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Nevada Nuclear Waste Storage Investigations Project

Proposed Preliminary Definition of the Disturbed-Zone Boundary Appropriate for a Repository at Yucca Mountain

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ABSTRACT

Some of the calculations that support the licensing of a repository for high-level radioactive waste will use the regulatory concept of a "disturbed zone." The Nevada Nuclear Waste Storage Investigations (NNWSI) project must determine the location of the boundary of the disturbed zone for use in these calculations. This paper summarizes results of computer analyses and laboratory experiments and suggests a preliminary definition for the boundary of the disturbed zone for the unsaturated environment at Yucca Mountain. Although the intent of this paper is to define the boundary of the disturbed zone at the edge of significant changes in intrinsic hydrologic properties, there is no evidence of changes in intrinsic hydrologic properties that could significantly change the groundwater travel time from the repository to the water table. Such a result suggests that the disturbed zone at Yucca Mountain is of minimal extent. Because the analyses and experiments reviewed here indicate that there are a variety of changes near the waste package and because the results are subject to uncertainty, the preliminary suggestion for the extent of the disturbed zone is a value larger than the results themselves would suggest: the boundary is proposed to be a plane 10 m below the lower boundary of the waste packages.

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1. Introduction

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project, managed by the Nevada Operations Office of the U.S. Department of Energy (DOE), is examining the feasibility of siting a repository for high-level radioactive waste at Yucca Mountain, a site on and adjacent to the Nevada Test Site, Nye County, Nevada. Yucca Mountain is one of three sites that are presently under consideration as the location for such a repository (DOE, 1986a). Yucca Mountain is composed primarily of ashflow and ashfall tuffs that form north-trending fault block ridges. The highest portion of Yucca Mountain has an elevation of approximately 1500 m, which is approximately 300 m above the surrounding valley floors. (See Figure 1 for the general location and topography of Yucca Mountain.)

Yucca Mountain is unique among the three sites presently under consideration because the proposed location for the repository is above the water table. The welded, nonlithophysal portion of the Topopah Spring Member of the Paintbrush Tuff is the rock unit being considered as the potential repository horizon. This unit varies in thickness but averages approximately 206 m in thickness (derived from product number CAL0152 produced by Whittet and South, 1986*). The base of the rock unit averages approximately 219 m from the water table, and the top of the unit averages approximately 220 m from the surface (derived from product numbers CAL0151 and CAL0153 produced by Whittet and South, 1986).

Before a repository at Yucca Mountain can be constructed and operated, it must be licensed by the U.S. Nuclear Regulatory Commission (NRC). To be licensed the repository must satisfy several regulatory requirements (for example, 10 CFR 60 and 40 CFR 191).

The NNWSI Project will make performance assessments that will be used to determine whether Yucca Mountain will be able to comply with postclosure regulatory requirements. Many of these assessments will be based upon numerical calculations. The numerical calculations that will be performed to show compliance with

*Whittet and South extrapolated site data using a computer graphics system, the Interactive Graphics Information System (IGIS), maintained for the NNWSI Project at Sandia National Laboratories, to produce isopach maps and histogram data.

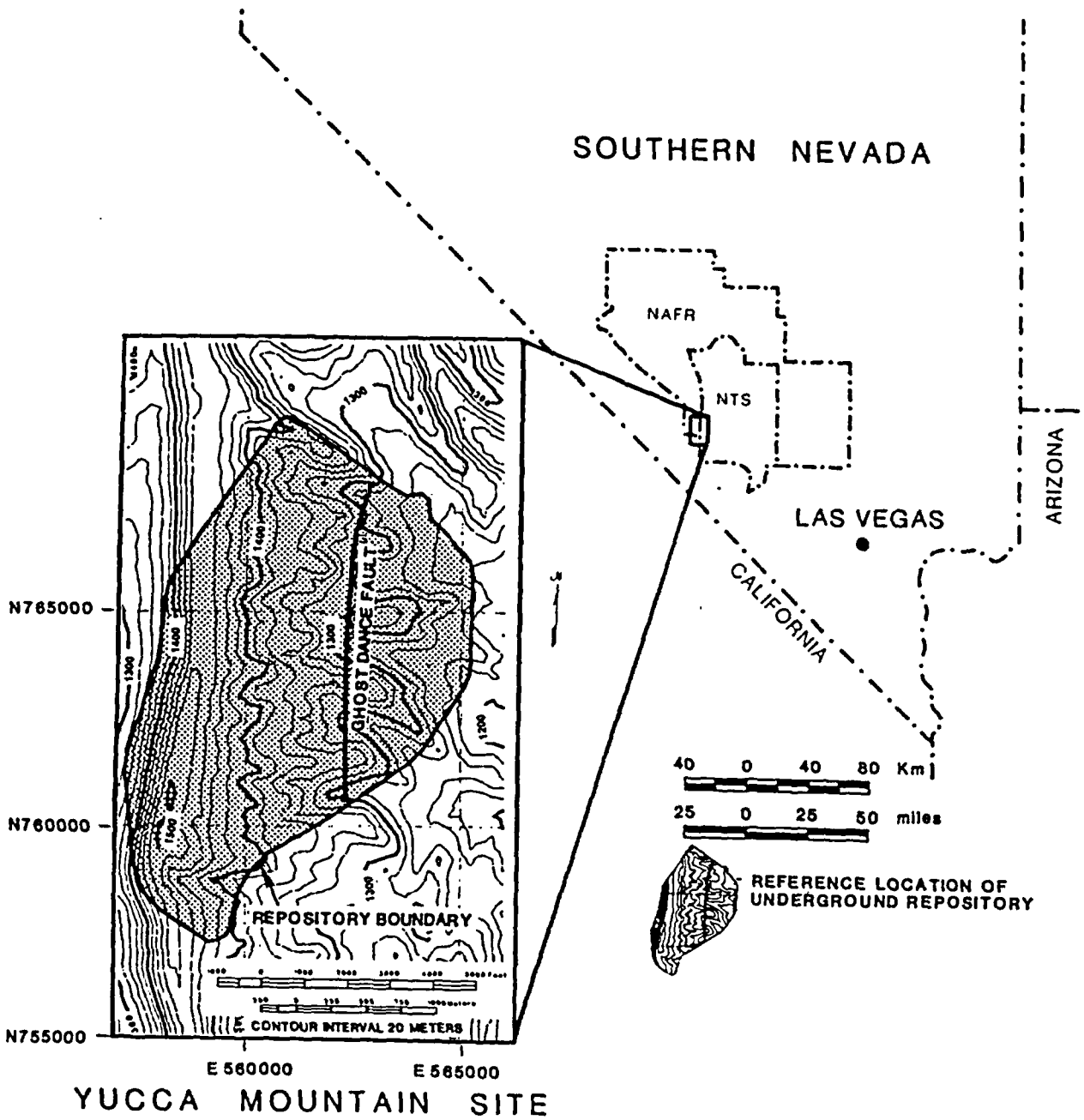


Figure 1: Location map of the Yucca Mountain Site, Nevada (derived from isopach map, IGIS product number CAL0149, produced by Whittet and South (1986))

10 CFR 60.113 (NRC, 1987), the requirement on pre-waste-emplacement groundwater travel time, will use the regulatory concept of a "disturbed zone." The NNWSI Project must determine the boundary of the disturbed zone for use in these calculations.

This paper presents site-specific information about Yucca Mountain: (1) conceptual ideas of how groundwater may flow in the unsaturated zone at Yucca Mountain, (2) reasonable expectations about the existing hydrologic properties, (3) some features of the repository design, and (4) results from preliminary analyses and laboratory experiments on the possible effects of constructing a repository. From this information, the paper derives a preliminary definition for consideration as the project develops a final definition for use in licensing. The definition proposed in this report may change as more information about the site becomes available and as the NRC and the DOE produce more definitive guidance on implementing the regulations. Plans for determining the final definition of the boundary of the disturbed zone will be included as part of the NNWSI Site Characterization Plan (SCP)(DOE, in preparation).

The remainder of this report contains the following sections:

- Section 2 – a brief discussion of the regulations and regulatory guidance that are of importance in defining the disturbed-zone boundary.
- Section 3 – a discussion of the premises that were adopted in defining the disturbed zone.
- Section 4 – a presentation of background information for Yucca Mountain including expected hydrological conditions (quantitative parameters such as hydrologic properties of the rock and groundwater flux), expected flow mechanisms, expected stress and thermal conditions, and repository design features.
- Section 5 – a review of the intrinsic hydrologic property changes that have been identified in computer, field, and laboratory analyses.

- Section 6 – a summary of expected hydrologic property changes and their effect on groundwater travel time* from the repository to the water table.
- Section 7 – a conclusion section that makes a recommendation for the location of the disturbed-zone boundary.

Those persons who are well-acquainted with the Yucca Mountain site and the regulations and regulatory guidance related to the disturbed-zone boundary may wish to skip Sections 2 and 4. Those who are only interested in the recommendation for the boundary of the disturbed zone, may wish to read only Sections 6 and 7.

*In this paper, the term "groundwater travel time" is not equivalent to the regulated "pre-waste-emplacement groundwater travel time," which only considers how long it would take groundwater to travel from the disturbed-zone boundary to the accessible environment before the repository is in existence. When the regulatory groundwater travel time is the subject, "pre-waste-emplacement" will be included as part of the term. Unless specified otherwise, the term "groundwater travel time" is the time it would take groundwater to travel from the midplane of the repository to the water table.

2. Regulations and Regulatory Guidance

The only regulations and regulatory definitions of interest in this paper are those that deal with the disturbed zone. In 10 CFR 60.2 (NRC, 1987), the disturbed zone is defined as "that portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result of heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository." The exact use of the disturbed zone is specified in 10 CFR 60.113 (a) (2) (NRC, 1987) as follows: "The geologic repository shall be located so that the pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 yr or such other travel time as may be approved or specified by the Commission."

The U.S. Nuclear Regulatory Commission (NRC) has produced several draft technical position papers (NRC, 1985; NRC, 1986a; NRC, 1986b) that give some guidance on how to determine the boundary of the disturbed zone. Each of the two later draft technical position papers has been a revised and updated version of the previous paper.

The rationale behind the disturbed zone is explained well in the latest (NRC, 1986b) generic technical position paper on the disturbed zone. A large portion of Section 2 from that paper is reproduced below.

> The volume of the rock which contributes to isolation of HLW [high-level waste] from the accessible environment clearly has its outer boundary at the accessible environment. For the inner boundary, the edge of the underground facility would at first seem a sensible choice. However, in establishing this inner boundary, there is good reason not to adopt the edge of the facility as the origin for travel time calculations.
>
> First, the travel time criterion is intended to provide for natural barrier protection from HLW releases to the accessible environment, as part of the multiple-barrier approach to HLW isolation. The staff considers that the

natural geologic barriers at a given site should not be permitted to depend exclusively or predominately on the favorable properties of the host rock directly adjacent to the underground facility. The staff considers that an acceptable repository site would be one where the bulk of the surrounding geologic setting contributes to isolation of HLW.

Second, the staff considers that credit towards the 1,000-yr pre-emplacement travel time should not be taken within that portion of the current geologic setting which might be substantially disturbed by construction of the facility or by the thermal effects of emplacement of HLW (irrespective of the possible offsetting benefits of engineered barriers such as waste containers and backfill). Because of potential changes in the rock properties, the geologic setting within this "disturbed zone" may not be well represented by pre-emplacement properties and conditions and thus it may be difficult to predict the contributions of this volume of rock to repository performance. The disturbed zone was chosen by the Commission as the starting point for determining the [pre-waste-emplacement] groundwater travel time because the physical and chemical processes which isolate the waste are "especially difficult to understand in the area close to the emplaced waste because the area is physically and chemically disturbed by the heat generated by those wastes. (46FR35280, 35281, July 8, 1981)". Therefore a pre-emplacement analysis based on existing conditions within this zone would not supply an appropriate measure of the quality of the geologic setting for the purpose of assessing future performance. To avoid the uncertainties of characterizing the rock very close to the emplaced waste, the "disturbed zone" was defined and established as the inner boundary from which travel time calculations are to be made for demonstrations of compliance with 10 CFR 60.113(a)(2).

The guidance included in the draft generic technical position papers for determining the boundary of the disturbed zone changed between the first and last versions. The most significant change was that the last paper did not include any quantification of "significant" changes in porosity and permeability. The first two draft generic technical position papers stated that an order-of-magnitude change in permeability or a factor-of-2 change in porosity should be considered significant changes in the hydrologic properties of the rock.

The most recent draft generic technical position paper (NRC, 1986b) included three major guidelines for use in determining the boundary of the disturbed zone:

- The extent of the disturbed zone should be calculated by the U.S. Department of Energy (DOE) on a site-specific basis, but should not be considered to extend less than 50 meters or five opening diameters, whichever is larger, from the edge of the underground facilities at any site.
- Four processes should be considered in determining the boundary of the disturbed zone: stress redistribution, construction and excavation, thermomechanical processes, and thermochemical processes.
- Only significant changes in intrinsic hydrologic properties caused by the above four processes need be considered in determining the boundary of the disturbed zone.

3. Premises Adopted in this Report to Determine the Boundary of the Disturbed Zone

The last two major guidelines from the most recent U.S. Nuclear Regulatory Commission (NRC) draft position paper agree well with the philosophy that the Nevada Nuclear Waste Storage Investigations (NNWSI) Project is using to define the disturbed-zone boundary. In this paper, to the extent possible, the effects of stress redistribution, construction and excavation, thermomechanical processes, and thermochemical processes on the groundwater travel time are considered. Considering the effects of these processes on the groundwater travel time on the basis of the site-specific qualities of Yucca Mountain has led the NNWSI to a different conclusion from that of the first point: the effects are significant at Yucca Mountain only in a zone whose extent is probably much less than the NRC-proposed 50-m minimum. A two-step evaluation of the available analyses led to this conclusion. First the available analyses were reviewed and regions of change delineated (Section 5) using the original suggestion by the NRC (1985) that an order-of-magnitude change in permeability or a factor-of-2 change in porosity should be considered significant changes in hydrologic properties of the rock. As a second step, the regions of change were evaluated in terms of how the changed hydrologic properties affected the groundwater travel time in the regions of changed rock properties (Section 6).

There are several points assumed in completing this two-step evaluation of the analyses that the NRC papers do not address specifically or that they do not address clearly. The additional premises that have been used in this paper to define the boundary of the disturbed zone are listed below; the list is followed by a brief explanation of each premise.

1. The disturbed-zone boundary is being defined strictly for use as a starting point for groundwater-travel-time calculations for comparison with the NRC regulation, 10 CFR 60.113 (a)(2), which requires that the pre-waste-emplacement groundwater travel time from the disturbed-zone boundary to the accessible environment be greater than 1,000 yr.

2. Only the predicted changes in the intrinsic hydrologic properties that are based upon <u>expected</u> conditions are used to determine the boundary of the disturbed zone. (Although 10 CFR 60 explicitly states that the pre-waste-emplacement groundwater travel time should be based on expected processes and events, there is no similar explicit statement for the disturbed-zone boundary.)

3. Changes in intrinsic hydrologic properties are defined to be repository-induced changes in the original permeability and porosity of the rock mass.

4. Only those intrinsic hydrologic property changes that could significantly affect the flow of groundwater away from the repository will be used to define the boundary of the disturbed zone.

5. Although the boundary of the changed hydrologic properties will probably be time dependent, the disturbed-zone boundary will be defined as the farthest extent of significant changes in intrinsic hydrological properties.

6. Because groundwater flow in the unsaturated zone is generally considered to be essentially vertically downward, the most meaningful boundary for the disturbed zone at Yucca Mountain is a generally planar surface below the repository that mirrors the repository shape; the NRC draft position paper implies that the complete boundary will be a closed surface in three dimensions, but premise 4 above requires that calculations of groundwater travel time (premise 1) deal only with flow away from the repository.

Premise 1 is based on the stated regulatory intent of the use for the disturbed zone. That is, its only specified use is for determining the ability of a site to meet the requirement on pre-waste-emplacement groundwater travel time. Therefore, as the most recent NRC draft position paper states, only significant changes in the hydrologic properties need to be considered in defining the disturbed zone. Changes in the sorption properties of the rock, which would relate to the possible transport of radionuclides, need not be considered. The boundary of the disturbed zone may not be the same as the boundary of significantly altered rock that could be used as a starting point for calculations of radionuclide transport from the repository to the accessible environment. Although repository-induced geochemical changes are not considered in determining the disturbed-zone boundary in the body of this report, Appendix A reviews the current understanding of such changes. This understanding suggests that they are not likely to affect the ability of the Yucca Mountain site to meet the regulations under expected hydrologic conditions.

Premise 2 is an explicit statement that the conditions used in determining the boundary of the disturbed zone are those that are expected to be in effect when the repository is put into operation. Alterations such as climatic changes and volcanism are not considered in defining the boundary of the disturbed zone.

Premise 3 is a more explicit definition of what is considered to be an intrinsic hydrologic property change. Changes in the state or condition (e.g., temperature, saturation) of the rock mass that do not cause changes in the permeability and porosity of the rock mass are not considered in defining the boundary of the disturbed zone.*

Premise 4 emphasizes that the pre-waste-emplacement groundwater travel time is based on the travel time of a nonsorbing radionuclide. In determining the boundary of the disturbed zone, only those changes in the intrinsic hydrologic properties that could cause significant changes in the travel time of an average water particle along its expected path away from the repository are considered. In other words, diffusion and dispersion are not considered as a means of fluid transport. Because of the limited use of the disturbed zone in the regulations, it should not be confused with other altered zones that may be defined for other purposes.

Premise 5 is assumed because, although the boundary of the changed hydrologic properties will change with time, there is no defined time at which the calculated pre-waste-emplacement groundwater travel must start. That is, the way the regulation is stated, the pre-waste-emplacement groundwater travel time could be regarded as a requirement that must be met from any starting point in time. In the absence of further guidance, premise 5 makes the most stringent assumption for the calculations: that the calculation of pre-waste-emplacement groundwater travel time will start at the place where the disturbed-zone boundary reaches its maximum extent in space.

There are two assumptions in premise 6. The first, that groundwater flow is essentially vertical and downward, is under investigation. Two sources have indicated that lateral flow may exist at Yucca Mountain. Rulon et al. (1986) have shown by means of computer modeling that, for some combinations of hydraulic properties and

*The NRC draft technical position paper on the disturbed zone recommended that only changes in intrinsic hydrologic properties be used as a basis for defining the boundary of the disturbed zone. At Yucca Mountain, in the unsaturated zone, hydraulic conductivity, which is not an intrinsic property but is highly dependent on the saturation state, can be changed by the repository. Before the NNWSI adopted the NRC recommendation, a simple study was conducted to determine whether changes in hydrologic properties (hydraulic conductivity and effective porosity) as a result of changes in saturation state could cause significant enduring changes along the path a nonsorbing radionuclide would take from the repository to the water table. This study is discussed in Appendix B.

infiltration rates, there is the potential for lateral flow at the base of the Topopah Spring welded unit. Deep lateral flow was hypothesized by Montazer and Wilson (1984). For this preliminary definition of the disturbed-zone boundary, it was decided to assume that flow is essentially vertical and downward; the definition of the disturbed-zone boundary will be reviewed if lateral flow is confirmed during site characterization.

The second assumption in premise 6 is that the disturbed-zone boundary can be defined as a plane that roughly mirrors the repository shape. In addition to the direction of groundwater flow, two major features of the repository were considered in defining the boundary of the disturbed zone as a plane. One is the shape of the repository, its drifts, and boreholes. The repository is presently being designed to follow an inclined plane. Therefore, the disturbed-zone boundary will also be an inclined plane. The boundary will not mirror small undulations such as those that could be created by the excavation of vertical emplacement holes. The other feature that was considered was the near-field geometrical effects of the concentrated heat sources produced by the waste packages. Near the repository, the volume of rock within which the intrinsic hydrologic properties change may have an irregular boundary that is a function of the distance from the concentrated sources of heat produced by the waste packages. For simplicity and added conservatism, the disturbed-zone boundary is assumed in this report to be a plane that is the same distance from the repository as the greatest extent of significant hydrologic-property changes. Figure 2 summarizes what the boundary of the disturbed zone could be as compared with the repository shape and the actual extent of significant hydrologic-property changes.

