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U.S. Nuclear Regulatory Commission
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Subject: Transmittal of "Hydraulic Conductivity and Permeability at Yucca Mountain—Letter Report" (IM 1402.861.000)

Dear Mr. Coleman:

This letter transmits Intermediate Milestone 20.01402.861.000 "Hydraulic Conductivity and Permeability at Yucca Mountain—Letter Report." The final title for this deliverable is "Review of Permeability Estimates Obtained from the Yucca Mountain Project."

This work was undertaken as an activity under the Unsaturated and Saturated Flow Under Isothermal Conditions Key Technical Issue. This report evaluates what is known about the distribution of permeable zones between the proposed Yucca Mountain repository and the proposed 20 km compliance point. Data and analytical methods are reviewed and assessments are made of the sufficiency of available data to support DOE models. The DOE approach to integrating permeability data into groundwater flow models is reviewed and a discussion of the uncertainty in DOE model parameter estimates is also provided.

The results of this work will be used to develop Revision 3 of the Unsaturated and Saturated Flow Under Isothermal Conditions Issue Resolution Status Report. This work will also inform preparation of the Yucca Mountain Review Plan Sections 3.2.1.3.5 Spatial and Temporal Distribution of Flow, 3.2.1.3.6 Flow Paths in the Unsaturated Zone, and 4.2.1.3.8 Flow Paths in the Saturated Zone, among others.

We appreciate your collaboration in the development of this report. If you have any questions about this deliverable, please contact me or Mr. James Winterle (210) 522-5249.

Sincerely yours,

E. C. Pe

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/ph
Enclosure

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REVIEW OF PERMEABILITY ESTIMATES OBTAINED FROM THE YUCCA MOUNTAIN PROJECT

Prepared for

Nuclear Regulatory Commission
Contract NRC–02–97–009

Prepared by

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February 2000

ABSTRACT

Available information regarding the distribution of permeability in the unsaturated and saturated flow paths between the proposed Yucca Mountain repository and the proposed 20 km compliance point was reviewed by Center for Nuclear Waste Regulatory Analyses and Nuclear Regulatory Commission staffs. This report provides conceptual models of the groundwater flow systems and descriptions of permeability in the context of importance to repository performance. Summaries are provided of available permeability, hydraulic conductivity, and transmissivity data. A review is given of the approaches used by the U.S. Department of Energy to incorporate permeability into models used to support total system performance assessments. Finally, a review of the uncertainty in permeability that could affect performance predictions is given.

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ACKNOWLEDGMENTS

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC–02–97–009. The activities reported here were performed on behalf of the NRC Office of Nuclear Material Safety and Safeguards, Division of Waste Management. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

The authors wish to thank David Farrell for his thorough technical reviews and useful insights, Barbara Long for her editorial expertise, and Budhi Sagar for his programmatic review. The administrative and format support provided by Paulette Houston is also greatly appreciated.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: This report is a review of existing data and analyses. Where statements are made based on independent analyses by CNWRA, pertinent Scientific Notebooks are footnoted. There are no CNWRA-generated original data contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

ANALYSES AND CODES: No computer codes were used for analyses contained in this report.

1 INTRODUCTION

The U.S. Department of Energy (DOE) is currently assessing the suitability of Yucca Mountain (YM), Nye County, Nevada, located approximately 135 km northwest of Las Vegas as a potential repository for high-level nuclear waste (HLW). The current waste isolation plan advocates a multiple barrier concept with the waste placed in corrosion resistant canisters prior to emplacement in drifts located within unsaturated fractured tuffs at the site. A key issue that may influence the licensing of the repository is whether the engineered containment system and the natural barrier system will provide effective long-term isolation of the waste from the accessible biosphere beyond a proposed compliance boundary 20 km from the repository (figure 1-1).

The purpose of this report is to provide a review of data on permeability, hydraulic conductivity, and transmissivity of the geologic formations that could potentially affect flow from the ground surface above the proposed HLW repository at YM to a compliance boundary 20 km south-southeast of the site. It is intended that the review contained herein will support the eventual review by the Nuclear Regulatory Commission (NRC) of a License Application (LA) for a HLW repository at YM.

In addition to a section on background information, this report contains two technical sections based on the logical division of unsaturated and saturated groundwater flow paths. The four topics addressed in the five technical review sections are

- System Description and Importance—discussion to provide a brief description of the hydrogeologic setting and overview of how various conceptual models for the distribution of permeable zones might affect repository performance.

- Review of Available Data—a discussion of what is known about the distribution of permeable zones that make up the groundwater flow paths from YM, including a review of the data sources and analytical methods, and an assessment of whether available data are sufficient to support DOE process-level and abstracted models.

- DOE Approach—a review of how permeability data are integrated into existing DOE models for groundwater flow used in total system performance assessment (TSPA) predictions and identification of important processes and model parameters.

- Review of Uncertainty—a discussion of uncertainty including an assessment of (i) whether model parameter estimates reflect an appropriate consideration of uncertainty and (ii) whether viable alternative conceptual models have been considered that cannot be ruled out with existing data.

