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NUCLEAR-WASTE ISOLATION IN THE UNSATURATED ZONE OF ARID REGIONS

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INTRODUCTION

The vadose zone or that subsurface region lying between the surface and the water table, is well developed in arid and semi-arid regions. In arid regions the vadose zone may be several hundred meters thick while in areas of higher precipitation it may be nonexistant 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 ground water, there would be a long hydraulic flow path between the nuclear waste 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--comprised of several rock types, may contain essentially dry or partially saturated conditions favorable for isolation. The 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. Some rock types may have the favorable characteristics of very low permeability and contain appropriate minerals for the strong chemical retardation of radionuclides. Environments exhibiting these hydrologic and geochemical attributes are the areas underlain by tuffaceous rocks, relatively common in the Basin and Range geomorphic province. Adjacent valley areas, where tuffaceous debris makes up a significant component of valley fill alluvium, may also contain thick zones of unsaturated material, and as such also lend themselves to strong consideration as repository environments. The distribution of tuffaceous highlands and adjacent alluvial valleys in the northwestern Basin and Range province is shown in Figure 1.

An appraisal of waste isolation in the Sedan Crater of the Nevada Test Site [1] brought to the attention of the scientific and engineering communities the attributes of alluvial environments. Partly for this reason and also because of the present focus of waste repository investigations at the Nevada Test Site, this paper summarizes the aspects of nuclear waste isolation in unsaturated regimes in alluvial-filled valleys and tuffaceous rocks of the Basin and Range province. (A more detailed report which furnishes the basis for this paper is in preparation [2].) 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.

REQUIREMENTS FOR A WASTE REPOSITORY SITE

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

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 must substantially exceed 1,000 years [3]. In order to meet this requirement, the proposed site must exhibit a number of favorable conditions:

- Groundwater access to and transport from the repository must be minimized; therefore, the site should have low groundwater content and its lithology should inhibit circulation within the host rock and between hydrogeologic units. Consideration must be given to potential changes in regional groundwater flow due to human activity or climatic changes.

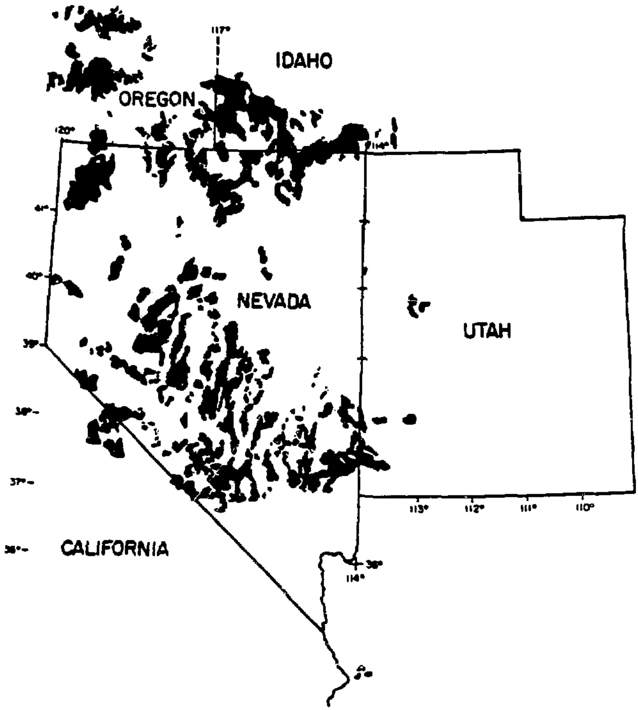

Figure 1. The northwestern portion of the Basin and Range province, showing highland areas that contain tuffaceous rocks. Valleys with appreciable components of tuffaceous alluvium lie between these highlands.

[XBL 8112-4898]

- The host rock must be of sufficient thickness and extent to maximize groundwater transit time to other geologic units.
- The mineralogical and geochemical characteristics should 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 rock encompassing the repository to its excavation and to the heating caused by the waste should have minimal effect on the hydrological integrity of the repository.
- Any major geologic discontinuity should contribute to isolation (such as a fault zone acting as an aquitard).