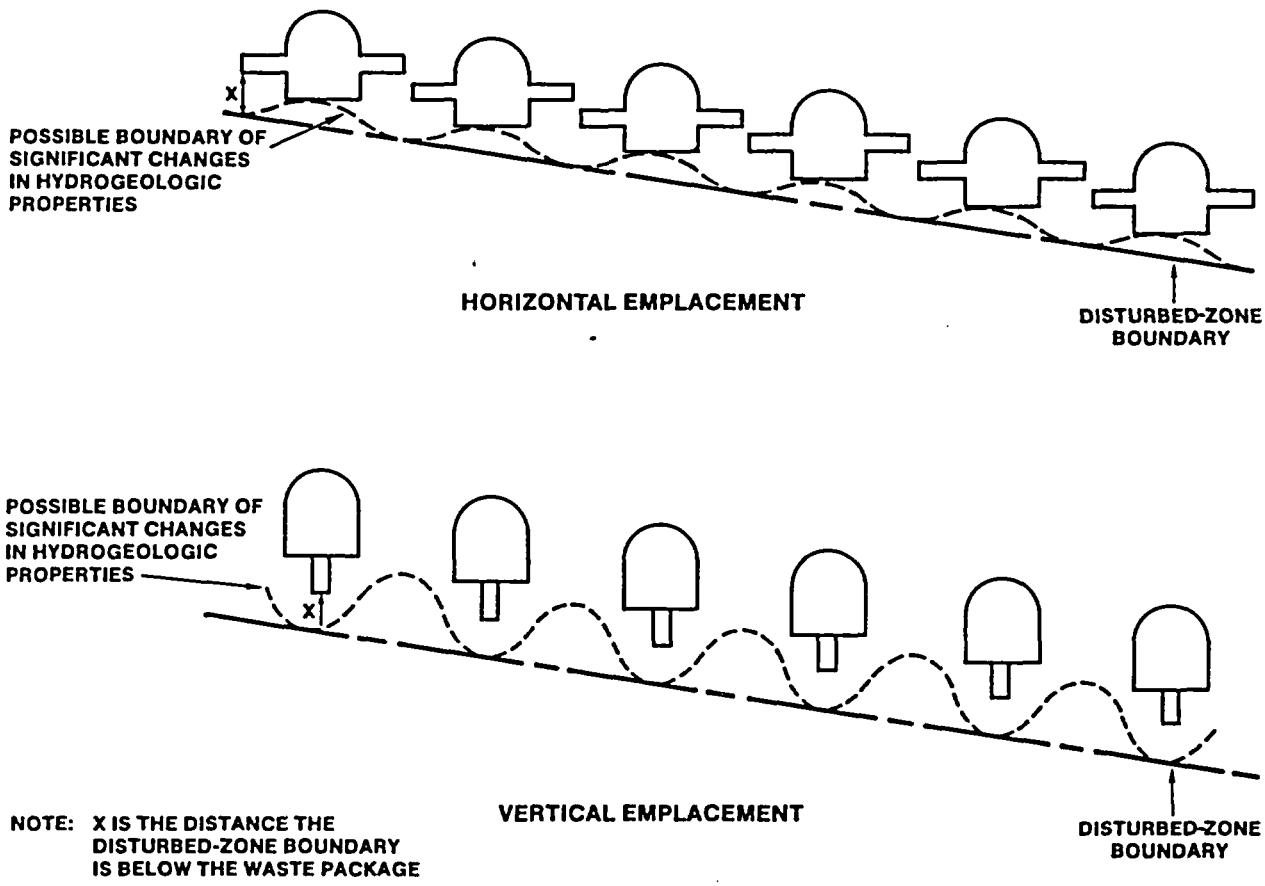


Figure 2: Schematic diagram showing the location of the disturbed-zone boundary

4. Background Information on Conditions Expected at Yucca Mountain

4.1 Expected Hydrological Conditions in the Unsaturated Zone at Yucca Mountain

The most important of the potential mechanisms for moving radionuclides from a repository is transport in groundwater. Many of the regulations governing a repository specifically deal with that mechanism. Knowledge about groundwater movement, which can be determined from hydrologic conditions, is therefore an essential ingredient to showing compliance with the performance regulations. This section of the report discusses the known and inferred quantitative values of the hydrologic rock properties and groundwater flux at Yucca Mountain. This information is used in the next section to summarize the flow mechanisms at the Yucca Mountain site. The expected flow path from the repository to the accessible environment at Yucca Mountain includes flow through both an unsaturated and a saturated zone. In the Environmental Assessment (EA) (DOE, 1986b, Section 6.3.1.1.5), the expected flow path from the repository to the accessible environment is stated to be vertically downward through the unsaturated zone and then laterally through the saturated zone to the accessible environment.* Only the unsaturated portion of this flow path is considered in this report because the disturbed zone is expected to be contained totally within the unsaturated rock units.

The hydrologic units through which groundwater travels in the unsaturated zone vary depending upon the starting point within the repository. The major hydrogeologic units in the unsaturated zone through which groundwater could possibly travel from the repository include, from the shallowest unit to the deepest unit: the Topopah Spring welded unit, the Calico Hills vitric unit, the Calico Hills zeolitized unit, the Prow Pass welded unit, the Prow Pass nonwelded unit, the Bullfrog welded unit, and the Bullfrog nonwelded unit. In the northeastern portion of the proposed repository boundary, large portions of some of these repository units are below the water table. Those that are in some places entirely below the water table include the Prow Pass welded unit, the Prow Pass nonwelded unit, the Bullfrog welded unit, and the Bullfrog

*There is a hypothesized possibility of lateral flow at rock unit interfaces in the unsaturated zone (Montazer and Wilson, 1984; Rulon, et al., 1986). This hypothesis is under investigation and was not used in this report; if additional investigation confirms the existence of lateral flow in the unsaturated zone, lateral flow will be considered in defining the boundary of the disturbed zone.

nonwelded unit. The percentage of the total repository underlain by each unsaturated unit is displayed in Table 1. The isopach contour maps of the portion of these units above the water table are shown in Figure 3. The isopach maps and the table help define the distribution of the unsaturated units at Yucca Mountain. Note that the three shallowest units are present within most of the repository boundary and that they constitute a substantial portion of the volume of rock between the repository and the water table, particularly in the northeast section of the repository. An east-west cross-section through the northern portion of Yucca Mountain is shown in Figure 4. This cross-section shows the relative location of the units and schematically indicates the path groundwater could follow from the repository to the accessible environment.

The average porosity and saturated hydraulic conductivity of these units, reported in Section 6.3.1.1 of the Nevada Nuclear Waste Storage Investigations (NNWSI) EA (DOE, 1986b), are summarized in Table 2. The EA also reported that the unsaturated-zone flux below the repository horizon is expected to be less than 0.5 mm/yr (DOE, 1986b;Wilson, 1985).

Note that the unsaturated-zone flux of 0.5 mm/yr is less than the mean matrix permeability of all the units reported in Table 2. The usefulness of this information will be discussed in the next section.

Table 1: Summary of the total repository area underlain by the major unsaturated hydrologic units (Lin et al., 1986)

Unsaturated Hydrogeologic Unit	Percentage of Total Repository Area Underlain by the Unit
Topopah Spring welded unit	98.5
Calico Hills vitric unit	95.3
Calico Hills zeolitized unit	94.5
Prow Pass welded unit	83.2
Prow Pass nonwelded unit	63.1
Bullfrog welded unit	25.6
Bullfrog nonwelded unit	7.5

Table 2: Summary of the mean saturated hydraulic conductivity and porosity of the matrix of the unsaturated hydrologic units (modified from Lin et al., 1986)

Hydrogeologic Unit	Mean Matrix Saturated Hydraulic Conductivity, mm/yr (m/s)	Matrix Porosity
Topopah Spring welded unit	0.7 (2.3×10^{-11})	0.11
Calico Hills nonwelded vitric unit	110 (3.4×10^{-9})	0.32
Calico Hills nonwelded zeolitized unit	0.5 (1.7×10^{-11})	0.27
Prow Pass welded unit	88 (2.8×10^{-9})	0.24
Prow Pass nonwelded unit	22 (6.8×10^{-11})	0.25
Bullfrog welded unit	120 (3.8×10^{-9})	0.22
Bullfrog nonwelded unit	22 (6.9×10^{-10})	0.25

Montazer and Wilson (1984) have reported some mean saturation data that are based on laboratory measurements of core samples: 65% in the Topopah Spring welded unit with a standard deviation of 19%, 90% in the vitric Calico Hills nonwelded unit[a] (only one measurement was available), 91% in the zeolitic or devitrified portions of the Calico Hills nonwelded unit[b] with a standard deviation of 6%, and 88% in the Crater Flat unit[c] with a standard deviation of 75%.

The Topopah Spring welded unit and the Prow Pass welded unit are expected to have higher saturated-fracture-system conductivities than the remainder of the unsaturated units (Klavetter and Peters, 1986b). This statement is primarily based on the frequency of fractures in each of these units. Scott et al. (1983, p. 318) have

[a]As reported by Montazer and Wilson (1984), this unit includes vitric portions of the Prow Pass nonwelded unit.

[b]As reported by Montazer and Wilson (1984), this unit includes zeolitized and devitrified portions of the Prow Pass nonwelded unit.

[c]This unit is a combination of the Bullfrog welded and nonwelded hydrogeologic units.

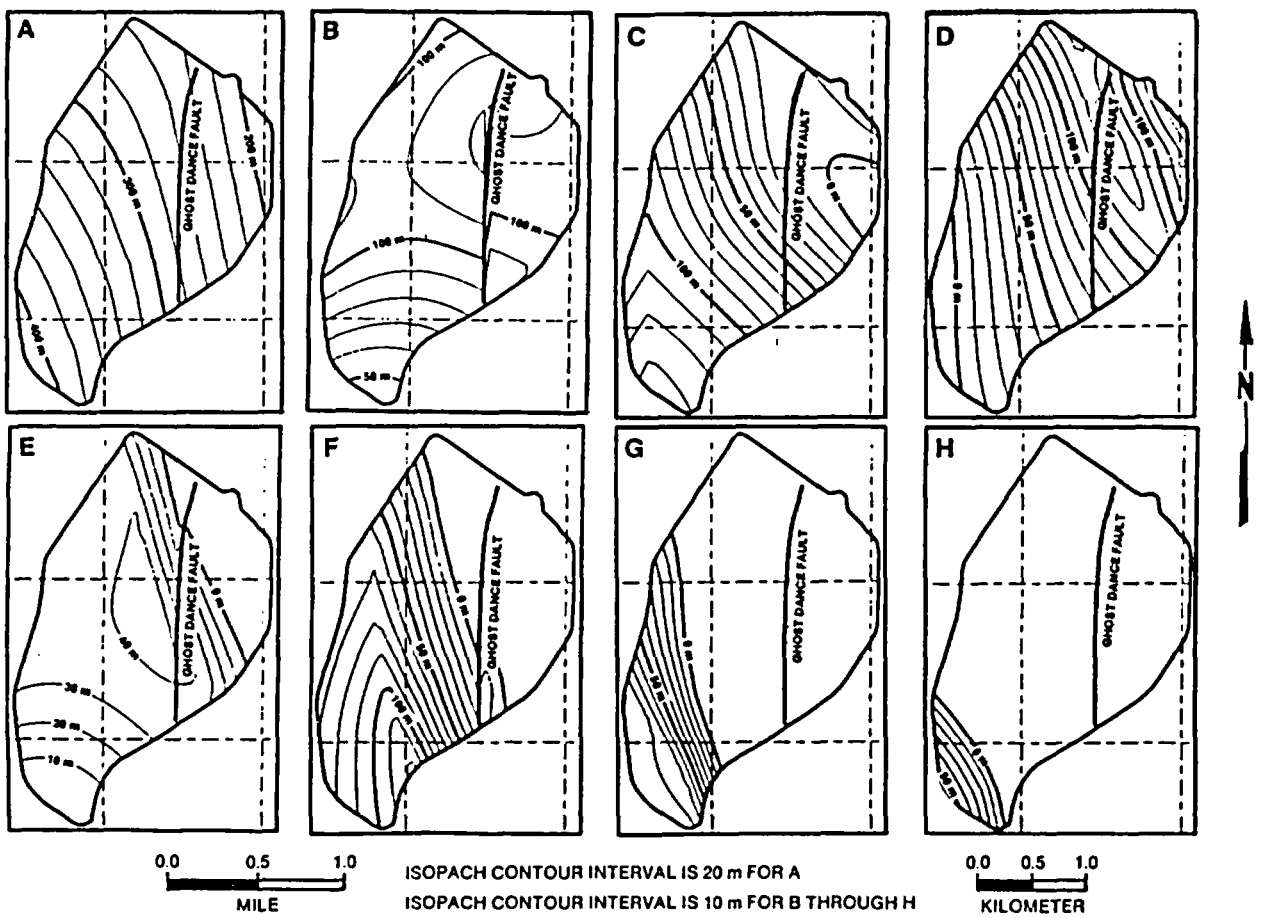


Figure 3: Isopach contour maps: (A) Total thickness of rock between the centerline of the repository and the water table; (B) Thickness of the undisturbed Topopah Spring welded unit; (C) Thickness of the Calico Hills vitric unit; (D) Thickness of the Calico Hills zeolitic unit; (E) Thickness of the Prow Pass welded unit; (F) Thickness of the Prow Pass nonwelded unit; (G) Thickness of the Bullfrog welded unit; and (H) Thickness of the Bullfrog nonwelded unit (derived from product numbers CAL0048 through CAL0053, CAL0136 and CAL0155 as produced by Whittet and South (1986, 1987))

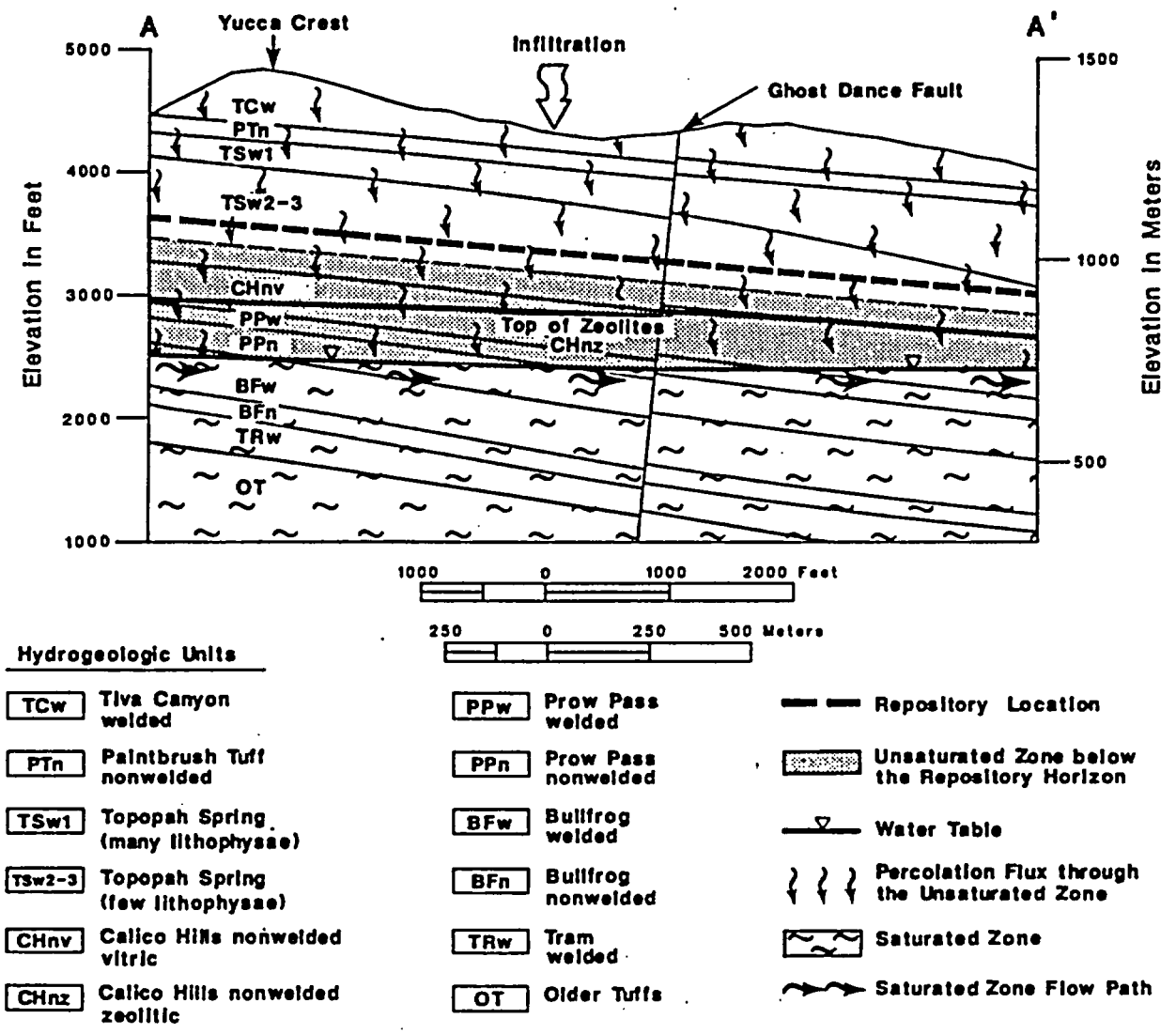


Figure 4: East-west cross section through Yucca Mountain modified from Lin et al. (1986)

made a general statement about the correlation between fracture density and lithology at Yucca Mountain:

> To depths of 940 m, the more elastic (lower Young's modulus or stiffness) zeolitized nonwelded and partially welded tuffs have as few as 1 to 3 fractures/unit m^3, whereas the more brittle (higher Young's modulus or stiffness) densely welded tuffs typically have 20 to 40 fractures/unit m^3.

Scott et al. (1983, p. 319) calculated the density of fractures in the Topopah Spring welded unit in drillhole USW GU-3/G-3 to be 42 fractures/m^3.

The fractures at Yucca Mountain are considered to be predominately near-vertical. Approximately 60% of the fractures encountered in vertical boreholes have inclinations greater than 60° (Langkopf and Gnirk, 1986). The statement that the fractures are predominately near-vertical is supported not only by the number of near-vertical fractures but also by the fact that so many are found in near-vertical boreholes. A horizontal hole should encounter an even larger percentage of near-vertical fractures.

Fracture apertures have not been measured directly in the laboratory or in situ, but a few values of hydraulic aperture have been inferred from field measurements (Sinnock et al., 1984; Zimmerman et al., 1986) and laboratory measurements of fracture hydraulic conductivity (Peters et al., 1984). Snow's equation (Snow, 1968), which relates a parallel array of fractures to a hydraulic conductivity or permeability, was used in all cases to infer fracture apertures from hydraulic conductivity and permeability measurements. This same relationship is used later in this report to correlate predicted changes in fracture aperture with permeability. Snow's equation is

$$K = \left(\frac{\rho g}{\mu}\right)\left(\frac{Nb^3}{12}\right) \quad \text{or}$$

$$k = \left(\frac{Nb^3}{12}\right)$$

where K is the hydraulic conductivity of the fractures, k is the permeability, ρ is the fluid density, g is the gravitational constant, μ is the fluid viscosity, N is the number of fractures per unit distance, and b is the fracture aperture.

The average aperture of fractures was inferred from a hydraulic conductivity value reduced from a pumping test on well J-13 near Yucca Mountain. Thordarson (1983) reported a hydraulic conductivity of 1 m/day for the Topopah Spring welded unit. Using this hydraulic conductivity, Sinnock et al. (1984) calculated an average aperture of 71 μm assuming that there were 40 parallel fractures per meter in the Topopah Spring welded unit. Another value of fracture aperture was derived from a field measurement on the basis of a permeability test performed on an average fracture in a tuff unit, the Grouse Canyon Member of the Belted Range Tuff, at another location, G-Tunnel at Rainier Mesa. The aperture inferred from the experiment was within the range of the apertures determined from laboratory measurements on Yucca Mountain tuffs (Zimmerman et al., 1986). The laboratory measurements, from a total of five samples, indicate that fracture apertures range from several micrometers to tens of micrometers. The laboratory measurements were from core samples from a drillhole at Yucca Mountain designated as USW G-4. The samples were part of the Topopah Spring welded unit, the Calico Hills vitric nonwelded unit, and the Calico Hills zeolitized nonwelded unit.