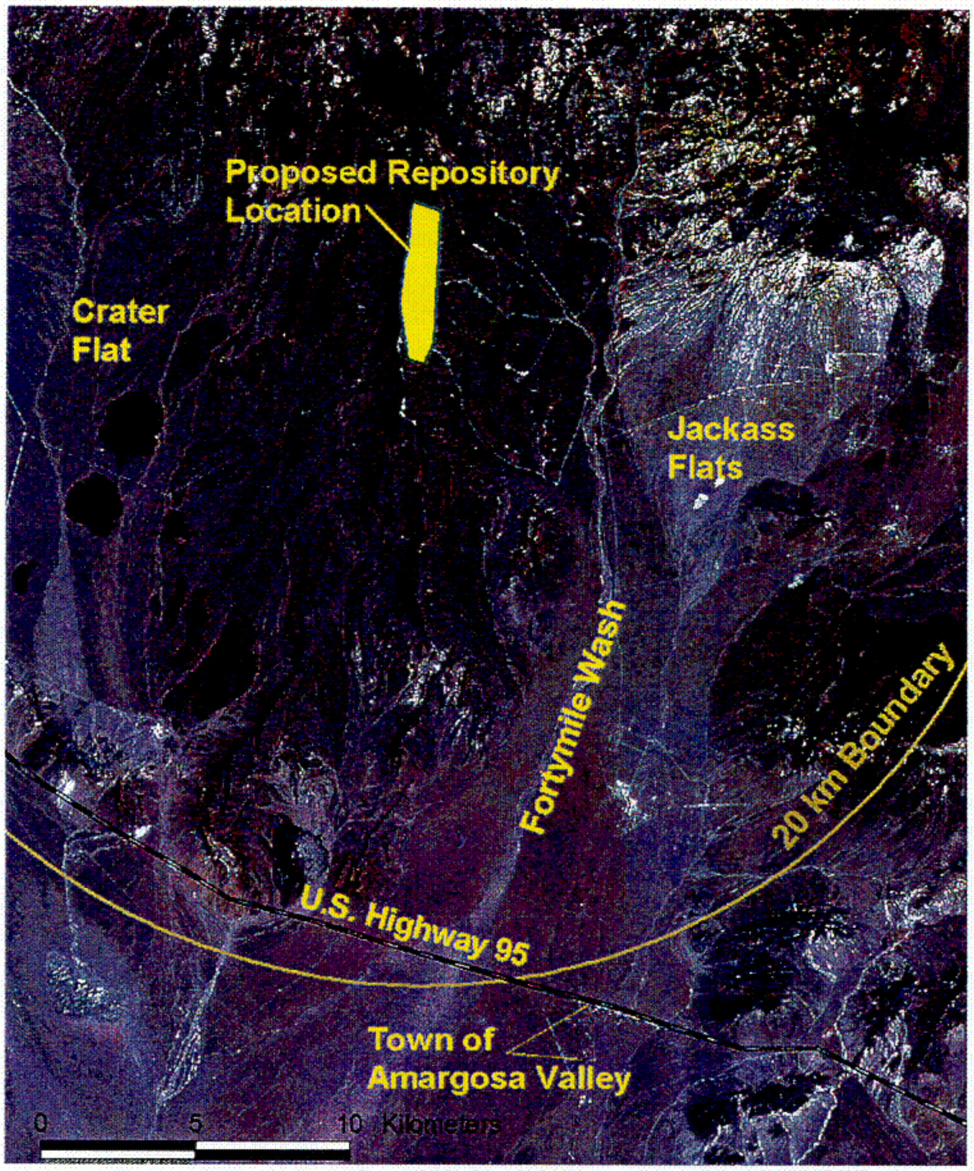

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Figure 1-1. Satellite map of the Yucca Mountain compliance area showing proposed locations of the repository block and the 20 km compliance boundary

2 BACKGROUND

This chapter provides a brief overview of the differences between permeability, hydraulic conductivity, and transmissivity, and the effects of heterogeneity and anisotropy on estimated values of these parameters. A discussion of the hydrostratigraphic units of interest at YM is also provided.

2.1 WHAT ARE PERMEABILITY, HYDRAULIC, CONDUCTIVITY AND TRANSMISSIVITY?

Permeability is an intrinsic property of a porous medium that proportionally affects the rate at which a fluid can flow through the medium at any given hydraulic head gradient. In an ideal porous medium composed of uniformly sized spheres, the intrinsic permeability (k) is proportional to the square of the sphere diameter (Freeze and Cherry, 1979). Accordingly, k has dimensions [L^2]. Because porous media consisting of uniform spheres rarely occur in nature, the simple relationship between grain size and permeability has little practical use. For this reason, several methods have been developed for estimating permeability based on analyses of grain-size distributions (e.g., Vukovic and Soro, 1992). However, even these methods are of limited use, because grain-size distributions can vary significantly over spatial scales of more than a few meters. In fractured-rock aquifers, permeability can vary by several orders of magnitude between open fractures and adjacent rock matrix.

A perhaps more useful parameter is hydraulic conductivity (K), which has dimensions [L/T], and incorporates properties of both the porous medium and the fluid: $K = \frac{k\rho g}{\mu}$, where ρ is fluid density, g is the gravity constant, and μ is the dynamic viscosity of the fluid.

