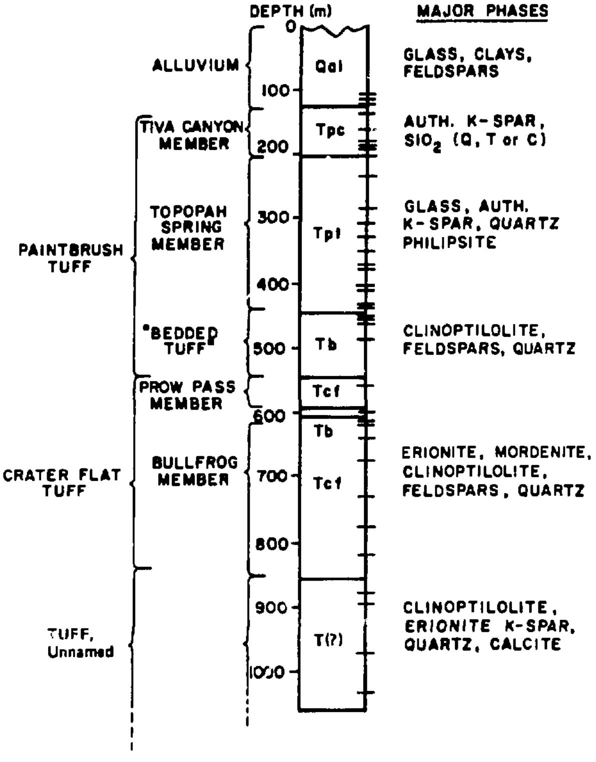


Figure 29. Stratigraphic section of test well J-13, showing major authigenic phases (from Smyth and Sykes, 1980). [XBL 832-8121]

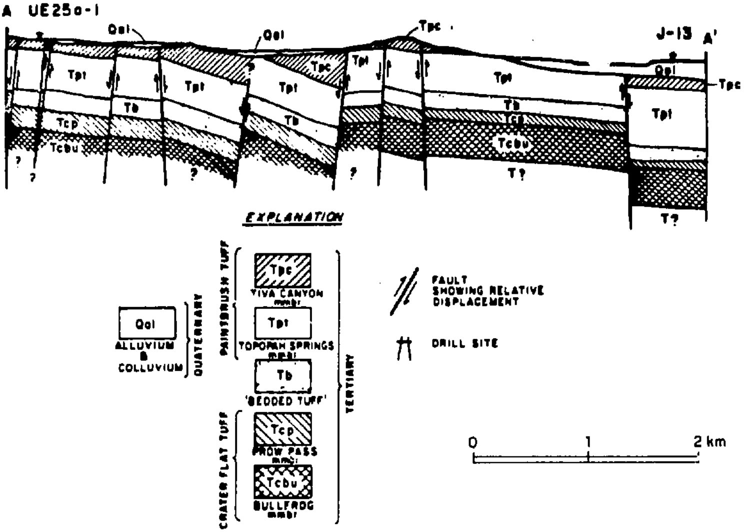


Figure 30. Cross section of units between drill sites UE25a-1 and J-13 (from Smyth and Sykes, 1980). [XBL 832-8120]

clase, quartz, biotite, and magnetite. The Bullfrog is poor in lithics, with no zeolites observed, nor were fractures observed.

Prow Pass Member. About 152 m of this unit was encountered in hole UE25a-1. The upper 60 m is crystal rich, containing 10 to 14% crystals, while the lower portion contains 5 to 8% crystals. The phenocrysts are predominantly sanidine, resorbed quartz, and albite or oligoclase, with some anorthoclase, biotite, pyroxenes, and magnetite. The upper zone is more densely welded than the lower, and no fractures were observed. The nonwelded portion of the Prow Pass Member is moderately fractured and completely zeolitized, with clinoptilolite and rare mordenite replacing both matrix material and pyroclasts.

Bedded Tuff of Calico Hills

Hole UE 25a-1 intersected an approximately 144-m-thick sequence of bedded tuff, air-fall tuff, pyroclastic flows, and volcaniclastic sediments. The lower portions contain sandstone, and the rest appear to be crystal-poor nonwelded tuffs, containing 2 to 4% oligoclase, sanidine, quartz, and biotite and up to 60 to 70% zeolites. Relatively few fractures were observed in the Calico Hills unit.

Paintbrush Tuff

Topopah Springs Member. About 333 m of the lower unit of the Paintbrush Tuff was encountered in hole UE25a-1. The basal zone is nonwelded, grading into a vitrophyric zone of dense welding overlain by thick sequences of devitrified, densely to moderately welded tuff.

The densely welded upper zone contains up to 17% crystals of sanidine, oligoclase, anorthoclase, pyroxene, biotite, and magnetite; the moderately welded zone and vitrophyre contain less than 3% crystals of sanidine, plagioclase, anorthoclase, biotite, and magnetite. The nonwelded base consists of 1 to 4% alkalai feldspar, oligoclase, magnetite, quartz, and occasional biotite.

Zeolites occur in the basal vitrophyre of the Topopah Springs Member as fracture fillings and minor vug linings at about 385 m depth. This is the shallowest occurrence of zeolites in UE25a-1. Below the vitrophyre, zeolitization is extensive, with clinoptilolite replacing pyroclasts and matrix. Filled fractures are abundant in the Topopah Springs.

Tiva Canyon Member. Only about 64 m of this unit was encountered in the UE25a-1 drill hole even though it is 100 to 200 m thick in other locations. The upper 60 m is densely welded, with a nonwelded base and 9 m of bedded tuff beneath the nonwelded zone.

The densely welded upper zone contains less than 5% crystals of sanidine, magnetite, plagioclase, hornblende, and sphene. The nonwelded base contains approximately 14% oligoclase, sanidine, biotite, magnetite, and orthopyroxene. The bedded tuff contains about 11% andesine/oligoclase, sanidine, biotite, magnetite, and orthopyroxene. Alteration occurs only in the upper zone and consists of granular devitrification products. The fracture density is relatively low in this member.

Potential repository horizons in the tuffs at Yucca Mountain were discussed by F. Caporuscio at the NNWSI Review Meeting. In addition to the units encountered in drill hole UE25a-1, he considered two units below the Bullfrog Member, the Tram unit and an unnamed lithic-rich tuff. The Tram unit has an upper densely welded zone and a lower nonwelded zone, while the lithic-rich tuff contains an upper nonwelded zone and a lower densely welded zone. The lithic-rich tuff is the oldest and deepest unit under consideration.

The degree of welding and predominance of alteration minerals in the tuff units are illustrated in Figure 31, presented by Los Alamos National Laboratory speakers at the NNWSI meeting. Four alteration zones are recognized over the depths penetrated: an upper zone dominated by opal and quartz, a second zone where clinoptilolite predominates, a third zone containing clinoptilolite and analcime, and a fourth zone dominated by analcime.

The units considered by speakers at the NNWSI Review Meeting as potential repository horizons were the Topopah Springs Member, Bedded Tuff of Calico Hills, the Bullfrog Member, the Tram unit, and the lithic-rich tuff. Table 7 lists their appraisal of the advantages and concerns of each.

4.2.2. Hydrologic Setting

The hydrologic setting of the Yucca Mountain area is presently under investigation by the U.S. Geological Survey. Information presented here is based predominantly on verbal progress reports presented by members of the Survey at the NNWSI Peer Review Meeting held in Las Vegas in August 1981. Such information should be considered as preliminary.

The regional hydrologic framework of the NTS is covered to some extent in Section 3.2 of this report. Yucca Mountain lies within the Oasis Valley-Fortymile Canyon groundwater basin. Groundwater moves south-southwestward from beneath Pahute Mesa toward the Amargosa Desert through rocks underlying Oasis Valley, Crater Flat, and the western portion of Jackass Flat (Fig. 32). The carbonate aquifer underlying the eastern portions of the NTS may not continue beneath the Oasis Valley-Fortymile Canyon groundwater basin. Rather, the thick sequence of volcanic rocks in this area (approximately 3 km) probably overlies magmatic intrusive rocks that form the root zones of the extensive igneous assemblage occupying the western portion of the NTS. Within tuffaceous rocks attributable to the Silent Canyon and Timber Mountain calderas, a substantial portion of this thick sequence of volcanic rocks occurs beneath the water table, although because of higher permeabilities, most of

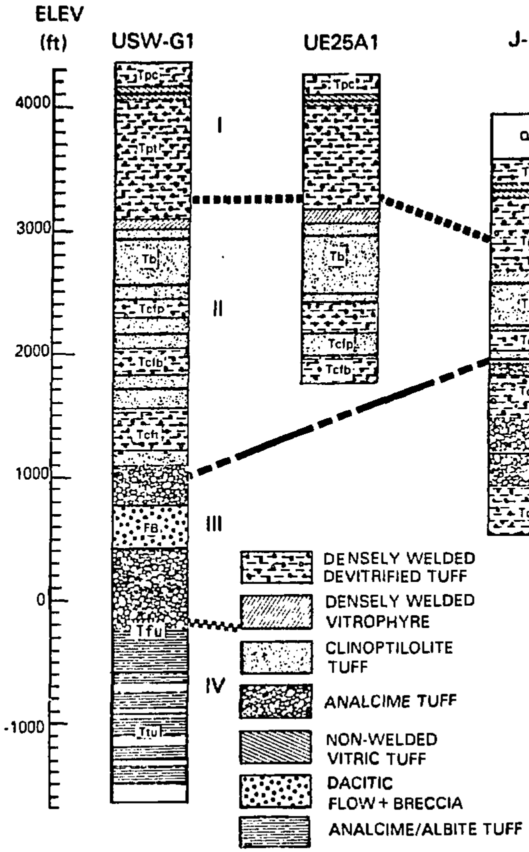


Figure 31. Alteration zones in tuff at Yucca Mountain (from LANL presentation at NNWSI meeting). [XBL 832-8127]

Table 7. Comparison of advantages and concerns of locating a repository in various tuff units.[a]

Formation	Advantages	Disadvantages
Topopah Springs Member	Above water table Thick devitrified zone High thermal conductivity High strength	High fracture density
Calico Hills	Low permeability High zeolite content	Variable thickness Low thermal conductivity Low strength
Bullfrog and Tram	Densely welded Zones surrounded by zeolitized zones	Thin zeolitized horizon Fracture flow predominant
Lithic rich	Thick, homogeneous	Hot, deep Lateral variability unknown

[a] Summarized from presentations at the NNWSI Review Meeting, August 1981.