Assuming that the approximately 40 fractures/m^3 reported by Scott et al. (1983, p. 318) are actually 40 vertical fractures/m and using the fracture apertures inferred from hydraulic conductivity tests, the porosity of the fractures in the Topopah Spring welded unit has been estimated to range from approximately 0.018% to 0.28% (Sinnock et al., 1984; Peters et al., 1986). The fracture porosity of the nonwelded and partially welded units at Yucca Mountain has been estimated to range from approximately 0.0013% to 0.07% (Sinnock et al., 1984; Peters et al., 1986).

Although many microfractures probably exist that are on the order of the larger pore sizes expected in the matrix, it is expected that many fractures are much larger in aperture than the pores in the matrix. Laboratory measurements (Klavetter and Peters, 1986b; Klavetter and Peters, 1987) of the pores in tuff samples from Yucca Mountain indicate that the average pore diameters for most of the rock units range from 10^{-1} to 10^{-2} μm. These laboratory measurements resulted from mercury-intrusion tests on samples of the Tiva Canyon welded unit, the Paintbrush Tuff nonwelded unit, the Topopah Spring welded unit, the basal vitrophyre of the Topopah Spring,* the Calico Hills zeolitized nonwelded unit, the Calico Hills vitric

*The basal vitrophyre of the Topopah Spring is a thin unit that underlies the Topopah Spring welded unit. It has hydrologic properties that are similar to those of the other welded tuffs at Yucca Mountain (Peters et al., 1984, p. 60).

nonwelded unit, the Prow Pass welded unit, and the Bullfrog welded unit. (The location of all these units except for the basal vitrophyre of the Topopah Spring is shown in Figure 4.)

4.2 Expected Flow Mechanisms in the Unsaturated Zone at Yucca Mountain

Several investigators have written reports that discuss how water could flow in the unsaturated fractured rock at Yucca Mountain (Montazer and Wilson, 1984; Peters et al., 1984; Wang and Narasimhan, 1985; Klavetter and Peters, 1986a, 1986b; Lin et al., 1986). Hydrologic characteristics similar to those given in the preceding section were used by these investigators to postulate possible flow mechanisms for water at Yucca Mountain.

Several pieces of information provide the basis for the conceptual model of flow at Yucca Mountain. One piece of information that is not presented in the previous section serves to indicate that the hydrologic flow field below the repository horizon is in a nearly steady-state condition. It is thought that transient infiltration pulses resulting from surface precipitation are transmitted through fractures in the Tiva Canyon welded unit, the uppermost tuff unit at Yucca Mountain, and then damped by matrix pores of the underlying less-fractured Paintbrush nonwelded unit. Thus, by the time the infiltrating water reaches the Topopah Spring welded unit, only small changes in saturation, pressure, and potential are exhibited relative to steady-state values (Wang and Narasimhan, 1986). This reasoning is the major part of the basis for the usual asumption that the Topopah Spring welded unit should have an approximately steady-state flux.

Because of the unsaturated conditions at Yucca Mountain, the capillary-bundle theory has been used to explain general water movement in the unsaturated zone. This theory is well established in the field of soil physics for use in predicting water movement in unsaturated soils. In partially saturated porous media, fluid pressure in the water phase is less than atmospheric, and the fluid saturation is a strong function of the water-phase pressure. The relation between fluid pressure and saturation is governed by the surface tension between the liquid particles, the adsorption between the liquid and solid phase, and the effective capillary radii of the pores (Baver et al., 1972; Kirkham, 1964). The surface tension between the liquid particles causes the

fluid pressure under unsaturated conditions to be negative. The fluid pressure is known to be inversely proportional to the capillary radius (Baver et al., 1972; Kirkham, 1964). Therefore, according to capillary-bundle theory, the smaller pores have a larger negative pressure, and liquid water tends towards the smaller pores in the unsaturated zone. As discussed in the previous section, fractures at Yucca Mountain generally have larger aperture sizes than pores in the matrix. Therefore, under equilibrium conditions, water will tend to move in the matrix pores rather than in the larger (on average) fracture apertures. The fractures are not expected to be of uniform aperture. In places the fractures may narrow enough to provide a passageway for water to flow from one matrix block to another.

This generalization, that flow is dominantly through the rock matrix at Yucca Mountain, may not be strictly true for several reasons. In some portions of the Yucca Mountain environment that are incompletely characterized, water flow may not always be through the matrix. Uncertainties about the Yucca Mountain environment include the following:

1. Contrasting physical properties between layers of rock at Yucca Mountain could cause enough perched water to accumulate in portions of Yucca Mountain to change the flow paths to those expected under saturated conditions.

2. Inhomogeneity of the rock matrix and fractures within rock layers, as well as variations in the groundwater flux, could cause localized fracture flow.

   (a) Where the groundwater flux is larger than the saturated matrix hydraulic conductivity, the water may move into the fractures.

   (b) Water may move in fractures in places where the apertures are smaller than the matrix pores that are transmitting water until it comes to a place where the fractures are wider or the matrix pores are smaller.

3. Pockets of air trapped in smaller pores of the rock could cause water to seek pathways through large pores in the rock, including fractures.

4. Periodic high-infiltration events at the surface could change the mechanism of flow.

Montazer and Wilson (1984) include a more thorough discussion of the characteristics at Yucca Mountain that could cause flow to be other than through the matrix. Yucca

Mountain will be more fully investigated to conclusively determine the characteristics of water movement there.

4.3 Expected Ambient Stress and Thermal Conditions at Yucca Mountain

Both stress and temperature can potentially affect the intrinsic hydrologic properties. The expected ambient stress and thermal conditions are presented here to provide a frame of reference for the computer analyses and laboratory and field experiments discussed later.

The information that is available about the in situ stress conditions at Yucca Mountain is based on the results of hydrofracture tests. The majority of the hydrofracture tests have been conducted below the water table (Stock et al., 1985). The results from below the water table indicate that "the stresses at Yucca Mountain are of gravitational origin and are affected by fracture-induced anisotropy and selectively by topography" (Swolfs and Savage, 1985). The minimum and intermediate principal stresses appear to be oriented nearly horizontally and the maximum principal stress vertically.

Three hydrofracture tests have been conducted in the unsaturated zone in USW G-2 near the depth of the proposed repository horizon. In all of these tests there were indications that excess downhole fluid pressure during drilling created fractures that made it impossible to determine the minimum principal stress or the intermediate principal stress. From the tests below the water table, Stock et al. (1985) were only able to (1) determine an upper bound for the minimum horizontal stress and (2) state that, if the fractures above the water table had similar orientations (within about 30°) with respect to the normal to the minimum horizontal stress, then the the upper bound on the horizontal stress is probably close to the minimum horizontal stress. On the basis of the tests at USW G-2, it appears that the minimum horizontal stress at the repository horizon will have a maximum value of approximately 5.0 to 5.5 MPa. To determine a minimum value for the minimum horizontal stress, the relationship for

rock that is only under a lithostatic load (Jaeger and Cook, 1977, p. 369) has been used:

$$\sigma_h = \frac{\sigma_v \nu}{1 - \nu}$$

where σ_h is the horizontal stress in the horizontal plane, σ_v is the vertical stress, and ν is Poisson's ratio. Using a value of 0.20 for Poisson's ratio (SNL, 1986) and an average value of 7.0 MPa for σ_v (SNL, 1987, Section 2.3.1.9), the minimum value for the horizontal stress would be 1.75 MPa.

The weight of the overburden has generally been used to estimate the value for the vertical stress at Yucca Mountain (Swolfs and Savage, 1985; Stock et al., 1985).

In the Site Characterization Plan Conceptual Design Report (SCP-CDR) (SNL, 1987, Section 2.3.1.9), a range of horizontal and vertical stress values has been suggested to bound the conditions expected at the repository horizon at Yucca Mountain. In arriving at the values, the information discussed above was considered (Bauer, 1987). The vertical stress range is given as 5.0 to 10.0 MPa, and the minimum horizontal stress range as 1.5 to 8.0 MPa.

The stresses that have been discussed thus far have been the total stresses in the rock. Another very useful quantity is effective stress. The general equation (Jaeger and Cook, 1977, p. 223) used to calculate effective stress is

$$\sigma_e = \sigma - kP_p$$

where σ_e is the effective stress, σ is the total stress, k is a constant that is usually taken as 1.0 in saturated media, and P_p is the pore pressure. The effective stresses at the repository depth are not well known because of uncertainties about the pore pressures at depth. To determine an approximate value for the effective stress at Yucca Mountain, three pieces of information and assumptions were used here:

1. The matrix pore pressure (P_p) is based on an isothermal, unsaturated-flow calculation that used a flux of 0.1 mm/yr (Peters et al., 1986).
2. The matrix pore pressure was assumed to be representative of the rock mass.

3. It was assumed that a unit change in the quantity "total saturation times pressure head," kP_p, at a point causes a unit change in the local stress field (Klavetter and Peters, 1986a, p. 20; McTigue et al., 1984). (This assumption has recently been substantiated in laboratory tests of the Topopah Spring welded unit (Nimick and Schwartz, 1987, Appendix C).)

The negative pore pressures calculated by Peters et al. (1986), ranged from -1.0 to -1.35 MPa for saturations of about 89% and 87%, respectively. On the basis of the concept that a unit change in the quantity "total saturation times pressure head" causes a unit change in the local stress field, the values for kP_p range from -0.9 MPa to -1.2 MPa. The possible range of effective stresses at Yucca Mountain, using the vertical and minimum horizontal stress ranges reported in the SCP-CDR (SNL, 1987) would then be approximately 2.4 to 9.2 MPa for the horizontal stress and 5.9 to 11.2 MPa for the vertical stress.

The other physical quantity addressed in this section of the SCP-CDR is temperature. The temperatures at depth in Yucca Mountain have been measured in several places. Most of the measurements that have been taken indicate that the temperature at the repository horizon will be about 23° to 29°C (Sass and Lachenbruch, 1982; SNL, 1987, Section 2.3.1.9).

4.4 Repository Design Features

The effect the repository may have on intrinsic hydrologic properties can depend on repository design features such as the sizes of rooms excavated in the rock and the heat loading of the repository. The main design features that were considered in this report include waste-emplacement geometry, waste-emplacement-room dimensions, allowable areal power density (APD), and waste age.

At present both horizontal and vertical emplacement geometries are being considered in the design process. The reference design (SNL, 1987) for horizontal emplacement of spent fuel calls for rooms 5.5 m wide and 4.0 m high; for vertical emplacement the rooms are 4.9 m wide and 6.7 m high. Dimensions of the drifts vary in the design studies consulted for this report. For horizontal waste emplacement, drifts vary from 4.0 to 4.4 m in height and 5.5 to 8.2 m in width; for vertical waste emplacement they vary from 5.0 to 7.0 m in height and 4.5 to 5.0 m in width.

The allowable APD that is currently used in the repository design is defined as the APD that deposits the same energy density through 2,000 yr as 10-yr-old spent fuel that is emplaced at 57 kW/acre (Mansure, 1986; SNL, 1987, p. 4-119). This equivalent-energy-density method of defining the APD approximately fixes the energy that is deposited in the far-field. The age and type of the waste dictate its initial heat output and decay characteristics. The waste age of the spent fuel used in the calculations as part of this report varies from 8.55 to 10 yr. Once the waste age and type have been chosen for use in analyses, the spacing between canisters and between emplacement boreholes is generally fixed so that the initial APD conforms with the allowable APD. The APDs used in the studies whose results are reported in this report are equivalent to APDs of approximately 54 kW/acre to 90 kW/acre when 10-yr-old spent fuel is emplaced. The studies from which most of the rock temperatures are taken for this report were completed by Johnson and Bauer (1987), Holland (1986), and Travis and Nuttall (in preparation). The study conducted by Johnson and Bauer used 10-yr-old spent fuel emplaced vertically with an APD of 57 kW/acre; this study was completed as part of the unit-selection activity (Johnstone et al., 1984). Holland used horizontally emplaced 8.55-yr-old spent fuel with an APD that was equivalent to 54 kW/acre for 10-yr-old spent fuel (Holland, 1986; Mansure, 1986). Travis also used horizontally-emplaced 8.55-yr-old spent fuel, but the APD was equivalent to 67 kW/acre for 10-yr-old spent fuel (Travis and Nuttall, in preparation; Mansure, 1986). Both Travis and Nuttall, and Holland modeled horizontally-emplaced waste.

5. Review of Analyses that Investigate Changes in the Hydrologic Properties of the Rock that Could Result from Repository Heat and Excavation

The hydrologic properties of the rock mass, and thus the characteristics of the groundwater flow, could be affected by repository construction and the emplacement of heat-producing waste. The processes related to repository construction and waste emplacement that are considered in this section are those suggested in the draft position papers by the U.S. Nuclear Regulatory Commission (NRC) (1985, 1986a, 1986b): stress redistribution, construction and excavation, thermomechanical processes, and thermochemical processes. The laboratory, field, and computer analyses that characterize the effects of these processes are presented below. In general, the studies that are available focus on the Topopah Spring welded unit and the changes in porosity and permeability that might occur in it.

The three major subsections in this section (*Computer Analyses of Changes in Fracture Aperture as a Result of Stress Changes, Computer Analyses that Investigate Changes in Porosity and Permeability as a Result of Silica Dissolution and Precipitation*, and *Field and Laboratory Results of Testing Fracture and Matrix Permeability at Elevated Temperature*) correspond to the types of analyses that are available for use in defining the location of the disturbed-zone boundary. This section has been subdivided in this manner because each analysis type may address more than one of the four NRC processes. At the beginning of each subsection, the NRC processes that the subsection addresses are identified.

These subsections include no judgments about the effect of the results on groundwater travel time or the location of the disturbed-zone boundary, but they review the intrinsic porosity and permeability changes that have been determined from the analyses. Where changes in intrinsic porosity and permeability have been observed, the factor-of-2 change in porosity or order-of-magnitude change in permeability has been used to identify regions of the host rock for further consideration in Section 6. Changes in the intrinsic hydrologic properties of the fractures are discussed in terms of aperture changes. Assuming a set of parallel fractures, an aperture change of a factor of 2 correlates to a change in porosity of a

factor of 2, and, according to Snow's relationship discussed in Subsection 4.2, also correlates to approximately an order-of-magnitude change in permeability.

Section 6, *Summary of Expected Changes in Hydrologic Properties and Their Effect on Groundwater Travel Time*, summarizes the regions of intrinsic hydrologic property changes and analyzes them in terms of their effect on the groundwater travel time. Then, on the basis of this information, the conclusion section, Section 7, gives a suggestion for the location of the disturbed boundary.

5.1 Computer Analyses of Changes in Fracture Aperture As a Result of Stress Changes

The computer analyses discussed in this section address three of the NRC processes: stress redistribution, construction and excavation, and thermomechanical processes. The focus of the discussion is the effect of these processes, as shown by the analyses, on the hydrologic properties of the fractures. Because groundwater flow is expected to be dominantly through the matrix, the changes in the hydrologic fracture properties are not expected to significantly change groundwater travel times. The thermomechanical processes are included here for completeness in addressing the processes recommended for consideration by the NRC.

Stress changes in the rock as the waste-emplacement rooms are excavated and heated by the emplaced waste will change the apertures of existing fractures and may create new fractures. Some of the existing fractures will close and others open. Possible changes in fracture permeability and porosity as a function of stress changes caused by heat and excavation as indicated by thermomechanical analyses are discussed in this section. Many thermomechanical calculations have been completed (Branstetter, 1984; Johnstone et al., 1984; Labreche, 1986a; Johnson and Bauer, 1987; St. John, 1987; Svalstad et al., 1983; Thomas, 1987) using the computer codes JAC, a compliant joint model (Biffle 1984); ADINA, a ubiquitous joint model (Bathe 1978); and SPECTROM-11, with a ubiquitous joint model (Yamada 1981) and with a joint empirical model (Blanford and Key, in preparation). These codes are able to predict approximate regions of joint movement within a modeled region. Most of the thermomechanical calculations (SNL, 1987, Appendix N) that have been completed to

date model (1) a time period from excavation up to 100 yr, (2) an areal power density (APD) of 57 to 100 kW/acre, (3) initial total horizontal stress conditions at the repository horizon of 1.5 to 10.8 MPa and initial total vertical stress conditions of 6.0 to 11.3 MPa, (4) horizontal- and vertical-emplacement schemes for waste packages, and (5) vertical joints. The majority of the analyses indicated that joint movement was limited to the rock within 2 or 3 m of the side of the excavated rooms (SNL, 1987, Appendix N). Thomas completed a set of mechanical calculations using the thermal calculations of vertically emplaced waste completed by Johnson and Bauer (1987), average and limit mechanical properties of the rock,* an initial vertical stress of 11.3 MPa, an initial horizontal stress of 10.8 MPa, and a set of perpendicular joints. He plotted joint normal displacement at excavation and 100 yr after waste emplacement. The plots of joint normal displacement included only three contours: a zero-displacement contour, a completely-closed-joint contour, and a contour for a factor-of-2 increase in joint aperture. Thomas modeled a region 8 m above and below the emplacement drift from the emplacement-drift centerline to the midplane between the emplacment drifts. At excavation, in the region between the emplacment rooms, the joints were reduced in aperture but not completely closed. Above and below the emplacement drifts, the joints were increased in aperture by less than a factor of two. At 100 yr after waste emplacement, the only joints that were increased in aperture were located within about 3 m of the side of the emplacement room. Other joints between and below the drifts were reduced in aperture but they were not completely closed.

A recent set of analyses (Labreche, 1986a; 1987) that modeled only the rock near horizontal boreholes (i.e., the drifts were not modeled) indicated global trends in fracture aperture changes similar to those reported by Thomas (1987). Labreche's analyses present a more detailed picture of the fracture aperture changes near the borehole. His results indicate that fracture aperture changes near the borehole are quite varied. The apertures vary as a function of the fracture location with respect to the borehole and the time since waste emplacement. The apertures of horizontal fractures above and below the boreholes (within about 2 m) increase by a factor of 2.0 to 2.5 for the total time modeled (600 yr) and those at the sides of the borehole (within less than 0.5 m) decrease by a factor of 2 to 5 from their original values. Nearly all the vertical joints within the modeled region (60 m above and below the borehole) close by a factor of 2 in approximately 100 yr. This closing reduced the apertures of the joints from about 50 to 25 μm in one calculation and from

*The limit properties are rock properties that were used in the unit-selection activity (Johnstone et al., 1984). They were chosen for to maximize rock damage on a room-and-pillar scale (Peters, 1987).

10 to 5 μm in the other calculation completed. Only those vertical joints near the side of the borehole (within 1 m) were ever greater than their original aperture. The apertures of these fractures, although greater than their original value for several hundred years, were always less than a factor of 2 greater.

These calculations used the empirically based Joint Empirical Model (JEM) in SPECTROM-31 (Blanford and Key, in preparation). They were completed for 600 yr. Thermal calculations at an APD equivalent to 67 kW/acre for 10-yr-old spent fuel (Holland, 1986) were used as input as well as an initial horizontal stress of 1.65 MPa, an initial vertical stress of 6.6 MPa, and a set of horizontal and vertical joints.

This study also reported stresses around the borehole. As a result of excavation and the heat from the emplaced waste, the horizontal and vertical stresses surrounding the canister generally increase. Approximate stress conditions within about 10 m of the borehole are summarized below for use as perspective in Subsection 5.3, *Field and Laboratory Results of Testing Fracture and Matrix Permeability at Elevated Temperature*. These results are an approximation of the detailed stress conditions reported by Labreche (1986a; 1986b). As a result of heat and excavation, the stresses above the borehole changed as follows:

- The horizontal stress from about 1.2 m to about 6 m above the borehole increased to approximately 15 to 25 MPa.
- The vertical stress from less than 4 m to about 10 m above the borehole increased to about 7.7 MPa, and the vertical stress from the borehole wall to about 4 m above the borehole ranged from 0 to 7.7 MPa.

The stresses at the side of the borehole also changed:

- The horizontal stresses at the sides of the borehole ranged from 0 at the borehole wall to more than 18 MPa approximately 5 m from the borehole.
- The vertical stress at the side of the borehole ranged from approximately 5 MPa, 1.2 m from the side of the borehole, to approximately 8 MPa, 10 m from the side of the borehole.