Another possible source of radionuclide escape is exhumation 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.

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, and climatologic conditions 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.

GEOTECHNICAL FACTORS

The unsaturated zone in alluvial-filled valleys of the Basin and Range province offers several factors that would help 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 if they should 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 (This is illustrated in an idealized geologic cross section in Figure 2.); (4) the thickness of the alluvium exceeds 1000 m at many localities and the thickness of the vadose zone exceeds 500 m. These factors, together with the presence of a tuff aquitard below the alluvium, provide a substantial hydrologic flow path between a repository at a depth of a few hundred meters and the underlying saturated zone.

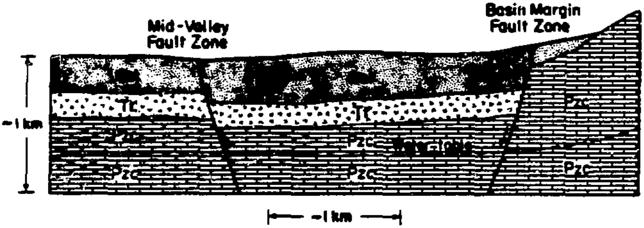

Figure 2. Schematic geologic cross section through an idealized Basin and Range valley, showing alluvium (Qal) overlying tuff (Tt) and Paleozoic carbonate rock (Pzc), with the water table at depth in the Paleozoic rock (based on [1]). [XBL 821-1621]

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, amenable to machine mining and requiring minimal ground support in underground workings, sandwiched between less competent but highly sorptive zeolitized units.

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 the tuff sequence comprising a topographic high (a mesa or range) or at a depth well below the local topographic relief, is less important 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 [1].

Tectonics, Volcanism and Seismicity

Properly chosen sites in alluvium of tectonically active areas may take advantage of local tectonism--situation of 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, alleviating the concern of future tectonic-erosive exhumation of the site [1]. 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 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. 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 distance be assessed for given site locations, and these should be taken into account in the design of the facilities.

Climatological Considerations

Evidence of the climate in the Basin and Range province during Pleistocene pluvial periods, when precipitation was 50 to 100% greater than today's [7, 8], indicates that future pluvial periods would result in increases in moisture infiltration rates. However, the saturation conditions and water table elevations at alluvial sites away from obvious locations of playa lakes would not differ significantly from those of today [9] 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, the effect of even doubling the infiltration rate should be insignificant because the rates are so low and the additional vegetative cover would enhance moisture transpiration.

Thermal Response

A principal concern of waste isolation in the unsaturated zone is the response of the host rock to heating. For a given waste form and thermal loading, the maximum temperature rise in the plane of a repository due to the introduction of

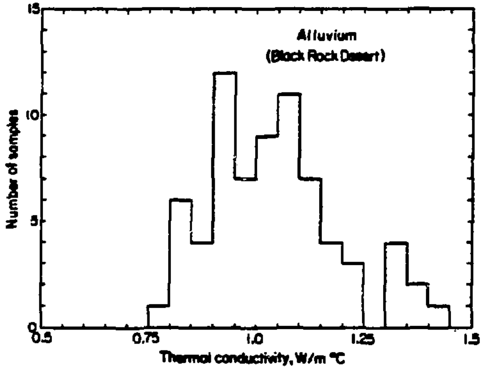

Figure 3. Thermal conductivities measured in situ in the southern Black Rock Desert (average value = 1.05 ± 0.15 W/m°C, 71 samples over 12 holes, data from [14]).
[XBL 8111-4849]

the waste varies with $1/\sqrt{K\rho c}$, where K is the rock's thermal conductivity, ρ its density, and c its specific heat [10]. The thermal conductivity of alluvium covers a large range, as shown in Figure 3, and depends strongly on the degree of saturation. The influence of thermal conductivity on repository temperature increase has been calculated [9] based on procedures developed by Wang et al. [10] and is illustrated in Figure 4. 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. These maximum temperatures are an average for the repository as a whole; the actual maximum local temperature will strongly depend on the emplacement geometry and the thermal loading of each 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, the increase in repository temperature with reduced water content was