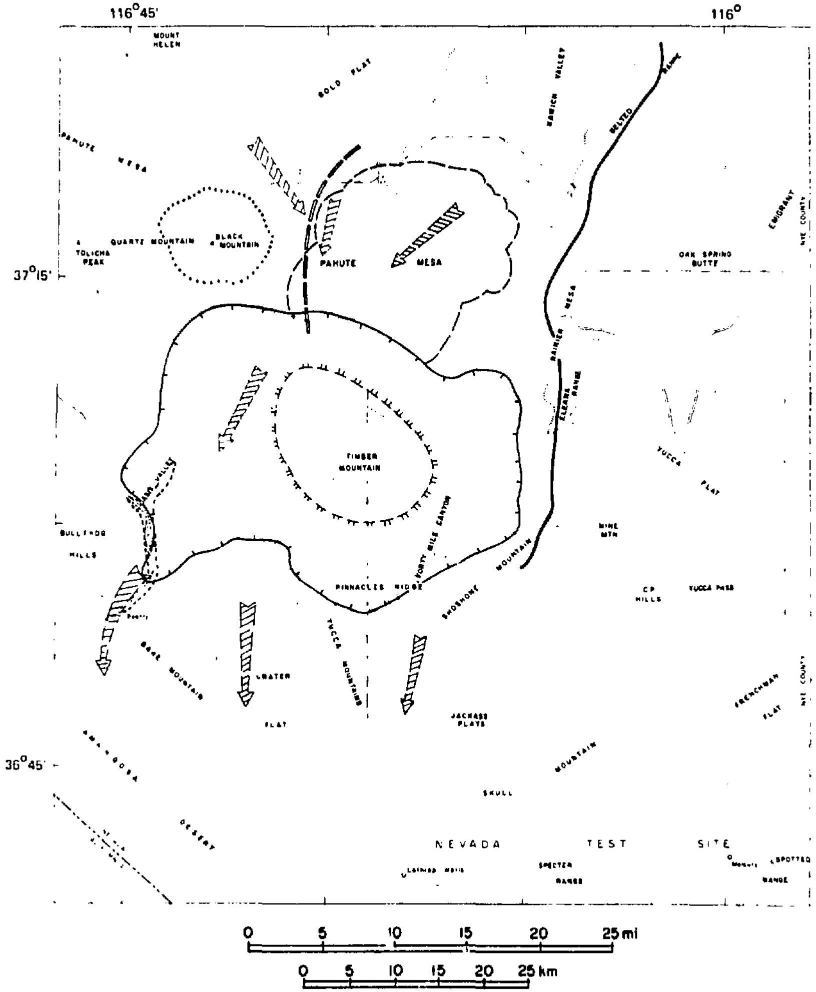


Figure 32. Map showing direction of groundwater movement from eastern Pahute Mesa toward discharge areas in Oasis Valley and Amargosa Desert, Nye County, Nevada (from Blankennagel and Wier, 1973).
[XBL 832-8106]

the groundwater occurs in the upper 2500 ft of the saturated zone. Depth to groundwater ranges from 850 ft in the extreme northwestern portion of the NTS to 1900 to 2400 ft within the Silent Canyon caldera. The hydraulic gradient ranges from 24 to 200 ft/mile. Therefore, in the Yucca Mountain area the tuffaceous rocks themselves are the principal aquifers. Lithologies of individual tuff units determine their permeabilities and, combined with the local structural setting, determine the flow characteristics of the regional groundwater system.

The details of these flow characteristics are presently being obtained from a series of boreholes (H-holes) drilled specifically for hydrologic purposes in the Yucca Mountain area. Earlier, limited hydrologic data were obtained from holes (G-holes) drilled primarily to determine the lithology and stratigraphic sequence of the tuff units. The distribution of these holes is shown in Figure 33.

Preliminary hydrologic findings of the USGS studies are summarized:

- The discharge area of the volcanic aquifers is in the Amargosa Desert, southwest of Yucca Mountain.

- Groundwater surface contours indicate a general north-to-south gradient, but with a pronounced northward-trending embayment accompanied by locally steeper gradients in the vicinity of the north-south-trending Fortymile Canyon. Such a steep gradient occurs between hole G-2 and holes G-1 and H-1, shown in Figure 33.

- Results of hydrologic modeling to date (summer 1981) indicate that hydraulic heads are greatly affected by low-transmissivity barriers; such a barrier may occur between northern Jackass Flat and Timber Mountain. The hydraulic properties of the Fortymile Wash and Canyon areas have a strong effect on the flow beneath Yucca Mountain to the west and Jackass Flat to the east. The question presently remains: Is Fortymile Canyon a high transmissivity zone?

- Heat flow measurements confirm speculations that the mass flow of meteoric water into the Yucca Mountain tuffs is small: a few millimeters per year. A mass flow of approximately 1 mm/year produces a heat flux roughly equal to the regional heat flow. In the vadose zone, where both water and air are present in void spaces, a downward mass flow can result in condensation and a resulting heat source, or conversely vaporization may result in a heat sink. In holes G-1 and H-1 below depths of approximately 1000 m, the geothermal gradient increases with depth; the observed heat flow is ~1.25 cal cm^{-2} sec^{-1}. Above the water table in hole VH-1, the gradient is approximately 50°C/km, resulting in a heat flow of ~2 cal cm^{-2} sec^{-1}; below the water table, geothermal gradients indicate downward as well as lateral groundwater movement.

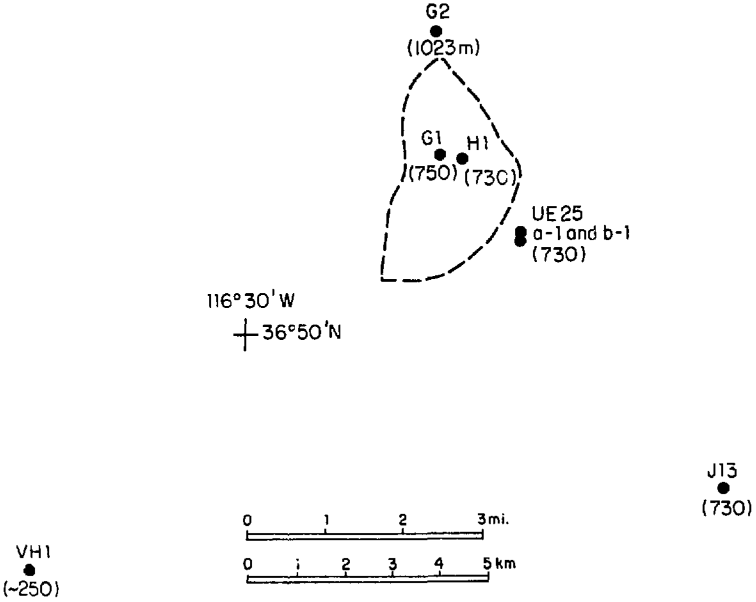


Figure 33. Location of geologic ('G') and hydrologic ('H') holes in the Yucca Mountain area. Elevations (above sea level, in meters) of the standing water level are indicated in parentheses. [XBL 826-2298]

- Table 8 summarizes the hydraulic properties of the tuff on the basis of preliminary information from measurements in holes G-1, H-1, and VH-1. The following general qualitative assessments can be made. In the unsaturated zone, the Topopah Springs unit is strongly fractured and contains lithophysal zones, and is therefore transmissive, but downward water flux is relatively low. In the saturated zone, the upper portions of the Bullfrog unit are highly transmissive, the permeability of the Tram unit is intermediate to high, and the lower tuff units have relatively low transmissivity.

4.2.3 Geologic Hazards

The considerations of the volcanism and seismicity of the Basin and Range province and of alluvial valleys at the NTS are discussed in Sections 3.1.4 and 3.2.4. In general, the considerations for volcanic hazards also hold for the Yucca Mountain setting: the risk of silicic volcanism is very small, the most recent volcanic activity in the region is basaltic (in Crater Flat), and the chance of disruptive volcanism at Yucca Mountain is 10^{-8} to 10^{-9} per year.