5.2 Computer Analyses that Investigate Changes in Porosity and Permeability As a Result of Silica Dissolution and Precipitation

This subsection addresses one of the three thermochemical processes, silica precipitation and dissolution, that could be expected at Yucca Mountain. The three thermochemical processes that might be expected at the Yucca Mountain site are silica precipitation and dissolution, clay alteration, and zeolite alteration. Of these three, only the first is important in defining the disturbed zone, because only large quantities of silica minerals are located in regions which may have large enough temperature changes to change permeability by an order of magnitude or porosity by a factor of 2.

Rock units containing large quantities of clay and zeolites, on the other hand, are far enough from the repository horizon for the repository design to ensure that their temperatures remain below values (115 to 125°C) at which significant changes in their hydrologic properties might occur (Bish et al., 1986). This expectation is subject to two uncertainties:

1. The temperature limits at which clay and zeolite alteration may occur when unsaturated rock is exposed to extended periods of elevated temperature has not been fully investigated.
2. The design of the repository might be changed to produce higher rock temperatures that would help confine radionuclides near the waste package for longer periods of time.

The alteration of rock at elevated temperatures for extended periods of time and the design strategy will be more fully investigated in the future.

Two studies have been conducted of the effect of silica dissolution and precipitation on the hydrologic properties of the Topopah Spring welded unit. One study (Braithwaite and Nimick, 1984) determined changes in porosity using the results of a far-field thermal-conduction study as a basis, and the other (Travis and Nuttall, in preparation) determined changes in matrix permeability using the results of a near-field two-phase flow calculation.

Braithwaite and Nimick (1984) completed a study of porosity changes as a function of time resulting from thermally induced host-rock dissolution and deposition. The

analysis of the dissolution and precipitation of minerals contained within Yucca Mountain was simplified by assuming that the groundwater always maintains saturation with respect to amorphous silica. That is, the quantity of material transferred between the groundwater and the rock can be followed by calculating thermally-induced changes in amorphous silica. The justification for this approach is detailed by Braithwaite and Nimick (1984).

The results of far-field thermal-conduction analyses were the source for the temperature distributions used by Braithwaite and Nimick. A variety of cases were considered: different saturations, different infiltration rates (0.1 to 1.0 mm/yr), two different APDs (57 and 90 kW/acre), and the inclusion and omission of water vaporization at elevated temperatures. The highest temperatures reported from the thermal-conduction analyses were approximately 165°C (for the 90 kW/acre analysis) at the repository horizon at 100 yr (Svalstad, 1984).

Higher initial saturations, higher percolation rates, and higher APDs increased the magnitude of porosity changes. Accounting for water vaporization, and therefore for the dryout of the rock, allowed more silica to deposit near the repository and thus reduced the porosity of the rock. In all the analyses, the porosity changes in the matrix rock were extremely small: the maximum changes were 3×10^{-3} to 3.5×10^{-3} absolute percentage change in porosity. These porosity changes are much smaller than the porosity variations inherent within a given rock unit, which can be several percent (Montazer and Wilson, 1984), and much smaller than variation of the calculated porosities themselves, which may vary by an average of 1% to 3% in absolute porosity (derived from Schwartz, 1983; Schwartz, 1985; Schwartz, 1987).

Braithwaite and Nimick also estimated how dissolution and precipitation could affect the bulk permeability of the fractures. In doing this study Braithwaite and Nimick (1984, p. 38) state that determining changes in fracture permeability is dependent upon "initial fracture aperture, fracture density and the volume of material dissolved or precipitated." By assuming 20 fractures per meter with apertures of 5 μm and spent fuel emplaced at 57 kW/acre, Braithwaite and Nimick determined that the aperture of the fractures could decrease by approximately one-third, to 3.4 μm, at the

repository horizon (modeled as 390 m below the surface). This change, which was the maximum change determined, occurred at 1,000 yr (Braithwaite, 1986).*

In general, their study indicates that, at times beyond about 75 yr, fractures well above the repository (more than 15-30 m) increase slightly in porosity (less than 2 x 10^{-3}%), and those from the repository horizon to several tens of meters below the repository (0-60 m) decrease in porosity (less than 3.5 x 10^{-3}% change in porosity). The analyses indicate that the decreases in porosity below the repository move further and further below the repository as the heat pulse from the emplaced waste moves out.

Another study was recently conducted by Travis and Nuttall (in preparation) to determine changes in permeability resulting from silica dissolution and precipitation. Travis and Nuttall used the temperature distribution resulting from a near-field two-phase flow analysis (performed with the computer code WAFE as the basis for predicting matrix permeability changes near the waste package as a result of silica dissolution and precipitation). A liquid flux of 4.5 mm/yr** and an APD of approximately 70 kW/acre were the main parameters of interest used in this study. The region near the waste package reached a maximum temperature of approximately 225°C at approximately 10 yr after waste emplacement and decreased to approximately 85°C 100 yr after waste emplacement. From this study, the matrix permeability was predicted to increase by about a factor of 3 approximately 1 to 3 m away from the waste package and to decrease by almost two orders of magnitude approximately 3 to 5 m away from the waste package by the end of the heat decay period (about 100 yr) (Travis and Nuttall, in preparation; Travis, 1987). Travis and Nuttall adapted the Kozeny-Carman equation (Bear, 1972) to relate changes in the volume of silica that they calculated to matrix permeability changes. The porosity changes that correspond to the matrix permeability changes were calculated to be a factor of 2 increase in the porosity when the permeability increased by a factor of 3 and about factor of 10 decrease in porosity when the permeability decreased by two orders of magnitude (Travis, 1987). The porosity change was calculated by assuming

*In the published report, the maximum dissolution that occurred in a fracture was reported to be at 150 m. This did not appear to be consistent with the figures in the report, and upon further investigation it was determined that this maximum change was only an apparent maximum resulting from the boundary condition that was used.

**This flux is much greater than that presently expected (Wilson, 1985).

that all the original pores in the matrix were spheres of about 0.03 microns and that the silica was uniformly precipitated or dissolved from the surface of each pore. Although the calculations that were completed are for the matrix, the concluding statements of Travis and Nuttall indicate that the fractures could also be affected by dissolution and precipitation. They concluded that the "...effect of permeability reduction should occur wherever a capillary pressure gradient arises. In particular it should occur at fracture faces, leading to sealing of fractures."

Although Travis and Nuttall (in preparation) have not reported calculated changes in porosity, it is likely that the porosities that would correlate to the order-of-magnitude changes in permeability would be much different from those reported by Braithwaite and Nimick (1984).

The difference in the results of the two studies could be attributed to several things including:

- The scale of the analysis used by Travis and Nuttall is different from the analyses used by Braithwaite and Nimick. The calculations from which Braithwaite and Nimick derived their temperatures, those completed by Svalstad (1984), were far-field calculations, and the calculation completed by Travis and Nuttall was a near-field calculation.

- There were differences in the power decay curve and APD used in the two studies. Svalstad used a power decay curve for combined BWR (boiling water reactor) and PWR (pressurized water reactor) spent fuel that was emplaced at 57 and 90 kW/acre. Travis and Nuttall used a decay curve for 8.55-yr-old PWR spent fuel that was emplaced at an APD of 70 kW/acre (this waste loading deposits the same energy as that of 10-yr-old average waste emplaced at an APD of 67 kW/acre).

- Svalstad used a constant thermal conductivity of 1.4 W/m-K for the Topopah Spring welded unit, and Travis and Nuttall used a thermal conductivity that varied as a function of saturation from 1.75 to 2.35 W/m-K.

- Different physical processes were modeled. Travis and Nuttall used a two-phase flow code that models convective and conductive heat transport, and Svalstad used a computer code that models only conductive heat transport.

- The boundary conditions that were used by Travis and Nuttall may not approximate the conditions at a similar boundary in Svalstad's calculations.

5.3 Field and Laboratory Results of Testing Fracture and Matrix Permeability at Elevated Temperature

The field and laboratory results of testing fracture and matrix permeability at elevated temperature, discussed in this subsection, provide some information about how two of the NRC processes – thermomechanical processes and thermochemical processes (silica dissolution and precipitation, and alteration of zeolites) – could cause changes in hydrologic rock properties.* Results of the laboratory permeability tests are discussed first.

Three different investigators performed laboratory tests on saturated samples of the Topopah Spring at elevated temperatures: Lin and Daily (1984), Moore et al. (1984), and Reda (1985). Another set of investigators (Blacic et al., 1986) attempted to determine the effects of temperature and stress on porosity and permeability in an indirect manner. They soaked samples in water at high temperatures for extended periods of time and measured the room-temperature properties of the samples after the soaking period. It is recognized that the saturated state of these samples at testing differs from the saturation state expected at Yucca Mountain. At present there are no results of unsaturated testing at Yucca Mountain, and it is not clear how the results might differ if the testing could have been conducted under unsaturated conditions. A brief description of all the saturated tests and their results is presented below.

Lin and Daily (1984) performed one permeability test on an intact sample and two on fractured samples. The samples were taken from Fran Ridge at Yucca Mountain and machined to be right circular cylinders about 9.0 cm long and 2.54 cm in diameter with the axes approximately perpendicular to the bedding. The fractured samples were machined from a large core so that a naturally occurring fracture approximately

*The only laboratory results presented here are from tests on the Topopah Spring welded unit and the Calico Hills zeolitic unit. There is also a set of tests on the Bullfrog welded unit (Byerlee et al., 1983; Morrow et al., 1983) that is not presented because the Bullfrog welded unit is not expected to experience the temperature increases used in the laboratory analyses.

bisected the cylindrical sample longitudinally. One of the fractured samples and the intact sample were subjected to a sequence of steps to investigate the permeability of the samples as a result of dehydration, rehydration, and full saturation (Lin and Daily, 1984 and Lin, 1986):

- A permeability measurement was made on the sample at room temperature. It is believed that water was added to the samples at pressures similar to those used in the remainder of the testing steps.
- The sample was heated to 140°C, and the water was allowed to evaporate. When the sample was dry, it was resaturated at 140°C by applying 2.5 MPa of water pressure to one end for the intact sample and 2.0 MPa of water pressure to one end of the fracture sample. The water permeability was again measured when the water flow became steady.
- The water in the sample was again allowed to evaporate at 140°C and then rehydrated by adding water to the sample at 0.25 MPa for the intact sample and 0.2 MPa for the fractured sample. The water was in the vapor phase during this portion of the testing. The steam permeability was measured during this phase of testing.*
- The sample was allowed to dehydrate a third time at 140°C. The temperature was lowered to 98°C; 2.5 MPa of water pressure was applied to one end of the intact rock to resaturate it, and 0.2 MPa of water pressure was applied to the fractured sample to resaturate it. The liquid permeability of the sample was measured when the flow became steady.
- The sample temperature was reduced to 21°C and the liquid permeability was measured again.

The results of this sequence of testing are displayed in Table 3.

During the permeability testing, the confining pressure of the fractured and intact samples was a constant value of 5 MPa, but the effective confining pressure was varied. Using the values stated in the above steps, it can be determined that the average effective confining pressure during liquid permeability testing was 3.7 MPa for the intact sample and 3.9 to 4.8 MPa for the fractured sample. (Note that the higher

*The steam permeability is not included in this report on the disturbed zone.

Table 3: Fluid permeability of Topopah Spring welded tuff samples

Sample State	Temperature °C	Intact Sample μdarcy	First Fractured Sample μdarcy
Before drying	21	0.34	850±59
After the first drying	140	0.31	40±5.1
After the first drying	98	0.32	34±4.8
After three drying cycles	98	0.35	0.24±0.07
After three drying cycles	20	-	0.40±0.03

average effective confining pressure was in effect when the permeability of the fractured sample decreased.) The effective stresses used in these tests are within the range of ambient effective horizontal stresses and below the estimated values for the ambient effective vertical stresses at the present repository horizon. The stress conditions are near those that might be found at the side of the borehole wall after excavation and waste emplacement.

The highest temperature at which the liquid permeability was tested, 98°C, is a temperature condition that has been predicted to extend approximately 10 m from the waste package in thermal calculations that model horizontally emplaced waste (Holland, 1986) and approximately the same amount in thermal calculations that model vertically emplaced waste (Johnson and Bauer, 1987).*

The intact sample testing was completed in 6,000 hours and the fractured sample testing in approximately 3,000 hours. The liquid permeability of the intact sample was essentially unchanged throughout the testing sequence, but the liquid permeability of the fractured sample changed by several orders of magnitude. The liquid permeability of the fracture decreased by approximately one order of magnitude after each drying and resaturation cycle. Because the liquid permeability of the fractured sample changed so greatly during the testing cycle, Lin and Daily completed another permeability test on a second fractured sample that appeared to have surface conditions similar to that of the first fracture. It is believed that water

*These calculations indicated that the 100°C isotherm was 6.0 m from the bottom of the waste package at 100 yr for the Topopah Spring welded unit. The maximum extent of the 100°C isotherm was not reported but, assuming that these calculations show trends similar to Holland's results, it appears the maximum extent of the 100°C isotherm is nearly the same as that reported by Holland.

was added to the second fractured sample at pressures similar to those used in the other permeability tests. In this test the fracture permeability decreased by one order of magnitude when the temperature increased from 23 to 96°C. After this major decrease in the permeability, the permeability essentially did not change throughout the remainder of the test. Additional time or temperature increases did not change the permeability. One of the major differences between this fracture permeability test and the previous one was that the sample was never allowed to dehydrate. Lin and Daily concluded that the reduction in fracture permeability was caused by migration of silica minerals to the fracture surface. This process was thought to be initiated as the temperature increases to about 100°C. The temperature distributions predicted by Holland (1986) indicate that the 100°C isotherm may reach approximately 10 m below the waste package.

Moore et al. (1984) conducted permeability tests in a temperature gradient in an attempt to determine what the permeability might be near a borehole. They measured the permeability of three intact samples of the Topopah Spring welded tuff that came from surface outcrops. The samples were cylinders 7.62 cm in diameter and 8.89 cm long with a 1.27-cm diameter borehole in the center that allowed flow along the direction of the bedding of the tuff. The center of each sample was heated – one to a temperature of 90°C and the other to 150°C. The samples were under a confining pressure of 300 bars (30 MPa) and a pore pressure of 100 bars (10 MPa). Moore et al. (1984) tried to maintain a pore-pressure differential of 1.5 bars (0.15 MPa) between the borehole and the outer edge of the sample. The average effective confining pressure was approximately 20 MPa. The confining-pressure and pore-pressure conditions that were used are higher than the ambient stress conditions expected at the repository horizon at Yucca Mountain. The horizontal stress above the borehole wall after heat and excavation will approach the confining pressure that was used in these tests (Labreche, 1986a; 1986b), but the pore pressure was much larger than is ever expected at the repository horizon (Travis and Nuttall, in preparation). The temperatures used are similar to those expected in the rock surrounding the waste-emplacement borehole – the rock approximately 40 m from the waste package is predicted to reach 90°C, and the rock temperature approximately 3 m from the waste package is predicted to reach 150°C (Holland, 1986).

The tests were run from 17 to 21 days. The authors summarized their testing by the following: "Permeability measurements made on samples of the Topopah Spring Member of the Paintbrush Tuff at room temperature and in a temperature gradient

show that the initially high (3-65 μda) permeabilities are little affected by heating to at least 150°C..."

Reda (1985) tested a core of unfractured, densely welded, nonlithophysal Topopah Spring welded tuff from the Busted Butte outcrop at the Nevada Test Site. The sample that was tested was a cylindrical core 5.54 cm in diameter and 6.36 cm in length. Reda used distilled water as the working fluid and subjected the core to a constant confining pressure of 15.2 MPa. By cycling the inlet pressure to the core once each workday from, he varied the average effective confining pressure from approximately 14.9 MPa to 8.3 MPa. The 8.3 MPa effective confining pressure is just above the highest expected values for the effective horizontal and vertical stresses at Yucca Mountain. The stresses that are predicted (Labreche, 1986a; 1986b) near the borehole as a result of heat and excavation are within the range of the stresses used in these tests.

Reda conducted four different measurements on the same piece of core. The experiments included

- measurement of the permeability of the sample at ambient temperature,
- measurement of the permeability of the sample as it was systematically increased in temperature from 25 to 90°C,*
- measurement of the permeability of the sample while its temperature was maintained at 90°C, and
- measurement of the permeability of the sample as it was systematically reduced in temperature from 90 to 25°C.

From these measurements Reda concluded: "Laboratory experiments conducted over a continuous three-month period showed that the liquid permeability of Topopah Spring welded tuff remained essentially constant, independent of temperature, over the range 25 to 90°C..."

*As stated earlier, the temperature in the rock approximately 40 m from the waste package is predicted to reach 90°C (Holland, 1986)

Blacic et al. (1986) performed "soak tests" on samples from the Topopah Spring welded unit and the Calico Hills zeolitic unit from UE-25a#1. Several properties of the samples were tested, including tensile strength, uniaxial compressive strength, grain density, porosity, permeability, and petrologic and mineralogic properties. Only the porosity and permeability tests are discussed here. The samples that were tested were cylinders 2.54 cm in diameter and 6.5 cm in length. Two side-by-side samples from a piece of core were used for a test. Both samples were tested at ambient temperature and pressure conditions. One sample was "soaked" at elevated pressure and temperature conditions (temperatures of 80 to 120°C, confining presures of 9.7 to 19.7 MPa, pore pressures of 0.5 to 19.7 MPa) for an extended period of time (2 to 6 months) before it was tested at ambient temperature and pressure conditions. The other sample was only tested at ambient temperature and pressure conditions. The confining-pressure conditions that were used in the soak test are at the high end of the ambient stress conditions expected at the repository horizon at Yucca Mountain. The horizontal stress above and at the side of the borehole wall after heat and excavation will approach the confining pressure that was used in these tests (Labreche, 1986a; 1986b), but the pore pressure is larger than that expected at the repository horizon (Travis and Nuttall, in preparation). Temperatures like those used in the soak test are expected to occur in the rock surrounding the repository – rock approximately 60 m from the emplacement borehole is expected to reach 80°C, and rock approximately 2 m from the emplacement borehole is expected to reach 100°C.

The possible inhomogeneities between the two samples make it impossible to conclusively state that the differences in the measured properties are a result of the difference in exposure conditions of the two samples. In the porosity tests of the Topopah Spring welded unit, the porosity increased up to 20% after exposure at 80°C but decreased up to 25% after exposure to higher temperatures. In the two permeability tests, the permeability of the Topopah Spring increased by about 22% after exposure. The porosity tests of the Calico Hills zeolitic unit showed an increase of up to 20%. and the permeability tests of the Calico Hills zeolitic resulted in insignificant changes.

Zimmerman et al. (1986) measured the permeability of a fracture in the field as a function of temperature and pressure. The permeability measurements were part of a heated-block experiment; numerous in situ measurements (including deformation, strain, air pressure, temperature, fracture permeability, and water levels) were performed on a block of rock that was approximately 2 x 2 x 3 m. The heated-block

experiment was located in the densely welded portion of the Grouse Canyon Member of the Belted Range Tuff in an underground facility called G-Tunnel located beneath Rainier Mesa on the NTS. Studies that have been completed indicate that the major element compositions and the chemical and mineralogical compositions of the Grouse Canyon Member are similar to those of the Topopah Spring Member (Connolly and Keil, 1985; Connolly et al., 1983).

The rock surrounding the fracture whose permeability was tested was subjected to three heat cycles. The first heat cycle increased the temperature of the fracture from an ambient temperature of 20°C to approximately 60°C; the fracture remained at approximately 60°C for approximately 10 days. The second heat cycle raised the temperature from 40°C to approximately 75°C; again the fracture remained at the higher temperature for approximately 10 days. The third heat cycle raised the temperature from 20°C to approximately 95°C; the temperature remained at 95°C for approximately 30 days. The fracture was also subjected to several pressure cycles. The pressure of the flatjacks surrounding the block of rock under study was varied from 0 to 10 MPa. These stress conditions are within the range that might be expected as ambient stresses or as stresses induced by heat and excavation. The largest permeability values were obtained when the flatjack pressure was 0 MPa. As long as the flatjack pressure was above the stress considered to be the preexcavation state of the block, the authors concluded that "the fracture permeability was relatively insensitive to stress changes." They also concluded that "the fracture permeability measurements proved to be only mildly sensitive to temperature increases."

