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EVALUATION OF ENGINEERED BARRIER DESIGNS AND PERFORMANCE FOR A HIGH LEVEL NUCLEAR WASTE REPOSITORY IN TUFF

DRAFT REPORT (TASK 4)
NOVEMBER, 1983

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U.S. Nuclear Regulatory Commission
Division of Waste Management
7915 Eastern Avenue - M/S 623-SS
Silver Spring, MD 20910

Attention: Mr. C. L. Pittiglio

Subject: Contract No. NRC-02-81-027
Performance of Engineered Barriers in a Geologic Repository
Draft Final Report - Tuff (Task 3 and 4)
Letter #92

Gentlemen:

We are pleased to submit ten (10) copies of the subject report "Evaluation of Engineered Barrier Design and Performance for a High Level Nuclear Waste Repository in Tuff". As required by the contract one (1) additional copy has been submitted to the NRC Contracting Officer for this contract.

As previously discussed with you, this report is the result of activities completed under both Tasks 3 and 4 of the contract. A comprehensive review of this report has been made by the project management at GAI. You should note that the report is based on information available to GAI in late 1982 and does not reflect data that was either not then publicly available or obtained since that time. This is significant in an area where major research and development programs are currently underway by DOE.

Any questions concerning this report should be directed to either David Pentz or Richard Talbot.

Sincerely,

GOLDER ASSOCIATES

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for David L. Pentz
Project Manager

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REPORTS IN SERIES

Report Number	Issuance Date	Contract Task	Title
(In preparation)		1	Reference Design and Environmental Data for Evaluation of Engineered Barriers in High Level Nuclear Waste Deep Geologic Repositories.
(draft)	11/30/82	2	Review of Technical Documents for Engineered Barriers Evaluation in High Level Nuclear Waste Deep Geologic Repositories.
(draft)	6/15/83	3	Engineered Barriers Systems Design for a High Level Nuclear Waste Repository in Deep Basalts.
(draft)	9/30/83	3/4	Evaluation of Engineered Barrier Design and Performance of a High-Level Nuclear Waste Repository in Bedded Salt.
(draft)	9/30/83	3/4	Evaluation of Engineered Barriers Designs for a High Level Nuclear Waste Repository in Tuff.
(draft)	Vol. I 1/27/83 Vols. II & III 2/17/83	4	Evaluation of Engineered Barrier Design and Performance in an Underground Basalt Repository.
(draft)	8/30/83	5	Design/Performance Criteria for Regulatory Guidance for High-Level Nuclear Waste Deep Geologic Repositories.

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1.0 INTRODUCTION

This report presents technical analyses of the portion of Task 4 of Nuclear Regulatory Commission Contract NRC-02-81-027 which considers a saturated and unsaturated repository in tuff at Yucca Mountain in the Nevada Test Site. This work has been performed by Golder Associates, Inc., with the assistance of The Analytic Sciences Applications, Inc. The U.S. Nuclear Regulatory Commission (NRC) has initiated this study to examine methodologies for evaluating the relative significance of individual engineered components of a mined geologic repository for high-level radioactive waste. This introductory section presents the objectives of the project, the approach and overview of the project, and a statement of scope and organization of this report.

1.1 PROJECT OBJECTIVE

This project was initiated to evaluate the relative performance of engineered barriers within a mined geologic repository, in terms of providing isolation of radionuclides within a waste package and the controlled release of radionuclides to the acessible environment. Specific objectives of the project are:

(1) to conduct a critical review of the selected alternative engineered barrier systems.

(2) to develop parts of a performance evaluation methodology which may be used by NRC in their ongoing review of the Department of Energy (DOE) design effort on engineered barriers.

(3) to recommend guidelines for the design and construction requirements, and performance verification of engineered barriers which could be used in regulatory guidance supporting NRC's rulemaking effort.

1.2 APPROACH

Analysis of engineered barriers in a tuff repository at this time requires that only a qualitative approach be used because fundamental information is lacking in the areas of models and associated parameters (e.g., geologic characterization, engineered system design, understanding of the fundamental geohydrology and uncertainties in modeling corrosion, leach, and transport which result from questions on the hydrology and thermohydrology). Thus, the approach used in this report is to describe the generalized methodology which could be applied to a tuff repository, to focus on those items which are currently unknown or quite uncertain, and to describe what is known or hypothesized for each. It is not within the scope of this report to attempt to develop an analytic model of thermohydrology ir a tuff repository.

This project has resulted in the development of a series of related reports, most of which are quantitative in content and some quantitatively applied the following methodolgy. These reports are indicated on the Reports in Series list which follows the title page.

1.3 SCOPE AND ORGANIZATION OF REPORT

The scope of this report includes the definition and analysis portions of this project, as applicable to a reference repository in Yucca Mountain tuff on the Nevada Test Site. This report presents qualitative analyses of the performance of engineered barriers, and includes a summary presentation of available relevant data on Yucca Mountain tuff and applicable repository development activities.

The work reported here focuses on the performance of potential repositories in both the saturated and partially saturated tuff in Yucca Mountain. Upon initiation of this project, DOE's primary repository choice was in the saturated tuff, for which established hydrologic and transport models exist. During FY81 and FY82, DOE shifted its program to the partially saturated tuffs, within which there is little technical consensus on the hydrologic and transport processes. Performance models are currently not available. This report presents available information on both horizons relative to long-term radiologic performance.

It should be clearly understood that the data related to this potential site is certainly out of date at the time of delivery of this final report. New data is continuously being produced at Yucca Mountain and alternative design concepts are also being produced. The reader is cautioned that conclusions drawn by others from this incomplete data base on the ultimate performance of a repository in tuff will almost certainly be equally incomplete. Currently, no performance or transport models of the site have attained adequate technical consensus. This is an area which should receive careful attention in the near future from all concerned parties.

The organization of this report is as follows:

Section 2, Methodology: This section discusses the general approaches which may be used to quantitatively model a saturated and partially saturated tuff repository.

Section 3, Geology: This section presents a brief summary of available geotechnical data at the time of execution of this project on the reference tuff site at Yucca Mountain.

Section 4, Hydrogeology: This section presents the available data as of 1982 on the hydrology and projected thermohydrology of the site and discusses hydrologic engineered barriers in the saturated and unsaturated zones.

Section 5, Tuff Repository Design: This section briefly summarizes available repository design information as of 1982 for the reference site at Yucca Mountain.

Section 6, Tuff Engineered System Design: This section presents existing design information as of 1982 on alternative engineered systems currently being examined for the reference tuff site.

Section 7, Waste Package Performance: This section presents a qualitative discussion of projected waste package performance in a tuff repository.

Section 8, Nuclide Transport: This section discusses nuclide transport in the reference tuff repository, focusing on the elements of the problem which are currently quite uncertain.

Section 9, Conclusions and Recommendations: This section presents study conclusions, and offers recommendtions which are applicable to both NRC and DOE in relation to reducing the uncertainty in the predicted performance of a repository in the reference tuff environment.

2.0 METHODOLOGY

In order to assess the performance of engineered barriers in a repository an understanding of the hydrologic conditions is required. The approach to performance assessment will clearly differ if the repository is in the saturated or unsaturated zone. The performance methodology, however, can be generalized into several similar major processes with only details varying for each medium and set of conditions as shown in Figure 2-1, and discussed below.

Four processes must be simulated to calculate repository performance. The first of these is waste package breach. In the saturated zone, the most likely means of this occurring is by saturation of the closed repository and subsequent corrosion of the waste package. Alternatively, mechanical degradation of the package by crushing is possible, but this likelihood should be prevented or minimized through careful design. In the unsaturated zone, again corrosion is viewed as the most likely potential means of breaching a package. However, saturation as for a repository in the saturated zone, will not occur unless the water table rises above the repository horizon. It is possible that a cyclic saturating and draining may occur, however, due to climatic changes that influence the water balance of the basin. If this occurs, presumably corrosion would occur during these periods. Even if saturation does not occur, there is both liquid and vapor phase water present in the unsaturated zone and corrosion can occur in such an environment albeit slowly. Mathematically, modeling these liquid and vapor phase corrosion processes will require an understanding of the site specific hydrology, an understanding of corrosion under variably saturated conditions, and an understanding of how heat and radiation effect the kinetics of both processes.

The second process is nuclide release from the waste form. For a saturated repository, this process is simulated as leaching, which is fundamentally a process of corrosion and solid diffusion, at a maximum rate limited by

GENERALIZED PERFORMANCE ASSESSMENT METHODOLOGY

Figure 2-1

	WASTE PACKAGE BREACH →	NUCLIDE RELEASE FROM WASTE FORM →	NUCLIDE TRANSPORT IN ENGINEERED SYSTEMS →	NUCLIDE TRANSPORT IN GEOLOGIC SETTING
SATURATED REPOSITORY	RESATURATION AND CORROSION	LEACHING LIMITED BY NUCLIDE SOLUBILITY	SORPTIVE TRANSPORT	SORPTIVE TRANSPORT
UNSATURATED REPOSITORY	CORROSION BY CYCLIC RESATURATION AND SUBSEQUENT CORROSION, MECHANICAL DEGRADATION, OR CORROSION WITHOUT RESATURATION	LEACHING DURING CYCLIC RESATURATION; LEACHING IN PARTIAL SATURATION	SORPTIVE TRANSPORT DURING CYCLIC RESATURATION OR IN PARTIAL SATURATION	SORPTIVE TRANSPORT DURING CYCLIC RESATURATION OR IN PARTIAL SATURATION

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solubility of individual elements in the leaching solute. In an unsaturated repository, leaching is also expected to be the release mechanism. It is possible that nuclides could, by solid diffusion, move to the exposed surface of a waste form, and subsequently move through engineered and geologic materials by mechanical dispersion in water that is present or even by solid diffusion. However, such mechanisms are believed to be exceedingly slow. Leaching may occur during the saturated period of a cyclic wetting and drying process, or it may occur in the partially saturated repository environment via percolating infiltration water, but both of these processes are currently not well defined.

The third and fourth process are nuclide transport in the engineered system and nuclide transport in the geologic setting. These are fundamentally the same processes. However, they occur in regions with vastly differing degrees of definition. The engineered system is presumably quite well defined, though its condition after long-times is uncertain. The geologic setting, however, is quite variable, so modeling becomes a spatial approximation of a large volume of materials. In the case of a saturated repository, modeling can simulate transport to various degrees of sophistication. Such processes as dispersion and matrix diffusion can be approximated. Sorption is typically modeled by using a retardation factor, although recent model development has moved in the direction of considering fundamental chemical thermodynamics and kinetics in spite of the absence of data to support such a simulation.

In an unsaturated repository, nuclides could be transported during saturated periods or by percolating recharge through specific fractures. There are large uncertainties in our understanding of these processes.

Modeling the performance of a saturated tuff repository would be accomplished in the following sequence:

- Define undisturbed hydrology, geology
- Define designs of waste package, engineered system and overall repository layout

- Model response of hydrology to thermal pulse of the waste form
- Model repository water ingress to determine time required to saturate the repository
- Model waste package performance to predict time of failure and the source term
- Model nuclide transport.

While the modeling sequence for an unsaturated tuff repository would be similar, at this time not even the first of these items can be completed due to the uncertainties in the host hydrology. The balance of this report discusses each of these items as they relate to a saturated or unsaturated tuff repository.

3.0 GEOHYDROLOGICAL MODEL RELATIVE TO ENGINEERED BARRIERS AT YUCCA MOUNTAIN

The primary target repository site at NTS is within Yucca Mountain. Two potential target horizons are the Topopah Springs Member in the unsaturated or vadoze zone and the deeper Bullfrog member of Crater Flat Tuff which is saturated. Appendices A and B of this volume describe our understanding of the geological and hydrological data base. Due to contractual constraints and the ongoing data acquisition program, this data base is incomplete and out of date. It should be stated that the available data on the unsaturated properties of the tuffs is very limited. In addition, there is considerable uncertainty of how groundwater moves in fractured unsaturated media. Thus, the conceptual models of the unsaturated zones are correspondingly uncertain. The following sections are divided into two categories, conceptual models related to a saturated repository and those models which may be considered for unsaturated conditions.

3.1 REGIONAL CONCEPTUAL GROUNDWATER MODEL OF THE SATURATED ZONE

According to Winograd and Thordarson (1975), lateral regional flow is controlled by fracture hydraulic conductivity in the lower carbonate aquifer and by its structural justaposition with the lower clastic aquitard. The tuff units are recharged in the highlands where they are exposed or only veneered with alluvial material. Presumably, flow in the tuff aquitard has a significant vertical component, which can locally recharge the carbonate aquifer. It is possible the piezometric low to the southeast of Yucca Mountain could be a local recharge area. Hydrogeologic and hydrochemical data suggest that an area of at least 11,600 square km (including 10 intermontane valleys) is hydraulically integrated into one groundwater basin by movement of groundwater through the widespread carbonate aquifer. Interbasin groundwater movement below Yucca Mountain is expected to be in a southerly direction. Discharge from this basin (a minimum of about 21 million cubic meters annually) occurs along a fault-controlled spring line at Ash Meadows (southeast of Yucca Mountain).

If the lower carbonate aquifer is present below the tuff section, it may have a strong influence on the site specific hydrology at Yucca Mountain. Efforts should be made to verify the existence of this unit and assess its impact on the groundwater flow regime of the area.

3.2 CONCEPTUAL UNSATURATED GROUNDWATER MODEL AT REPOSITORY SCALE

It is impossible to confidently describe the groundwater flow regime in the area of Yucca Mountain because little data is available to support interpretations. As a result, in order to assess the performance of a repository in Yucca Mountain and comment on the effectiveness of engineered barriers, at least one conceptual model of the flow pattern must be assumed and a reasonable range of parametric values for that model must be considered.

For the purpose of this study, it is assumed that Yucca Mountain is a local recharge area because of its intermediate elevation and thin to no alluvial cover. Reports on the degree of saturation of the Topopah Springs Unit range from 17 to 91* and reports on the underlying tuff aquitard range from 82 to 100 percent (as do reports on degree of saturation below the phreatic surface, i.e., 82 to 100 percent). The rate of percolation of infiltrating water has not been measured and could span a wide range. Estimates of the velocity of downward percolation in the fractured vadose zone of Rainier Mesa at NTS (a similar setting to Yucca Mountain) range from 25 to 400 meters per year based on Tritium age dating of perched water (Thordarson, 1965). Clasen (GEI, 1979) confirmed these estimates by observing seasonal water level fluctuations in the perched zone. It appears that the unsaturated zone has reached an equilibrium condition with each material storing a "constant" amount of water as dictated by pressure conditions and material properties (i.e., critical saturation) therefore any percolating infiltration water is not absorbed by the matrix, but is either transmitted through fractures and/or replaces water in storage carrying a net flux through the system. Thordarson (1965) demonstrated that the perched water leaks slowly to the regional water table. At the other extreme, if the unsaturated materials comprising Yucca Mountain behave as a porous instead of a fractured media then downward percolation rates could be as low as 2 x 10^{-3} meters per year, as estimated by Winograd (1981) for the Yucca Flat area where there are considerable thickness of alluvium (i.e., porous media). Currently we believe that the unsaturated materials of Yucca Mountain will not behave like a porous media.

After reaching the phreatic zone and entering the saturated zone, it is currently assumed that the recharge water will slowly continue in a generally downward movement through the tuff aquitard. Any sections of higher transmissivity are probably discontinuous due to heterogeneities or faulting but some local lateral components of flow may occur within topographic basins. Winograd and Thordarson (1975) estimate downward movement of water through the aquitard to range from 10^{-4} to 10^{-1} m/yr, which they expect is the controlling factor of recharge to the carbonate aquifer.

Groundwater reaching the carbonate aquifer can flow laterally because it is continuous over a large area. Hydraulic gradients are low, typically 2 x 10^{-4} to 4 x 10^{-3} (Winograd and Thordarson, 1975) due to the lack of barriers to flow in the area.

3.3 REPOSITORY FLOW REGIME - SATURATED ZONE

At the time of this writing, it is assumed that if a repository were to be constructed in the saturated zone at NTS it will be located in the Bullfrog member of the Crater Flat Tuff. This setting would be 700 to 800 m below the ground surface and 125 to 225 m below the phreatic surface. Packer tests in USW-G1 indicate horizontal hydraulic conductivity of the target horizon may fall within the approximate range of 10^{-7} to 10^{-9} m/s. No other horizon specific information is available.