Investigations of the seismicity of the Yucca Mountain site area are in progress, and findings as of August 1981 were reported at the NWTS Review Meeting by L. Scully of Sandia, who stated that the primary concern is ground response to underground nuclear weapons testing. Ground motion from some underground tests is equivalent to that from earthquakes of magnitude 5 to 6. From a hypothesized test of 700 kilotons' yield beneath Buckboard Mesa (approximately 30 km north of the Yucca Mountain site), the near-surface ground motion at Yucca Mountain was calculated to be 0.6 g. At depths in tuff comparable to those of the Bullfrog Member of the Crater Flat Tuff, the observed peak acceleration from body waves is usually 1/2 to 1/3 that at the surface; at shallower depths in the unsaturated zone the fraction may be somewhat larger. Scully reported that seismic monitoring is presently underway at Yucca Mountain to see if there is anomalously large ground motion in response to underground tests being conducted in tuffaceous rocks of Pahute Mesa.

4.3 ADVANTAGES AND CONCERNS OF WASTE ISOLATION IN THE VADOSE ZONE OF TUFFACEOUS ROCKS

Some assets, concerns, and unknowns of siting a repository in tuff above the water table are listed in Table 9. Several of the advantages of waste isolation in the vadose zone of alluvium in arid regions discussed in Section 3.3 also pertain to isolation in tuffaceous rock: low moisture flux, high sorptive capacity, and substantial thickness of rock above the water table. Specific to tuff is the attribute of having competent rock units amenable to machine mining and requiring minimal ground support in underground workings, sandwiched between less competent but highly sorptive zeolitized units.

Table 8. Hydraulic properties of tuffaceous units.[a]

Hole	Standing water elevation (a.s.l.)	Standing water depth, below surface	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)
G-1 drilled w/mud	750 m	557 m	5 (in saturated zone)	10^{-4} to 10^{-6} based on injection test in packed-off zones
H-1	730 m	573 m	150 in Prow Pass unit, 1 in deeper zones	Relatively high in Prow Pass and top part of Bullfrog; 10^{-5} to 10^{-6} in deeper zones
VH-1[b]	250 m	183 m	2400	avg. 5.6

[a] From presentation of USGS personnel at the NNWSI Review Meeting, August 1981.

[b] Unable to set packers, so transmissivity and conductivity are for the entire length of hole. However, the principal aquifer here is thought to consist of the Tiva Canyon-Topopah units.

Table 9. Assets, concerns, and unknowns of siting a repository in tuffaceous rock above the water table at Yucca Mountain.[a]

Assets	Concerns	Unknowns
Low downward or lateral water flux	Variations (rise) in water level with climatic changes	Rate of water influx (probably not high)
Approximately 600 m to water table	Human intrusion	Amount of potential water rise (probably not significant)
Good thermal and strength properties in welded zones	Presence of fractured and lithophysal zones in some welded horizons and their effects on drainage	Water quality
Relatively low cost of construction compared to below water table (in fractured welded unit)	Zones of relatively low thermal conductivity and low strength	Reliability and applicability of models
	Possible enhancement of movement of radionuclide gases if a vapor phase is formed by heating of partially saturated rock	Flow paths to accessible environment (until accessible environment is defined)

[a] Based partly on presentations by USGS personnel at NNWSI review meeting, August 1981.

It is emphasized that even though tuffs underlie highland areas, the depths at which a repository would be located should be determined primarily by the occurrence of a favorable stratigraphic setting. Whether the repository is in tuff situated within a topographic high (a mesa or range) or situated well below the local topographic relief is of less importance than its location above the water table in a competent tuff unit encompassed by zeolitized units. It is conceivable that a favorable setting might be a tuff unit overlain by alluvium beneath a Basin and Range Valley (Winograd, 1981).

The hydrological properties of densely welded, strongly fractured tuff units which may also contain lithophysal zones are of concern insofar as they influence drainage around a repository. In this case, considerations of rock mass permeability, in the context of waste isolation, would be similar to those for other hard rock types: principally the effect of heating on the near- and mid-field hydrologic system. The coupled thermomechanical-hydrological effects of heating must also be taken into careful consideration.

Climatological considerations for tuff are essentially the same as those for alluvium: significantly increased moisture infiltration rates in a future pluvial period may affect the position of the water table. However, as with alluvial areas in arid regions, the effect of even a doubling of the infiltration rate should be insignificant, because the rates are so low, and the additional vegetative cover would enhance evapotranspiration.

Thermal considerations with regard to thermal loading and the size of the repository are of less concern for tuff than for alluvium because of the significantly higher thermal conductivity of dry or partially saturated tuff units. However, the structural stability of some tuff minerals in response to heating is of some concern. A loss of strength of up to 30% may occur if poorly welded zeolitized tuff is heated to > 200°C. Non-zeolitized, strongly welded tuff is much less affected by heating--an attribute in siting a repository in this type of tuff unit.

The formation of a vapor phase in response to heating of unsaturated tuff and the ramifications of its effects on radionuclide transport are not well understood and should be assessed by appropriate calculations and experiments.

Unless the site is unfortunately located in or closely adjacent to a caldera which will have volcanic activity associated with it in the near geologic future (a possibility which should be laid to rest by appropriate geological and geophysical investigations in the course of site selection), the concerns of volcanism and seismicity are similar to those for the case of an alluvial repository. Obviously, the location of the repository astride an active Basin and Range fault must be avoided; otherwise, the response of surface and underground facilities to ground motion associated with earthquakes of given magnitude and epicentral distance should be assessed for given site locations, and these should be taken into account in the design of the facilities.

Compared with alluvial sites, there is a greater potential for conflict of a waste repository location wih mineral resource potential in the tuffaceous rocks. The occurrence of precious metals is relatively widespread in ash-flow tuffs associated with magmatic-hydrothermal systems of Tertiary calderas. A resource assessment should therefore be an important part of the site investigations.

5. CONCLUSIONS

Carefully selected sites in the vadose zone, either in alluvium or tuff, would generally fulfill the repositorv requirements expressed in Section 2.

A major advantage of locating a repository in the vadose zone in an arid region is that groundwater access to the repository and transport from it would be minimal. Some tuff sequences and alluvial deposits in some valleys are sufficiently thick, and depths to the water table sufficiently great, that a repository could be sited at a depth of several hundred meters, and the most direct groundwater flow path to the saturated zone would still be several hundred meters below the repository.

The composition of alluvium in tuffaceous bedrock regions, and of the tuff itself, favors the retention of radionuclides in the vicinity of the repository because of the presence of highly sorptive minerals.

The climatological record indicates that, though conditions were considerably wetter during past pluvial periods, most of the lower slopes and valleys of the Basin and Range province would be arid to semiarid in future pluvial periods of similar magnitude.

With an assumed thermal loading on the order of 40 kW/acre, a partially saturated tuff setting would permit a repository of roughly the same size as that envisioned for saturated conditions. In dry alluvium, approximately twice the area of a repository in saturated hard rock might be required.

Because the Basin and Range province is tectonically active and has a relatively recent history of volcanism, sites selected there would require careful consideration of their seismic response characteristics and of their position with respect to areas of recent volcanism. Siting of a repository in alluvium on the basinward side of an active normal fault may be advantageous because rapid sedimentation would increase the thickness of cover.

Preparation of repository workings and subsequent ground support in alluvium (less than 200 m depth) or tuff would be comparable to other proposed hard rock mined repositories, judging by experience in these environments at the NTS.

The Basin and Range province is a region of relatively low population density, and though its mineral resource potential in places is high, especially in tuffaceous rocks, large areas exist where the near- and long-term mineral resource potential is minimal. At locations in these areas it is expected that the probability of future human intrusion is low. Because conditions would remain relatively arid in the Basin and Range valleys, even in future pluvial periods, and the site would be located where the water table depth is great, the possibilities of future agricultural activities are also low.

In comparing the attributes of waste isolation in the unsaturated zone of arid regions and saturated hydrologic regimes, major advantages and concerns are clearly identifiable in the considerations of transport of radionuclides, thermal effects, and the potential for human intrusion. These are presented briefly in Table 10. Given appropriate study, beyond the scope of this report, similar comparisons of advantages and concerns of unsaturated and saturated regimes may be made for the considerations of the effects on the waste form, its surrounding canister, and the overpack material. Considerations would include the effect of saturated and unsaturated conditions at repository temperature and pressure on (1) corrosion of the canisters, (2) the leaching of waste forms, and (3) the mechanical and hydrological integrity of overpack, backfill, and sealing material. Borehole and shaft plugs and seals associated with a repository in an unsaturated environment would be required, but their level of performance would not be as critical as that of plugs and seals in a repository in the saturated regime.

It is concluded that the unsaturated zones in alluvium or tuffaceous rocks of the Basin and Range province are strong candidate environments for consideration as sites for nuclear waste repositories, and as such should be investigated as comprehensively as the other geologic settings presently being considered.

5.1. TOPICS FOR FURTHER INVESTIGATION

From the preceeding discussions it has become evident that several topics require further investigation in order to properly appraise the aspects of waste isolation in the vadose zone.

- The state of the art of modeling flow in the unsaturated zone needs to be evaluated. Emphasis should be on modeling intergranular flow and flow through fractures in unsaturated conditions and comparison with flow under saturated conditions.

- It is necessary to determine thermomechanical properties of alluvium and tuffaceous rock as functions of varying degrees of saturation in order to calculate the thermomechanical response of these rock types.