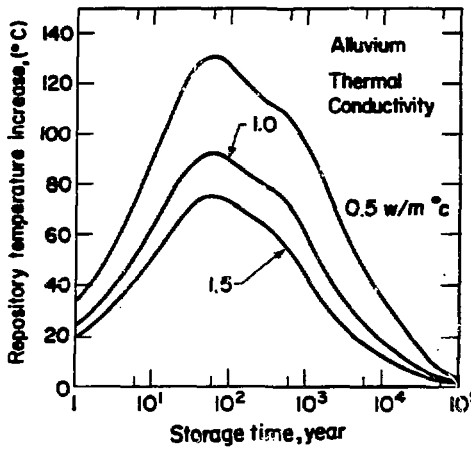

Figure 4. Effects of thermal conductivity on alluvial repository temperature, spent fuel, 10 years out of the reactor. [XBL 825-1391]

determined. Figure 5 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 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.

These results and those in Figure 5 are conservative as they are based on constant material properties for all the material surrounding the repository. They 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.

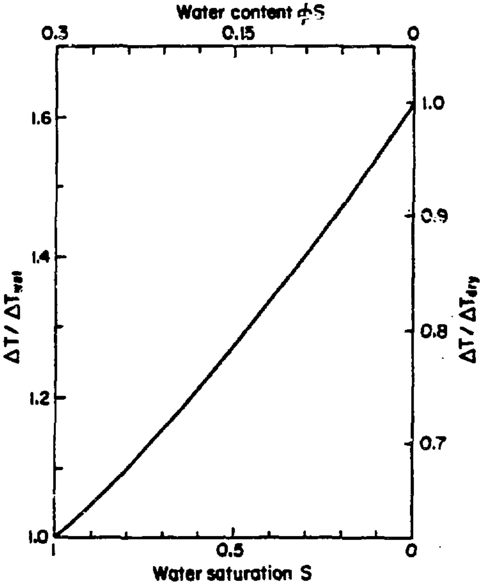

Figure 5. Variation of temperature rise with water saturation. [XBL 8111-4883]

Other factors affecting repository temperature in alluvium 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 76°C, 35 years after emplacement, compared with 92°C for spent fuel, assuming a thermal conductivity of 1 W/m°C and 40 kW/acre thermal loading. Varying the repository depth from 150 to 600 m has negligible effect on the maximum temperature, but results in a reduction in temperature for repositories at shallower depths after 300 years of storage.

Similar calculations to those for alluvium have been made for the thermal response of a repository in tuff. Based on 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 influance of thermal conductivity on repository temperature increase has been calculated, curves are shown in Figure 7. (The range of conductivity in tuff is shown in Figure 6.) For a conductivity of 0.9 W/m°C,

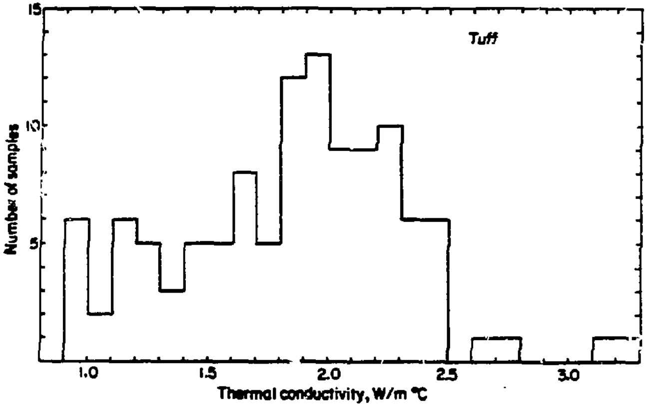

Figure 6. Histogram on the thermal conductivity of tuff; data from [15]. [XBL 8111-4850]

representative of a dry, nonwelded tuff and 2.7 W/m°C for a saturated welded tuff, the increases in temperature are 87 and 51°C, respectively. These maxima occur 50 years after emplacement of the waste and, as for alluvium, are average temperatures for the repository.