6. Summary of Expected Changes in Hydrologic Properties and Their Effect on Groundwater Travel Time

This section summarizes the hydrologic property changes determined in the work described in Section 7 and then discusses their possible effect on groundwater travel time. The summary of hydrologic property changes is further subdivided into two subsections: changes in matrix hydrologic properties and changes in fracture hydrologic properties. The factor-of-2 change in porosity and order-of-magnitude change in permeability suggested as significant changes in one of the U.S. Nuclear Regulatory Commission (NRC) draft technical position papers (1985) is used as a starting point for delimiting regions of changed hydrologic properties. As explained in Section 3, however, the effect of these changes on groundwater travel time is the basis for defining the boundary of the disturbed zone.

6.1 Changes in Matrix Porosity and Permeability

All but one of the analyses reviewed in this report indicated that there will be no significant changes in the matrix porosity and permeability (Braithwaite and Nimick, 1984; Lin and Daily, 1984; Reda, 1985; Moore et al., 1984; Blacic et al., 1986). The investigators (Moore et al., 1984) who subjected the Topopah Spring tuff to the highest temperatures in the laboratory indicated that the matrix permeability was little affected by temperatures of up to 150°C. Accordingly, these analyses suggest no significant effect on groundwater travel time through the host rock at any distance from the emplacement hole.

The results of the currently unpublished computer analysis by Travis and Nuttall (in preparation) differed from those of the remainder of the computer and laboratory analyses. Their study indicated that the matrix permeability would increase by about a factor of 3 within approximately 3 m of the borehole (Travis, 1987) and decrease by an order of magnitude 3 to 5 m from the borehole. If these computer results prove, after final review and publication, to be more representative of an actual repository than the laboratory and other computer studies, they would suggest that groundwater travel time might be significantly changed in the rock within several meters of the emplacment borehole. To determine which of the results most closely represents a repository will require careful review of all the studies and, probably, supplemental

analyses. Until such a determination has been made, the unequivocal summary of the results is that five of the six studies report no significant effect on groundwater travel time through the rock affected by the repository. They also report no changes that would meet the NRC draft criteria of April 1985 for significant changes.

It should be noted that even the effects predicted by Travis and Nuttall are contained within such a small region that they will not have a significant effect on the total groundwater travel time from the disturbed zone to the water table. The cumulative distribution curves determined from calculations of groundwater travel time using varying locations of the disturbed zone (Appendix C), indicate that changing the disturbed-zone location from 0 to 100 m does not significantly change the cumulative distribution curves of pre-waste-emplacement groundwater travel time. In other words, such variations in location do not cause the site to fail to meet the NRC performance objective for groundwater travel time.

6.2 Changes in Fracture Apertures (Porosity and Permeability)

This section discusses the changes in the intrinsic hydrologic properties in terms of fracture apertures because most of the information available about the changes in fractures is in terms of apertures. As discussed earlier (see Subsection 4.1), a change in all the fracture apertures of a factor of 2 is equivalent to a factor-of-2 change in porosity and approximately an order-of-magnitude change in permeability. As regions of fracture aperture changes are discussed in this section, there is a reference to the laboratory, computer, or field investigators from whom this information is derived and a reference to the subsection where their study is discussed in this report.

The computer analyses and laboratory results point to two regions of possible change in the fractures. The region within approximately 10 m of the waste packages (Lin and Daily, 1984; Subsection 5.2) appears to show the greatest changes in fracture apertures, and these changes appear to be caused by silica dissolution and precipitation and by stress changes. In the other region, which extends farther beyond the waste packages, the greatest changes in fracture apertures appear to be caused by stress changes.

Computer analyses indicate that, near the waste package,

- thermomechanical stresses may cause horizontal fractures to open by approximately a factor of 2 to 2.5 within approximately 2 m above and below the waste canister and to decrease in aperture by a factor of approximately 2 to 5 within approximately 0.5 m at the sides of the waste package (Labreche, 1986a; Labreche 1987; Subsection 5.1).

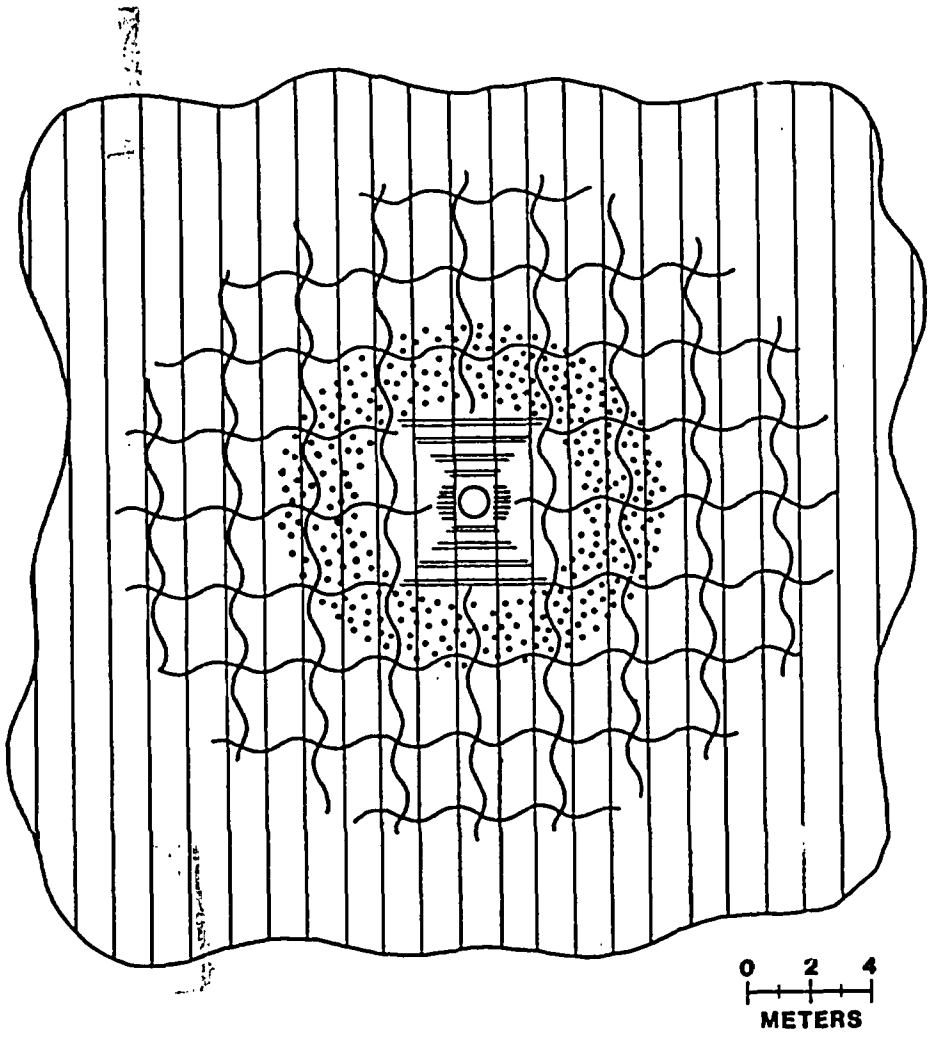
- thermomechanical stresses may cause nearly all vertical fractures to reduce in aperture by a factor of 2 (Labreche, 1986a; Subsection 5.1).

- silica dissolution may cause fractures to increase in aperture within approximately 3 m of the waste package, and silica deposition may cause the fractures to decrease in aperture 3 to 6 m away from the waste package (Travis and Nuttall, in preparation; Subsection 5.2). As a result of silica deposition, fracture apertures at the repository horizon could decrease by about one-third (Braithwaite and Nimick, 1984; Subsection 5.2).

Laboratory results (Lin and Daily, 1984; Subsection 5.3) suggest that fracture apertures may decrease by more than a factor of 2 (i.e., more than an order-of-magnitude change in permeability) wherever the fractures are subjected to dehydration and rehydration. In this report, the volume of rock subjected to dehydration and rehydration is assumed to be confined within the 100°C isotherm.* The heat-conduction analyses by Holland (1986) and Johnson and Bauer (1987) indicate that the 100°C isotherm is within approximately 10 m of the waste package canister, and the two-phase-flow calculations by Travis and Nuttall (in preparation) predict that the extent of the 100°C isotherm in 100 yr will be within approximately 3 m of the canister. In the following discussion the more conservative number of 10 m for the extent of the 100°C isotherm has been used.

The near-waste-package picture that is produced by the combination of all this information is complex. An attempt has been made to schematically summarize the information in Figure 5.

*The isotherm that bounds the region of dehydration and rehydration will be different from 100°C at Yucca Mountain. It will be a function of the ambient pressure at the repository horizon. The barometric pressure at the repository horizon at Yucca Mountain is approximately 85 KPa (Weeks, 1987); this pressure corresponds to a boiling point for water of approximately 95°C.



Factor-of-2 reduction in fracture apertures predicted from laboratory tests (Lin and Daily, 1984)

Factor-of-2 increase in horizontal fracture apertures predicted by thermomechanical calculations (Labreche, 1986a)

Factor-of-2 reduction in horizontal fracture apertures predicted by thermomechanical calculations (Labreche, 1986a)

Factor-of-2 reduction in vertical fracture apertures predicted by thermomechanical calculations (Labreche, 1986a)

Order-of-magnitude reduction in matrix permeability predicted by thermohydrological calculations (Travis and Nuttall, in preparation)

Figure 5: Schematic figure that indicates the possible extent of order-of-magnitude changes in fracture and matrix permeability

The increases in fracture apertures near the borehole are expected to have a very minimal effect on groundwater travel time through the affected rock because the groundwater flow is expected to be primarily through the matrix. Increases in horizontal fracture apertures could increase the groundwater travel time only on a very local scale, i.e., in the immediate vicinity of the fracture itself. Because groundwater flow is predominantly vertically downward, an enlarged horizontal fracture aperture will cause the groundwater to either seek another path that bypasses the larger fracture aperture or to accumulate until the groundwater can advance across the fracture.* Increases in vertical fracture aperture, when groundwater flow is vertically downward and primarily through the matrix, will probably cause even less perturbation in the groundwater travel time than a horizontal fracture.

The most far-reaching change in intrinsic hydrologic properties that has been predicted is the decrease in fracture apertures. This change mainly results from thermomechanical stresses. Continuing from the 10-m boundary of fracture changes discussed previously, a thermomechanical calculation suggests that the stresses resulting from heat produced by waste packages may decrease the apertures of vertical fractures by a factor of 2 to distances greater than 60 m from the waste package (Labreche, 1986a; Subsection 5.1).

The effect of a factor-of-2 decrease in fracture aperture on groundwater travel time is dependent on the predominant flow path and the relative size of the fracture apertures and matrix pores. Because the groundwater flow at Yucca Mountain presently believed to be mainly through the matrix, a decrease in fracture aperture will have a negligible effect on groundwater flow time. For this reason, the fracture-aperture changes predicted by Labreche, as well as the changes predicted within the 100°C isotherm, are not significant in determining the extent of the regulatory disturbed zone.

*This latter phenomenon was observed in a laboratory experiment conducted by Reda (1986).

7. Conclusion: Preliminary Definition of the Disturbed-Zone Boundary

The U.S. Nuclear Regulatory Commission (NRC) adopted the regulation of pre-waste groundwater travel time from the disturbed zone to the accessible environment to ensure that a natural barrier would contribute to isolation of radioactive waste from the accessible environment. The location of the disturbed-zone boundary must be identified before calculations of pre-waste groundwater travel time can be completed. The NRC has provided draft guidance for determining the boundary of the disturbed zone that suggests significant changes in hydrologic properties should be the criteria for determining the disturbed-zone boundary. The Nevada Nuclear Waste Storage Investigations (NNWSI) Project finds this suggestion reasonable. Therefore, the boundary of the disturbed zone defined in this paper relies on the identification of the volume of rock in which significant changes occur in intrinsic hydrologic properties. The meaning of "significant" in this context logically rests on the significance of the effects that the changes could exert on the flow of groundwater through the rock. The analyses summarized in this report predict that some changes will occur in the intrinsic hydrologic properties of the unsaturated rock at Yucca Mountain, but the changes are not significant; they would not meaningfully affect groundwater travel time. Only an unpublished analysis, which appears to disagree with several others, offers any expectation that flow through the rock matrix could be significantly affected, even in the few meters of rock closest to the emplacment borehole. And none of the studies of changes in fracture apertures offers such an interpretation . Furthermore, few of the analyses predict changes that would meet the draft numerical criteria for significance that the NRC once proposed but has now apparently withdrawn.

Under the present knowledge of the unsaturated hydrologic environment at Yucca Mountain, then, the predicted changes are not significant. Using this information, the disturbed-zone boundary could logically be placed at the edge of the emplacment borehole. Such a choice could not be considered conservative, however. A variety of changes (both increases and decreases in the fracture apertures and in the matrix permeability) can, in principle, occur in the host rock, and several processes (thermomechanical stresses and precipitation and dissolution) are their causes. Recognizing that the existing estimates of these changes and their causes are subject to uncertainty, this paper proposes a conservative choice, 10 m, for the extent of the

disturbed zone. That is, the disturbed-zone boundary to be used by the NNWSI is proposed to be a plane that is 10 m below the waste-package boundaries.

This value is based upon the information presented in the preceding sections of this paper: (1) conceptual ideas of how groundwater may flow in the unsaturated zone at Yucca Mountain, (2) reasonable expectations about the existing hydrologic properties, (3) the repository design, and (4) results from preliminary analyses and laboratory experiments on the possible effects of constructing a repository. As we gain more information about the Yucca Mountain site or change the repository design, the resulting definition of the disturbed zone boundary may change.

It is recognized that this suggested location for the disturbed-zone boundary differs from the most recent draft recommendation by the NRC. The June 1986 draft position paper (1986b) states

> The extent of the disturbed zone should be calculated by DOE on a site-specific basis, but should not be considered to extend less than fifty meters or five opening diameters, whichever is larger, from the edge of the underground facilities at any site.

The reference design for vertical-waste-emplacement drifts at Yucca Mountain repository (the drift dimensions for vertical waste emplacement are larger than those for horizontal waste emplacement) calls for underground openings approximately 4.9 m (16 ft) wide and 6.7 m (22 ft) high (SNL, 1986; SNL, 1987, p. 4-99). Using the NRC recommendation of five opening diameters, these dimensions would suggest a disturbed zone extending 24.5 to 33.5 m from the edge of the underground facility. Both of these values are less than the suggested minimum. Therefore, on the basis of the draft guidance, the NRC would recommend that the disturbed-zone boundary for the Yucca Mountain site be 50 m from the edge of the underground facilities.

Although there are no significant deleterious changes in hydrologic properties at a distance of 50 m, the NNWSI Project could decide to follow such a recommendation. As the calculations in Appendix C suggest, a change in the boundary from 10 to 50 m would probably have little effect on the ability of the site to meet the performance objective for pre-waste-emplacement groundwater travel time. On the other hand, there is no technical or logical reason for defining a disturbed zone that is made up

almost entirely of undisturbed rock. Extensions of the analyses summarized in this report can be used to support more-rigorous future recommendations for the boundary of the disturbed zone if the NRC does not adopt a fixed, nonnegotiable minimum boundary.

Appendix A

Consideration of the Effects of Geochemical Changes on the Postclosure Performance of the Repository

Introduction

The definition of the disturbed zone is directed at considering those changes that have a significant effect on the performance of the geologic repository. In the body of this report, only changes in the intrinsic hydrologic properties (porosity and intrinsic permeability), which are related to groundwater travel time, are considered in determining the boundary of the disturbed zone. This assumption is consistent with the current U.S. Nuclear Regulatory Commission (NRC) guidance on determining the boundary. It also reflects the fact that the disturbed-zone concept appears solely in the performance objective for groundwater travel time. Changes in other properties could, however, affect the postclosure performance of a repository. Because they would not directly affect groundwater travel time, they would not be expected to contribute to the formation of a disturbed zone defined for use in determining groundwater travel time. Nevertheless, it may be worthwhile to examine whether changes in properties other than intrinsic hydrologic properties would be expected to significantly affect the postclosure performance of a repository in the rock outside the disturbed zone defined in the body of this report.

This appendix briefly addresses what is known about how a nuclear repository at Yucca Mountain could affect properties, other than intrinsic hydrologic properties, that are important to the transport of radionuclides under expected conditions. Although the repository will also affect the immediate environment of the waste package and thus the containment of radionuclides and their release from the engineered-barrier system, the effect of the repository on these aspects of postclosure performance is not addressed in this appendix, because the waste package and the engineered-barrier system currently lie within the boundary of the disturbed zone defined in the body of this report.

The main parameters of interest in determining the travel time of radionuclides to the accessible environment include

- the source term
- hydrologic properties
- solubility
- sorption

The first parameter, the source term, is not addressed in this report because the source of radionuclides is within the presently defined disturbed-zone boundary.

Changes in the intrinsic hydrologic properties are discussed in the main part of the text. By the definition of the disturbed zone, the changes in intrinsic hydrologic properties that could possibly be significant to radionuclide travel time are contained within the disturbed-zone boundary.

The remaining two parameters, solubility and sorption, are host-rock properties that are different for different radionuclides. Therefore, the next section is a brief discussion of those radionuclides that are of most concern to repository performance. The remainder of the appendix contains the following sections:

- a brief summary of the present solubility data available
- a brief summary of the present sorption data available
- a brief preliminary review of the transport time of radionuclides to the water table under expected conditions.
- a statement of conclusions

Radionuclides of Importance

After considering the quantity of the radionuclides in waste, U.S. Environmental Protection Agency (EPA) release limits, solubility, sorption, potential for vapor transport, and colloid transport, Kerrisk (1985) has drawn the following conclusions about the important radionuclides:

1. Isotopes of the elements americium, plutonium, neptunium, and uranium are of primary importance because they are present in the largest quantities in the waste relative to their EPA release limits.
2. Isotopes of the elements strontium, cesium, carbon, nickel, zirconium, technetium, thorium, radium and tin are present in lesser amounts at most times but are also important.

3. Isotopes of the elements carbon, technetium, and iodine are important because they appear to have high solubility and low sorption at Yucca Mountain.

4. Isotopes of the elements carbon and iodine are important because they could be transported in the gas phase at Yucca Mountain.

The rest of the discussion in this appendix will deal only with the radionuclides that Kerrisk concluded were important.

Available Solubility Information

To date, there are limited measurements and predictions of radionuclide solubilities expected at Yucca Mountain. The solubilities that have been estimated for Yucca Mountain are based on some experimental measurements and some equilibrium thermodynamic calculations. Nitsche and Edelstein (1985) have measured the solubilities of plutonium, americium, and neptunium in J-13 water* at a pH of 7 and a temperature of 25°C. Ogard and Kerrisk (1984) have calculated the solubilities of uranium, plutonium, americium, strontium, radium, and technetium assuming water at a pH of 7, temperature of 25°C, and oxidizing conditions.

Available Sorption Information

In the Yucca Mountain Environmental Assessment (EA) (DOE, 1986b), there is a table (Table 6-48) of values of sorption ratios and retardation factors that are considered to be representative of spatial averages in the welded and nonwelded tuffs. Table A-1 is mainly derived from that table in the EA. Table A-1 includes only those radionuclides listed previously as important at Yucca Mountain. It is noted in the EA (DOE, 1986b, p. 6-375) that although sorption ratios may be overestimated by factors of 10 or even 100, it is unlikely that the spatially averaged sorption ratios could be overestimated by factors of 100. It can be noted from this table that those radionuclides (carbon and iodine) with a sorption value of 0 have a retardation factor of 1; this is the lowest possible value for the retardation factor.

*This water is from the saturated zone within well J-13. This water is highly used in experiments because it is abundantly available and because there are no water samples available from the unsaturated zone.

Table A-1: Approximate Sorption Ratios and Calculated Retardation Factors of Important Radionuclides for Yucca Mountain[a]

Element	Sorption Ratio ml/g		Retardation Factor[b]	
	Welded Tuff	Nonwelded Tuff	Welded Tuff	Nonwelded Tuff
Americium†	1200	4600	28,000	24,000
Carbon	0[c]	0[c]	1	1
Cesium	290	7800	6700	41,000
Iodine	0	0	1	1
Neptunium‡	7	11	160	58
Nickel	No data	No data	No data	No data
Plutonium†	64	140	1500	740
Radium‡	25,000[d]	25,000[d]	580,000	130,000
Strontium‡	53	3900	1200	21,000
Technetium	0.3	0[c]	8	1
Thorium	500[e]	500[e]	12,000	2600
Tin	100[e]	100[e]	2300	530
Uranium‡	1.8	5.3	27	45
Zirconium	500[e]	500[e]	12,000	2600

†Sorption is higher in the presence of clinoptilolite and smectite clays.
‡Sorption is higher in the presence of zeolites.
[a] Unless otherwise indicated, sorption ratios were taken from Table 6-25 of the EA (DOE, 1986b) or were inferred from the sorption ratios quoted by Daniels et al. (1982), and retardation factors were taken from Table 6-48 of the EA (DOE, 1986b).
[b] The retardation factor was calculated assuming bulk densities of 2.33 and 1.48 for the welded and nonwelded tuffs, respectively.
[c] No data available. Assumed to be zero.
[d] Barium used as a chemical analog (Kerrisk, 1985).
[e] Inferred from the mid-range retardation factor for tuffs in the compilation by Krauskopf (National Research Council, 1983).