- The effects of the unsaturated zone on the waste package and waste form need to be investigated. Pertinent questions are: In the high-temperature environment expected near the canisters, is corrosion of the canister enhanced in unsaturated conditions? What are the effects of the vapor phase on corrosion of the canisters? Should backfill/overpack be designed to ensure constant moisture content of the material in the immediate vicinity of the canisters? If the canister is breached is the waste form more easily leached if the water content and water chemistry vary over time as they might in the unsaturated zone? What waste forms might be most resistant to leaching in conditions of varying saturation?

- Thermal effects associated with a repository in the unsaturated zone need to be evaluated in detail. Though the overall repository temp-

Table 10. Major advantages and concerns of waste isolation in unsaturated and saturated regimes.

	Major advantages	Major concerns
	Thermal Effects	
Unsaturated zone in arid regions	Relatively shallow emplacement of waste will result in lower repository temperature earlier in the life of the repository, compared to deeper burial in a given medium. Diffusion of water vapor in response to heating may result in bulk thermal conductivity comparable to that of saturated material.	At relatively low temperatures, bulk thermal conductivity will depend on the degree of saturation. Variations in thermal conductivity will control maximum temperature rise experienced in a repository for a given waste form and thermal loading. Data on thermal expansion of unsaturated media are scarce. Formation of vapor phase in response to heating and its ramifications for radionuclide transport are not well understood.
Saturated zone	Mechanical and hydrological responses of saturated (or nearly saturated) media to heating are becoming better understood as experiments progress in various rock types.	Potential exists for formation of convective cells in the hydrologic system of saturated media in response to heating.
	Transport of Radionuclides	
Unsaturated zone in arid regions	Repository not in direct contact with groundwater regime; wastes would remain hydrologically isolated as long as partially saturated conditions persisted.	Difficulty in predictive modeling of mechanisms of transport and pathways of radionuclides in unsaturated regimes. Degree of saturation may vary.
Saturated zone	Deep burial affords long pathways for radionuclides to the accessible environment. Mechanisms of transport of radionuclides in saturated rocks are presently better understood than are transport mechanisms in the unsaturated zone.	Direct contact of the repository with the groundwater regime that could transport radionuclides to the accessible environment.
	Potential for Human Intrusion	
Unsaturated zone	Generally low population density; little potential conflict with future utilization of groundwater resources.	Relatively shallow emplacement of waste compared with deep burial below water table.
Saturated zone	Deep burial decreases likelihood of human intrusion.	Possible future development of groundwater resources in the vicinity of the repository where aquifers occur.

erature may remain below 100°C, local heating to a greater-than-boiling temperature in a partly saturated environment will result in formation of a vapor phase in the immediate vicinity of the canisters. The ramifications of driving off moisture in response to heating and the time required for return to original moisture content should be assessed. Convective systems may be set up incorporating a vapor as well as a liquid phase. The effects these systems may have on the movement of radionuclides (including the potential for outgassing at the surface) and on the integrity of engineered barriers should be investigated.

- Evaluation of the state of the art of modeling two-phase flow in the vadose zone is needed, followed by formulation of appropriate models incorporating hydrological and thermomechanical considerations.

APPENDIX

THERMAL CALCULATIONS FOR RADIOACTIVE WASTE REPOSITORIES IN ALLUVIUM AND TUFF

J.S.Y. Wang and C.F. Tsang

A.1 INTRODUCTION

The unsaturated zones in alluvium and tuff are among the environments being considered for a nuclear waste repository. Within the Great Basin, including the Nevada Test Site (NTS), valleys with alluvial thicknesses of up to 600 m (Smyth et al., 1979) and stratified tuff formations at depths greater than 700 m (Bulmer and Lappin, 1980) are being evaluated as repository sites. The suitability of these rock types to dissipate the waste heat is an important consideration in the evaluation. The low thermal conductivities of these rocks, especially under partially saturated conditions, are the primary concern. This report presents two sets of calculations, one for each rock type, to obtain the dependence of repository temperature on a range of thermal conductivities as well as on different waste types, repository depths, and repository sizes. The dependence of the repository temperature rise on water saturation will also be discussed.

A.2 THE REPOSITORY

The standardized repository discussed in the "Statement of Position" (Department of Energy, 1980) has the following characteristics:

Waste:	Spent fuel: 10 years old
Repository:	Thermal Loading: 40 kW/acre Area: 2000 acres
	Total Capacity: 68,000 MTHM or 160,000 canisters

The reprocessed wastes with plutonium and uranium removed from the spent fuel are also being considered as a principal waste form. Figure A1 compares the waste heat power densities of spent fuel and reprocessed waste originated from the same amount of fuel, 1 metric ton of heavy metal (MTHM), charged to a pressurized water reactor (PWR) (Kisner et al., 1978). The spent fuel, with higher heat power from long-lived actinides, will result in higher temperatures at long times.

To study the long-term changes, the repository is idealized to be a flat circular disk loaded uniformly with nuclear waste at time t = 0. The principal mode of the heat transfer from the nuclear waste to the rock mass is assumed to be by heat conduction, controlled by the constant thermal conductivity and heat capacity of the rock. A semianalytic program is used to calculate the temperature field below the ground surface (Wang et al., 1981).

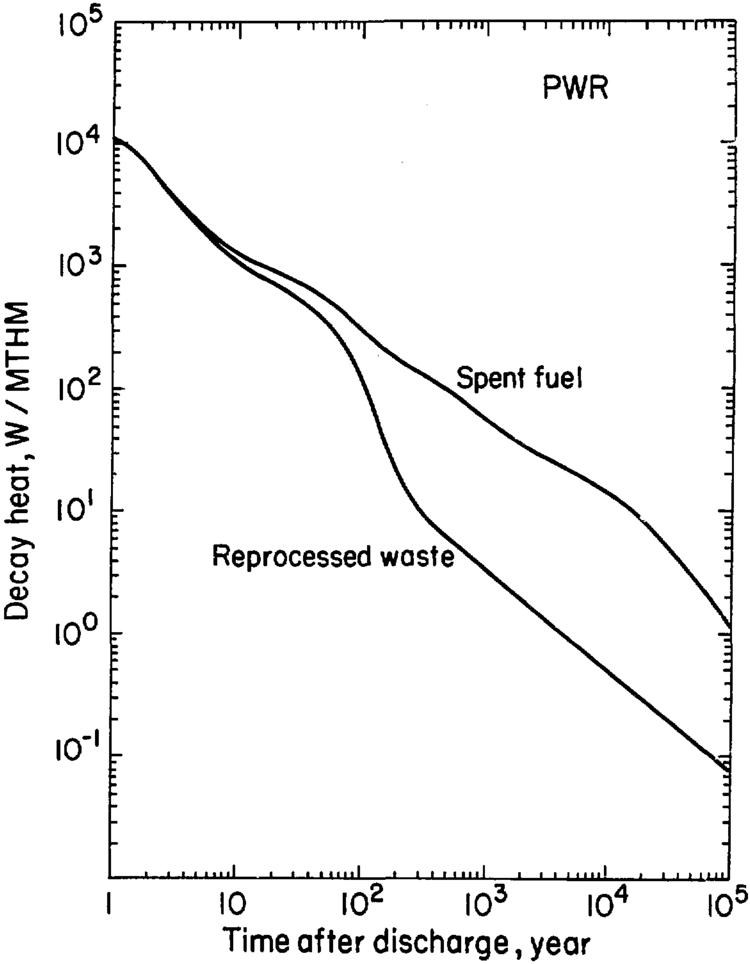


Figure A1. Power densities of spent fuel and reprocessed waste originated from the same amount of fuel (1 MTHM) charged to a PWR.
[XBL 8111-4881]

A.3 ALLUVIUM

The baseline case for a repository in alluvium calculated in this work has the following characteristics:

Repository:	Depth: 150 m
	Area: 2000 acres (radius = 1605 m)
Rock:	Thermal conductivity: 1 W/m°C
	Specific Heat: 1000 J/kg°C*
	Density: 1600 kg/m^3

The disk heat source, of radius 1605 m and at depth 150 m, represents a mined repository in an alluvium-filled valley (for example, Yucca, Frenchman, or Jackass Flats in Nevada). A backfilled repository using a smaller and shallower man-made crater has also been suggested as an alternative scheme (Winograd, 1981).

The values of the rock thermal properties are based on a review of measurements in the literature. Figure A2 is the histogram of one set of thermal conductivity data obtained by in situ probes in 12 holes at the southern Black Rock Desert, Nevada (Sass et al., 1979a). These results and other values measured in the laboratory with cores or rock chip samples from heat flow holes at various sites are summarized in Table A1. These measurements are mainly from areas outside geothermal anomalies where the conductive transfer controls the heat flow. The thermal conductivities of rock chips from laboratory measurements represent the intact rock values and are generally higher than the bulk thermal conductivity of a porous rock mass. If the rock mass is partially saturated, some pores are water filled while others are occupied only by low-conductivity air. The value 1 W/m°C is chosen for the baseline case in this study to represent typical alluvium. To evaluate the sensitivity of the temperature rise to thermal conductivity, a lower value of 0.5 W/m°C is used to represent partially dry alluvium, while a higher value of 1.5 W/m°C is employed for high-porosity alluvium saturated with water. It is of interest to note that 0.2 W/m°C was chosen as the lower limit for dry *alluvium in general, 0.5 to 0.8 W/m°C for unsaturated unconsolidated alluvium,* and 1.0 to 1.2 W/m°C for indurated unsaturated alluvium by Smyth et al. (1979).