3.3.1 Water Ingress

Water ingress in a saturated tuff repository is much like that described for basalt (Golder, 1983a). Based on the approximate range of conductivity of the

Bullfrog unit and the surrounding hydrologic environment, it is likely water ingress will range from 10^{-1} to 10^{2} m^3/yr per square meter of excavation in plan view of the repository (roughly 10^1 to 10^4 GPM for for the entire repository depending on the design). Such volumes would not present a problem to repository operations. If the repository is backfilled with material of higher conductivity than the host rock, the time required for the repository to refill with water ranges from months to as long as 50 years. Such a time frame is insignificant to the period of waste containment. Backfilling the repository with a tight clay could increase the time required to flood the repository by at most two orders of magnitude. However, even five thousand years is short with respect to long term containment requirements.

3.3.2 Flow to the Accessible Environment and Discharge Points

Once the repository is saturated, it is expected the system will repressurize rapidly and the flow regime will revert to the general configuration of the pre-repository regime with minor perturbations caused by the repository excavation and subsequent backfilling (if carried out) and, during the first 10,000 - 20,000 years of performance, with modified gradients resulting from the thermal loading. As the magnitude of the assumed downward vertical gradient is unknown, it is not currently possible to predict if an upward gradient will prevail as a result of thermal loading or if the downward gradient will remain at lesser magnitude. Regardless of the magnitude of the thermal effect on the gradient, the flow direction is expected to be predominantly vertical because aquitards are characterized by vertical flow and this character would be accentuated by the assumed prevalence of continuous vertical fractures.

Once waste is released from the repository, if upward movement does occur, it will be temporary and it is possible that the flow regime will return to the initial configuration before waste is discharged. Such a scenario would increase the transit time.

At first glance, groundwater travel time to the hypothesized distant (20-100 km) discharge points are long because hydraulic conductivities and gradients are low, and Carbon-14 dating of water emerging at Ash Meadows implies an average groundwater residence time of over 10,000 years (Grove et al, 1969; Winograd and Pearson, 1976). However, even the approximate path that wastes would traverse between the repository and discharge point is unknown and this path is certain to traverse almost exclusively fractured media. Effective porosity of fractured materials is typically low; thus, groundwater travel times can be surprisingly short under such circumstances. Estimates of groundwater travel time to the 10 km accessible environment measuring point range from 102 to 105 years (Dove et al, 1982).

3.3.3 Effectiveness of Engineered Barriers in Saturated Zone

As the local flow field in the tuff repository is assumed currently to be very similar to that of the basalt repository (vertical flow field in fractured media) similar barriers to those suggested for basalt would be effective (see Golder 1983a for discussion of basalt). That is, if waste can be located upgradient from excavated cavities, then backfilling with high hydraulic conductivity (relative to the host), high porosity material will promote flow through the backfill which can be designed to yield low interstitial velocities and high sorption.

If horizontal flow through storage rooms is found to be significant, then the need for tunnel seals must be considered. Tunnel seals would act to reduce the flow rate in the permeable room backfill. Whether or not this is beneficial is dependent on the design and site conditions. As previously noted, groundwater velocities in the porous backfill are much lower than in the fractured host rock. Flow through long tunnels of porous backfill can be beneficial. If room seals divert flow into the host rock then they could prove to be counterproductive.

It is not possible to determine the absolute effectiveness of engineered barriers without knowledge of the nature of the waste movement through the geologic system. If transit time to the accessible environment is short, room backfills along with waste orientation can substantially delay and decrease release. If, however, the transit time is long, then the further delay of release by additional thousands or tens of thousands of years with the use of engineered barriers may be relatively insignificant and could require substantial funds to achieve.

3.3.4 Effects of Thermal Loading

The effect of thermal loading on flow magnitude and direction are qualitatively discussed in Section 3.3.2. Two other items are worthy of mention. First the thermal loading is likely to influence fracture aperature, hence conductivity. Studies in this area are somewhat contradictory in that some suggest closure and others expect widening of fractures. It is likely both phenomena will occur as the stress from the thermal load flows through the system. Although this process is an interesting subject it appears its impact on release will be minor relative to the importance of many of the unknown parameters previously discussed. Secondly, tuff is susceptible to chemical alteration at low temperatures (beginning at 100°C). Peak temperatures near the waste package in the basalt analyses (Golder, 1983a) were approximately 140°C for the low thermal loading and 240°C for the high thermal loading. Waste emplacement will have to be more dispersed in a tuff repository to keep peak temperatures in the vicinity of 100° to 125°C. As a result, all thermal impacts will be reduced. Thermal effects in zeolitized tuff could potentially cause volume loss leading to shrinkage fractures and evolution of water vapor (Sandia Laboratories, 1980).

3.4 REPOSITORY FLOW REGIME - UNSATURATED ZONE

Under current programmatic assumptions, if a repository was constructed at the NTS, it will more likely be located in the unsaturated zone in the Topopah

Springs Member of the Paintbrush Tuff. This setting would be 300 to 400 m below the ground surface and 300 to 200 m above the phreatic surface. No horizon specific testing has been undertaken. The impetus for siting a repository in the unsaturated zone has primarily been to take advantage of low flow rates and capillary forces which keep large openings dry. The fractured nature of the Topopah Springs Tuffs and the recharge it is likely to receive may reduce these benefits.

3.4.1 Conceptual Groundwater Model of the Unsaturated Zone

Currently hydrologic data that has been collected in the unsaturated zone at Yucca Mountain is too preliminary to utilize in the development of a conceptual model of the site. However, Scott et al, 1983, have utilized physical property data, regional hydrogeologic investigations, and regional conceptual models to construct a simple model of unsaturated flow within Yucca Mountain. They believe the unsaturated zone has probably reached equilibrium conditions where each layer is "as saturated as possible with a balance of capillary forces, gravity and back pressure of trapped gases." Therefore, any recharge to the surface of Yucca Mountain will be in excess of what the rock matrix can hold, hence such infiltrating water is expected to move downward through the fracture systems of the Tiva Canyon and Topopah Springs members with temporary delays in perched zones. Below these zones recharge is expected to filtrate slowly (in the style of porous media flow) through the basal, nonwelded unit of the Topopah Springs; the nonwelded, zeolitized Calico Hill Tuffs; and a portion of the partially welded Prow Pass member, before reaching the water table (provided a highly transmissive fault does not short-circuit flux through the individual stratum). Faults may be of low conductivity if filled with fault gouge or alteration products, but Scott et al, 1983, offer some evidence that, at least locally, high conductivity faults occur. Low conductivity faults may cause perched zones to form.

The amount of recharge entering the system is not known. The authors are not aware of any data for precipitation or infiltration at Yucca Mountain. It is reasonable to assume that recharge will be low. Scott et al, 1983, estimated infiltration to be approximately 0.6 cm/yr.

Figure 3-1 is a schematic of the conceptual models of unsaturated flow within Yucca Mountain. In the drawing of this schematic, it was assumed the Tiva Canyon and Topopah Spring Members have similar hydraulic properties. The bedded and partially welded tuffs at depth may transmit water rapidly due to their high matrix conductivities. The conductivity of these units is much lower where they are altered to clays and zeolites and fracture densities are low. The low conductivity units will control flux rate through the sequence; they will exhibit a higher degree of saturation and may cause perched water zones. Within perched zones at any level in the sequence, it is possible that lateral flow may occur in the downdip direction. There is potential that such flow may discharge on slopes of washes that cut Yucca Mountain.

Some "perched zones" may be quite limited in lateral extent. For example, a vertical fracture may be "dead-ended", (i.e. the fracture terminates or butts into an altered zone) and if such a fracture receives a slug of infiltrating water, the only discharge for that water is via slow seepage from the fracture to the surrounding porous media or downward through the underlying unit. This may cause localized saturated zones to occur.

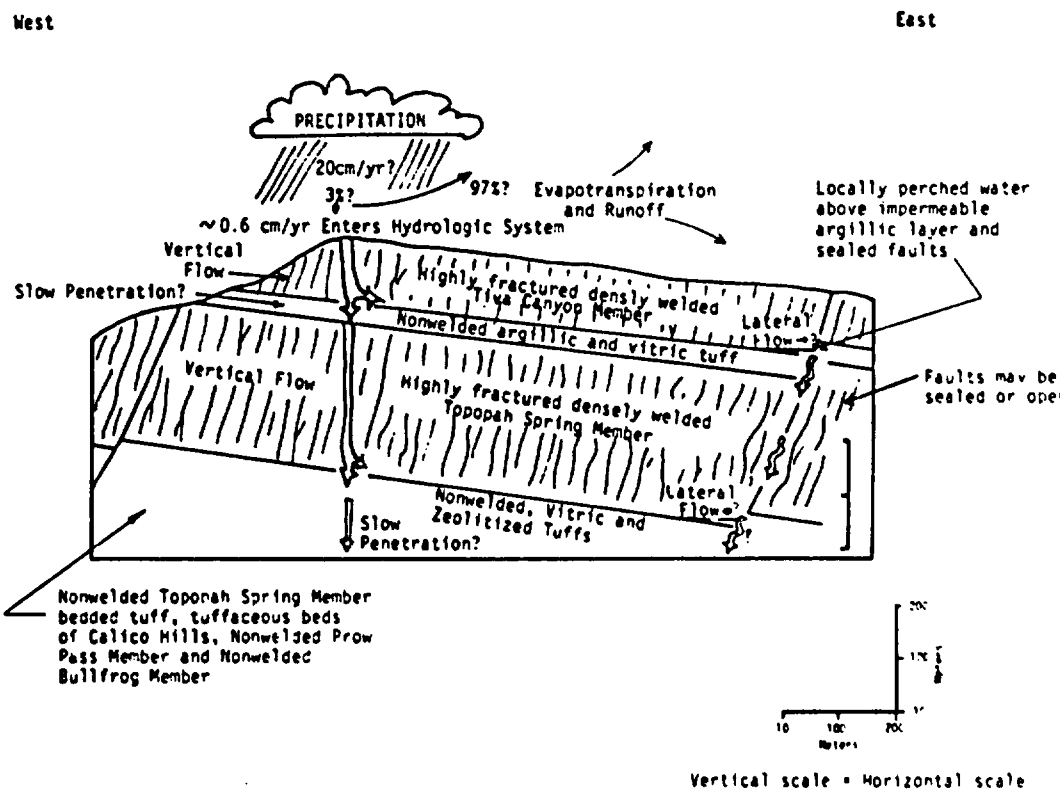
3.4.2 Water Ingress

In a fine grained unsaturated material, the surface tension of water at the air/water interface in the small pores or fractures prevent water from flowing into an open cavity where there is no evaporation. If evaporation is significant due to heat and/or ventilation, the saturation level in the matrix near the walls of mined openings will be reduced and a moisture gradient will induce unsaturated flow towards the opening. After closure, unsaturated flow will continue towards the opening until vapor pressure in the mined opening becomes high enough to stop evaporation. Elevated temperatures will increase the evaporation potential of the air in the opening, inducing "flow" until a new equilibrium is reached and the process will reverse as the opening cools.

A phenomena which may arise in the Topopah Springs units is that the fracture apertures may be too large for surface tension forces to prevent infiltration

CONCEPTUAL HYDROGEOLOGIC MODEL OF THE UNSATURATED ZONE OF YUCCA MOUNTAIN

Figure 3-1



NOTE: Positive net recharge for the mountain is assumed Determination of vertical and possible horizontal rates of transmission of recharge through densely and moderately welded Tiva Canyon and Topopah Spring Members and through less welded vitric, argillic and zeolitized tuffs awaits hydrologic testing specifically designed for the unsaturated zone. If faults are locally sealed, they may create local perched water tables, but if they are open, the faults may rapidly transmit water.

From Scott et al., 1983

of water from flowing out of the fractures in the mined openings. Being in the unsaturated zone these fractures transmit only limited and intermittent amounts of water. This is due to the hypothesis that only limited infiltration will occur and this will be almost entirely restricted to fracture systems or more pervasive perched water zones. Flow from the matrix will be limited by equilibrium conditions. Similarly, as infiltration rapidly reaches the perched water table at Rainier Mesa (discussed in Section 3.2), infiltrating water would flow into the repository. The annual volumetric inflow would be dependent on the surficial recharge. Once water enters the repository, subsequent movement of this infiltrating water will be dependent on the repository design.

3.4.3 Flow to the Accessible Environment

Control of water which enters the repository is discussed in the following section. If water does pass through the repository, it will continue downward percolation to the saturated zone at a rate controlled by the properties of the material, more rapidly through fractured layers and more slowly in the fractured nonwelded and altered tuffs. The water may be temporarily stored in a perched water zone if present. Assuming most of the material is fractured and percolation rates are similar to those in Rainier Mesa, groundwater travel time to the phreatic surface will range from 1 to 10 years. After entering the saturated zone downward movement will probably continue in the tuff aquitard and the remainder of the flow path to the 10 km accessible environment will be similar to that experienced by flow from a repository located in the Bullfrog (travel time range 10^2 - 10^5 year). If even a minor horizontal flow component exists, flow from the unsaturated repository will remain higher in the section than flow from the saturated repository and travel times may be shorter. However, the reduced flux of water past waste in the unsaturated zone relative to the saturated zone will result in a lower level of nuclide release.

3.4.4 Effectiveness of Engineered Barriers

From the foregoing discussion it becomes apparent that the primary design objective for engineered barriers in an unsaturated repository is to prevent water from entering the repository. A secondary design objective is to route water that does enter out of the repository without encountering waste.

The relevant design variables for meeting these hydrologic objectives include emplacement geometry (e.g., in room, vertical boreholes below rooms, horizontal boreholes beside rooms) and grain size distribution of backfill in rooms and adjacent to the waste package. Sorption properties should be considered in the event that transport should commence. This is discussed in Chapter 7.

First consider grain size of the backfill. If fine grained backfill is placed around the waste package and adjacent to partially saturated, fine grained, tuff matrix material, water will enter the fine grained backfill, albeit slowly, until the backfill reaches a saturation level similar to that of the surrounding rock matrix. Then the flux through the backfill (unsaturated flow of small quantities of water) will commence unless the backfill is so fine that capillary pressures prevent the contained water in the backfill from flowing back into the rock matrix. Regardless of which condition (i.e., stationary or flux) prevails, corrosion will take place, though at different rates. Actually, corrosion rates may exceed those observed in saturated zones because highest corrosion rates occur at air-water interfaces. Once the waste package is breached, waste will be leached and transported through the system if an unsaturated through-flow condition prevails or waste may diffuse through the backfill if it is so fine grained that water cannot flow from the backfill to the matrix.

If a coarse grained backfill is placed around the waste package, capillary pressures in the fine grained rock matrix prevent water from entering the coarse backfill. However, water percolating through fractures could enter the backfill and although most of this water would likely flow through the repository without contacting the waste package, over the years, enough water may contact the package to cause ultimate failure. Also, such water could carry waste exposed by other potential modes of package failure. Alternatively, if some event (possibly a climatic change) caused the repository to become inundated (an unlikely but possible scenario) the waste packages would be immediately saturated.