Comparison of Figures 4 and 7 reveals the significant difference in predicted repository thermal responses for underground waste disposal in tuff and alluvium. This difference is not only related to the relatively higher thermal conductivity of tuff as compared to alluvium, but also the higher density of tuff. In both cases the maximum temperatures occur 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. On establishing a 100°C maximum temperature for the repository, 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. To more accurately determine the allowable areal thermal loading for a prescribed temperature requires detailed modeling of the dehydration process, including the fluid and vapor pressure, heating rate, and pressure release path length.

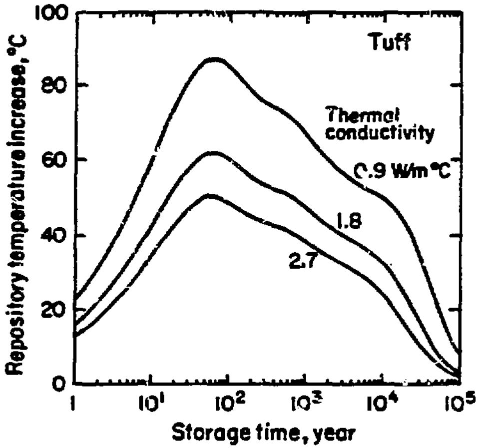

Figure 7. Effects of thermal conductivities on tuff repository temperature, spent fuel, 10 years out of the reactor. [XBL 8112-4888]

Calculations, similar to those for alluvium, were made for tuff, taking into account other factors influencing repository temperature--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 a longer storage time, the influence is relatively minor with a greater depth and larger area, resulting in slightly increased temperature rises.

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 [12]. 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 experimental measurements clearly indicated the dominance of the diffusion mechanism. Furthermore, an in situ heater experiment at G tunnel in the Grouse Canyon tuff [13] basically confirms the results of the laboratory experiment.

The thermal-hydrological properties of densely welded, strongly fractured tuff units which may contain lithophysal zones must also be considered. Considerations of rock mass permeability in tuff, in the context of waste isolation, would be similar to those of other hard rock types--principally the effect of heating on the near-field and mid-field hydrologic systems. The coupled thermomechanical-hydrologic effects of heating are also of concern, as are the presence of minerals subject to volume change in response to heating [14] and the effects of varying degrees of saturation on these responses.

Construction Considerations

Construction of 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, is comparable to construction costs in harder rock under saturated conditions [4]. Based on experience at the Nevada Test Site [5], 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.

Only underground construction is considered applicable to a site in unsaturated tuff. This would take advantage of a competent, most likely densely welded unit, amenable to machine mining, and requiring minimal ground support of the workings [6]. The stratigraphic position of such a unit between zeolitized units to furnish sorptive barriers would be highly desirable.

Resource Potential

The Basin and Range province has a very low population density--the vast majority of the land is under federal jurisdiction; large alluviated areas exist where there is no present mining activity. 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.

Table I. 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 [17].	At relatively low temperatures, bulk thermal conductivity will depend on 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 may lead to a two-phase convective system; 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 pertained.	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 in Arid Regions: 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

Compared with alluvial sites, there is a greater potential for conflict of a waste repository location with 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.

Advantages and Concerns of Waste Isolation in the Unsaturated and Saturated Zones

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 in brief in Table 1. Given appropriate study, beyond the scope of this paper, similar comparisons of advantages and concerns of unsaturated and saturated regimes may be made for the considerations of the effects on the waste form and on its surrounding canister and overpack material. Considerations would include the effect of saturated and unsaturated conditions at repository temperature and pressure on corrosion of the canisters, on the leaching of waste forms, and on the mechanical and hydrological integrity of overpack and backfill material.

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.

ACKNOWLEDGEMENT

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