The density value (1200 kg/m^3) used by Smyth et al. (1979) in modeling the thermal response of alluvium may be too low to represent partially saturated, consolidated alluvium at depth. A density of 1570 kg/m^3 was measured for a 175-m-deep sample in the Ue3-ct hole at the Merlin test or the NTS (Bonner et al., 1972), and a mean value of 1870 kg/m^3 was determined by Ramspott and Howard (1975) for Yucca Flat alluvium. A value of 1600 kg/m^3 was used in calculations for this report. According to the

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*Specific heat from Smyth et al. (1979).

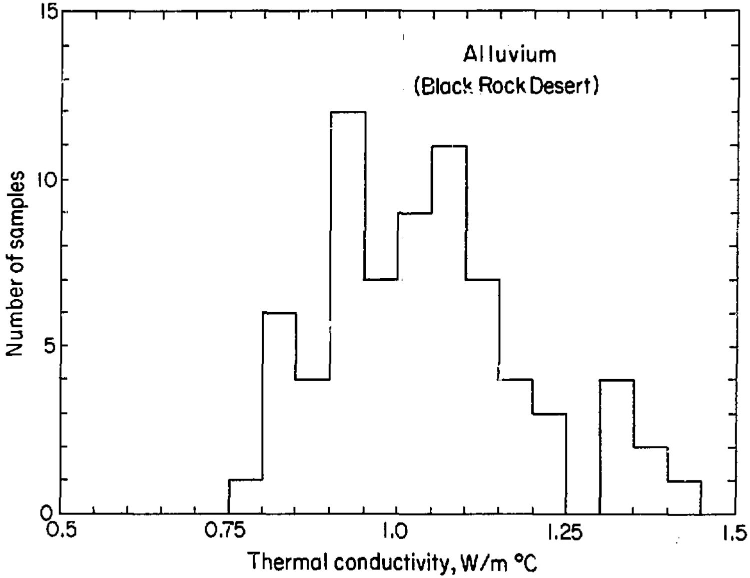

Figure A2. Thermal conductivities measured in situ in the southern Black Rock Desert (average value = 1.05 ± 0.15 W/m°C), 71 samples over 12 holes (data from Sass et al., 1979a). [XBL 8111-4849]

Table A1. Thermal conductivities of alluvium.

Location	Number of holes	Method of measurement	Range of mean value[a] (W/m°C)	References
Black Rock Desert[b]	12	Downhole probes	0.91-1.14	Sass et al. (1979b)
Black Rock Desert[b]	4	Chips[c]	1.19-1.41	Mase and Sass (1980)
Buffalo Valley[b]	2	Cores[c]	0.98-1.42	Sass et al. (1976a)
Grass Valley[b]	7	Cores or chips[c]	1.21-1.81	Sass et al. (1976a)
Saline Valley[b]	8	Cores or chips[c]	1.51-2.00	Mase et al. (1979)

[a] Harmonic mean value of thermal conductivity for each hole.

[b] In situ measurements in the Black Rock Desert were in holes drilled in fine-grained unconsolidated lake sediments, containing abundant clay and some sandy layers a few centimeters thick (Sass et al, 1979a). Cores and chips measured from the western arm of the Black Rock Desert and from Buffalo, Grass, and Saline Valleys consisted predominantly of silty alluvium with varying amounts of sand and clay.

[c] The thermal conductivity of the rock is deduced from those of solid rock and water phases by the geometric mean model:

$$K = K_{\text{rock}}^{(1-\phi)} K_{\text{water}}^{\phi} ,$$

where the porosity ϕ is assumed to be 0.3. The measurements on cores and chips are made at saturated conditions (J. Sass, private communication, 1981).

analytic formula expressed in Section A5, the maximum repository temperature will vary inversely with the square root of the product of density, conductivity, and specific heat. Therefore, depending on site conditions, the maximum temperature can be scaled accordingly.

In our calculations, the following parametric variations were studied:

1. Effects of different thermal conductivities (Fig. A3):

   0.5 W/m°C
   1.0 W/m°C
   1.5 W/m°C

2. Effects of different waste types (Fig. A4):

   spent fuel
   reprocessed waste

3. Effects of repository depths (Fig. A5):

   150 m
   300 m
   450 m
   600 m

4. Effect of repository sizes (Fig. A6):

   500 acres
   2000 acres
   8000 acres

The average repository temperature rises are found to be insensitive to the repository depths and sizes, as shown in Figures A5 and A6. Since the repository model in this study assumes a uniformly distributed thermal load, the maximum temperatures in Table A2 are average temperatures. The actual maximum temperature will depend strongly on the emplacement geometry. The dependence of the maximum temperature rises in Figures A3 and A4 on thermal conductivities and waste types are summarized in Table A2. These results will be discussed after we present similar calculations for tuff. The dependence of repository temperature on repository depth after hundreds of years, shown in Figure A5, results from the heat leakage to the atmosphere. The rock between the repository and the ground surface can be regarded as an insulating layer. The deeper the repository, the thicker the layer; therefore, more heat remains in the rock for a longer period, resulting in a higher temperature in the repository. A similar mechanism controls the areal dependence of repository temperature, shown in Figure A6. The influence of lateral heat transfer to the surrounding geologic setting is less for a larger repository and results in somewhat higher temperatures thousands of years after waste emplacement.

Table A2: Temperature rises in alluvium repository.[a]

Thermal conductivity (W/m°C)	Waste type	ΔT^{max} (°C)	Time of occurrence (year)
0.5	Spent fuel	130.0	58
1.0	Spent fuel	91.9	58
1.5	Spent fuel	75.0	58
1.0	Reprocessed waste	75.6	35

[a] Thermal loading 40 kW/acre, 10-year old waste, specific heat 1000 J/kg°C, density 1600 kg/m^3.

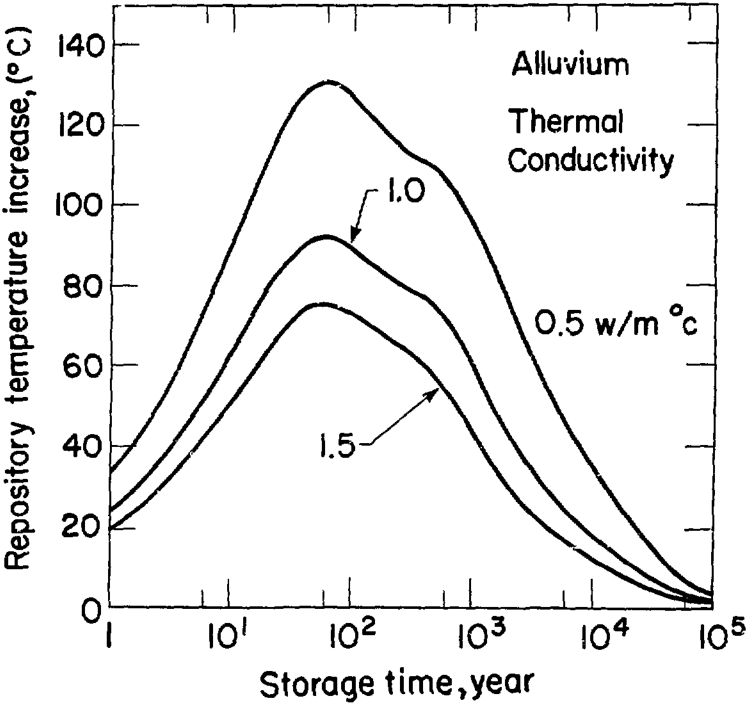

Figure A3. Effects of thermal conductivities on alluvium repository temperature. [XBL 825-1391]

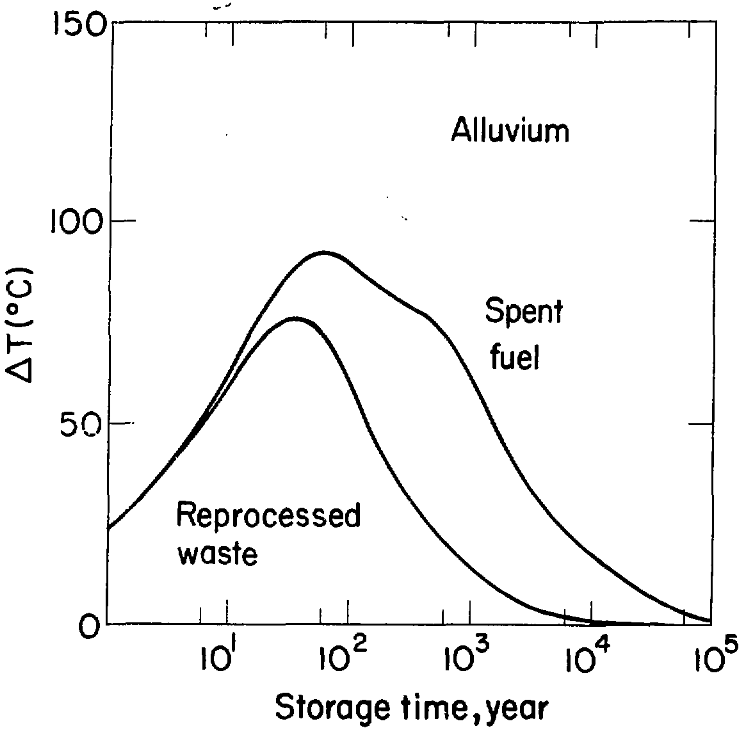

Figure A4. Effects of waste types on alluvium repository temperature. [XBL 825-1390]