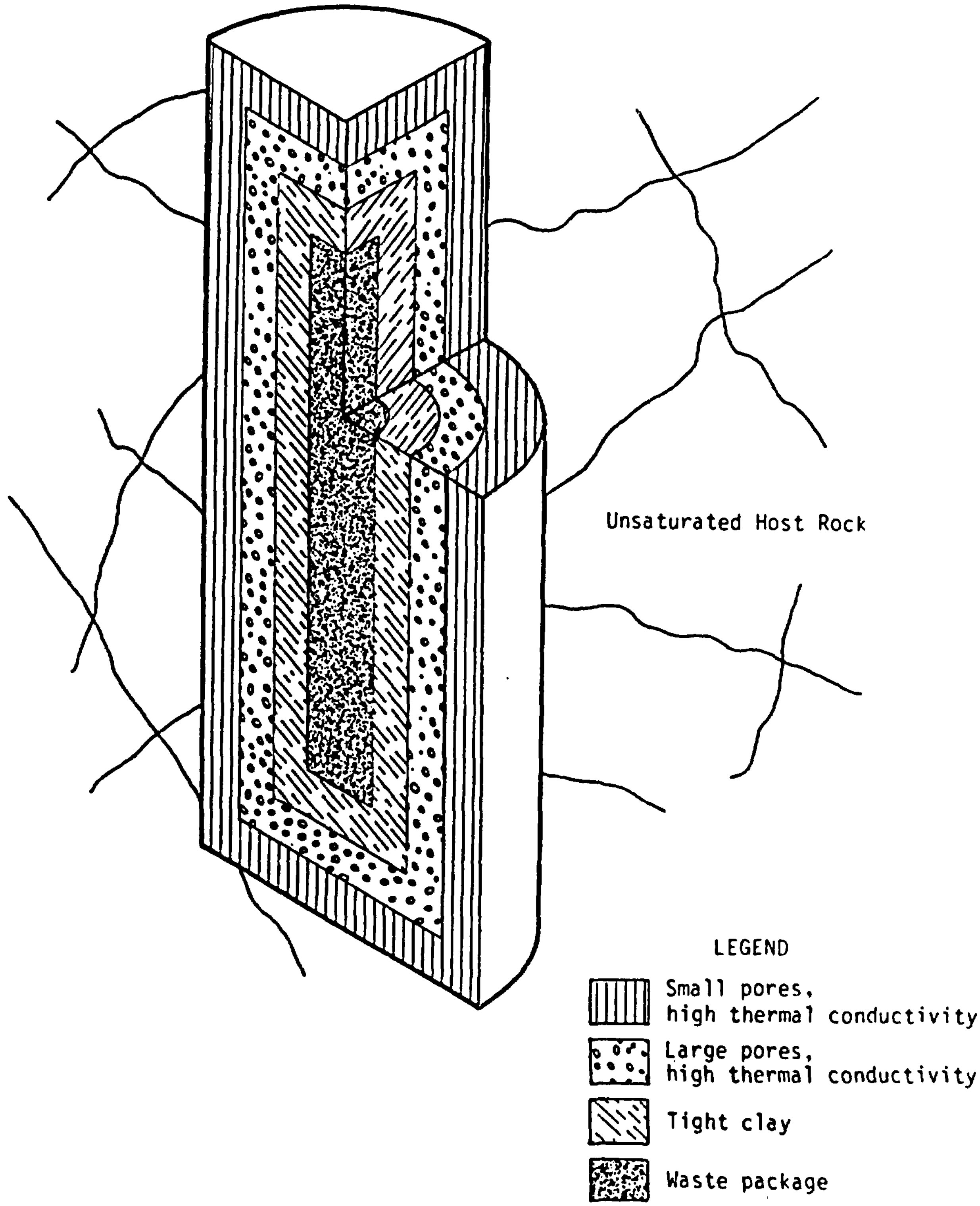
The above considerations suggest a layered backfill design which takes advantage of fine and coarse grained materials. A three layer design is suggested: fine grained, coarse grained, fine grained (Figure 3-2). A fine grained material adjacent to the host rock takes on water but the water cannot enter the next coarse grained layer because capillary pressures prevent this and no fractures exist in the fine grained layer to allow entry, as was the problem with having coarse material near the host rock. Hence, the intermediate coarse layer keeps the waste package dry. The central fine layer slows water contact in the event of inundation.

Such a complex fill design could not be constructed with high quality assurance in horizontal emplacement holes. In-room emplacement has typically been ruled out elsewhere for operational safety and retrievability matters. Procedures can be defined to surmount the problem of in-room emplacement. However, in-room placement offers no performance related benefit when compared with vertical hole emplacement. Therefore, in-room and horizontal emplacement are not discussed.

One problem with such a layered design is that usually clays and gravels are used for fill material and the multilayer design may result in unacceptably high temperatures. The solution to this is to use high thermal conductivity material. Possibly a relatively inexpensive and abundant metal like copper or iron formed into appropriate grain sizes. These could also be meshed into annular cylinders for ease of emplacement. The inner fine grained layer should be clay since its purpose is to impede water entry in a saturated environment.

WASTE PACKAGE DESIGN FOR UNSATURATED ZONE

Figure 3-2



3.4.5 Effects of Thermal Loading

If the repository is designed to maintain temperatures below about 125°C near the waste package, then chemical alteration of the tuff (which likely causes decreased strength and sorption potential) should not be a problem and the waste package can easily be designed to withstand such temperatures. Then, during the thermal period (first 10,000 plus years) the heat will provide two hydrologic benefits. First, moisture flows from areas of high temperature to areas of low temperatures in the unsaturated zone. Therefore, as long as the temperature in the repository is significantly higher than the surrounding rock, unsaturated flow will be in the direction away from the repository. Secondly, water that will be present in the repository will probably exist in a vapor phase due to the high temperature and low pressure. Water movement in the vapor phase cannot transport nuclides.

3.5 HYDROGEOLOGIC SUMMARY

Quantitative estimates of time and level of nuclide release from a repository at the NTS is not possible because there is not enough information to determine the nature of the flow regime. Qualitative discussion of repositories located in the saturated and unsaturated zone of Yucca Mountain suggest groundwater travel time from the two repositories may be quite similar but the level of nuclide release from the unsaturated zone repository would be relatively lower due to the reduced water flux past the waste. A repository located in unfractured, unsaturated tuff would exhibit substantially longer travel times to the phreatic zone than a repository in fractured unsaturated tuff. However, conditions expected to prevail at the Yucca Mountain site are more closely modeled by fractured unsaturated conditions.

Effective engineered barriers in a saturated tuff repository are similar to those suggested in basalt with rooms backfilled with high hydraulic conductivity, high porosity, sorping material placed down gradient of the waste. Effective barriers in an unsaturated tuff repository are those designed to keep water away from the waste package. They include the induced thermal barrier (due to waste heat) at early times and if required, multilayered (fine, coarse, fine) materials of high thermal conductance for long-term protection.

4.0 TUFF REPOSITORY DESIGN

A repository in tuff has the principal design objectives of allowing safe access to the repository horizon. To emplace wastes, and to retrieve them, if necessary. At present, DOE has not completed a reference conceptual repository design for the partially saturated tuff at Yucca Mountain. The material which follows details generally applicable information which is relevant to repository design in tuff.

4.1 WASTE RECEIPTS

For planning purposes, the repository in tuff will be designed to receive unpackaged BWR and PWR fuel assemblies, solidified high-level waste from commercial reprocessing, from West Valley, and from defense operations at Savannah River, transuranic wastes from general commercial and commercial fuel reprocessing, iodine wastes from commercial reprocessing and hulls and hardwork from commercial reprocessing. Wastes received will assume an overall commercial spent fuel discharge of 70,000 MTHM. A portion of that fuel will be assumed to be disposed of as-discharged, and a portion reprocessed removing the uranium and plutonium inventory (Best, Voss, and Brooks, 1983).

4.2 SURFACE FACILITIES

Surface facilities at a repository in tuff will typically include the following (DOE, 1979).

- o Waste receiving
- o Spent fuel packaging
- o Supply ventilation
- o Exhaust ventilation
- o Radiowaste processing
- o Men and material facility
- o Other administrative and infrastructure support

Because of the difficult topography at Yucca Mountain, it is possible that some of the facilities may not be located at the repository entry, but may be sited some distance away, though within the Nevada Test Site. In particular, the waste receiving and spent fuel packaging facilities might be so located. It is also possible that major facilities at the repository entries may be located at the base of Yucca Mountain, and not on top of it.

4.3 ENTRIES

The unique topography of Yucca Mountain may not lend itself to the development of vertical shafts from the top of Yucca Mountain. Thus, it is possible that sloped entries or inclines from the surface or base of Yucca Mountain into the repository horizon may serve as the major access routes.

It is also likely that at least one entry will be a vertical shaft from Yucca Mountain. The precise number of entries is a design variable which has not been resolved. Recent repository conceptual designs have had 4, 5 and 6 shafts, depending on waste receipts, ventilation philosophy and material handling.

4.4 UNDERGROUND DEVELOPMENT

The underground development at the repository horizon will be a function of the geology the structural characteristics of the target host rock, and the design philosophy, particularly as it relates to waste package placement. At present, DOE is exploring both horizontal and vertical waste emplacement schemes (Scully and Rothman, 1982). DOE appears to favor a horizontal emplacement shceme in which a 4-foot diameter horizontal waste emplacemen hole is drilled 600 to 700-feet long off of secondary subsurface entries (Scully and Rothman, 1982; Peters, 1983). This design scheme reduces tuff extraction for repository development, in contrast to more traditional vertical emplacement schemes.

5.0 TUFF ENGINEERED SYSTEM DESIGN

This section discusses the designs for engineered barrier systems appropriate to the repository in a tuff medium. The designs are suggested based on analogy to the salt and basalt system.

5.1 FUNCTIONAL DESIGN CRITERIA

The engineered barrier system serves two purposes:

- o The prevention or delay of water contact with waste packages
- o The prevention or attenuation of radionuclide releases to the geologic setting.

The first purpose is actually part of the second since water borne transport is generally the only viable means for radionuclide escape. However, it is singled out for its importance. The functional design criteria for the engineered barrier system are all centered on these two purposes.

5.1.1 Water Exclusion

The current, primary target horizon for the tuff repository is in the unsaturated zone in the Topopah Spring Member of the Yucca Mountain area. This member extends from near the surface to about 380 meters. This is a change from earlier plans which considered horizons in the Bullfrog Member (700-800 m) or the Tram Member (850-950 m), both in the saturated zone.

As previously summarized, there is little applicable data on the unsaturated candidate horizon. Notwithstanding the lack of data, it is reasonable to assume that the potential for a large amount of water infiltration is low and that water exlcusion may not be a major issue.

A likely engineered barrier design strategy is to avoid surrounding waste forms with materials which have high tendency to attract moisture such as finely divided solids (small pore-size, therefore, high capillary potential). These will cause moisture to migrate toward waste forms rather than aid in the exclusion of water. Provision for drainage in the repository may be a practical approach to keeping the waste package dry in the vadose zone during the operational period at least.

5.1.2 Creep Deformation

The strain characteristics for tuff, based on limited data, show a possible plastic component indicating that some time-dependent deformation will result (Golder Associates, 1983b).

The creep characteristic could be important to package life. The protection of the waste form from crushing is a significant issue in salt but could also be important for tuff. The waste package is a primary component of the barrier system which functions to delay or prevent water intrusion and to delay or prevent migration of radionuclide to the environment. Thus, an important goal for the waste form and associated package it to provide defense against crushing due to rock deformation by creep. It should be noted this phenomena is distinct from displacement along faults as a reuslt of seismic activity.

5.1.3 Backfill Degradation

Selction procedures should lead to designs including backfills which will not be susceptiple to processes which might significantly alter the desirable properties of the backfill. If a backfill is used because of an unique property, such as high sorption or swelling properties, but subsequently looses such properties through diogenesis then clearly its effectiveness is lost. At issue are the undefined hydrothermal conditions which influence the diogenesis of backfills.

The thermal conductivity of tuff in situ may be highly variable because it is dependent on grain size, orientation, composition and geologic heterogeneity. These properties are highly variable in tuff. Silicic tuffs display thermal conductivities ranging from about 1 to 6 W/m-°C. Placement of waste in low conductivity backfill material could result in high temperature which may accelerate backfill alteration.

5.2 ANALOGIES TO SALT AND BASALT

The tuff system can be roughly compared to salt and basalt as shown in Table 5-1. The values in the table are approximate and represent a conglomeration of data from a large number of sources. The intent of the table is to make qualitative comparisons.

Chemically, the tuff environment is somewhat similar to basalt with a reducing environment and high pH. In terms of important failure modes of waste packages, the potential for rock creep is more like salt while the concern for hydrostatic pressure which exists for basalt does not exist for the tuff vadose zone horizon. Thus, a package design for rock movement is probably needed in some locations, but a barrier resistant to high water pressure is not needed. The need for barriers both in the operational and post closure phase cannot be defended until there is substantially greater consensus or understanding concerning the release mechanism than currently exists.

Under normal post-emplacement scenarios and some of the potentially disturbed conditions, the repository would be in the unsaturated state. Like salt and unlike basalt the predominant transport mechanism for any escaping nuclides would likely be diffusion rather than advection although there are currently significant uncertainties in the demonstration of this hypothesis. Because of the unsaturated environment backfills with high capillary potential (finely divided solids or any small-pore-size material) around the package would be undesirable, unless incorporated in the three-layer design, as they would tend to induce moisture migration to the package.

Horizontal flow in the repository horizon is not likely unless induced flow by capillary action results from high capillary potential materials as discussed above. Vertical flow induced by heat, infiltration or water table rise is a more realistic scenario. Barriers to horizontal flow may not be needed a repository located in unsaturated tuff.

TABLE 5-1

Comparison of Tuff, Salt and Basalt for Concerns Related to Engineered Barriers

	Tuff (Vadose Zone)	Salt	Basalt
Water Oxidation Potential (Eh)	Mildly Reducing	Oxidizing	Reducing
Water Salinity	Low	Very High	Low
Rock Creep Deformation	Moderate	High	Essentially None
Water pH	Nearly Neutral (7.1)	Slightly Acidic (6.5)	Very Basic (9.5)
Hydrostatic Pressure (Gage)	0	0	1400 psi
Expected Normal Water Flow Rate For the Package	nil	Nil except for some brine migration	on the order liters/year
Thermal Conductivity (W/m-°C) at 100°C	1-6	4	1.9-2.2
Kd for Pu(IV) in Rock (approx) ml/g	29	6×10^3	10^4

6.0 WASTE PACKAGE PERFORMANCE

The hydrogeology, geochemistry and hydrochemistry of the repository environment, and the response of that environment to engineered materials, heat and radiation will influence repository performance in the vicinity of the waste package. These fundamental system data, combined in a comprehensive engineered system performance model will allow the calculation of waste package life, nuclide release from the waste package, and nuclide transport in the vicinity of the package.

As previously discussed in Section 3, there is considerable current uncertainty surrounding the data and model of hydrogeology of the fractured unsaturated tuff horizons. More is known about the hydrogeology of tuff below the phreatic surface. Also, there is currently very little data describing the geochemistry and hydrochemistry of the unsaturated tuff horizon. The use of the limited hydrochemical and geochemical data which has been measured for the purpose of calculating radionculde transport is quite uncertain, partially due to system complexity and variability, as well as to problems of scale (Gillham and Cherry, 1982).

It data were available, defensible hydrogeologic models existed for an unsaturated tuff horizon, the calculation of near-field performance would be done in three steps. Initially, waste package lifetime would be calculated. A waste package model which incorporated corrosion as well as possible crushing forces would calculate a predicted waste package breach time. This calculation is, of course, closely linked to the hydrogeologic model. Corrosion is expected to be much slower and possibly non-existent in the unsaturated zone due to the minimal or nil flux of water. The second performance phase would predict nuclide release from the waste forms. Geochemical, hydrochemical and hydrgeologic data would again serve to describe the release environment, along with the respone of that environment to repository conditions. The result of this modeling phase would be a nuclide flux from the waste form as a function of time. Again this flux is expected to be low in the unsaturated zone where the flux of water through the system is low or nil. The final near-field performance phase would calculate nuclide transport through the package backfill. The package backfill may interface with either room backfill or the geologic setting, depending upon repository design and hydrogeology (i.e., direction of nuclide transport). The result of the calculation will be spatially defined nuclide flux out of the package backfill as a function of time.

7.0 NUCLIDE TRANSPORT

Nuclide transport from a tuff repository depends on the local hydrology, hydrochemistry, and geochemistry and on the properties of the engineered barrier system. None of these is sufficiently well known at the present time to warrant anything but a qualitative discussion of nuclide transport. Three studies have explicitly modeled transport from a tuff repository at Yucca Mountain (Giuffre, et al., 1982; Siegel and Chu, 1983; National Research Council, 1983). Each of these studies relied on data which is admitted to be highly uncertain and which often represented only an educated guess of the expected conditions. The results of these studies, therefore, have little significance as an indication of actual repository performance. None of the studies investigated the effect of engineered barriers on performance (excluding the waste package).

This chapter, therefore, focuses not on anticipated performance but on identifying the issues of importance in assessing engineered barrier performance. The discussion is divided into two parts: waste transport in the saturated zone and waste transport in the unsaturated zone. Insights into saturated zone transport are based on the results of this projects study of engineered barriers in a basalt repository (Golder Associates, 1983a). The discussion of unsaturated zone transport is, per force, more speculative as the information base for assessing such transport is virtually non-existent.

7.1 WASTE TRANSPORT FOR THE SATURATED ZONE

Some insights into waste transport in a tuff repository may be obtained by comparison to transport in a hard-rock fractured media such as basalt. Table 7-1 compares rock properties of basalt and tuff which are directly relevant to waste transport.