A repository could, in theory, affect sorption by heating the rocks that sorb radionuclides. The repository might change sorption ratios through direct effects of heating, through heat-induced changes in mineralogy, or through heat-induced changes in groundwater composition. The remainder of this section briefly addresses what is known about the effects of these parameters on sorption.

Direct Measurement of the Effect of Elevated Temperature on Sorption

There are direct sorption results from short-term (less than 4 months) sorption tests performed at elevated temperature. The results of these tests could be used directly to give a preliminary assessment of how the repository could affect sorption properties.

Of the list of radionuclides in Table A-1 there is information on sorption at elevated temperatures of 70 and 85°C for Am and Pu (Daniels et al., 1982; Ogard et al., 1983). There is also information on sorption at an elevated temperature of 70°C for Ra, Sr, Cs, Ba, Eu, and U (Daniels et al., 1982).

The EA (DOE, 1986b, p. 6-223), which was written before the sorption tests at elevated temperatures of 85°C were completed, states that "the direct effect of higher water temperatures on the sorption process has been superficially investigated (Erdal et al., 1979; Johnstone and Wolfsberg, 1980; Daniels et al., 1982). These limited studies showed, that in general, temperature changes between 20 and 70°C have only a minor effect on sorption. For most elements studied, sorption is slightly greater at the higher temperatures (sorption coefficients increased by up to a factor of 5). The exceptions include a few lanthanides and actinides, which showed very little or a slightly negative temperature response. As the temperature is increased, retardation because of diffusional processes will not be decreased."

Heat-Induced Alteration of Sorbing Minerals

Correlations of mineralogy with the sorptive behavior of the radionuclides have been identified and summarized in the EA (DOE, 1986b, pp. 6-184 and 6-189). The three points that follow are taken from the EA:

1. "For the alkali metals (e.g., cesium) and alkaline earths (e.g., strontium, barium, and radium), which probably exist in groundwater as uncomplexed ions and sorb by ion exchange, sorption is correlated with the presence of clinoptilolite and the smectite clays, which contain exchangeable cations. Since there are large quantities of clinoptilolite directly below the proposed repository horizon, cesium, strontium, and radium should be strongly sorbed, and their movement along the flow path should be retarded."

2. "A correlation with mineral composition is also found for the sorption of cerium, europium, plutonium, and americium, but the relation is not as clear as for the alkali metals. However, the sorption ratios are high (100 to more than 1,000 milliliters per gram). The sorption ratios of these elements are undoubtedly influenced by the formation of hydroxyl and carbonate complexes."

3. "Geochemical sorption will not offer much retardation for anionic species like pertechnetate [TcO^{-4}]."

The sorption of Th (Rundberg et al., 1985) and Sn (Crowe and Vaniman, 1985) has been stated to be independent of mineralogy. The sorption of Np and U, which is low, less than 10 ml/g, has been stated to be higher in the zeolitic tuffs, but the higher sorption has not been related to a particular mineral (Daniels et al., 1982).

In the EA (DOE, 1986b, p. 6-193) it is stated that "Under expected repository conditions, the present high radionuclide-retardation capacity of the tuffs at Yucca Mountain is not expected to be significantly degraded and may in fact be increased." Thus we claimed the favorable condition that says that there are mineral assemblages at Yucca Mountain that, when subjected to expected repository conditions, either remain unaltered or alter to mineral assemblages with equal or increased capability to retard radionuclide transport. There are now thoughts that zeolites may alter to other minerals when subjected to elevated temperature of tens of degrees C for extended periods of time. The zeolite of most concern is clinoptilolite. The alteration of clinoptilolite may not be a simple function of temperature. There is evidence (Keith et al., 1978) that clinoptilolite occurs with cristobalite. As the cristobalite converts to quartz with elevated temperature, the clinoptilolite alters to analcime. This suggests that the alteration of clinoptilolite is largely dependent upon the silica activity. In those cases where the radionuclides have high sorption ratios because of the existence of clinoptilolite, their sorption value will probably decrease wherever clinoptilolite is altered.

Although most of the rock that would provide sorption is not expected to be adversely affected by the repository, the available data leave open the possibility that some sorption might be reduced. Whether the effect would be significant would depend on the currently unknown amount of clinoptilolite that would be converted. These effects can be bounded by the data in Table A-1. If mineralogy is the dominant factor in determining sorption ratio rather than groundwater conditions or temperature, the values listed under the column headed "Welded Tuff" should provide an estimate of the lower bound for the sorption ratio if the nonwelded (zeolitic) tuffs are altered.

Heat-Induced Changes in Groundwater Composition

There is some information in the EA (DOE, 1986b, p. 6-223) about how the groundwater composition may change in the Topopah Spring Member as a result of the increased temperatures caused by the repository. This information is reproduced below.

> Heat-driven rock and ground-water interactions along with absolute temperature increases could affect radionuclide sorption and thus the retardation capability of the host rock. The rock and ground-water interactions could cause this by altering the mineral phases present and the ground-water solution chemistry. However, elevated-temperature experiments on the interaction of Topopah Spring tuff with water from well J-13 indicate that an emplaced heat source should produce very little change in ground-water chemistry and primary mineralogy of the Topopah Spring Member (Oversby, 1983). This study also noted that the anionic composition (radionuclide-complexing agents) of the water remains relatively constant. Therefore, the effect of increased temperature on radionuclide solution chemistry should be minimal.

Brief Review of the Transport Time of Radionuclides Under Expected Conditions

There are three sets of calculations in the EA (DOE, 1986b) that provide some information about transport time of radionuclides under expected conditions and releases to the accessible environment at Yucca Mountain. Two of the sets deal directly with transport time and releases to the accessible environment.

One of the calculation sets provides results for the transport-time distribution for uranium (DOE, 1986b, p. 6-377). With the exception of carbon-14, iodine-129, and technetium-99, uranium has the lowest retardation factor of the radionuclides listed in Table A-1. The transport time that was calculated in the EA is that between the disturbed zone and the accessible environment. The disturbed zone was assumed to be 50 m below the repository. The predicted upper bound on the groundwater flux of 0.5 mm/yr was used in the calculations. The calculations were completed under expected conditions. The sample mean of the transport-time distribution was

452,303 yr, and the standard deviation was 77,115 yr. As stated in the EA, "this result suggests that cumulative releases of uranium (and also any radionuclide with a retardation factor greater than that for uranium) would be minuscule, even over a 100,000-year period . . ."

The EA (DOE, 1986b, p 6-382) also presents results of transport calculations for carbon-14 and iodine-129, which have the lowest possible retardation factor of 1. The reference case calculation, completed under conditions similar to those of the previous calculation described in this section, indicated that there could be some releases of these radionuclides at the accessible environment in 10,000 yr but that the curies released would be less than 0.00001% of the permitted releases.

The EA (DOE, 1986b, Section 6.3.1.1.5) also contains results of groundwater travel time from the disturbed zone to water table. These calculations provide some insight into the possible transport time for any radionuclide that has a zero sorption ratio. In these calculations the disturbed zone was 50 m and the groundwater flux was 0.5 mm/yr. The hydrologic properties were assumed to vary over elements approximately 3 m thick; the variable properties were chosen from the expected range of properties in each hydrologic unit modeled. The calculations (DOE, 1986b, Figure 6-7) showed a negligible probability of groundwater travel time less than 10,000 yr. With a retardation factor of 1 (i.e., a sorption ratio of zero), the transport time of most of the radionuclides would be greater than 10,000 yr. The radionuclide transport time is likely to be shown to be much greater than 10,000 yr because detailed calculations of the transport time will not make several conservative assumptions implicit in the existing calculations of groundwater travel time. For example, the transport calculations will probably assume a retardation factor greater than 1 for most of the important radionuclides, and they will probably not exclude the entire 50 m of rock that the travel-time calculations excluded. Transport times much longer than 10,000 yr will allow the repository system to meet the regulations for releases at the accessible environment under expected hydrologic conditions.

Conclusion

The first portion of this appendix discussed what is known about how the repository may change solubility and sorption ratios at Yucca Mountain. The only solubility information available is based on a temperature of 25°C. Some tests indicate that the heat from the repository may increase the sorption ratios while other information indicates that repository-induced changes may reduce sorption ratios. Although these

results do not definitively establish bounds on the possible effects induced by the repository, none of them suggests that the effects will significantly alter the ability of the repository to meet regulations governing radionuclide transport. In fact, the existing calculations suggest strongly that groundwater travel times alone, without any beneficial geochemical effects, will be long enough to allow the standards to be met. For bounding the repository-induced effects that might compromise the ability of the repository to meet the standards, then, the 10-m disturbed zone suggested in the main text of this report appears adequate; that zone includes the effects that are most likely to be significant – i.e., the changes in intrinsic hydrologic properties.

Appendix B

Scoping Analyses of Groundwater Flow after Waste-Package Emplacement

This appendix deals with changes in the groundwater flow induced as a result of the heat generated by waste packages emplaced in the repository. Results of a far-field isothermal calculation have been used to conduct a preliminary study of the possible changes.

Changes in the groundwater flow caused by the heat produced by the waste packages are of interest because it is known that these changes will cause changes in the saturation state and thus changes in the hydrologic properties. In this study the changes in the saturation state and the related changes in the hydrologic properties are assumed to be temporary. As the repository cools, the saturation state is expected to return to near its original state. The changes in hydrologic properties are assumed to be only a function of the saturation state. This study was completed to determine whether saturation-related, hydrologic-property changes would cause deleterious long-lasting changes to the groundwater travel time. No changes in the intrinsic hydrologic properties are considered in the calculations presented in this appendix.

The following sequence was assumed as the basis for this study: (1) vaporization of water near the emplacement boreholes as a result of heating by the waste package, (2) movement of the water vapor away from the waste package (the water vapor will probably travel mainly through the fractures), (3) condensation of the water vapor in a cooler region away from the waste package, and (4) suction of the condensed water vapor into the surrounding unsaturated rock matrix (including liquid movement toward the waste package which is surrounded by rock at a saturation lower than the original saturation).

The heat produced by the waste may cause temperatures near the waste package to be above vaporization for hundreds of years. The water vapor that moves from the waste package to condense in the cooler region away from the waste package was postulated in these calculations to uniformly increase the flux of liquid water below the repository and thus the saturation of the rock below the repository. The postulated increased flux from the repository will cause the rock mass below the repository to be at a higher level of saturation and also cause the matrix hydraulic conductivity to be higher. The saturation level may be high enough in portions of the region to cause water to flow in fractures in which it did not originally flow.

The set of calculations discussed in this section is a set of far-field isothermal calculations that use information from a far-field heat-conduction analysis to approximate an increased flux boundary condition. The isothermal one-dimensional (1-D) flow code TOSPAC that simulates partially-saturated flow in a porous media was used to complete the far-field calculations. The hydrogeologic units and the associated values for the hydrologic parameters that were used are summarized in Table B-1.

The top boundary condition for the TOSPAC calculation was based upon a heat-conduction calculation completed by Holland (1986). The heat-conduction calculation was used to (1) determine the approximate bound of the zone of vaporization by assuming that a temperature isotherm of 100°C encompassed the zone of vaporization and (2) approximate the amount of liquid water that might be driven below the repository as a result of vaporization and condensation. The heat-conduction calculation by Holland modeled horizontally emplaced waste at an

Table B-1: Tuff properties

	Topopah Spring welded unit	Calico Hills zeolitic nonwelded unit
MATRIX PROPERTIES		
Porosity (n_m)	0.11	0.28
Saturated Hydraulic Conductivity (K), (m/s)	1.9×10^{-11}	2.0×10^{-11}
Residual Saturation (S_r)	0.080	0.110
Alpha (α^*) - 1/m	0.00567	0.00308
Beta (β)	1.798	1.602
FRACTURE PROPERTIES		
Porosity (n)	18.0×10^{-5}	4.6×10^{-5}
Compressibility ($\partial n_f / \partial \sigma'$), 1/m	12.0×10^{-8}	2.8×10^{-8}
Saturated Hydraulic Conductivity (K), m/s	3.1×10^{-9}	9.2×10^{-9}
Fracture Saturation Coefficients are $S_r = 0.0395$, $\alpha = 1.285$/m, $\beta = 4.23$		
Rock Mass Coefficient of Consolidation (α'_{bulk} - 1/m)	5.8×10^{-7}	26.0×10^{-7}
Compressibility of Water (β') is 9.8×10^{-7}/m		

*α and β are curve fit parameters for the relationship between pressure head and hydraulic conductivity

initial areal power density (APD) of 57 kW/acre.[a] The calculation also accounted for vaporization of water within the rock. It indicated that the 100°C isotherm reaches its maximum extent 10 m below the centerline of the waste package 90 yr after waste emplacement and that the 100°C isotherm remains beyond the borehole wall for approximately 1,000 yr. Another set of thermal-conduction calculations that included groundwater vaporization was used to confirm the approximate bounds of the zone of vaporization. These calculations were completed for vertically emplaced waste as part of the unit-selection activity (Johnson and Bauer, 1987). They were completed for an APD of 57 kW/acre. Using average for the Topopah Spring, at 100 yr the 100°C isotherm was 6.0 m from the bottom of the waste package. The maximum extent of the 100°C isotherm was not reported but, assuming that these calculations show trends similar to Holland's results, it appears the maximum extent of the 100°C isotherm is nearly the same as that reported by Holland.

In the TOSPAC calculations (Gauthier and Peters, 1986), the top boundary of the modeled region was 10 m below the centerline of the canister (i.e., at the maximum extent of the 100°C isotherm below the waste package as determined in Holland's calculation). The initial unperturbed flux at this top boundary was assumed to be 0.1 mm/yr.[b] At a steady-state flux of this magnitude, the Topopah Spring is approximately 87% saturated.[c] To determine the effect of the repository on the groundwater flow, it was assumed that all the water from the canister centerline to the 100°C isotherm was vaporized and transported downward beyond the 100°C isotherm within the 90-yr period that it took the 100°C isotherm to reach its maximum extent. Within this zone, there was assumed to be 10 m of dry rock that should hold approximately 1 m of groundwater (using a matrix porosity of 0.1 and 87% saturation for the Topopah Spring welded unit). In a 90-yr period, the addition of this 1 m of water to the assumed initial flux of 0.1 mm/yr would increase the flux, on average, to 11 mm/yr. Therefore, for 90 yr, the top boundary condition used in the TOSPAC

[a]The age of the waste used in these calculations was 8.55 yr. Because this waste age was used, the initial APD of 57 kW/acre does not conform with the present definition for the allowable APD of 57 kW/acre. The present allowable APD of 57 kW/acre is defined as that thermal loading that deposits the same energy through 2,000 yr as 10-yr-old spent fuel at 57 kW/acre initial APD. Using this definition, the APD of 57 kW/acre used in Holland's calculations deposits 4.4% less energy in 2,000 yr than the baselined allowable APD of 57 kW/acre (Mansure, 1986).

[b]The flux for Yucca Mountain has been calculated by several defferent methods (Wilson, 1985). The most conservative value, based on the approximated annual rate of recharge at Yucca Mountain, is 0.5 mm/yr. The value of 0.1 mm/yr is near the upper limit of values determined from analysis of field measurements.

[c]This is near the upper limit of the saturations reported by Montazer and Wilson (1984).

calculations was increased to 11 mm/yr. Two calculations were completed, both using 0.1 and 11.0 mm/yr as the first two top boundary conditions. Each calculation also included a third top boundary condition. In one calculation (case 1), it was assumed that the flux returned immediately to 0.1 mm/yr after the 90-yr period of higher flux, and in the other calculation (case 2), it was assumed that the 90 yr were followed by a 1,000-yr period of no flux and then a flux of 0.1 mm/yr. The normalized groundwater travel times determined from these calculations are essentially the same.

The results of case 1 are shown in Figure B-1 in the form of several curves. Each curve is a plot of the groundwater travel time at a given time after waste emplacement normalized to the steady-state groundwater travel before waste emplacement. The normalized travel times for groundwater particles that start near the repository are near 1.0 after approximately 100 yr, although the normalized travel time for those groundwater particles that originate approximately 75 m from the water table are significantly less than 1.0 for several thousand years. The groundwater travel time after waste emplacement used to calculate the normalized groundwater travel time in Figure B-1 represents water particles that will be traveling much faster than the average groundwater particle released near the repository. This is true for several reasons:

1. As the region surrounding the waste package cools, some of the water vapor that has been condensed away from the waste package will probably be drawn back toward the heat source by suction in addition to being drawn away from the heat source by suction. This would reduce the amount of water moving away from the repository.

2. Some calculations completed by Hopkins et al. (1987) indicate ventilation of the repository will probably remove some of the water from the rock surrounding the drifts; therefore, the amount of water available near the repository will be less than that available before the repository was constructed.

3. Figure B-1 actually shows groundwater travel times for some of the fastest water particles. "When tracking a water particle, the particle was assigned the fracture water velocity if the fracture water contributed to more than one percent of the total flux; otherwise, the particle was assigned the matrix water velocity" (Gauthier and Peters; 1986).

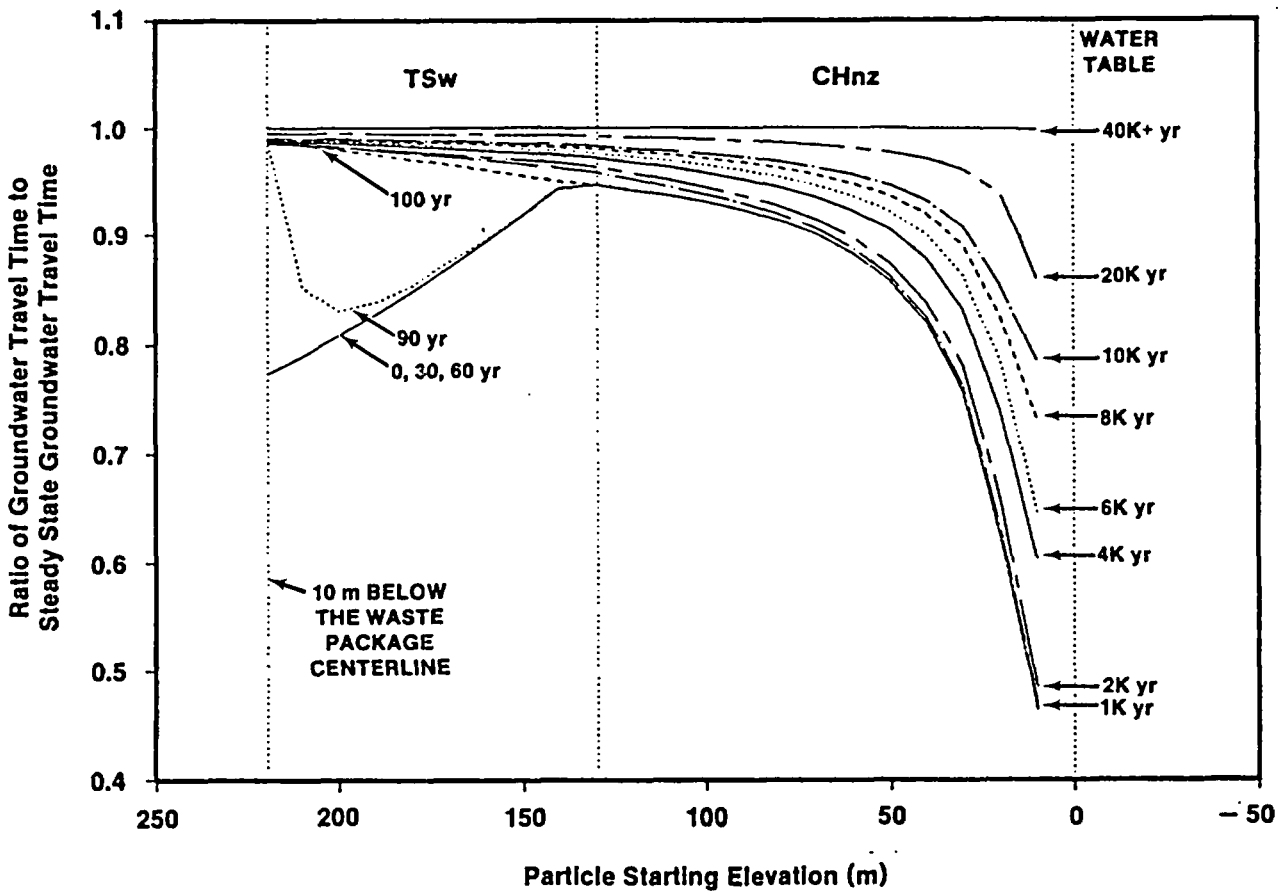


Figure B-1: Normalized groundwater travel time for analysis case 1

4. Regions of rock at lower temperatures (i.e., the rock near access drifts and the rock surrounding the repository) and saturations near the regions of higher temperature will suck some of the water from a vertically downward path and dampen the vertical extent of the higher saturation zone.