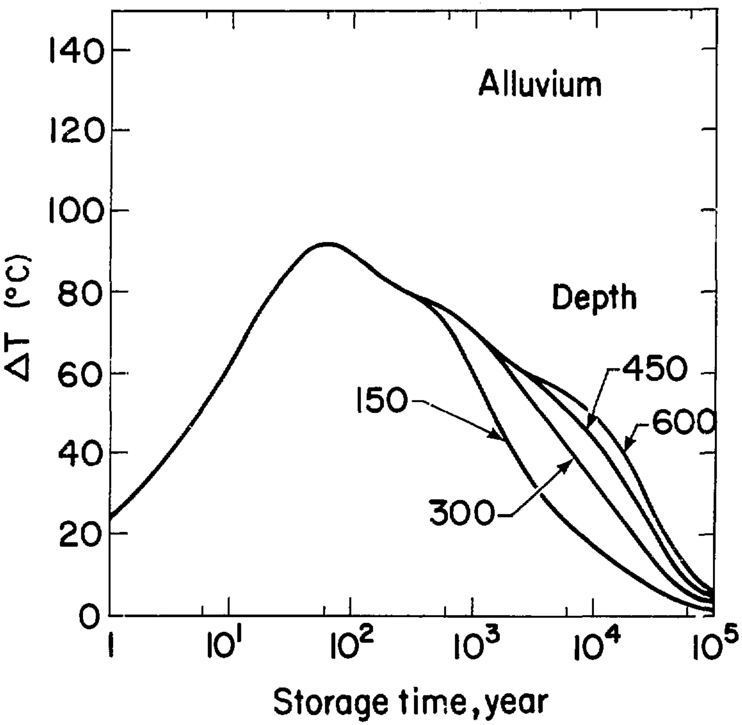

Figure A5. Effects of repository depths on alluvium repository temperature. [XBL 825-1389]

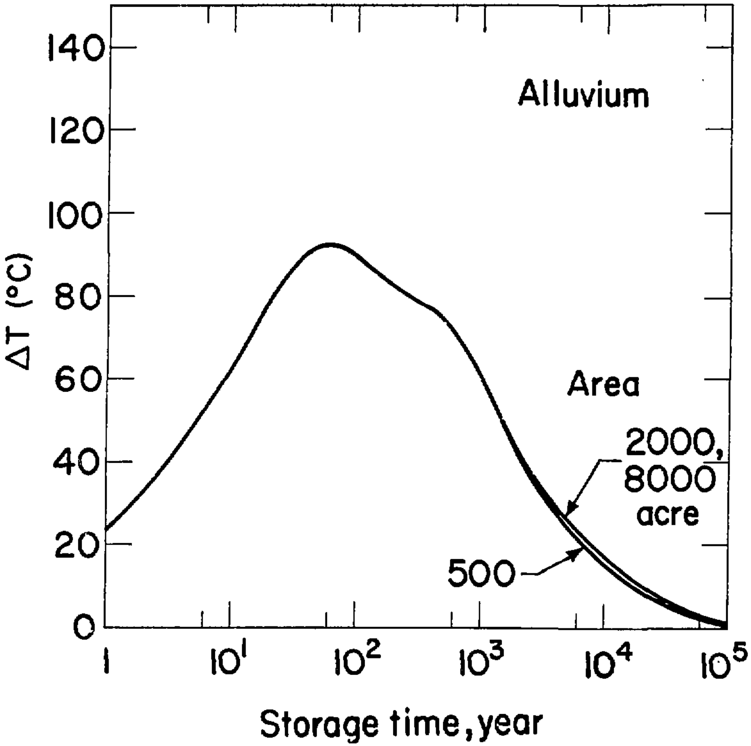

Figure A6. Effects of repository size on alluvium repository temperature. [XBL 825-1378]

A.4 TUFF

The baseline case for a repository in tuff calculated in this work has the following characteristics:

Repository:	Depth: 800 m
	Area: 2000 acres (radius 1605 m)
Rock:	Thermal conductivity: 1.8 W/m°C
	Specific heat: 837 J/kg°C
	Density: 2350 kg/m^3

The National Waste Terminal Storage Program has considered an 800-m depth for the reference repository in tuff (Raines et al., 1980). The thermal properties represent the Bullfrog Member of Crater Flat Tuff below 711 m, which was encountered in the Yucca Mountain exploratory hole UE25A-1 (Bulmer and Lappin, 1980). The Bullfrog tuff is partially welded and is below the water table. The shallower welded tuff layer of the Topopah Spring Member, at a depth of 84 to 401 m, is assumed to be 80% saturated and to have the same thermal conductivity, 1.8 W/m°C. This value agrees with the mean value of the Sass and Munroe data shown in Figure A7 (Touloukian and Ho, 1981).

The following parametric variations were studied:

1. Effects of different thermal conductivities (Fig. A8):

    0.9 W/m°C
    1.8 W/m°C
    2.7 W/m°C

2. Effects of different waste types (Fig. A9):

    spent fuel
    reprocessed waste

3. Effects of repository depths (Fig. A10):

    400 m
    800 m
    1200 m
    1600 m

4. Effects of repository sizes (Fig. A11):

    500 acres
    2000 acres
    8000 acres

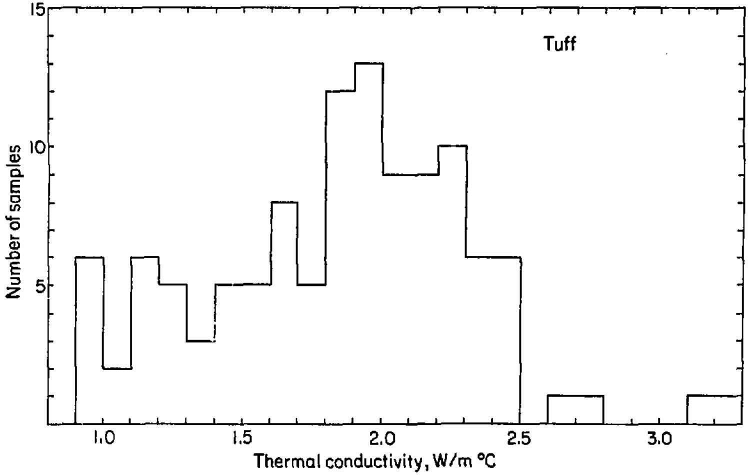

Figure A7. Histogram of the thermal conductivity of tuff (after data by Sass and Munroe in Touloukian and Ho, 1981). [XBL 8111-4850]

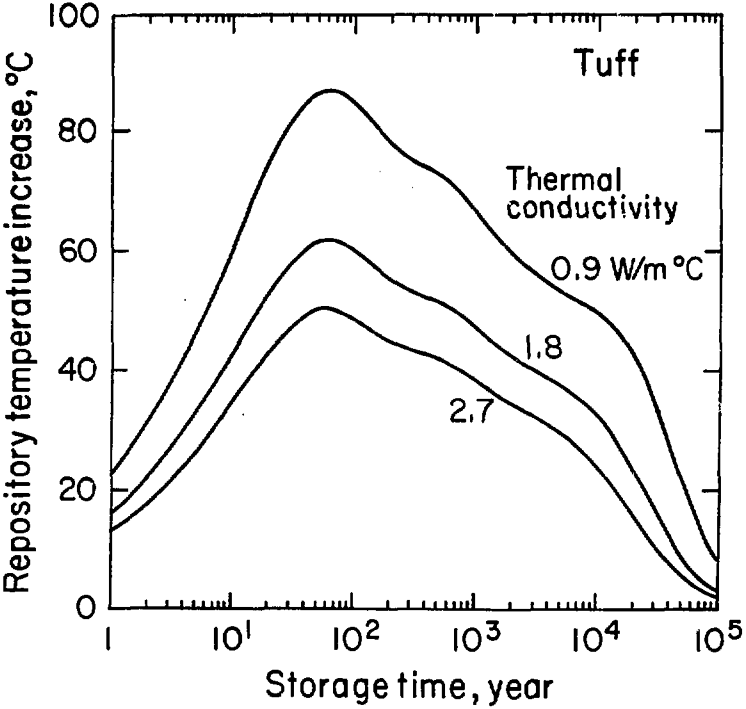

Figure A8. Effects of thermal conductivities on tuff repository temperature. [XBL 8112-4888]

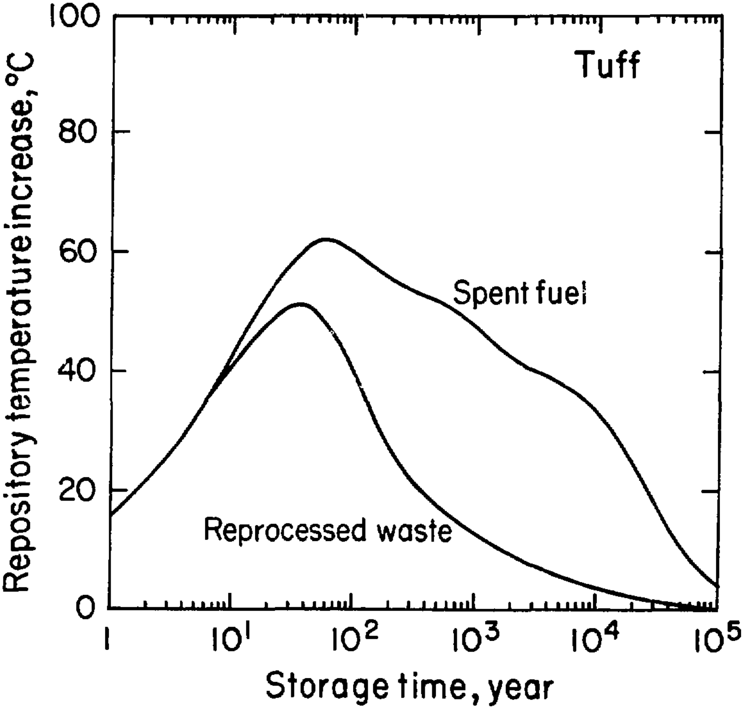

Figure A9. Effects of waste types on tuff repository temperature. [XBL 8112-4887]