Like basalt, transport at the repository horizon would take place within a low porosity, fractured material. This means that groundwater transport away from

TABLE 7-1

ESTIMATED VALUES OF SELECTED PROPERTIES

TRANSPORT PROPERTIES	BASALT (Umtanum)	TUFF (Bullfrog)
Fracture Porosity	10^{-5}	$< 10^{-3}$
Vertical Hydraulic Conductivity (m/sec)	10^{-9}	10^{-7}
Horizontal Hydraulic Conductivity (m/sec)	10^{-11}	10^{-8}
Adsorption/Retardation*	Moderate	Good
Eh	Reducing	Probably Oxidizing
Vertical Hydraulic Gradient**	2×10^{-2} (upward)	Unknown, probably downward
Alteration	Insignificant	Significant potential for alteration
Matrix Diffusion	Potentially Significant	Potentially Significant
Lateral and Vertical Inhomogeniety	Significant	Very Significant

* Retardation coefficients for the repository horizon rock mass will vary for each radionuclies considered, and thus only a qualitative description is used here to represent the average condition.

** The existing vertical gradient will be altered by the thermally-induced gradient at early times (<10,000 years)

Note: The values of the properties presented here represent "best guess estimates for the repository horizon based largely on Golder Associates, 1983b. These values are considered sufficient for the qualitative comparisons made in this section, but should not be assigned any absolute significance.

the engineered system would involve fracture flow, which is typically associated with low volume and high velocity when compared to flow through a high porosity medium. Therefore, as in basalt, groundwater velocities can be reduced by backfilling rooms with a high porosity material. If it can be arranged to have flow proceed from the waste package and through the backfilled rooms, then waste transport times will be increase. Since tuff, like basalt, appears to have good sorption properties, the room backfill could be the crushed tuff from the mining operations.

Several properties of tuff are less favorable to waste isolation than basalt. Table 7-1 indicates that hydraulic conductivity may be higher in tuff than in basalt. This implies that the quantity of groundwater flowing past the repository may be greater in tuff if similar hydraulic gradients prevail. This would tend to increase nuclide release rates.

A further negative factor in tuff is the likelihood that redox conditions may be oxidizing. For most radionuclides, solubilities tend to be higher and sorption tends to be lower in oxidizing rather than reducing conditions. The above factors suggest that engineered barriers may be more necessary for a tuff repository than they were for the basalt repository.

In addition to the data on rock properties listed in Table 7-1, an assessment of engineered barrier performance also requires data on the properties of the engineered barriers. For backfill barriers, this would include hydraulic conductivity, effective porosity, sorption characteristics and diffusivity. The properties of backfill utilized in a tuff repository are expected to be similar to those considered for a basalt repository.

7.1.1 Assessment of Transport in the Engineered System

Table 7-2 ranks barriers in tuff (assuming vertical flow) depending on the flow rate through the repository (unknown at the present time). The ranking is based on the relative importance of the barrier to repository performance

TABLE 7-2

QUALITATIVE RANKING OF RELATIVE IMPORTANCE OF BARRIERS
(VERTICAL FLOW SCENARIO)

BARRIERS	IMPORTANCE RANKING		
	HIGH FLOW (MEAN x 100)	SAME AS MEAN FLOW BASALT	LOW FLOW (MEAN x 1/100)
Package Backfill (Low Hydraulic Conductivity)	Major	Moderate	Minor
Room Backfill (High Hydraulic Conductivity)	Minor	Moderate	Major
Seals	Minor	Minor	Minor
Repository Horizon Rock Mass	Minor	Moderate	Major
Overall Need for Engineered Barriers	Major	Moderate	Minor

(minor importance, moderate importance, major importance). The ranking by flow rate spans the likely range and is given relative to the mean estimated flow rate in basalt (Darcy velocity on the order of 10^{-10} m/sec). It should be noted the uncertainty of characteristics at the basalt site indicate that flow in basalt could fall outside of the range considered here.
If the flow rate in tuff is similar to the mean flow rate estimated in basalt, then the basalt results suggest that there is a moderate need for engineered barriers. Both package and room backfill can contribute to nuclide retention. Neither repository seals nor the repository horizon rock mass act as significant barriers to release because flow is predominantly vertically upward at the repository horizon. Repository seals are probably not necessary for vertical flow scenarios.

If the flow rate in tuff is very high, then the need for engineered barriers to reduce release rates is much greater. The most important barrier is then likely to be the waste package backfill. Due to its low hydraulic conductivity, package backfill performance is not strongly affected by an increase in flow rate because transport is by diffusion. The room backfill, on the other hand, is strongly affected and the transport time across the backfill drops in proportion to the increase in flow rate.

If the flow rate in tuff is much lower than the mean flow estimated in basalt, then the overall need for engineered barriers is minor. At such low flow rates, solubility limits would suffice to limit release rates for most of the important radionuclides. Room backfill would have a significant effect on release rates since advection of groundwater through the room would be extremely slow.

Table 7-2 focuses on a vertical flow scenario. If horizontal flow through storafe rooms is found to be significant, then the need for tunnel seals should be considered. However, as discussed in Chapter 3, they may be detrimental to the waste containment effort.

7.1.2 Assessment of Transport in the Geologic Setting

Far-field waste transport, at present, is as uncertain as waste transport in the engineered system. Estimates of groundwater travel times to the accessible environment (10 km away from the repository) range from 10^2 to 10^5 years (Dove, et al., 1982). Because of the strong sorption properties of the zeolitized tuff, many radionuclides can be expected to reach the accessible environment only at times much greater than 10,000 years. Nuclides which may reach the accessible environment in significant quantities at earlier times are long-lived, weakly sorbed, high solubility nuclides. These would probably include Tc-99, I-129, and C-14.

The effect of retardation in tuff could be significantly enhanced as a result of matrix diffusion. Matrix diffusion is migration of solute into the surrounding porous rock during transport through rock fractures. Neretnieks has shown that this process could be very significant in retarding transport in granite (Neretnieks, 1979). However, no field data has yet been produced to validate this concept in any hard rock media. One would nevertheless hypothesize this process to be important in tuff, due to its relatively high matrix porosity.

7.1.3 Conclusions and Summary of Important Issues in the Saturated Zone

Based on the available data it appears that backfill barriers are likely to be an important part of the engineered barrier system in saturated tuff. A good waste package backfill would be a low hydraulic conductivity, non-smectite clay. An adequate room backfill would appear to be the crushed tuff from the excavation process. The need for tunnel seals within the repository is uncertain. By analogy to the results for basalt, such tunnel seals appear to be unnecessary if no detrimental to performance. However, this conclusion is dependent upon assumed repository flow scenarios. Scenarios involving horizontal flow in repository tunnels followed by transport to the accessible environment have not been analyzed in tuff. Flow scenarios are, however, likely to be complex owing to the pronounced vertical and lateral inhomogeniety in tuff horizons.

Important requirements and issues that need to be resolved in assessing engineered barrier performance in a saturated tuff repository are listed below:

- o Minimum Data Requirements

  - Flow Rates and Direction at Repository Horizon (hydraulic condutivities)
  - Hydrochemistry (solubility limits)
  - Rock Properties (diffusivity, dispersivity, effective porosity, retardation)
  - Barrier Properties (diffusivity, hydraulic conductivity, effective porosity, retardation)

- o Model Requirements

  - Transport models similar to those used in basalt are probably adequate (SWIFT, BARRIER, NUTRAN or equivalent)
  - Need evaluation of effect of heat on rock (opening or closing of joints, alteration)
  - Need near-field chemistry model to determine solubility limits sorption phenomena, etc.

- o Assessment of potentially unfavorable scenarios

- o Impact of Horizontal Flow

  - Tunnel seal requirements
  - Repository layout
  - Placement of waste packages

- o Significance of matrix diffusion during fractured flow in tuff

7.2 WASTE TRANSPORT IN THE UNSATURATED ZONE

One method proposed for enhancing the performance of a tuff repository is to place it 200 m above the water table in the unsaturated Topopah member within Yucca Mountain. This section provides a preliminary qualitative assessment of nuclide transport in unsaturated engineered and geologic systems. Thermal effects are important to consider for waste transport in the unsaturated tuff system. Because there have been reported in situ moisture content values of up to 91 percent saturation and low probability scenarios involving climatic changes, consequences of sudden saturation are also discussed. A brief discussion of available mathematical models is also included.

7.2.1 Solute Transport in the Engineered System

Alternative emplacement considerations and backfill materials (focusing on grain size options) as they effect flow in the unsaturated zone are discussed in Chapter 3. A triple layer design appears to be most versatile in surmounting potential processes which might cause wetting and flow past the waste package. A fine smectite clay near the package retards wetting in the event of inundation. A surrounding coarse material of high thermal conductivity prevents water inflow from a fine grained matrix. A surrounding fine grained, high thermal conductivity material ensures small pore sizes adjacent to the coarse material. The hydrologic advantages and disadvantages of alternative designs are not discussed in this chapter. But the relative merits of these materials in the event water is present and the package is breached are discussed with respect to transport processes.

Transport will not occur until water contacts the package in either a saturated flow condition, unsaturated condition or "static" condition where diffusion can occur.

Once transport is initiated (either in the saturated or unsaturated mode) the following considerations are important. The fine grained material near the package which serves to retard saturation in the event of inundation should be tight sorbing material to delay and decrease release of nuclides as was illustrated in analyses performed for saturated basalt. A coarse grained material may be placed around the tight sorber to prevent water entry from the fine grained matrix into the cavity. Coarse grained materials do not retard nuclides as well as fine grained material of the same chemical composition. Since little sorptive advantage can be gained in the coarse material the possibility of using a non-sorbing material to attain high thermal conductivity may actually retard and decrease nuclide release by substantially increasing package life. An outer layer of fine grained material may be included in the design to prevent water entry from large aperture fractures to the coarse material. A tradeoff may have to be made between high thermal conductivity and high sorption capability of this material. Maintaining low temperatures may allow the host rock to maintain its sorption properties where as insulating the package with a granular sorper may result in high enough temperature to hinder the sorption capabilities of the fill and the host rock.

Table 7-3 summarizes the advantages and disadvantages of alternative materials. As discussed in Chapter 3 some combination of materials may be necessary to account for all plausible failure scenarios. The most suitable of the engineered systems cannot be selected until more is known about in situ moisture conditions at the proposed site and critical saturation levels in unsaturated tuff.

When more is known about plausible far field scenarios, the capillary and adsorptive advantages of unsaturated tuff can be optimized in a properly designed engineered system.

7.2.2 Solute Transport in the Geologic Setting

The primary pathway for solute transport from an unsaturated tuff repository includes a path similar to that discussed for a saturated tuff repository

TABLE 7-3

ADVANTAGES AND DISADVANTAGES OF ALTERNATE BARRIER MATERIALS

Material	Advantages	Disadvantages
Non-smectite Clay	Retards water entry if inundated high sorption diffusion controlled flow	Keeps water in if wetted and dried. Attracts water if contacts wet fine grained rock matrix Low thermal conductivity
Tuff gravel	Water won't enter in unsaturated zone with small openings Water will drain if wetted and dried	Low thermal conductivity Water ingress rapid above critical saturation level. Poor sorption Low Thermal Conductivity
Conducting Metal Small pores (possibly copper)	Will prevent water entry into coarse material high thermal conductivity	High hydraulic conductivity Uncertain alteration/ Corrosion behavior or sorption
Large pores (possibly copper)	Water won't enter in into coarse material high thermal conductivity	High hydraulic conductivity Uncertain alternation/ Corrosion behavior or sorption
Combinations	o enhance adjacent materials advantages	o more complex construction

(Section 7.1). In addition, nuclides from an unsaturated tuff repository must travel at least 200 meters from the repository to the water table. This additional flow through unsaturated tuff may be relatively slow because vertical hydraulic conductivity of the tuff sequence is expected to be low and will be further decreased due to the unsaturated conditions. However, the effective moisture content is uncertain as is the nature of the interaction of infiltrating water and water stored in the porous matrix and feasible variations of these parameters could vary travel time by orders of magnitude. Recharge water may infiltrate rapidly as at Rainier Mesa, or may enter the porous matrix, increasing storage, or if thick, relatively unfractured zones exist in the sequence infiltration may be very slow. The conclusion is that if the porous matrix is at or above its water holding capacity and the effective moisture content (ratio of unretainable water volume to total volume) is low, travel time from the repository to the water table could be relatively short. However, if the waste is kept dry this water would not be contaminated.

The low level of saturation may enhance proposed repository performance by inhibiting waste transport in several other ways. First of all, diffusion in the unsaturated zone may be slower than in the saturated zone because nuclides would travel tortuous paths along grain faces. Unsaturated diffusion could not, in any event, be faster than diffusion through the same materials under saturated conditions.

Secondly, the heat produced by the nuclear waste would inhibit water flow into the repository in two ways. Moisture will flow away from the repository as long as the temperature gradient remains high. And for several thousands of years when the temperature of the air in the repository is above 100° C, all water that does enter the repository will be in vapor form (assuming the repository remains unsaturated). Water movement in the vapor phase cannot transport nuclides. Both the thermal gradient and thermal (boiling) barrier prevent water from contacting the nuclear waste and transporting radionuclides out of the repository and into the geologic system.

7.2.3 Available Mathematical Models

Mathematical models that have been written to describe the various flow and transport processes in unsaturated geologic settings primarily describe these processes in the upper few meters of the soil profile. Several of the unsaturated flow and transport codes identified in the NRC-sponsored review of unsaturated flow and transport models (Oster, 1982) are technically flexible enough to apply to the proposed unsaturated tuff repository. Only one of these codes goes beyond flow and solute transport to include heat transport, obviously an important unsaturated tuff repository issue. None of these codes have been field validated. Furthermore and most importantly, fracture flow has not been included in any of these codes since this process is currently poorly understood.

There are several aspects of an unsaturated tuff repository that would enhance system performance over a saturated tuff repository. The most substantial problems lie in the lack of hydrologic data and understanding of water flow in fractured unsaturated geologic systems. Mathematical representations of unsaturated flow do exist, but until more is known about in situ unsaturated flow conditions at the NTS, use of such models is of limited value.

7.2.4 Summary

Siting a nuclear waste repository in unsaturated tuff rather than saturated tuff would enhance repository performance by:

- Preventing water from entering the engineered system (capillary and thermal effects)
- Reducing the flux of water passed the waste
- Increasing the flow distance to the accessible environment
- Reducing the continuity of diffusion paths

None of these enhancements can be quantified until more is known about in situ hydrologic parameters and unsaturated flow mechanisms. It should be repeated here that performance codes with specified uncertainty at any instant of time in the licensing process are essential to defend the need (if at all) and specification of engineered barriers.

8.0 CONCLUSIONS AND RECOMMENDATIONS

The effectiveness of engineered barriers in a repository must be measured by their contribution to overall repository performance requirements. At present, these requirements include:

- o nuclide transport to the accessible environment (Draft EPA,1982)
- o waste package life (NRC,1983)
- o nuclide transport from the engineered system to the geologic setting (NRC, 1983)

Demonstration of the effectiveness and necessity of engineered barriers requires defensible models of:

- o waste package lifetime
- o nuclide release from waste form
- o nuclide transport through engineered system (including package and room backfills, if present)
- o nuclide transport through geologic setting

Construction of these defensible models, in turn, requires a fundamental understanding of the hydrogeology, geochemistry and hydrochemistry, as well as of the response of these to man-induced environmental changes in the repository, including heat, radiation, repository construction, and engineered materials.

At present, the data and models necessary to evaluate engineered barrier performance in an unsaturated tuff repository do not currently exist.

As a result, a defensible and conclusive statement on barrier and repository performance cannot be made at this time. Current indications are that the partially saturated repository environment currently favored by DOE may offer significant performance advantages when compared to a saturated repository environment. It is cautioned, however, tht such speculations are based on a desirable but currently indefensible hydrogeologic models.