These calculations indicate that there are temporary but not long-lasting changes in groundwater travel time that must be accounted for as a result of repository-induced changes in saturation. Therefore, it appears that significant changes in intrinsic hydrologic properties can be the primary method used to determine the boundary of the disturbed zone without overlooking important changes resulting from redistribution of groundwater induced by heat produced by the waste packages. These calculations of relative groundwater travel times are preliminary calculations that simplify the movement of water from the repository. The results of these calculations will be checked as new information becomes available.

Appendix C

Calculations of Pre-Waste-Emplacement Groundwater Travel Time

This appendix discusses how placing the disturbed-zone boundary at different distances from the repository could affect the pre-waste-emplacement groundwater travel time.

The U.S. Nuclear Regulatory Commission (NRC) regulation for pre-waste-emplacement groundwater travel time provides a measure of the quality of the site. The disturbed zone appears to be a factor of safety to ensure that even if hydrologic behavior in regions near the repository changes as a result of excavation and heat generated by waste emplacement, the groundwater travel times in regions farther removed are large enough to maintain the quality of a site (i.e., the pre-waste-emplacement groundwater travel time is greater than 1,000 yr).

For perspective on how the pre-waste-emplacement groundwater travel time varies as a function of the boundary of the disturbed zone, Lin (1985) completed several pre-waste-emplacement groundwater-travel-time calculations through the unsaturated zone (from the disturbed-zone boundary to the water table) to produce cumulative distribution curves like those presented in the Nevada Nuclear Waste Storage Investigations (NNWSI) Environmental Assessment (Lin et al., 1986). The method used to arrive at the cumulative distribution curves and the properties used to produce the curves are the same as those documented in Lin et al. (1986). The only difference is that, in the calculations presented in this appendix, the location of the the disturbed-zone boundary was varied. It was placed at several different distances below the repository centerline. The calculations were completed for groundwater fluxes of 0.5 mm/yr and 1.0 mm/yr. The calculations assumed no knowledge of the vertical correlation length within each hydrogeologic unit [i.e., these curves were determined in the same manner as those curves in Lin et al. (1986) that are labeled "ρ_v = unit thickness"], and it was assumed that groundwater flow is vertically downward. The results are shown in Figures C-1 and C-2, which show cumulative probability distributions for values of pre-waste-emplacement groundwater travel time. Moving the disturbed-zone boundary from 0 to 100 m from the repository centerline does not significantly change these curves and does not cause the Yucca Mountain site to fail to meet the NRC regulation on pre-waste-emplacement groundwater travel time.

When the disturbed-zone boundary is varied from 0 to 100 m from the repository centerline, the rock unit thickness through which groundwater travels changes for only two units: the Topopah Spring welded unit and the Calico Hills vitric nonwelded unit.

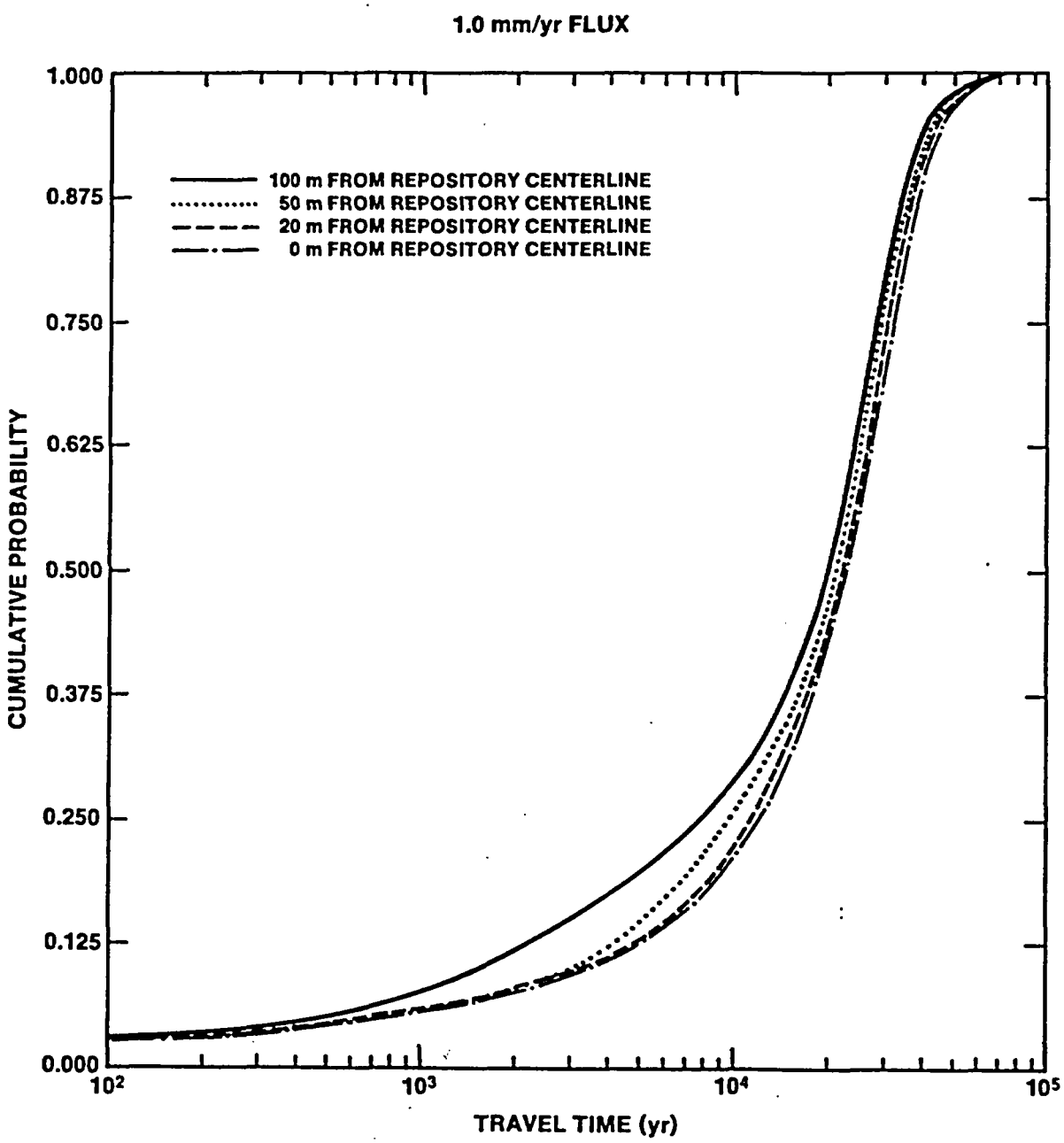


Figure C-1: Cumulative distribution curve of groundwater travel time for 1 mm/yr flux for varying locations of the disturbed-zone boundary (derived from Lin, 1986)

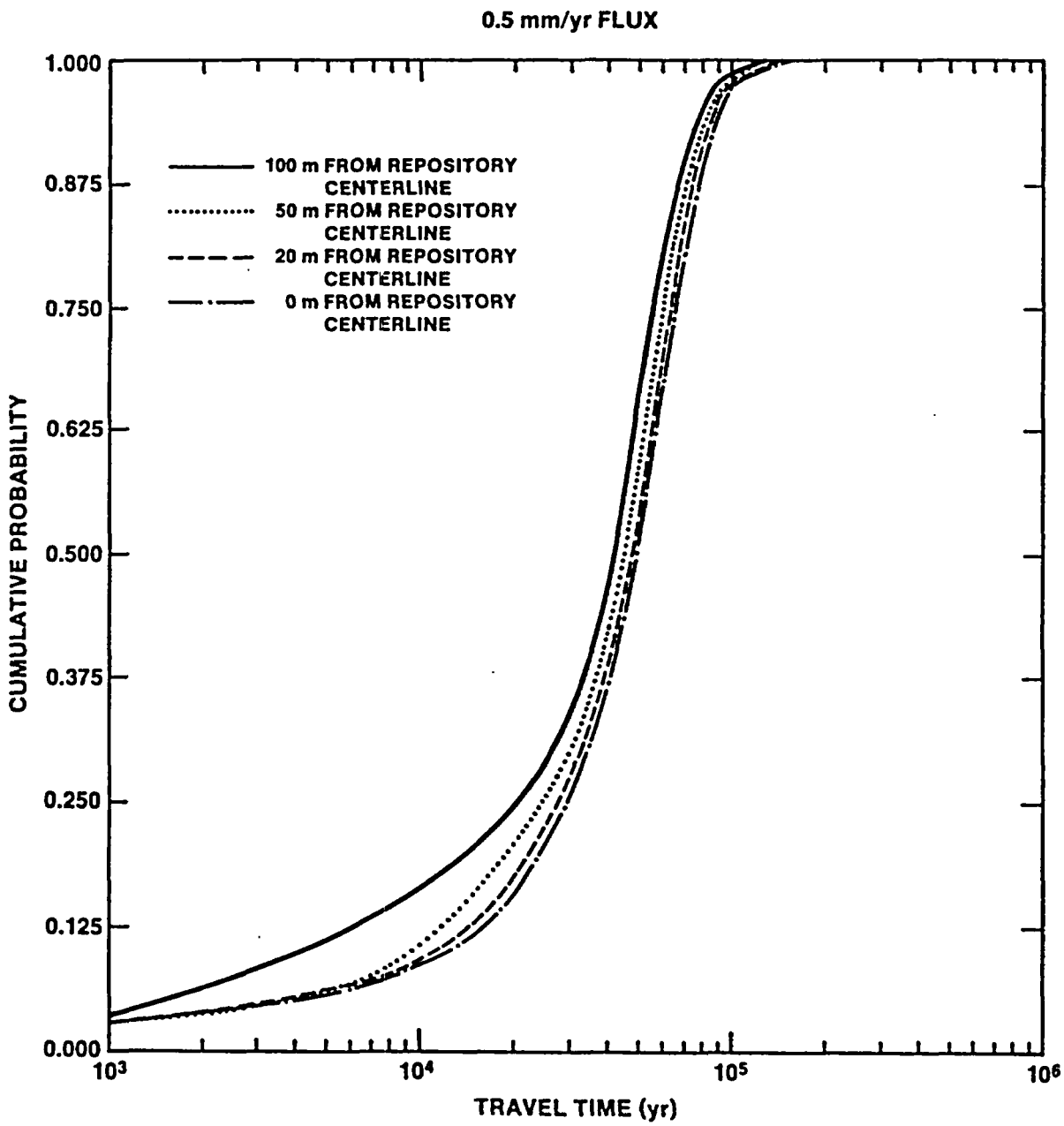


Figure C-2: Cumulative distribution curve of groundwater travel time for 0.5 mm/yr flux for varying locations of the disturbed-zone boundary (derived from Lin, 1986)

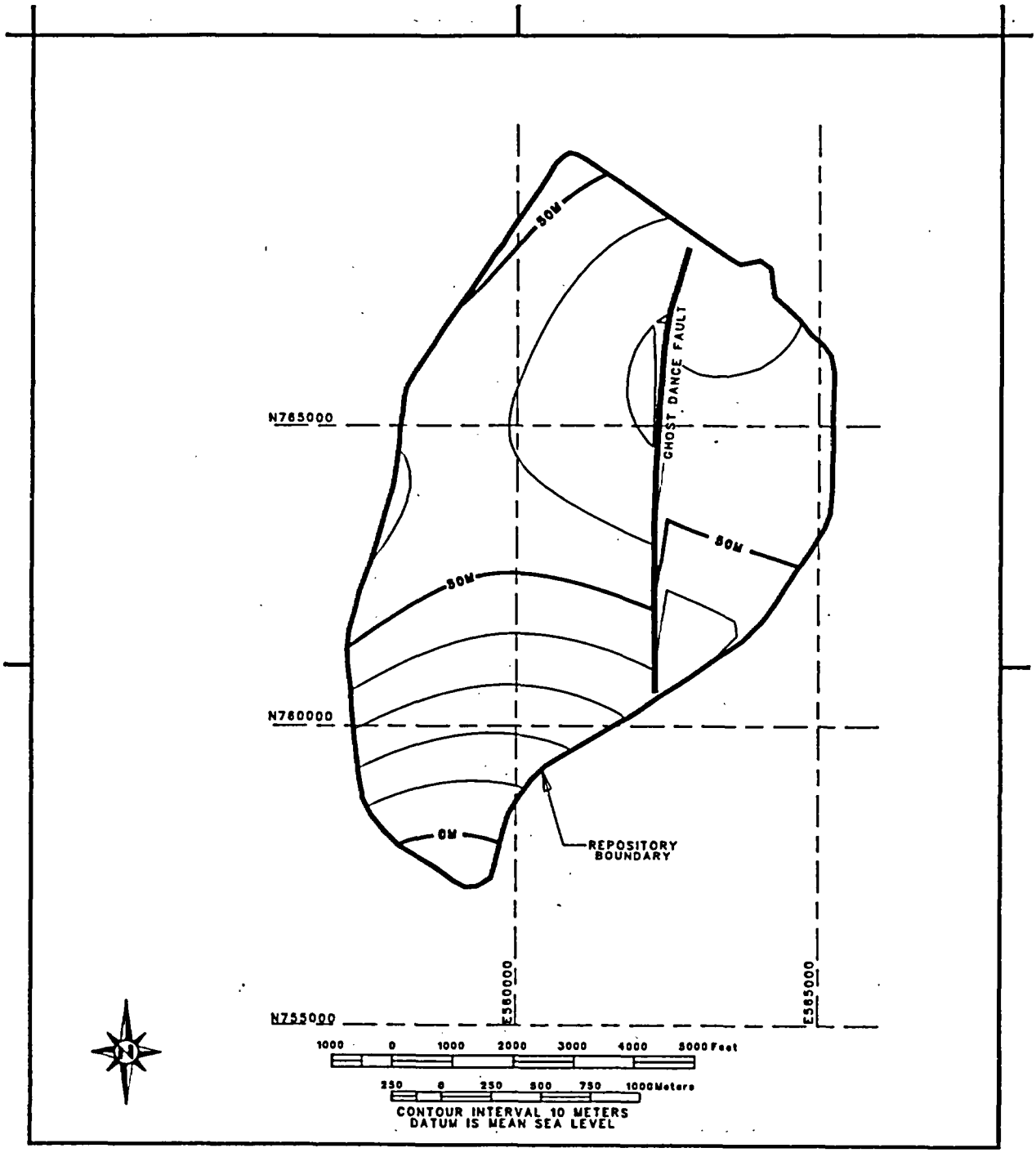


Figure C-3: Contour map of the thickness of the Topopah Spring welded unit if the disturbed-zone boundary is 50 m (derived from product number CAL0047 produced by Whittet and South (1986))

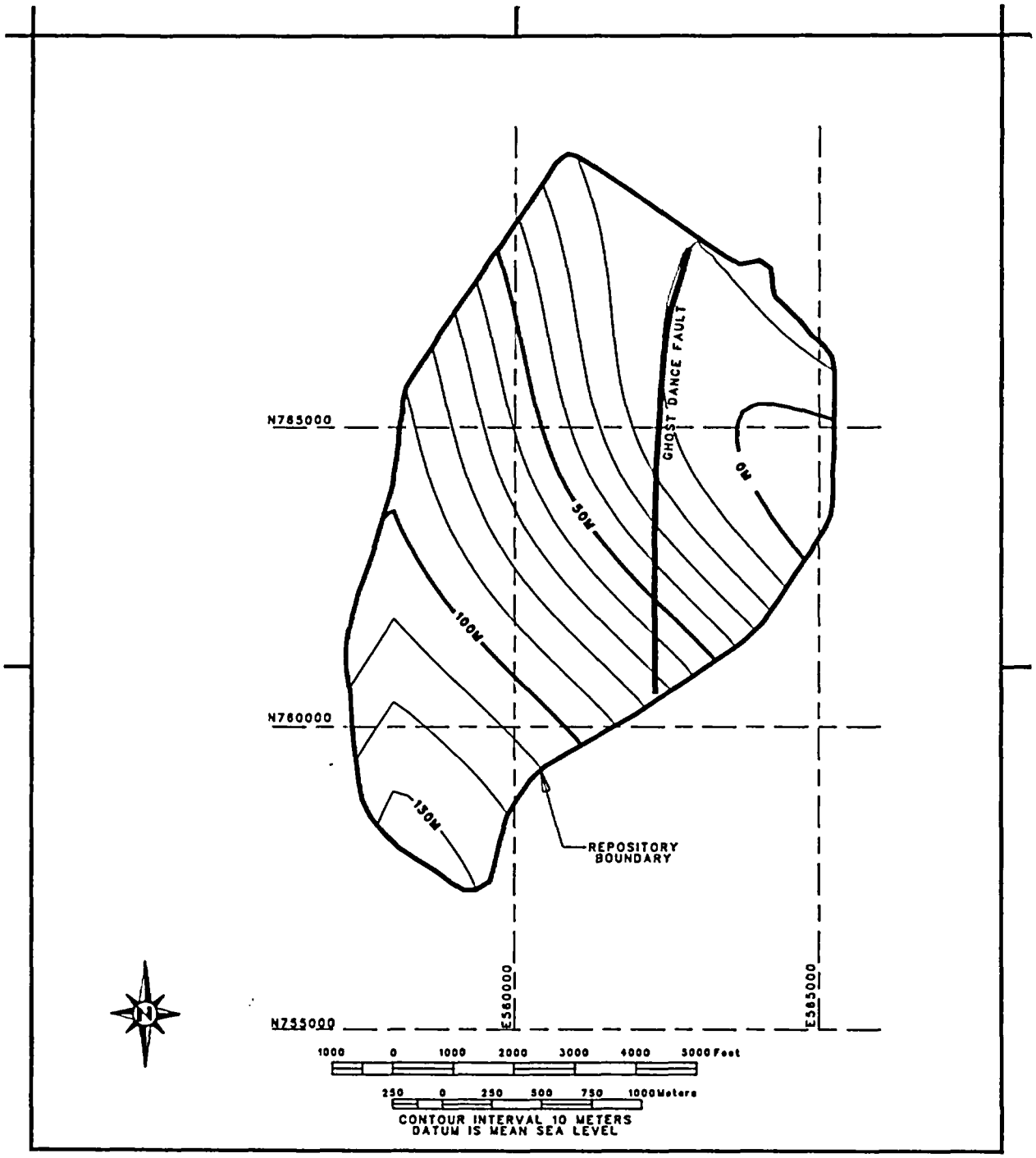


Figure C-4: Contour map of the thickness of the Calico Hills vitric nonwelded unit if the disturbed-zone boundary is 50 m (derived from product number CAL0048 produced by Whittet and South (1986))

Figures C-3 and C-4 indicate the thicknesses of the welded Topopah Spring and vitric Calico Hills through which the groundwater flows when the disturbed-zone boundary is 50 m. Figures C-5 and C-6 indicate the thickness of these units when the disturbed-zone boundary is 100 m. The decrease of the thickness of these units has little effect on the mean value of travel time and almost no effect on the variance of the travel time.