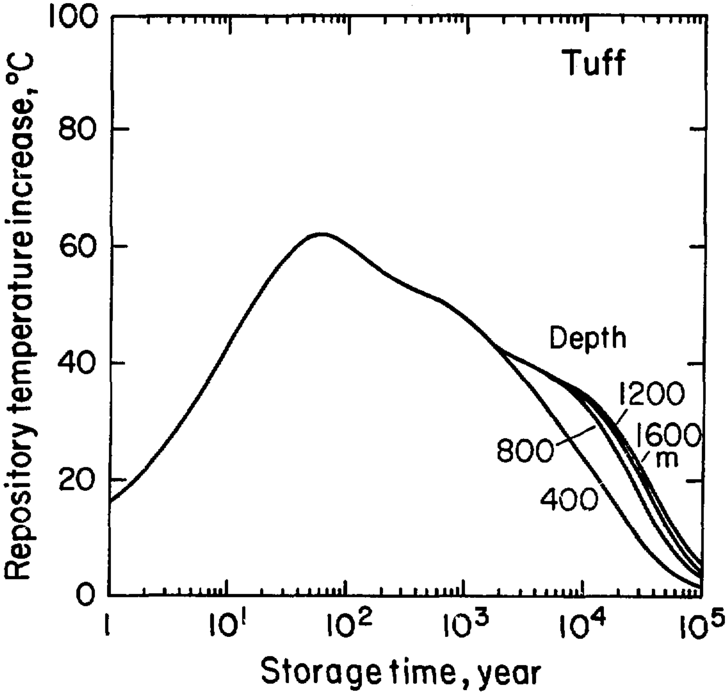

Figure A10. Effects of repository depths on tuff repository temperature.
[XBL 8112-4886]

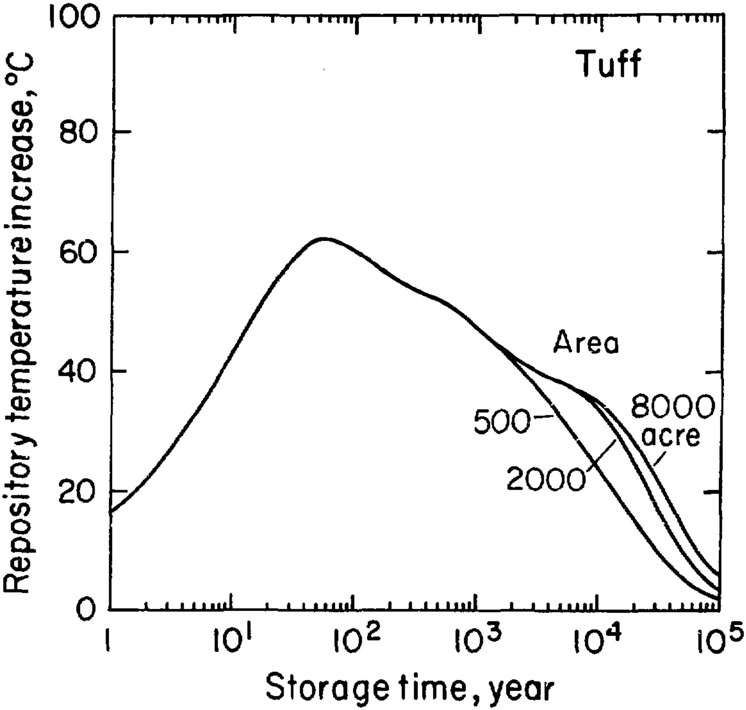

Figure A11. Effects of repository size on tuff repository temperature. [XBL 8112-4885]

As with alluvium, the repository temperature rises are insensitive to the repository depths and radii, as shown in Figures A10 and A11. The dependence of the maximum temperature rises in Figures A8 and A9 on thermal conductivities and waste types are summarized in Table A3. The maximum temperatures in this table are average repository temperatures, calculated with the model of a uniformly distributed thermal load.

A.5 ANALYTIC FORMULA

A simple formula was derived to illustrate the dependence of the maximum repository temperature on the thermal loading and thermal properties of the rock medium. If the heat power of the radioactive waste is represented by a single exponential function, the maximum repository temperature is

$$\Delta T^{max} = 0.3 \frac{Q_r(0)}{\sqrt{K\rho c \lambda}},$$

where $Q_r(0)$ = thermal loading density, W/m^2,

K = thermal conductivity, $W/m^\circ C$,

ρ = rock density, kg/m^3,

c = specific heat, $J/kg^\circ C$,

λ = decay constant, $\ln(2)/t_{1/2}$, sec^{-1}.

The single exponential function with a 30-year half-life has been used in the literature to represent the decay of reprocessed wastes. For spent fuel, additional exponential terms are needed to represent the temporal change of heat power decay. The equation above underestimates the maximum temperature for spent fuel. However, the scaling of temperature rise with

$$\frac{1}{\sqrt{K\rho c}}$$

is a good approximation.

Thus, the maximum repository temperature for spent fuel and reprocessed waste can be approximated by

$$\Delta T^{max} = \frac{0.3\ Q_r(0)\sqrt{t_{max}}}{\sqrt{K\rho c}},$$

where t_{max} = 58 years for spent fuel and t_{max} = 35 years for reprocessed waste. This formula has been checked against the results for alluvium and

Table A3. Temperature rises in tuff repository.[a]

Thermal conductivity (W/m°C)	Waste type	ΔT^{max} (°C)	Time of occurrence (year)
0.9	Spent fuel	87.4	58
1.8	Spent fuel	61.8	58
2.7	Spent fuel	50.5	58
1.8	Reprocessed waste	50.8	35

[a] Thermal loading 40 kW/acre, 10-year old waste, specific heat 837 J/kg°C, density 2350 kg/m^3.

tuff, as well as results for granite, basalt, and shale (Wang et al., 1981). Thus this formula gives a simple, quick estimate of the expected maximum temperature.

A.6. UNSATURATED ROCKS

For rocks with high porosity (approximately 0.3 for alluvium and 0.18 for Bullfrog tuff), the key parameter, thermal conductivity, depends sensitively on the degree of water saturation. If the rock mass is dry, the pore spaces will be filled with air. Dead air is a poor thermal conductor in comparison with water. The ratio of conductivities is $K_{water}/K_{air} = 24.83$ (Carslaw and Jaeger, 1959).

The functional dependence of the thermal conductivity on water saturation is likely to be rock specific and site specific. Many models have been proposed in the literature to determine the effective thermal conductivity of the rock-water mixture. The weighted arithmetic mean for parallel element distribution and the weighted harmonic mean for series element distribution result in maximum and minimum effective conductivity, respectively (Woodside and Messmer, 1961a). The weighted geometric mean model has no established physical basis, yet it seems to work well over a wide range of porosities (Touloukian and Ho, 1981). The thermal conductivities of several quartz-rich, consolidated sandstones of different porosities are shown in Figure A12.

For unsaturated rocks, the generalization of the different rock-water weighted means to a rock-water-air mixture are:

Arithmetic:

$$K = (1-\phi)\,K_{rock} + \phi S\,K_{water} + \phi(1-S)\,K_{air}$$

$$= K_{wet} - \phi(1-S)\,(K_{water} - K_{air}),$$

Geometric:

$$K = K_{rock}^{(1-\phi)}\,K_{water}^{\phi S}\,K_{air}^{\phi(1-S)}$$

$$= K_{wet}\left(\frac{K_{air}}{K_{water}}\right)^{\phi(1-S)},$$

Harmonic:

$$\left[K = \frac{1-\phi}{K_{rock}} + \frac{\phi S}{K_{water}} + \frac{\phi(1-S)}{K_{air}}\right]^{-1}$$

$$= \left[\frac{1}{K_{wet}} + \phi(1-S)\,\frac{1}{K_{air}} - \frac{1}{K_{water}}\right]^{-1},$$

where K_{wet} is the conductivity for saturated rock with saturation $S = 1$.