In order to defensibly predict barrier and repository performance, it will be necessary to develop models and gather data which will allow comprehensive modeling. The immediate emphasis should be placed on developing a defensible hydrogeologic model of the partially saturated repository horizon and geologic setting. Once quantified, this model will contribute to the design of virtually every part of the engineered system, provide that basis for performance assessment and will also dictate many aspects of site characterization. To this end we recommend that NRC strongly encourage DOE to embark on a series of in situ tests to understand flow in fractured unsaturated tuff away from Yucca Mountain and prior to sinking the Exploration Shaft. Additionally, an assessment of the likelihood, as a function of time, that the phreatic surface will rise to the repository must be made. If the likelihood of this is such that complete resaturation must be considered (as driven by the current draft EPA standard), then a saturated hydrogeologic model must also be developed. Additionally, a fundamental understanding must be developed of hydrochemistry and geochemistry as it exists undisturbed, and as it will respond to repository development and operation. It is recommended that further research and development on tuff be directed towards these ends.

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APPENDIX A

A1.0 SUMMARY OF GEOLOGY AT YUCCA MOUNTAIN

The Nevada Test Site (NTS) is situated within the south central part of the Great Basin Section of the Basin and Range province and is located approximately 79 km (50 miles) northwest of Las Vegas in Nye County (Figure A-1). The stratigraphic sequence at the NTS may be divided into pre-Tertiary rocks (older than 65 million years), Tertiary rocks (between 65 and 1.8 million years old) and valley-fill. Pre-Tertiary rocks are predominantly carbonates with some argillites and clastic rocks. The rocks of Tertiary age are primarily tuffaceous and are currently being evaluated for the siting of an underground repository for high level nuclear waste at Yucca Mountain. Our knowledge of the full sequence of rocks at the potential site is incomplete. Only one deep drillhole (USW-G1), which penetrated 6000 feet of tuffaceous rocks before drilling was discontinued, was available to this study.

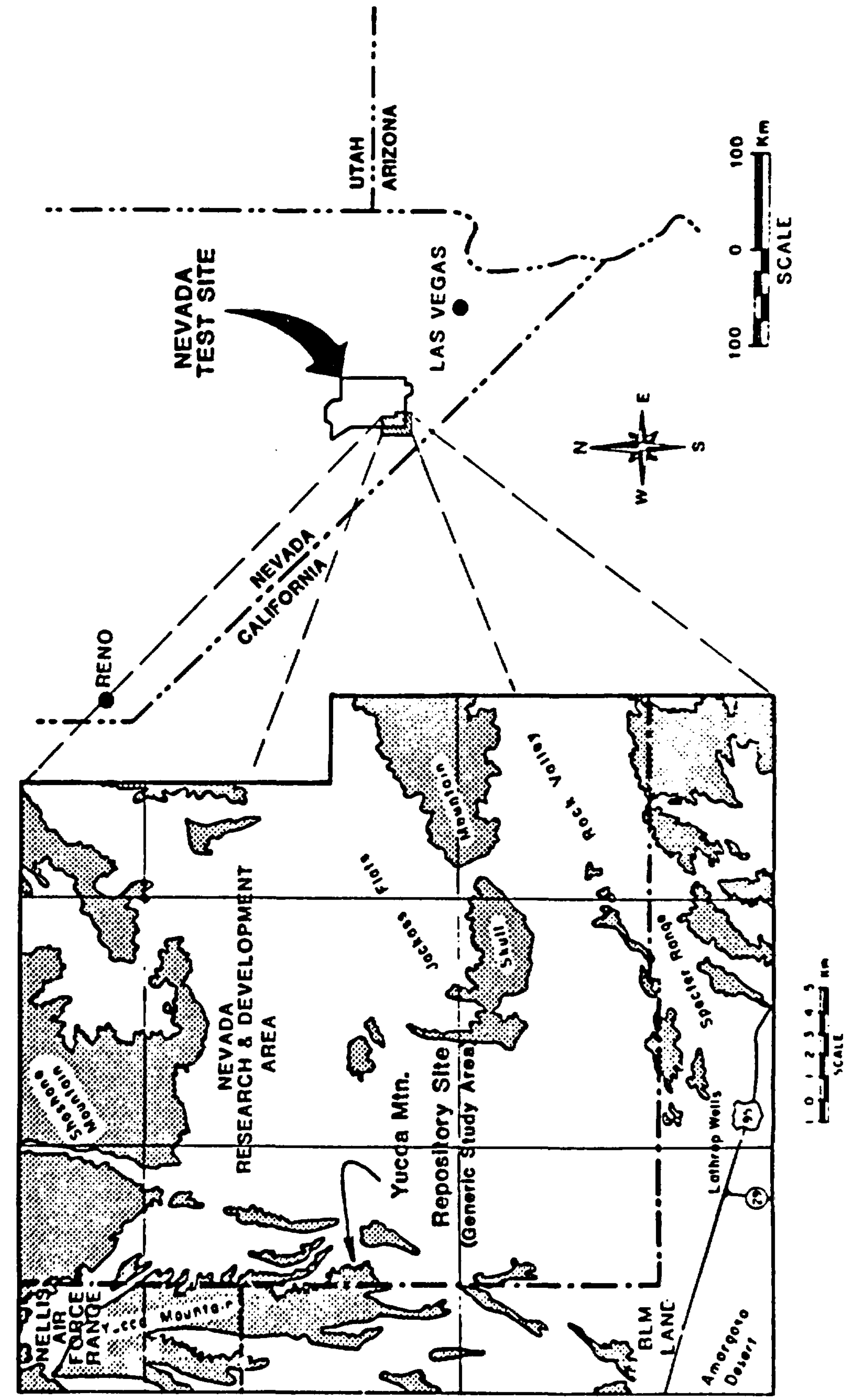
A1.1 TUFF MORPHOLOGY

Tuffs are explosive volcanic deposits produced when the gas content of a magma is suddenly lost. More specifically they are lithified volcanic ash deposits. They may be deposited either directly from explosive volcanic eruptions or as reworked and redeposited sediments. Because of the explosive origin of tuffs, these deposits tend to be fairly widespread (tens of kilometers from their source) and a high degree of variation may result between different tuff deposits.

Tuffs may be classified by composition depending on their content of glass, crystal, and rock debris. Those composed mainly of glass particles are known as vitric tuff; those made up chiefly of crystals are designated crystal tuff; and those in which accessory and accidental rock fragments (originating from the pre-existing rocks) predominate are termed lithic tuffs. Ejecta generally become finer away from the eruptive vents, though exceptions to this rule may

LOCATION OF GENERIC STUDY AREA WITHIN NTS

Figure A-1



After DOE, Aug. 1981

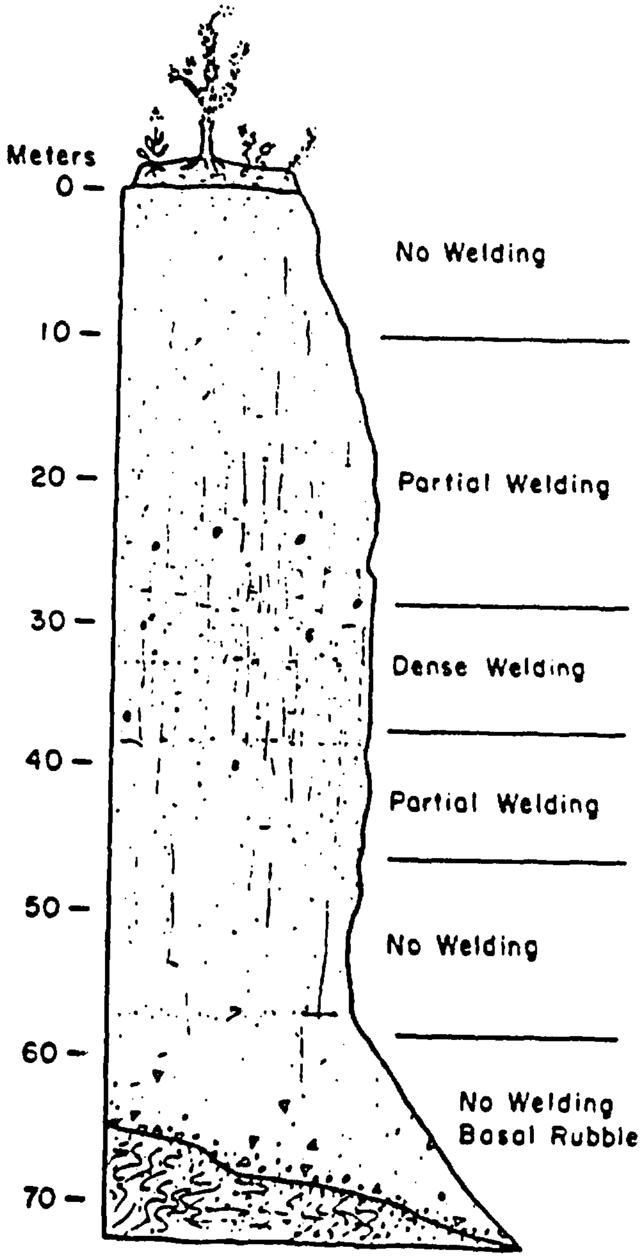
Project No. 813-1177 Reviewed EP Date 7-86 result from changes in wind velocity during transport and from differences in density of the airborne particles. Generally, lithic and crystal rock fragments fall nearest the source, while the less dense glassy fragments (especially vesicular fragments) tend to be carried greater distances from the source. At any one location, the products of a single ash fall may exhibit graded bedding. The coarser, more crystalline, and more basic ejecta and those richer in mafic minerals grade upward into finer ejecta richer in glass, feldspar, and quartz to form layers with a more siliceous composition. Corresponding lateral transitions may often be observed as a layer of tuff is followed away from the parent source.

Most vitric tuffs form by being blown high into the atmosphere and cool before they are deposited upon the surface forming air fall tuffs. Some ashes are discharged as a nuee ardente (turbulent, gas-charged avalanches) that move rapidly downslope from a crater or fissure forming ash-flow tuffs. These gas-charged masses are extremely mobile and consequently may spread over vast areas. Because ash flows are deposited so rapidly and accumulate to great thicknesses, many remain hot after emplacement, particularly in the central part of the flows. The shards of volcanic glass, while still hot and under high overburden pressures, are squeezed and flattened and at the same time pumiceous lapilli are deformed into disks, som paper thin. All the constituents thus become firmly annealed to form a welded tuff. The majority of the tuffs discussed in this report at Yucca Mountain are ash flow tuffs with some air fall tuffs.

Tuff deposits that cool as a single entity are commonly referred to as a cooling unit (Figures A-2 and A-3). Such a deposit typically has a core of welded material, most of which may have devitrified to quartz and feldspars with or without cristoblite. The welded zone is characterized by columnar jointing, and spherulitic structures, and a lack of bedding. At the base of the welded zone, there is typically a layer of densely welded material that has not devitrified, but, instead remains a dense glass called a vitrophye. The degree of welding decreases outward from the core so that the welded zone

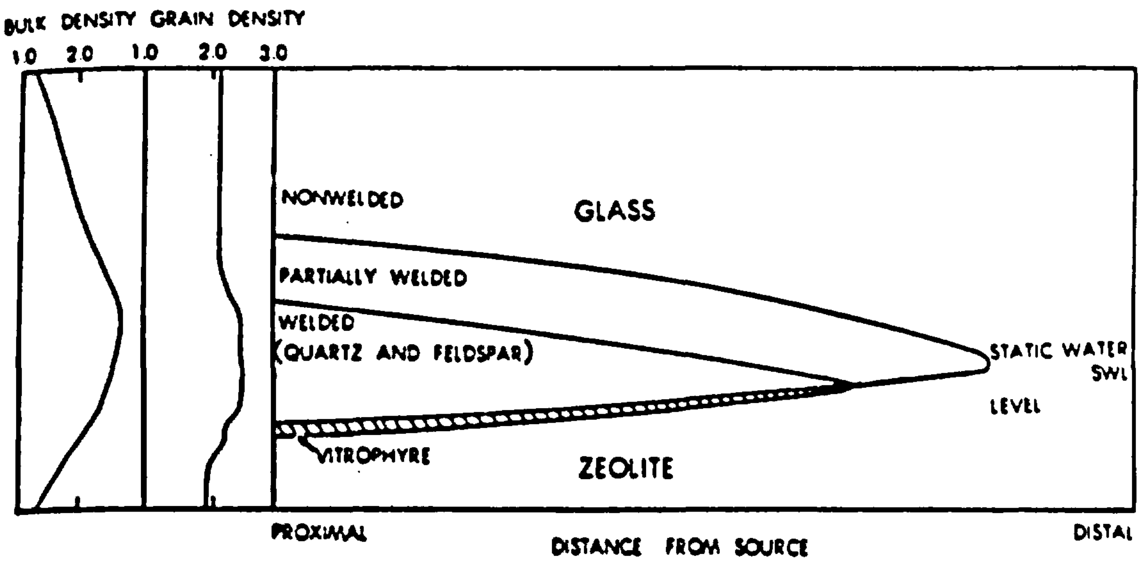
SCHEMATIC STRUCTURAL SECTION THROUGH A SINGLE ASH FLOW TUFF BED

Figure A-2



After Winograd, 1971

SCHEMATIC CROSS SECTION THROUGH AN ASH FLOW TUFF COOLING UNIT WITH TYPICAL BULK AND GRAIN DENSITIES — Figure A-3



After Smyth and Sykes, 1980

is surrounded by zones of decreasing density, competence, and strength. An unsorted, nonwelded horizon of loosely aggregated pumice and ash similar to the air fall unit described previously is commonly present at the base of the ash flow deposit. The transition between the soft unwelded upper and lower portions to hard, welded zone is commonly gradational.

Because the surface of the deposit is loose and poorly consolidated, it is radily reworked by surface processes and may be redeposited by streams, in ponds, or as volcanic mud flows (lahars). Such processes give rise to sorted, bedded deposits termed bedded tuffs. A wide gradation exists between true tuffs and sedimentary deposits with a tuffaceous content.

A1.2 ALTERATION

Pyroclastic rocks, particularly fine-grained varieties, are readily altered, both chemically and physically. This is because of their high porosity, the large surface area of constituent particles, and the inherently unstable nature of the glassy fragments. Their alteration may be due to simple surface weathering or may result from the influence of circulating groundwater either in the waning stages of the volcanic activity or subsequently.

Devitrification of glass is the initial alteration phase. In the case of nuee ardente, deuteric alteration may occur while the ejecta are still hot and permeated by fumarilic gases. The glass of some welded tuffs may thus be altered to crypto and microcrystalline aggregates to tridymite, sanidine or albite, while pores may become coated with tridymite, crisobalite, and hematite. In other vitric tuffs, the glass may be replaced by dense felsic mixtures of quartz and orthoclase or sodic plagioclase.

Deuteric alteration of acidic and intermediate glasses to opal and clay minerals is widespread. Opalization is usually confined to hot spring areas, but clay may form in any environment. One of the more common products of devitrification is the clay mineral montmorillonite which is of the smectite group. Montmorillonite is an expanding-lattic clay mineral which exhibits swelling on wetting and shrinking upon drying due to the introduction or removal or interlayer water.

Feldspars, as well as glass, may alter to clay or sericite. Mafic constituents tend to be replaced by chlorite and iron oxides.

If porosity is high and water of suitable composition is present, glass may alter completely to zeolites in as little as 10,000 years, even at temperatures below 100°C (Shepard and Starkey, 1964). Zeolite mineral assemblages may therefore be considered as characteristic of low-temperature groundwater alterations of glass in a circulating hydrologic system (Sykes et al, 1979). If water is not present, or if the porosity is low (as in vitrophyres) alteration will not occur and the material may remain glassy for millions of years. There is no evidence that the material once crystalized to quartz and feldspar will later alter to zeolites in the geochemical environment thought to exist in these rocks. However, feldspars may alter to clays, particularly in the presence of acidic groundwater. Many acidic and intermediate tuffs are extensively silicified due to deposition of quartz, chalcedony, or opal from groundwater enriched in silica during devitrification of the glass.

Alteration of tuffs, particularly to zeolites of potentially high sorptive properties, indicates that alteration is a characteristic upon which the repository design may critically depend. The presence of zeolites and clays in some tuff units results in highly favorable mineralogic compositions from the standpoint of inhibiting radionuclide migration. However, the complex mineralogical variability of tuff units will require extensive individual teting of specific candidate horizons to adequately assess their potential for geochemically retarding radioactive contaminants that escape from the waste package.

A1.3 ZEOLITES AND CLAYS

Most welded tuff do not contain a high percentage of zeolites and are thermodynamically stable. Welded, devitrified tuff typically contains as little as 1 to 2 percent adsorbed water and constituent phases are generally anhydrous and stable at high temperatures. Nonwelded tuffs contain more zeolites than welded tuffs because they are generally more porous. Zeolite formation requires both high porosity and pore waters of suitable composition. Because of their high porosity, nonwelded tuffs reportedly contain up to 18 percent structurally bonded water and are thermodynamically unstable at relatively low temperatures.