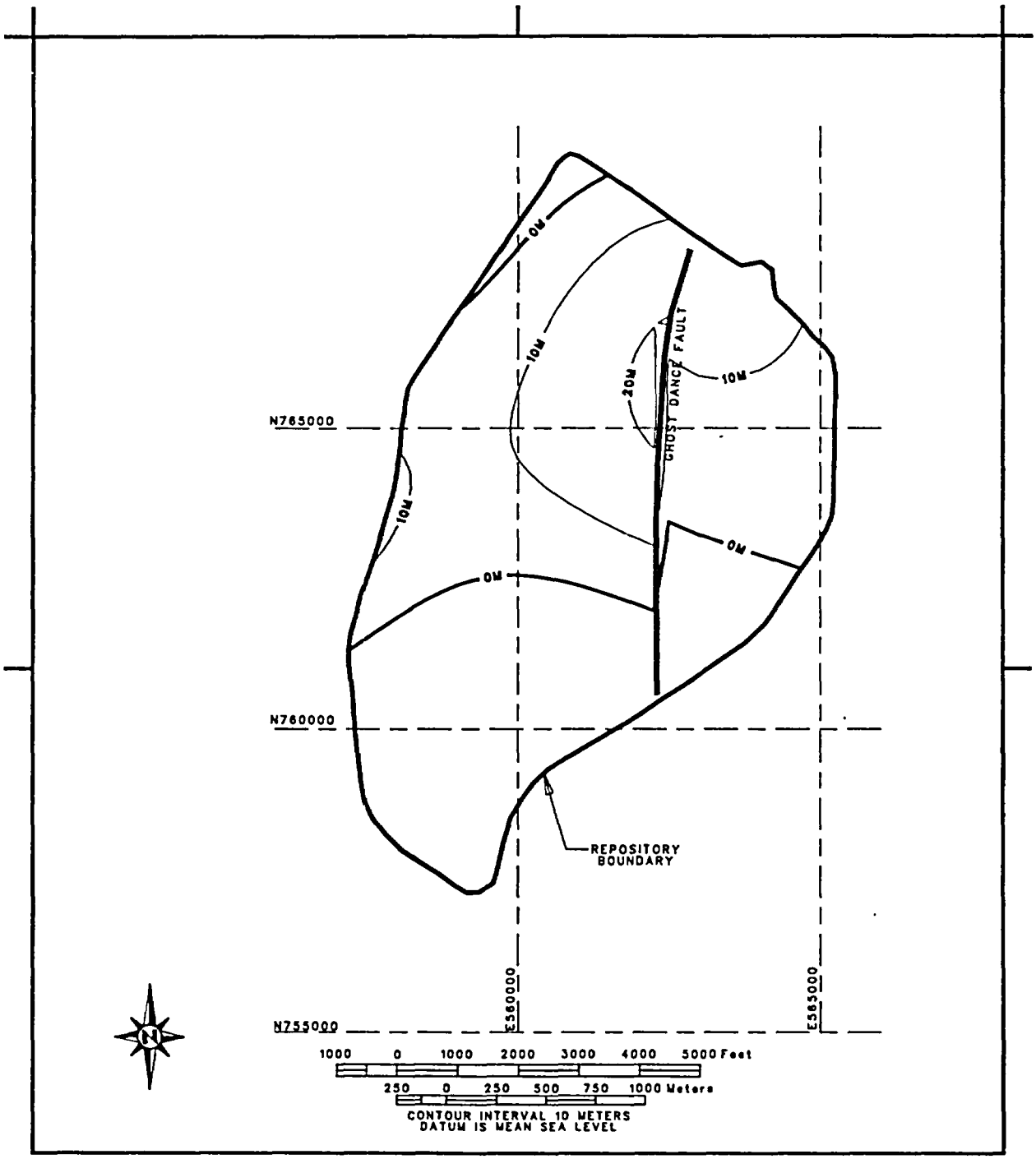


Figure C-5: Contour map of the thickness of the Topopah Spring welded unit if the disturbed-zone boundary is 100 m (derived from product number CAL0139 produced by Whittet and South (1986))

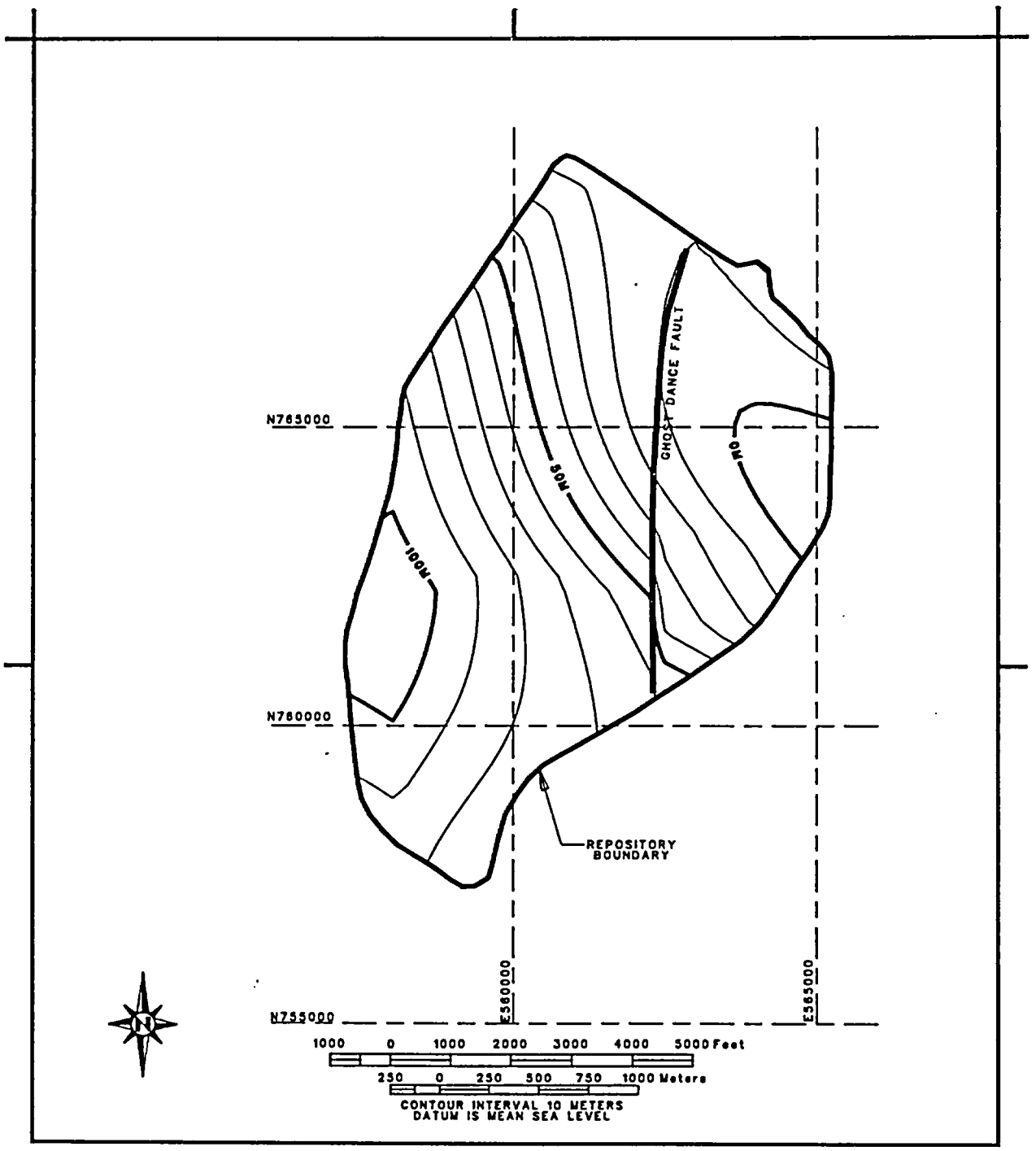


Figure C-6: Contour map of the thickness of the Calico Hills vitric nonwelded unit if the disturbed-zone boundary is 100 m (derived from product number CAL0140 produced by Whittet and South (1986))

Appendix D

RIB and SEPDB Appendix

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 1	Average thickness of overburden above the Topopah Spring welded unit	220 m	None	1.3.1.1.2	--	--	Either this information or information based on the location of the repository should be input to the RIB.
	Average distance of water table from base of Topopah Spring welded unit	219 m	None	1.3.1.1.2	--	--	The following three forms of this information would, I believe, be of the greatest use: isopach maps, histograms of thickness, and thickness averages. Derived from histograms of isopachs, IGIS product numbers CAL0151 through CAL0153 (Whittet and South 1986).
	Average thickness of the Topopah Spring welded unit	206 m	No average value, only isopach	1.3.1.1.2	--	--	
	Topographic map of Yucca Mountain in meters	See Figure 1	None	1.16.1	Yes	--	IGIS product number CAL0149 (Whittet and South, 1986).
Section 4.1	Percentage of repository area underlain by particular hydrologic units	See Table 1	--	None	--	--	These values are reported in Lin et al. (1986).
	Flux below the repository horizon	0.5 mm/yr	None	1.1.5	Yes	--	Reported in EA (DOE 1986b) and by Wilson (1985)

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 4.1 (cont'd.)	Mean and standard deviation of the saturation data for the:						The saturation values for the Crater Flat unit do not correspond to those for thermomechanical unit CFU. The thermomechanical unit CFU displayed in the RIB is part of the Prow Pass member of the Crater Flat tuff. The Crater Flat unit referred to in this report is as designated by Montazer et al. (1984) and corresponds to the Bullfrog Member of the Crater Flat tuff and the thermomechanical unit designated as BF in the RIB. Therefore, the saturation values for the Crater Flat unit used in this report correlate with the thermomechanical unit BF.
	Topopah Spring welded unit	65%, 1σ = 19%	Same as reported in the RIB	1.1.3	--	--	
	Vitric Calico Hills nonwelded unit	90%	"	"	--	--	
	Zeolitic or devitrified portion of the Calico Hills nonwelded unit	91%, 1σ = 6%	"	"	--	--	
	Crater Flat unit	88%, 1σ = 75%	"	"	--	--	
	Hydrologic cross-section of Yucca Mountain	See Figure 3	None	1.1.1	--	--	Same figure as that used in Lin et al. (1986).
	Summary of mean permeability and porosity of the matrix of the unsaturated hydrologic units	See Table 2	Same as reported in the RIB	1.1.4.2 and 1.1.8.1			It is IGIS product number CAL0115 (Whittet and South, 1986).

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 4.1 (cont'd.)	Range of average laboratory fracture apertures	Several micrometers to tens of micrometers	None	1.3.2.4.2.3	--	Individual values could be input to SEPDB	Approximate range of values is from Peters et al. (1984).
	Average fracture aperture inferred from pump tests of well J-13	71 micrometers	None	1.3.2.4.2.3	--	Individual value could be input to SEPDB	This value was calculated and reported by Sinnock et al. (1984). It could be useful in producing a range of reference fracture apertures to be included in the RIB.
	Range of pore diameters of the rock matrix of individual units	10^{-1} to 10^{-2} micrometers	--	None	--	Plots could be input to SEPDB	Approximate range of values is from Klavetter and Peters (1986).
	Range of fracture porosity	0.00018% to 0.0028%	None	Section needed	Yes	--	This would be a useful range for the RIB. The value is derived from (1) apertures reported by Peters et al. (1984) and (2) the assumption that the 40 fractures/m^3 reported by Scott et al. (1983) are all vertical.
	Volumetric fracture density in the Topopah Spring welded unit	42 fractures/m^3	None	1.3.2.4.2.1	--	--	The rounded value of this number, 40 fractures/m^3 is heavily used.

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 4.1 (cont'd.)	Percentage of vertical fractures	60%	None	1.3.2.4.2.2	--	--	An approximate distribution of fracture inclinations may often be useful in analyses.
	Isopach contour maps:	See Figure 2	None	1.1.1	--	--	Isopach maps A and B are IGIS products CAL00136 and CAL00155, and isopach maps C through H correspond to IGIS products CAL0048 through CAL0053 (Whittet and South, 1986 and 1987). Isopach maps C through H are the same as those used by Lin et al. (1986). Lin et al. (1986) associated values used within their report to RIB values.
	(A) total thickness from the repository to the water table						
	(B) thickness of the Topopah Spring welded unit						
	(C) thickness of the Calico Hills vitric unit						
	(D) thickness of the Calico Hills zeolitic unit						
	(E) thickness of the Prow Pass welded unit						
	(F) thickness of the nonwelded Prow Pass unit						
	(G) thickness of the Bullfrog welded unit						
	(H) thickness of the nonwelded Bullfrog unit						

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 4.3	Vertical stress range	5.0 to 10.0 MPa	None	1.3.1.9	Yes	--	The stress ranges are those reported in the SCP-CDR by SNL (1987). Steve Bauer should be consulted for the range to be input to the RIB.
	Minimum horizontal stress range	1.5 to 8.0 MPa	None	1.3.1.9	Yes	--	
	Effective vertical stress range	5.9 to 11.2 MPa	None	1.3.1.9	--	--	This information was calculated using (1) the horizontal and vertical stress ranges from above, (2) suction pressures calculated by Peters, et al. (1986) and (3) the assumption that a unit change in the quantity "total" saturation times pressure head" causes a unit change in the local stress field (see Section 4.3 for more detail).
	Effective horizontal stress range	2.4 to 9.2 MPa	None	1.3.1.9	--	--	
	Minimum horizontal stress determined from hydro-fracture measurements in USW G-2	5.0 to 5.5 MPa	--	None	--	SEPDB	This information should be put in the SEPDB. It was reported by Stock et al. (1985).
	Range of temperatures at the repository horizon	23° to 29°C	None that corresponds	1.3.1.10	Yes	--	This information was reported in the SCP-CDR (SNL, 1987) and derived from SASS & Lachenbruch (1982). The temperature range presently reported in the RIB is only for USW G-4.

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 4.4	Allowable Areal Power Density (APD)	57 kW/Acre, 10-yr-old spent fuel	49.5 kW/acre 12.8-yr-old spent fuel	2.2.1.15.2 and 2.2.2.17.5	--	--	The value referenced in this report is consistent with that in the RIB when the APD is adjusted to account for the age of the waste. More information should be included in the RIB regarding the areal heat load (i.e., the basis for changing the areal heat load when the waste age changes).
	Reference design for dimensions of horizontal waste-emplacement drifts	18 ft wide x 13 ft high	18 ft wide x 13 ft high	2.2.1.1.2 and 2.2.1.1.3	--	--	The emplacement room dimensions are those that were reported in the SCP-CDR (SNL, 1987). They are the same as those reported in the RIB.
	Reference design for dimensions of vertical waste-emplacement drifts	16 ft wide x 22 ft high	16 ft wide x 22 ft high	2.2.1.2.4 and 2.2.1.2.5	--	--	

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 5.1	Results of thermomechanical studies	See the named report section	None	3.1.1.1 and 3.1.1.2	--	--	Most of the referenced reports are pre-RIB (Branstetter, 1984; Johnstone et al., 1984; Svalstad and Brandshaug, 1983). The values used in the reports by LaBreche (1986), St. John (1987), Thomas (1987) and, Johnson and Bauer (1987) have been compared to those in the RIB. A section for plots of fracture movement may need to be added to the Analysis Results Section (3.3.1.1) of the RIB.
Section 5.2	Results of thermomechanical studies	See text in the named report section	None	3.1.1.4.4	--	--	The report by Braithwaite and Nimick (1984) is pre-RIB. The report by Travis and Nuttal (1986) is in preparation. Information similar to that in the above two reports should probably be included in the RIB.

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 5.3	Comparison of laboratory and field tests of permeability results at ambient and elevated temperatures, and discussion of the porosity and permeability changes of samples that were soaked in water at elevated temperature and pressure	See Table 3 and the named Report Section	--	None	--	Individual values from the reports referenced could be input to the SEPDB	Only values of laboratory permeability tests from Lin and Daily (1984) are reported. Personal communication with Lin (1985) resulted in different values of driving pressure being reported here than reported in Lin and Daily (1984). Values of permeability are not included from Reda (1985), Moore et al. (1984), Blacic et al. (1986), and Zimmerman (1986), but these values are available in the published literature. The results reported by Zimmerman are field tests on the welded Grouse Canyon. Blacic et al. (1986) discuss the porosity and permeability changes that were apparent in ambient tests after the samples were soaked in water at elevated temperature and pressure.
Sections 5.3 and 6.2	Description of results from thermal calculations	See Sections 5.3 and 6.2	None	3.1.1.2	--	--	The suitability of this information for candidacy to the RIB should be judged in the future report by Holland.

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Section 7	Location of the disturbed-zone boundary	A plane 10 m below the boundary of the waste package	None	3.1.1.5	Yes	--	
Appendix B	Matrix Properties Topopah Spring Welded Unit						
	Porosity	0.11	0.1062±0.0458	1.1.8.1	--	--	The values used in this study are within the range of those reported in the RIB.
	Saturated hydraulic cond.	1.9×10^{-11} m/s (0.60 mm/yr)	0.722 mm/yr [0.128 to 4.073 mm/yr]	1.1.4.2	--	--	The values used are within the one standard deviation (in brackets) of the mean reported in the RIB.
	Alpha	0.00567	None	1.1.4.1	--	--	These values are reported in Peters et al. (1986) and Peters et al. (1984). The USGS also has some values which should be considered in determining the values input to the RIB.
	Beta	1.798/m	None	1.1.4.1	--	--	
	Residual saturation	0.08	None	1.1.4.1	--	--	

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Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Appendix B (cont'd.)	Fracture Properties Topopah Spring Welded Unit						
	Porosity	18×10^{-5}	None	1.3.2.4.2.1 and 1.3.2.4.2.3	--	--	These values are reported in Peters et al. (1986).
	Saturated hydraulic cond.	3.1×10^{-9}	None	1.1.4.3	--	--	
	Alpha	1.285/m	None	Section Needed	--	--	
	Beta	4.23	None	Section Needed	--	--	
	Residual saturation	0.0395	None	Section Needed	--	--	
	Rock mass coefficient of consolidation	5.8×10^{-7}	None	Section Needed	--	--	
	Matrix Properties Calico Hills Zeolitic Unit						
	Porosity	0.28	0.2693 ± 0.0468	1.1.8.1	--	--	The values used in this study are within the range of those reported in the RIB.
	Saturated hydraulic cond.	2.0×10^{-11} m/s (0.63 mm/yr)	0.535 mm/yr [0.0374 to 7.648 mm/yr]	1.1.4.2	--	--	The values used are within the one standard deviation (in brackets) of the mean reported in the RIB.

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Appendix B (cont'd.)	Matrix Properties Calico Hills Zeolitic Unit (cont'd.)						
	Alpha	0.00308	None	1.1.4.1	--	--	These values are reported in Peters et al. (1986) and Peters et al. (1984). The USGS has some values which should be considered in determining the values input to the RIB.
	Beta	1.602/m	None	1.1.4.1	--	--	
	Residual saturation	0.11	None	1.1.4.1	--	--	
	Fracture Properties Calico Hills Zeolitic Unit						
	Porosity	4.6×10^{-5}	None	1.3.2.4.2.1 and 1.3.2.4.2.3	--	--	These values are reported in Peters et al. (1986).
	Saturated hydraulic cond.	9.2×10^{-9}	None	1.1.4.3	--	--	
	Alpha	1.285/m	None	Section Needed	--	--	
	Beta	4.23	None	Section Needed	--	--	
	Residual saturation	0.0395	None	Section Needed	--	--	
	Rock mass coefficient of consolidation	$26. \times 10^{-7}$/m	None	Section Needed	--	--	

COMPARISON OF DATA USED IN THIS SAND REPORT (SAND86-1955) WITH DATA IN THE RIB VERSION 01.001

Report Section	Parameter	Author's Value	RIB Value	RIB Subsection	Candidate	SEPDB or IGIS	Remarks
Appendix B (cont'd.)	Fracture Properties Calico Hills Zeolitic Unit (cont'd.)						
	Flux through Topopah Spring	0.1 mm/yr	None	1.1.6	--	--	
	Plot of normalized groundwater travel time	See Figure B-1	--	None	No		This was a scoping calculation. Its use is expected to be limited to this report.
Appendix C	Cumulative distribution curves of groundwater travel time as a function of the disturbed zone location	See Figures C-1 and C-2	None	3.4.1.3	Yes		Methods used to determine the groundwater travel time and the properties used are the same as those reported in Lin et al. (1986); only the location of the disturbed zone was varied. Lin et al. (1986) associated values used within their report to RIB values.

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