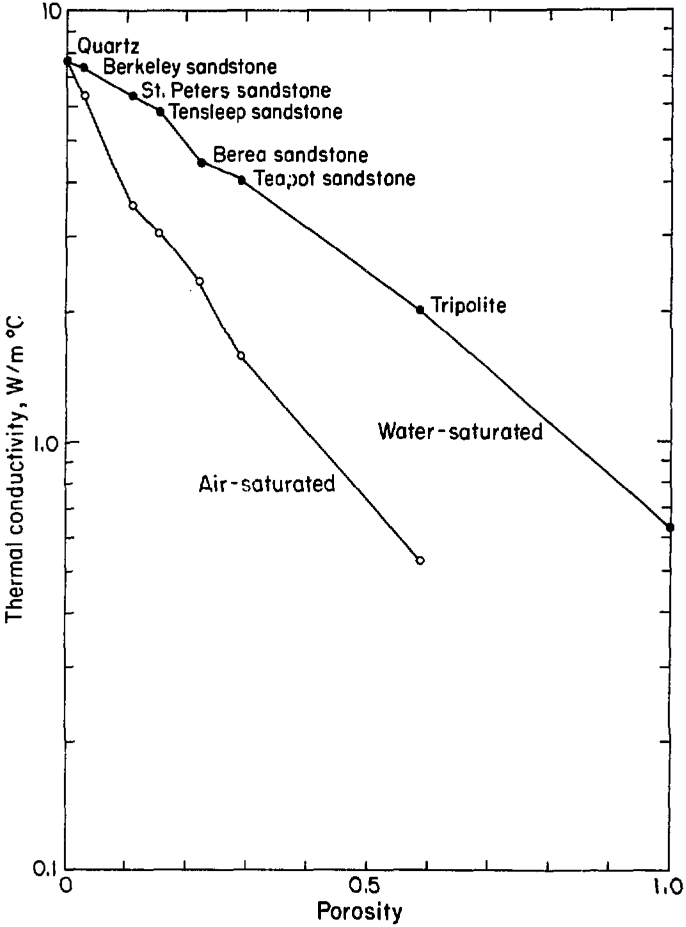

Figure A12. Thermal conductivities of quartz-rich, consolidated sandstones (data from Woodside and Messmer, 1961b). [XBL 8111-4882]

Figure A13 illustrates the dependence of the ratio of the effective thermal conductivity of the unsaturated rock to that of the saturated rock, K/K_{wet}, on the water saturation. The value $K_{wet} = 1$ W/m°C and the porosity $\phi = 0.3$ are assumed. These results indicate that the estimation of the effective thermal conductivity depends on the model chosen. Careful measurements should be made to determine the thermal conductivities of partially saturated rocks for the given conditions at specific sites.

These models describing the dependence of thermal conductivity on liquid saturation do not take into account the contributions by water vapor. The transport of latent heat by water vapor driven by temperature gradients can effectively increase the thermal conductivity of unsaturated rocks. Therefore, the models used in this study underestimate the apparent thermal conductivity of unsaturated rocks. Experimental study in the moderate temperature range 25 to 45°C by Sepaskhah and Boersma (1979) and a theoretical model by DeVries (1963) indicated that the apparent thermal conductivity of earth materials with a liquid saturation of 0.2 to 0.5 can equal or even exceed the liquid-saturated thermal conductivity (comment on this report by D. Pollock, USGS). The unsaturated flow systems in this temperature range of interest have not been extensively documented in the literature (Childs and Malstaff, 1982).

The increase in repository temperature with a decrease in the degree of saturation of the rock was determined by using the geometric mean model for the dependence of the thermal conductivity on the water saturation and the inverse square root dependence of the maximum repository temperature on thermal conductivity. The result is shown in Figure A14. The validity of this dependence should be carefully studied as more data are obtained for alluvium and tuff at potential repository sites.

A.7 DISCUSSION

Unsaturated alluvium and tuff are potential host rocks for radioactive waste isolation in the Great Basin, and especially within the NTS. If vapor transport of radionuclides is slow, a thick unsaturated formation could be an effective medium for a waste repository. However, the advantage of a dry medium is questionable because of its low thermal conductivity, which results in a higher temperature rise in response to waste loading. On the other hand, the liquid convection induced by the waste heat is less likely to be a potential mechanism for the transport of radionuclides to the accessible environment in an unsaturated rock mass.

Temperature rises can be reduced by lowering the thermal loading. The thermal loading can be decreased by a combination of surface storage (Wang et al., 1981) and increased spacing between waste canisters. The allowable loading depends on the thermal criteria used in the repository design. The allowable thermal loadings for wet and dry alluvium and tuff (with a <100°C-average-rock-temperature restriction) are summarized in Table A4. A preliminary estimate of the worst case is, therefore, dry alluvium with a thermal conductivity of 0.38 W/m°C, which can accommodate 51% of the thermal loading of a standardized 40-kW/acre repository.

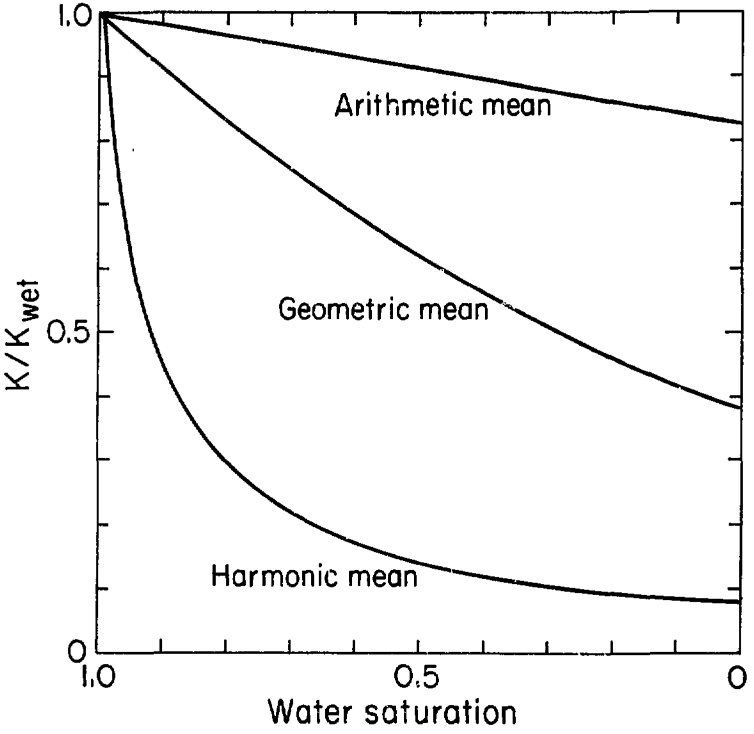

Figure A13. Ratio of the effective thermal conductivity of unsaturated rock to that of the saturated rock deduced from different weighting models. [XBL 8112-4884]

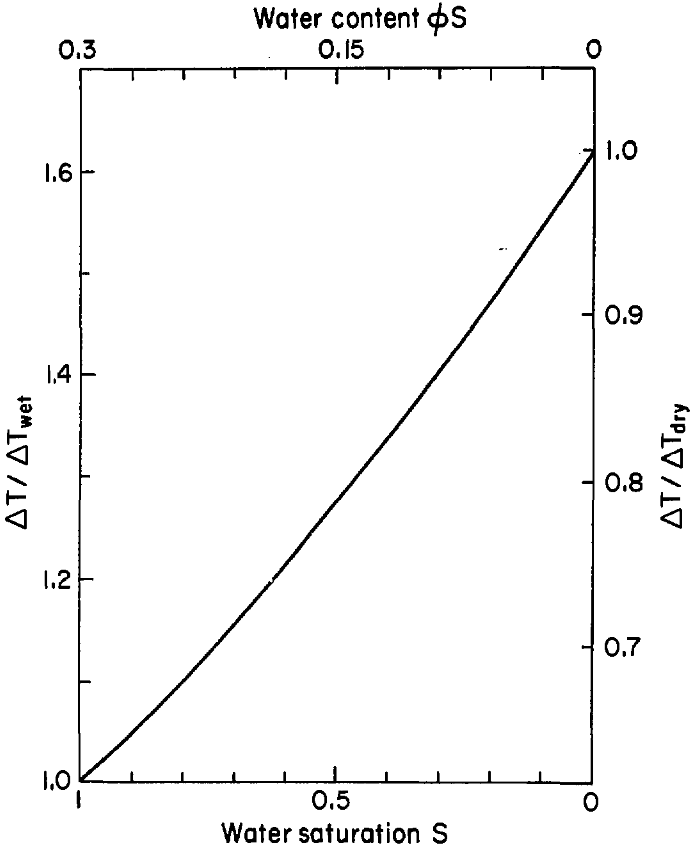

Figure A14. Increase in repository temperature in a dry rock medium based on geometric mean model. [XBL 8111-4883]

Table A4. Thermal loading determined by 100°C criterion.[a]

Rock	Thermal conductivity W/m°C	Thermal loading[b] (kW/acre)	Ratio to 40 kW/acre
Dry alluvium	0.38[b]	20.3	0.51
Alluvium	1.0	32.9	0.82
Dry tuff	1.01[b]	27.2	0.68
Tuff	1.8	36.3	0.91

[a] $\Delta T + T_{ambient} < 100^\circ C$, ambient temperature: 24.5°C for alluvium, 44°C for tuff, based on 20°C surface temperature with 30°C/km geothermal gradient and a depth of 150 m and 800 m for alluvium and tuff, respectively.

[b] Geometric mean model, $K_{dry} = K_{wet}\,(K_{air}/K_{water})^{\phi}$, with $\phi = 0.3$ for alluvium, $\phi = 0.18$ for tuff.

Additional studies are recommended to determine the dependence of thermal properties on water saturation, the adequacy of the current thermal criteria, and the behavior of the thermal environment in the very near-field and far-field. The low thermal conductivity of unsaturated rock is expected to have more severe effects in the canister-rock interface, which is not addressed in this study. In the far-field, the thermally induced vapor transport should be modeled to determine the suitability of unsaturated rock as an effective waste barrier.

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