The principal zeolite phase is high silica clinoptilolite. Calcium tends to be the dominant large radius cation, but grains with dominant potassium or sodium cations are not uncommon, particularly with increasing depth (Sykes et al, 1979). Compositional variations in clinoptilolite may be due to groundwater composition or original pyroclast composition. Minor amounts of mordenite, characterized by lower silica content and high alkali content, occur as vug fillings at depths below 550 m in hole UE25a-1. The presence of mordenite may indicte slightly elevated alteration temperatures, but more likely reflects alkali enrichment with depth.

Recent work by Los Alamos National Laboratory has shown the mineralogic phase change in zeolites (Clinoptilolite-analcime-albite) is very sensitive to temperature. Clinoptilolite, which is highly sorptive, begins to alter to less sorptive analcime at approximately 100°C (DOE, 1981). [Therefore, to utilize clinoptilolite's good cation sorption qualities, temperatures within zeolite horizons should be limited to less than 125°C.] These breakdown reactions, as well as dehydration of zeolites, result in the formation of denser, less hydrous phases. [Thermal effects in zeolitized tuff could potentially cause volume loss leading to shrinkage fractures, and evolution of water vapor (Sandia Laboratories, 1980)].

The primary clay minerals at Yucca Mountain are sodium saturated montmorillonite-beidellites with some illite. Zeolites are generally more abundant than clays and are stratified. Clays are ubiquitous throughout the tuff units due to the mode of alteration of the units. Montmorillonite has a high cation exchange capacity, and its presence in the repository rock horizon could provide an additional barrier to the migration of radionuclides. The authors of this document are unaware of the temperature effects on clays at Yucca Mountain. However, the capacity of both clays and zeolites to trap ions becomes reduced with continued passage of radionuclides migrating in solution at temperatures greater than 100°C. Thus, the effects of heating will diminish tne near-field effectiveness of clays for retarding radionuclide migration through the saturated repository rock horizon.

A.1.4 STRATIGRAPHIC SEQUENCE

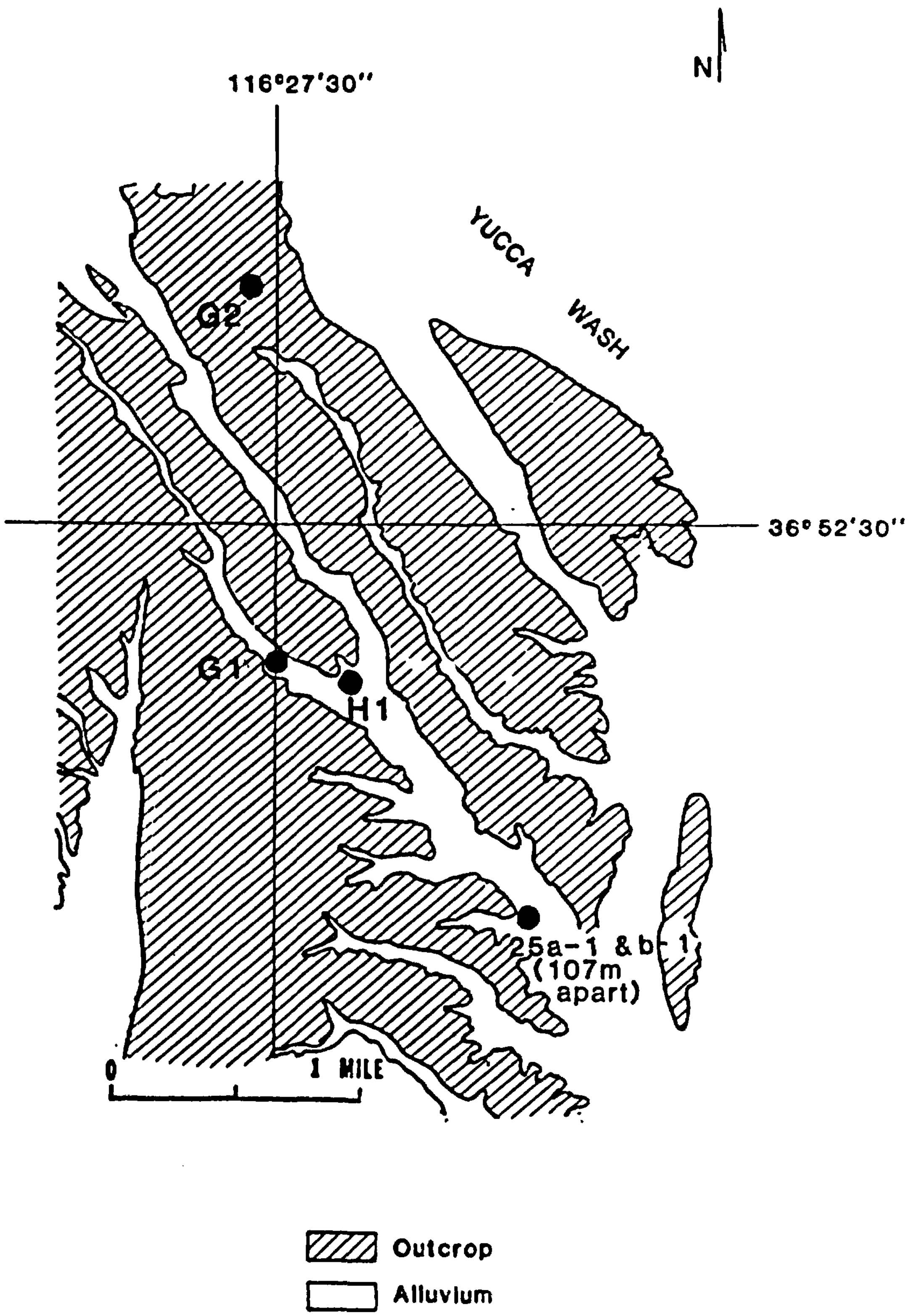
The stratigraphy at Yucca Mountain is based on a series of holes that have been drilled for investigation of potential repository sites by the Nevada Nuclear Waste Storage Investigations (NNWSI). The location of these holes are shown in Figure A-4 and a stratigraphic column is presented in Figure A-5. The tuff penetrated by the drillholes at Yucca Mountain are composed of three informal tuffaceous units (the Ashflow and Bedded Tuff, Lithic Rick tuff, and the Flow Breccia) the Crater Flat tuff, and the Paintbrush Tuff. Separating the Crater Flat Tuff from the overlying Paintbrush Tuff are the tuffaceous beds of Calico Hills. The Crater Flat is subdivided, in ascending order, into the Tram, Bullfrog, and Prow Pass Members. The overlying Paintbrush Tuff is comprised of, from oldest to youngest, the Topopah Springs, Pah Canyon, Yucca Mountain, and Tiva Canyon Members.

These tuffs comprise a sequence primarily of welded and nonwelded ashflow tuffs, flow breccias and tuffaceous sediments over 1730 m thick.

The Bullfrog Member of the Crater Flat Tuff, approximately 140m thick, is a possible target horizon for a repository in the saturated zone. The top of

DRILL HOLE LOCATIONS AT YUCCA MOUNTAIN AREA

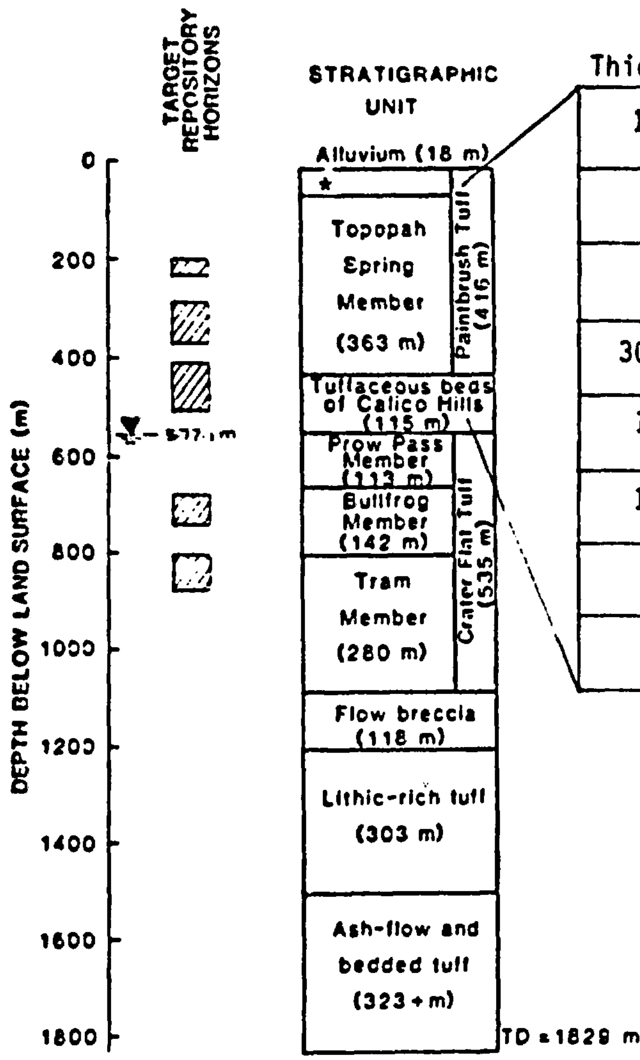
Figure A-4



After DOE, August 1981

STRATIGRAPHY AT YUCCA MOUNTAIN

Figure A-5



Data from drill hole USW-G 1
After DOE, August 1981

TOPOPAH SPRINGS MEMBER IN USW-G1

Surface elevation 1326.5m

Thickness	Lithology	Elevation
		1254.9m
10.7m	Non-welded; vitric tuff	
		1244.2m
3.1m	Vitrophyre	
		1241.1m
3.8m	Densely welded; vitric tuff	
		1237.3m
303.3m	Densely welded; devitrified	
		934.0m
16.9m	Vitrophyre	
		917.1m
15.8m	Mod. densely welded; vitric	
		901.3m
2.9m	Non-welded; devitrofied (Zeolitized)	
		898.4m
6.6m	Bedded tuff	
		891.8m

*

12m	Paintbrush
8m	Yucca Mtn.
34m	Pah Canyon

the piezometric surface is situated at approximate elevations 760m in drillhole USW-G1 and the top of the Bullfrog Member is at an approximate elevation of 660m. The Bullfrog is a partially to moderately welded, divitrified tuff with local vapor phase crystallization and contains a zeolitized horizon between 793.5 m and 805 m in drillhole USW-G1.

The upper 44 m of the Bullfrog Member in drillhole USW-G1 consists of nonwelded, devitrified ash-flow tuff which is locally argillic from 665 m to 707 m. This nonwelded tuff is separated from an underlying partially welded vapor phase zone by 0.05 m thick, moderately indurated, bedded and reworked tuff. The partially welded zone beneath this reworked tuff is 39 m thick and exhibits vapor phase crystallization. Underlying the partially welded zone, is a 31 m thick zone of moderately to densely welded, devitrified tuff exhibiting some vapor phase crystalization in the upper 5 m. Beneath the moderately to densely welded zone, is a 17 m thick moderately to partially welded, devitrified tuff. The base of this unit is reported to dip 10 degrees relative to the core axis. The basalt portion of the Bullfrog Member is characterized by a 11.5 m thick bedded and reworked tuff with beds containing from 5 to 80 percent pumice which is commonly zeolitized. A light red to moderate-reddish brown, thin bedded, highly silicified unit occurs at the base of the bedded interval. Phenocryst content ranges between 10 and 25 percent and typically are plagioglase, quartz, sanidine, biotite, or hornblende.

One target repository horizon in the unsaturated zone is the Topopah Springs Member of the Paintbrush Tuff. The Topopah Springs Member is 363 m thick in drillhole USW-G1, extending from elevations 1255 m to 892 m. This member represents at least one and possibly two cooling units. Two vitrophyres were observed in core samples of drillhole USW-G1, extending from elevation 917.1 m - 934 m and between elevation 1241.1 - 1244.2 m. These vitropohyres are typically densely welded, glassy and are largely unaltered (Waters and others, 1981). Overlying the upper vitrophyre is a 10.7 m thick nonwelded ash-flow tuff.

Beneath the vitrophyre is a thin 3.8 m densely welded, vitric ash flow tuff. Underlying this tuff unit is a 303.3 m thick section of densely welded, devitrified ash-flow tuff which locally contains up to 30 percent lithophysae. This unit is highly fractured and clay gouge is found along some of the fractures (Nimick and others, 1982). A thin .12 m thick, unconsolidated to poorly consolidated ash occurs at elevation 1187 m. Underlying this thick sequence of densley welded, devitrified tuffs is the second vitrophyre. Beneath the vitrophyre is a moderately-densely welded, vitric ash-flow tuff.

A 3 m thick nonwelded devitrified ashflow tuff, which is slightly zeolitized, is located beneath the nonwelded to moderately welded tuff. Finally, a basal bedded-reworked tuff about 6.6 m thick overlies the tuffaceous beds of Calico Hills.

A1.5 STRUCTURE

The NNWSI Peer Review (DOE, August 1981) suggested that the tuffs at Yucca Mountain, being primarily of ash flow origin are laterally continuous. Bedding dips reportedly are relatively shallow and range from 9 to 12 degrees relative to the core axis of the Prow Pass Member in hole USW-G1. Dip direction is to the east and southeast (Nimick and others, 1982).

Joints measured in the Topopah Springs Member showed a preferred, near vertical, inclination in the 80 to 90 degree range. These joints are believed to represent columnar joints generated in response to tensional forces active during cooling of the flow. The average number of joints per 3 m interval of core is 4.5 for the Topopah Springs Member. The presence of these vertical joints and the brittle nature of some of the welded tuffs makes joint spacing almost impossible to evaluate confidently from vertically drilled coreholes. The method of fracture reporting by USGS is certainly conservative since each rubble core piece is counted. Thus, highly fractured zones reported from core logging may be single vertical features broken by the coring process, thus the number of in situ joints would probably be less than stated.

Most of the major faults at Yucca Mountain are Basin and Range faults. Both confirmed and inferred faults bound most of the Yucca Mountain structural block which contains the proposed repository site. Most of the faults are normal with no indication of major strike-slip displacement (Lipman and McKay, 1965). Dips of the faults are expected to be approximately 60° (Nimick and others, 1982). The predominant orientation of the faults is approximately north-south; other orientations are present, but most of these faults are minor. Steeply dipping north-south normal faults delineate a system of horsts and grabens along the eastern flank of Yucca Mountain. East-west oriented washes along the east edge of the Yucca Mountain block are not the result of preferential erosion along fault zones (Nimick and others, 1982).

The Yucca Mountain site is situated along the east-west hinge line located at approximately 36°52' latitude. North of the hinge line, dense north-south normal faulting predominates while south of the line, major faulting is less abundant and displacements are of smaller magnitude. It is believed that repository construction within the Yucca Mountain block would avoid intersecting the major faults at depths of less than 1200 m (Doyle and others, 1981).

No Quaternary faulting has been observed in the southwest quadrant of the NTS but is known to occur in the northeast and southwest quadrants. Two faults were encountered in drillhole USW-G1 both within the Tram Member. Although it has been shown that the potential repository sites at Yucca Mountain have avoided the worst zones of faulting, the existence of additional sympathetic faults cannot be precluded, as two of the holes drilled to date have intersected faults. This would indicate that the occurrence of faults may be more widespread than initially supposed. It should be emphasized that the presence of faults may not be critical to performance of a repository in unsaturated horizons. If faults are shown, however, to be important, then it will be necessary to define them hydraulically and to this end there will be a need to define their geometric limits more carefully.

APPENDIX B

B1.0 SUMMARY OF HYDROGEOLOGY AT YUCCA MOUNTAIN

At this time, the primary target repository site at NTS is within the Yucca Mountain fault block in the Topopah Springs Member of the Paintbrush Tuff (unsaturated). Secondary sites are located beneath in the Bullfrog Member of the Crater Flat Tuff (saturated). This area falls on the boundary of the Pahute Mesa and Ash Meadows Groundwater Basins (Figure B-1).

B1.1 REGIONAL HYDROGEOLOGY

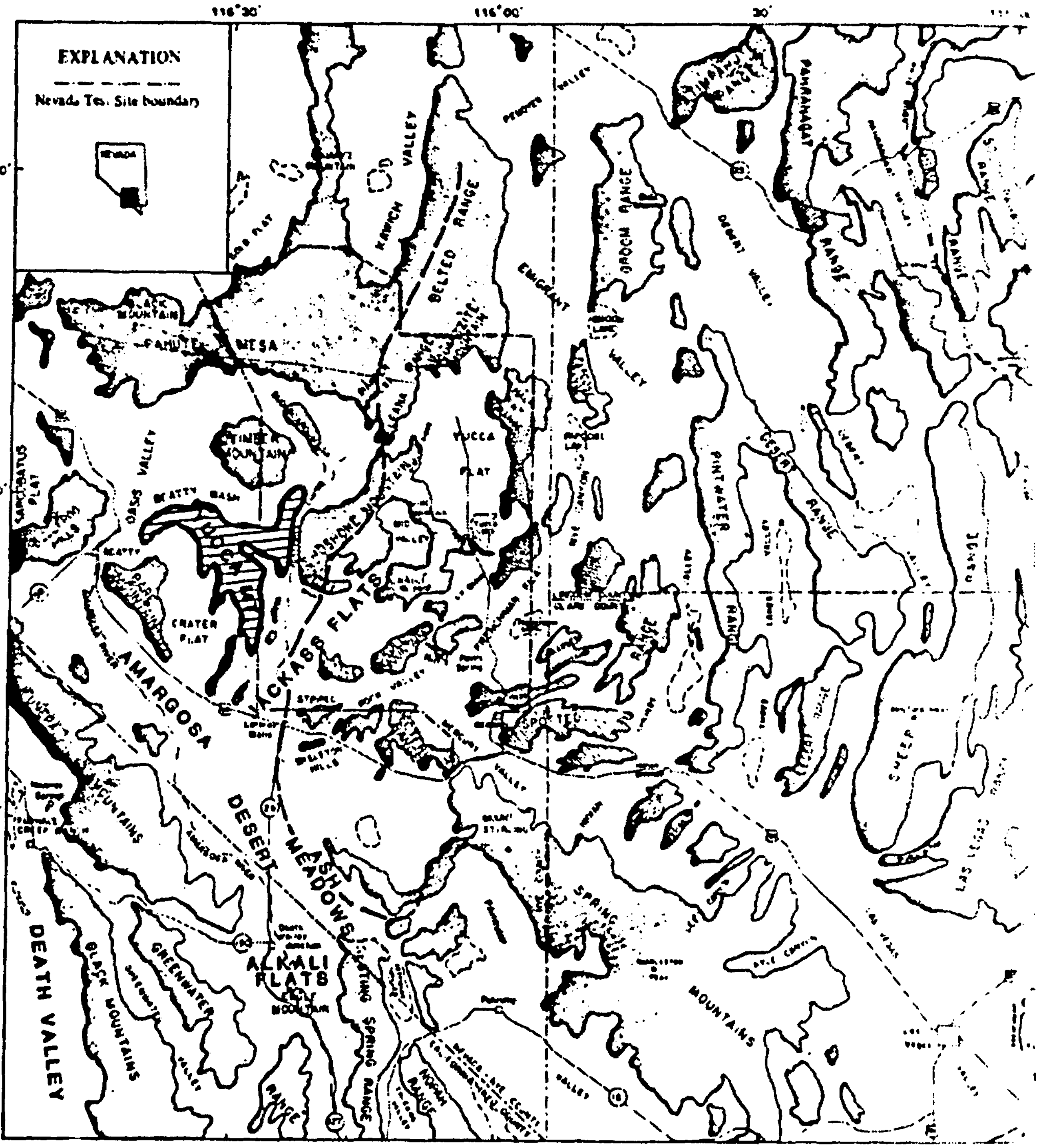
Knowledge of the hydrogeology of the region is currently incomplete, and when coupled with the complex geologic structure of the area renders extrapolation from distant data points difficult. It appears the groundwater system is recharged by infiltrating precipitation water in the highlands. Various hypothesized discharge areas include the Armagosa Desert, Ash Meadows, Death Valley, Alkalai Flat, and Jackass Flats (Winograd and Thorderson 1975; Guzowski et al 1982). These areas are noted in Figure B-1. Figure B-2 illustrates inferred trends of groundwater movement within the saturated tuff units in the vicinity of the NTS (Winograd and Thordarson 1975; Borg et al 1976). It is reasonable to assume that regional groundwater flow occurs in generally a southerly direction in the deep carbonate aquifers (Winograd and Thordarson 1975).

B1.1.1 Hydrogeologic Units

Hydrogeologic units may be divided into Pre-Tertiary and Tertiary. Within the Pre-Tertiary units, carbonate rocks are aquifers and clastic units are aquitards. The Tertiary hydrogeologic units are the tuffaceous deposits with vitric and welded units as aquifers and altered units as aquitards.

Winograd and Thordarson (1975) have delineated the following regional hydrogeological units (in descending order):

INDEX MAP OF NEVADA TEST SITE AND VICINITY — Figure B-1



Modified from Winograd and Thordarson, 1975

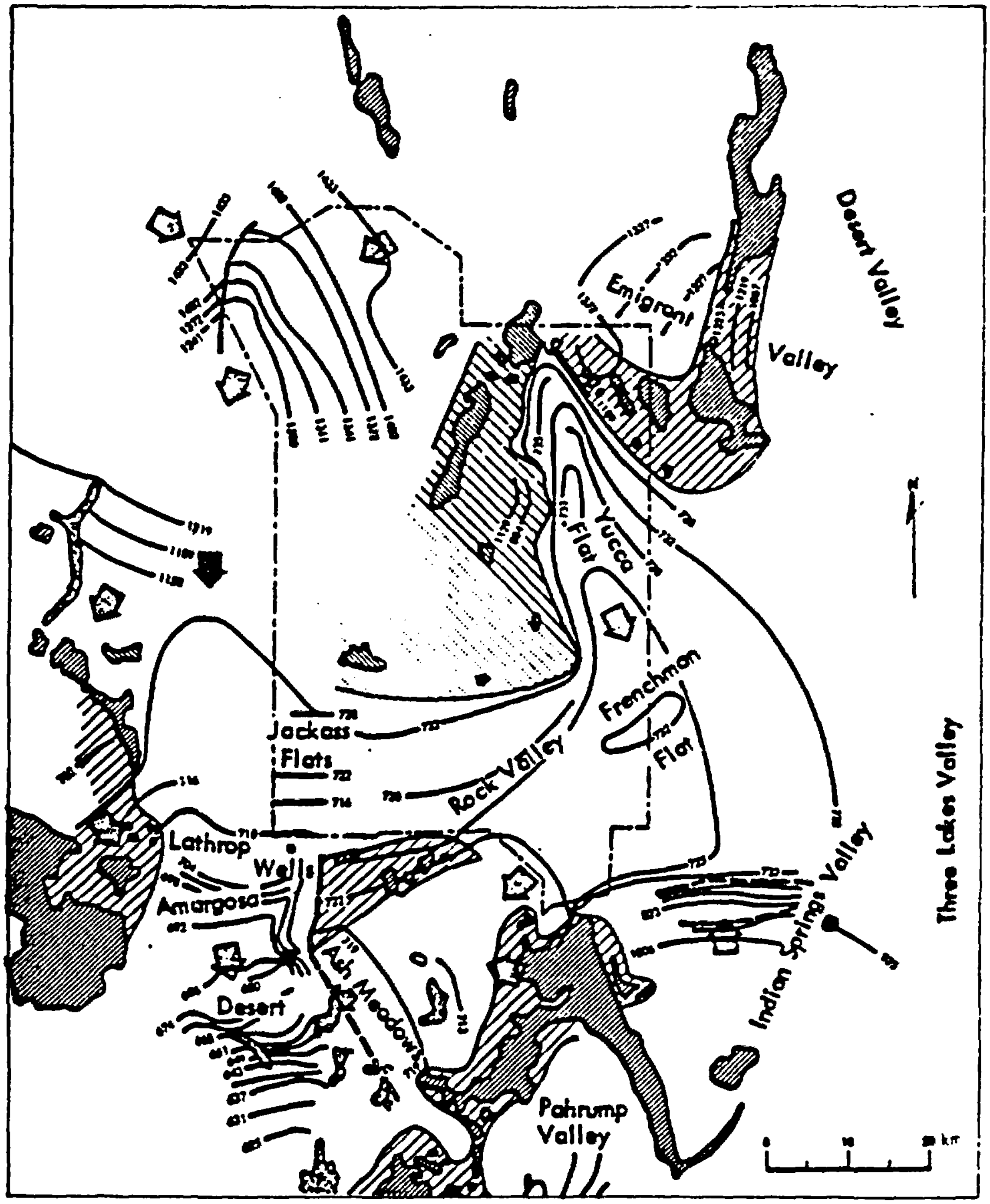
0 10 20 30 MILES
0 10 20 30 KILOMETERS

—·—·— Outline of Nevada test site

— — — Approximate boundary between Pahute Mesa and Ash Meadows groundwater systems according to Guzowski et al, 1982

HYDROGEOLOGIC MAP OF NEVADA TEST SITE AND VICINITY

Figure B-2



Areas of groundwater discharge

Inferred groundwater barrier

Potentiometric contour. Shows altitude of hydraulic head potential in meters Interval varies.

Arrow indicates inferred direction of groundwater flow.

Spring

Closely ruled areas represent surface exposure of Upper Clastic Aquitard. Widely ruled areas represent areas where Upper Clastic Aquitard is dominent unit in sense of saturation.

Closely ruled areas represent surface exposure of Lower Clastic Aquitard. Widely ruled areas represent areas where Lower Clastic Aquitard is dominent unit in sense of saturation.

after Winograd and Thordarson, 1975
as reproduced in Borg et.al., 1976

Rev. ___ Dwg. No. ___ Date ___ Eng. ___

- Valley fill aquifer
- Lava-flow aquifer
- Welded and bedded tuff aquifer
- Lava flow-aquitard
- Tuff aquitard
- Upper carbonate aquifer
- Upper clastic aquitard
- Lower carbonate aquifer
- Lower clastic aquitard.

The Bullfrog which is within the saturated zone, is a part of the tuff aquitard. The Topopah Springs, located in the unsaturated zone in drill hole USW-G1, is part of the welded and bedded tuff aquifer overlying the lava flow (where present) and tuff aquitards.

The lower carbonate aquifer has an aggregate thickness of roughly 4600 m. This aquifer has the widest areal extent of the aquifrs of the region and according to Winograd and Thordarson (1975), controls the regional movement of groundwater at the NTS. Boreholes drilled (as of 1982) through Yucca Mountain to a maximum depth of 1829 m did not intercept the carbonate formation and, therefore its relationship to the site hydrology is unknown to the authors. It has been hypothesized that this deep aquifer may provide the "drainage" which (along with low recharge) maintains the deep phreatic level (GEI, 1979).

B1.1.2 Material Characteristics of Saturated Zone

B1.1.2.1 Hydraulic Conductivity

Volcanic tuffs in the area of Yucca Mountain exhibit large variations in lithology, mineralogy, degree of welding, and fracture density (see Appendix A). Therefore, vertical and horizontal hydraulic conductivities are likely to range over many orders of magnitude. The upper and lower portions of tuff units are generally nonwelded and contain little fracturing. These zones grade inward to a more densely welded control zone which typically has primary cooling joints and secondary stress related joints.

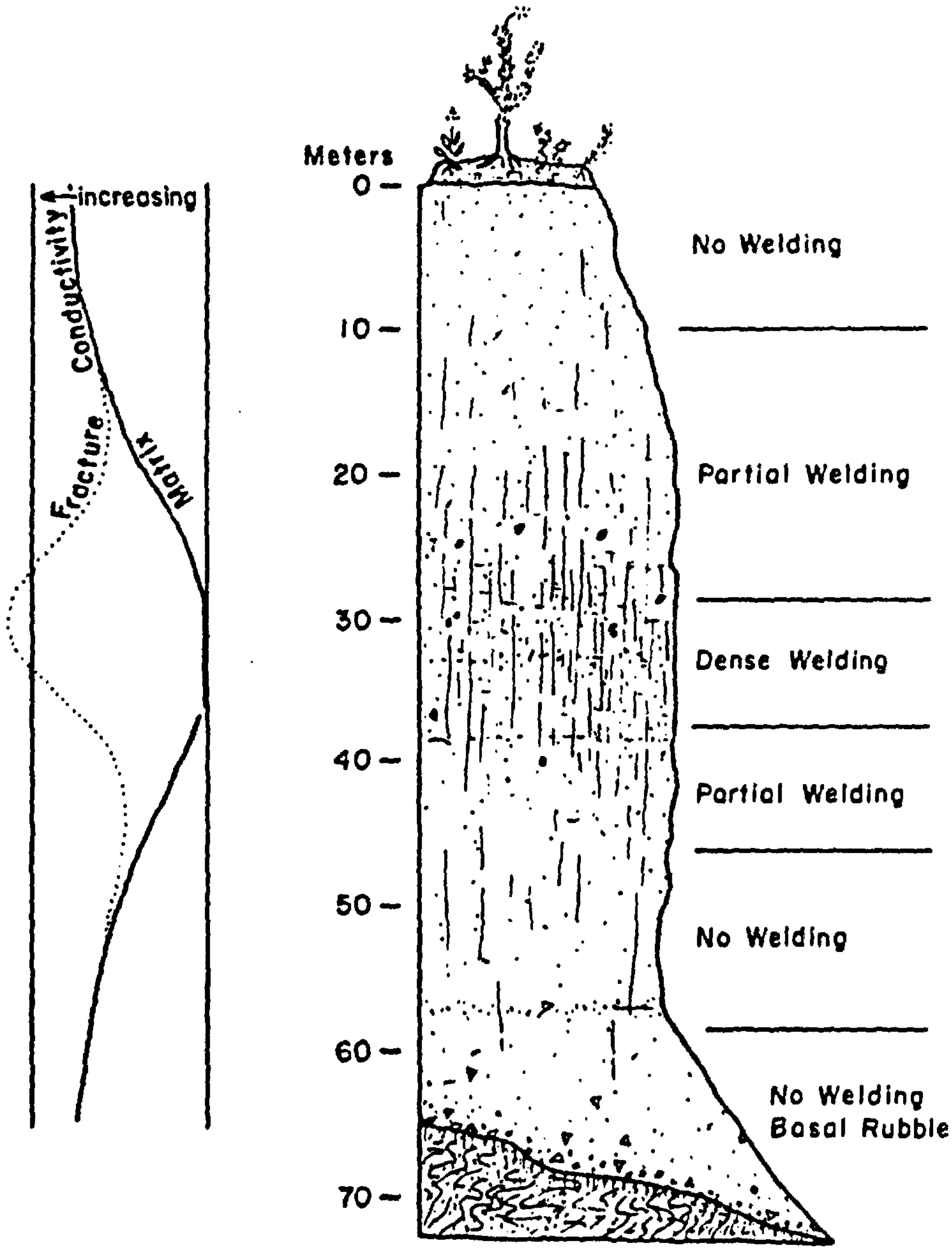
In situ hydraulic conductivity in the nonwelded zones is mainly controlled by the matrix hydraulic conductivity. An irregular rubble zone is common along the base of some flows, but since the rock fragments are completely surrounded by matrix material, these zones do not exhibit high hydraulic conductivity. Open cavities of varius origins can constitute up to 10 percent of the total rock volume, but they are generally unconnected and have not been shown to affect the hydraulic conductivity of the rock mass.

Within the partially and densely welded zones, hydraulic conductivity is controlled exclusively by joints and fractures. Observations of tuff outcrops and core samples (Winograd, 1971) indicate that the cooling joints tend to form perpendicular to bedding. For tuffs at the Nevada Test Site, spacing ranges from a centimeter to several meters and the joints tend to be more closely spaced in the zones of dense welding (Winograd and Thordarson, 1975). Horizontal partings are common in many tuff outcrops and have been observed to a lesser extent in core samples. They are thought to represent stress relief jointing due to removal of superincumbent load and are generally not likely to be open at depth. Jointing occurs in welded zones that are assumed to be anisotropic with respect to hydraulic conductivity. Since the jointing has a preferred vertical orientation and continuity (in shallow dipping strata) the vertical hydraulic conductivity (K_v) is assumed to be greater than the horizontal hydraulic conductivity (Kh).

Hydraulic conductivity characteristics of welded tuff core samples at the Nevada Test Site have been described by Winograd and Thordarson (1975). Laboratory analysis indicates matrix hydraulic conductivities that vary inversely with the degree of welding (Figure B-3), ranging from 10-6 m/s in nonwelded zones to 10-12 m/s in zones that are densely welded. In unfractured nonwelded tuff, the matrix hydraulic conductivity of core samples

DIAGRAMMATIC REPRESENTATION OF A TUFF COOLING UNIT SHOWING VARIATIONS IN MATRIX AND FRACTURE HYDRAULIC CONDUCTIVITY

Figure B-3



After Winograd, 1971

is probably similar to the in situ hydraulic conductivity, but such a relationship is not valid in the welded zones where hydraulic conductivity is controlled by fracturing.

Observations of underground workings in saturated zeolitic tuff of the Indian Trails Formation were made by Thordarson (1965). Although this tuff unit is not saturated below Yucca Mountain, the descriptions of fracturing and groundwater inflows provide useful comparative qualitative information on the in situ nature of tuff hydraulic conductivity. The workings contained more than five miles of tunnels and shafts, some of which were constructed in a perched groundwater zone below Rainier Mesa. Most joints had near vertical attitudes and were generally closed. Open joints, however, had widely variable apertures and could be nearly closed at one location and open as much as 5 cm just a few meters away. Only a small percentage of the joints were water bearing. About 50 to 60 percent of tunnel inflows resulted from faults or breccia zones and 40 to 50 percent was attributed to fractures or joints. The initial discharge of water from most fractures was less than 1.3 l/s but the initial discharge from one fault zone was about 13 l/s. The discharge from all intersected fractures or faults decreased rapidly with time and, within a few days, was a small fraction of the initial flow rate due to initially high gradients dropping off with time. Waterbearing joints tended to be poorly connected as demonstrated when further tunneling often intersected additional saturated joints on the order of hundreds of meters away from joints which had been dewatered several days earlier. Five thousand joints were mapped at the U12e tunnel complex by McKeown and Dickey (1961). Joint densities reached a maximum of one per meter of tunnel, but many sections of tunnel up to 10 m long were unjointed. This frequency of jointing is less than inferred from vertical core holes.

Wier (in Winograd and Thordarson, 1975), documented groundwater inflows in two deep test chambers in tuffaceous rocks benet Pahute Mesa. In a chamber located 300 m below the regional water table, Wier observed that most of the water seemed to be entering through that part of the chamber containing the most fractures. However, all the chamber walls were damp to wet which suggested that some water was also moving through the rock matrix, rather than entirely through the joint or fracture system. The total flow rate into this chamber was estimated at less than 0.25 l/s. In another deep chamber 600 m below the water table, groundwater flowed only from microfractures on one side of the room at a rate of about 0.06 l/s and the remainder of the chamber walls were dry (i.e., seepage rate less than evaporation rate). Wier noted that the yield from the microfractures tended to decrease with time. These flow rates did not take into account water removed by the ventilation system which could be several times greater than the small reported flows. Thus, any inference about the relative quantities of inflows from these two chambers should be viewed with caution.

Single borehole packer tests were conducted by the U.S. Geological Survey in two boreholes at Yucca Mountain. Horizontal hydraulic conductivities ranged from 10^{-5} to 10^{-12} m/s and they decreased with depth (DOE, August 1981). However, fracture densities and rock lithologies suggest that in situ hydraulic conductivity is quite variable within individual cooling units.

In summary, estimated ranges of horizontal hydraulic conductivity for welded tuff, vitrophyre and nonwelded tuff are 10^{-12} to 10^{-5} m/s with wide variation occurring throughout individual units. Vertical hydraulic conductivity is probably higher than horizontal conductivity in individual units. However, the section as a whole is likely to be more transmissive in the horizontal direction. Winograd and Thordarson (1975) estimate hydraulic conductivity of the lower carbonate aquifers to range from 10^{-7} m/s to 10^{-5} m/s in the vicinity of Yucca Flat.

B1.1.2.2 Effective Porosity

Effective porosities have not been measured in welded and nonwelded tuff. Total porosities vary inversely with the degree of welding, ranging from 50 percent in nonwelded zones to 5 percent in the central densely welded zones (Winograd and Thordarson, 1975). In nonwelded tuff, groundwater flow is primarily through the rock matrix and, therefore, effective porosity may be similar to total porosity. In densely welded tuff, where flow is controlled by fractures, effective porosity is likely to be much less than the total porosity.

For zeolitic nonwelded tuff, the total porosity is affected by temperature, as mineral assemblages break down and new ones are formed. Porosity of the zeolitic Calico Hills tuff increased by 20 percent upon heating from 25 to 80 degrees Celsius. In samples of Topopah Springs tuff, porosity increased 20 percent from 25 to 80 degrees and then decreased 25 percent from 80 to 180 degrees Celsius (DOE, August 1981).

Fracture porosity has not been measured in tuff units. It is likely to fall in a similar range as fracture porosity of basalt flows which generally are believed to range from 10^{-6} to 10^{-3}.

B.1.2.3 Dispersivity

Dispersivity is a length property of the medium which controls the degree of dispersion of a solute and is largely dependent on the scale of the flow region under investigation. Values can range from 10^{-2} cm for laboratory tests to 10^{4} cm for regional systems (Cherry et al, 1975). At the microscopic (laboratory) scale, it is a consequence of the tortuosity of the medium pore or fracture space. At the macroscopic (field) scale, it is primarily due to the divergence of flow paths resulting from heterogeneities in aquifer properties particularly hydraulic conductivity. Dispersivity varies with direction and is described using both a lateral dispersivity (perpendicular to flow direction) and a longitudinal dispersivity (in the direction of flow).

As far as we are aware, dispersivity has not been measured at any scale in the vicinity of the NTS. Utilization of values similar to those in other fractured media is reasonable for the purpose of undertaking simple initial computations.

B1.1.3 Composition of Pore Fluids in the Saturated Zone

Winograd and Thordarson (1975) discuss the factors that affect groundwater chemistry at the Nevada Test Site. They include:

- o Chemical characteristics of groundwater as it enters the zone of saturation
- o Adsorption-desorption capacity of the rocks
- o Solubility of rock minerals
- o Porosity and permeability
- o Groundwater velocity and flow paths
- o Geochemical conditions (i.e., temperature, pressure, Eh, pH)
- o Mixtures of waters from different sources.

At the Nevada Test Site, fresh sodium-potassium bicarbonate type water is characteristic of groundwaters that have moved only through rhyolitic tuff, lava-flow terrain, or valley-fill deposits rich in volcanic detritus. Groundwaters which have moved only through the lower carbonate aquifer are a calcium-magnesium bicarbonate type. In Figure B-4, the chemical analyses of groundwater from the Yucca Mountain tuffs are compared with the nearby hydrochemical facies described by Winograd and Thordarson (1975).

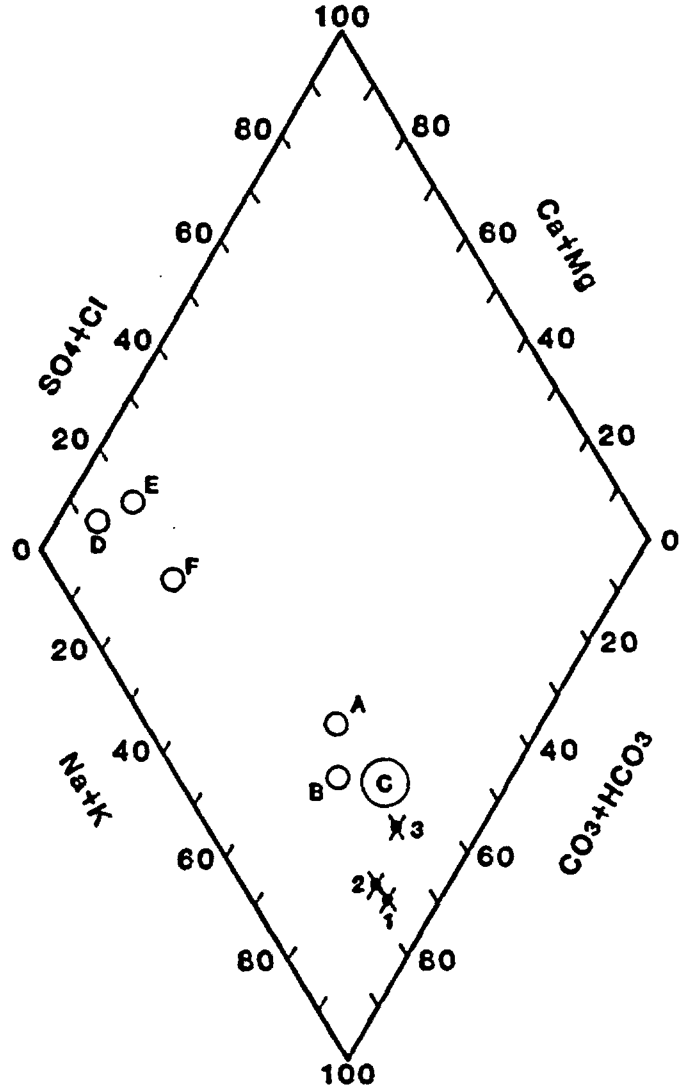
The hydrochemical data indicate that the sodium-potassium bicarbonate type groundwaters of the Yucca mountain tuffs have not flowed through the lower carbonate aquifer. This is consistent with preliminary measurements of vertical hydraulic gradients which suggest downward flow at Yucca Mountain.

B1.1.4 Hydraulic Gradient

In groundwater flow systems, hydraulic gradients are estimated by extrapolating the spatial distribution of hydraulic head from point measurements in piezometers. A piezometer data base does not exist at Yucca Mountain and therefore, the three-dimensional distribution of hydraulic head is unknown.

CHEMICAL COMPOSITION OF GROUNDWATER IN THE VICINITY OF YUCCA MOUNTAIN

Figure B-4



HYDROCHEMICAL FACIES (Winograd And Thordarson, 1975)

Sodium-Potassium Bicarbonate Facies (volcanic tuffs)

A. Hills west of Yucca and Frenchman Flats (9 samples)
B. Jackass Flats (3 samples)
C. Oasis Valley (17 samples)

Calcium-Magnesium Bicarbonate Facies (carbonate aquifer)

D. Northwest Las Vegas Valley, southern Three Lakes Valley, southern Indian Springs Valley (10 samples)
E. Pahrump Valley (26 samples)
F. Pahranagat Valley (3 samples)

YUCCA MOUNTAIN TUFFS (DOE, August 1981)

1. Borehole H1; Prow Pass and Bullfrog Members (TDS = 176 mg/l)
2. Borehole H1; Bullfrog to older ash flow and bedded tuffs (TDS = 188 mg/l)
3. Borehole VH1; depth interval 336 - 762m (TDS = 277 mg/l)

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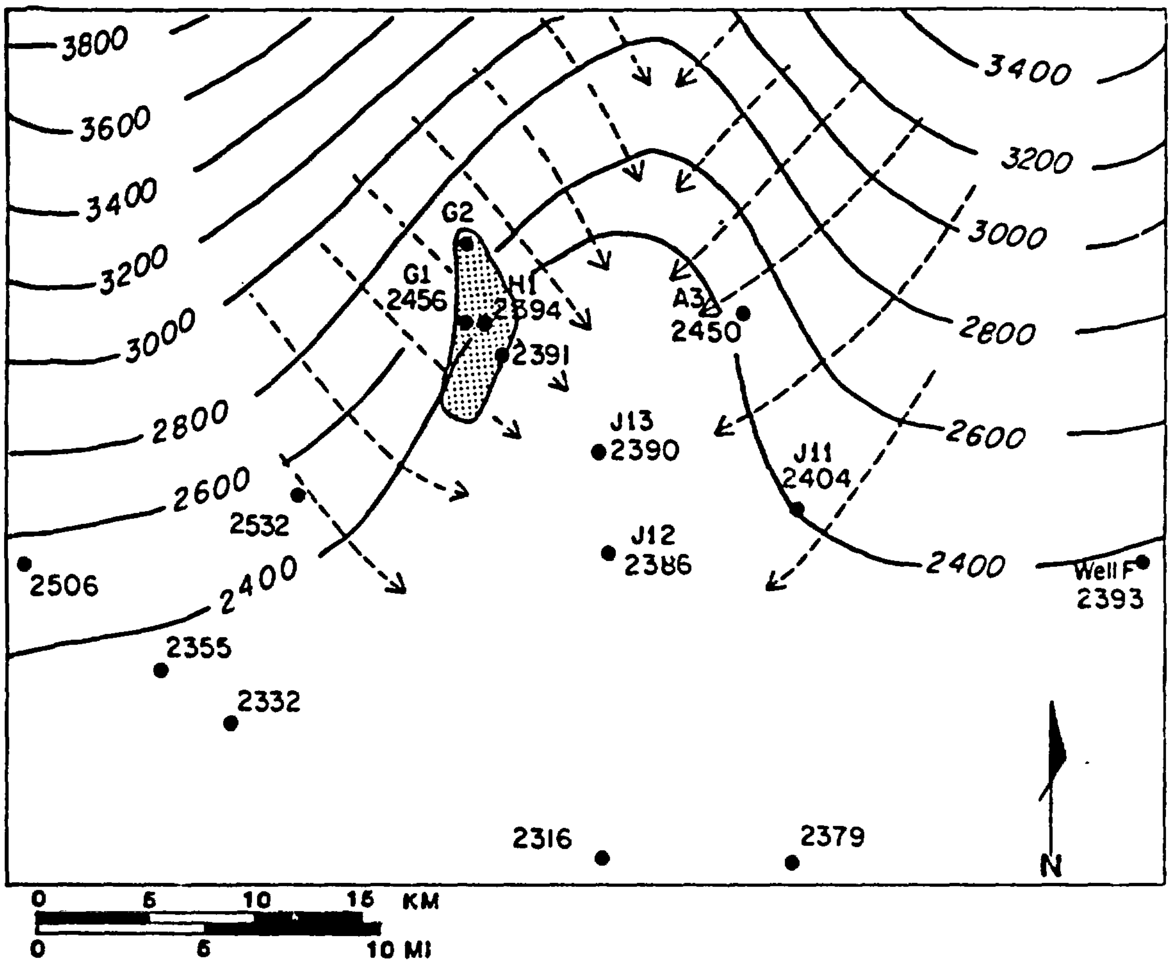
If vertical gradients are small, the horizontal gradient can be estimated from the slope of the piezometric surface, which represents a horizontal distribution of hydraulic head. In Figure B-5, water level measurements from 14 wells completed in tuff have been used to construct a piezometric contour map in the area surrounding Yucca Mountain. Due to a lack of data, the contours in the northern patt of the map are inferred. The map suggests a groundwater sink east of Yucca Mountain. No spring discharges have been documented in this area and, therefore, the map might suggest downward vertical flow along a local geologic structure in the vicinity of Forty Mile Canyon. It must be pointed out, however, that water-level measurements in wells represent an average hydraulic head along the uncased portion of the borehole. If vertical gradients are significant, the water level will be affected by the depth interval of the uncased portion. Because of this uncertainty, the piezometric contour map in Figure 4-5 is considered to be speculative.

Little data exists with regard to vertical hydraulic gradients in the tuff sequence below Yucca Mountain. During the drilling of two deep boreholes by the U.S. Geological Survey the vertical gradient was estimated by monitoring water levels during drilling. Although the measurements are not accurate, the data suggest a decrease in hydraulic head with depth which would indicate downward vertical flow (DOE, August 1981). In northern Yucca Flat, to the northeast of Yucca Mountain, the piezometric head in the tuff aquitard is as much as 40 m higher than that of the underlying carbonate aquifer (Winograd and Thordarson, 1975).

Horizontal gradients in the deep carbonate aquifer range from 0.06 to 1.1 m/km in a general southerly direction. This unit has not been encountered in holes as deep as 1829 m on Yucca Mountain.

WATER-LEVEL ELEVATIONS IN THE VICINITY OF YUCCA MOUNTAIN

Figure B-5



EXPLANATION:

- ● Water-Level Elevation in Observation Well (ft.)
- —— Water-Level Elevation Contour (ft.)
- - -› Inferred Horizontal Flow Direction
- ▒ Shaded area represents Yucca Mountain Block

NOTE: Water-level elevation represents average hydraulic head in open portion of boreholes terminating in various tuff units.

After DOE, August 1981