For flow in unsaturated porous media, it is important to recognize that permeability is a function of saturation. Several empirical models have been developed to describe the relationship between relative permeability and the degree of saturation (e.g., Brooks and Corey, 1964; Mualem, 1976; van Genuchten,1980). Relative permeability is a parameter with a value between zero and unity that is used to scale the saturated permeability or hydraulic conductivity to an appropriate value according to saturation. At residual gravity-drained saturation, the relative permeability is zero; under fully saturated conditions, relative permeability is unity. The parameters used to describe saturation-permeability relationships are often referred to as moisture retention properties or, simply, hydraulic properties.

For saturated flow in horizontal aquifers, it is common to use transmissivity (T) instead of hydraulic conductivity. Transmissivity represents the hydraulic conductivity vertically integrated through the saturated thickness of the aquifer, and has dimensions [L^2/T]. In a homogenous aquifer, T is simply equal to the product $K_h \times b$, where K_h is the horizontal hydraulic conductivity, and b is the saturated vertical thickness of the aquifer. In layered or fractured-rock aquifers, transmissivity is the sum of the products $K_h \times b$ for each transmissive layer or fracture. It is seldom possible, however, to obtain *in situ* hydraulic conductivity estimates for individual fractures or thin transmissive layers. For this reason, transmissivity is often a more useful parameter than hydraulic conductivity for modeling aquifer-scale flow.

2.2 ANISOTROPIC PERMEABILITY

It is often neglected that the parameters *k*, *K*, and *T* are tensor quantities. That is, to fully specify the parameters *k* and *K* for a three-dimensional (3D) Cartesian coordinate system, a 3 × 3 matrix of parameter values is required; because *T* is a two-dimensional (2D) parameter, only a 2 × 2 matrix is required. If coordinate systems are carefully chosen, the required number of values can be reduced to three for *k* and *K* (e.g., K_{xx}, K_{yy}, K_{zz}) and two for *T*. This is accomplished by aligning model coordinate systems to parallel the minimum and maximum directional permeabilities. In a purely isotropic system, the permeability of a representative volume is the same in any direction, in which case, a single value can be used to specify these parameters without regard to flow direction.

2.3 HYDROGEOLOGIC UNITS OF CONCERN

The relationship between geologic units and the hydrostratigraphy discussed in this report is shown in table 2-1. The hydrogeologic units have been categorized based roughly on the degree of welding (Montazer and Wilson, 1984). The units of interest in this report include the Tiva Canyon welded (TCw), the Paintbrush Nonwelded Tuff (PTn), consisting primarily of the YM and Pah Canyon members and the interbedded tuffs, the Topopah Spring welded (TSw), the Calico Hills nonwelded (Chn), and the Crater Flat undifferentiated (CFu) units. The welded units typically have lower matrix porosities and are highly fractured, while the bedded and nonwelded tuffs tend to have higher matrix porosities and low fracture densities (Montazer and Wilson, 1984). According to Bodvarsson et al. (1999), fracture density is correlated with increasing degree of volcanic rock welding at smaller scales.

For the saturated zone (SZ), all the units listed in table 2-1 occur beneath the water table for some part of the distance between YM and the proposed 20 km compliance boundary (figure 1-1). The nomenclature of the major SZ hydrostatic units defined by Luckey et al. (1996) is also used in this report and related to geologic units in table 2-1.

Table 2-1. Division of geologic and hydrogeologic units and nomenclature used by Luckey et al. (1996) to describe the major hydrogeologic formations

Geologic Unit	Hydrogeologic Unit	Description	Nomenclature
Alluvium (Valley Fill)	Quaternary Alluvium (Qal)	Valley fill sediments	Alluvial Aquifer
Paintbrush Group	Tiva Canyon welded (TCw)	Partially to densely welded; fracture flow	Upper Volcanic Aquifer
	Paintbrush Nonwelded (PTn)	Nonwelded, relatively few fractures; matrix flow	
	Topopah Springs welded (TSw)	Partially to densely welded; fracture flow	
Calico Hills Formation	Calico Hills Nonwelded vitric (CHnv)	Nonwelded, relatively few fractures; matrix flow	Upper Volcanic Confining Unit
	Calico Hills Nonwelded zeolitic (CHnz)	Nonwelded, altered; few fractures and low matrix permeability causes perched water formation	
Crater Flat Group	Undifferentiated Units (CFu)	Thin discontinuous, nonwelded ash flows; primarily matrix flow	Lower Volcanic Aquifer
	Prow Pass Tuff	Non- to moderately welded; mainly fracture flow	
	Bullfrog Tuff	Non- to moderately welded; fracture flow	
	Tram Tuff	Non- to moderately welded; mineral filled fractures common; mainly fracture flow	
Lithic Ridge Tuff		Non- to partially welded; fracture fillings increase with depth; few transmissive fractures	Lower Volcanic Confining Unit
Older Lavas, Tuffs, and Breccias		Partially to moderately welded, few isolated transmissive zones; mineral-filled fractures	
Paleozoic Carbonates		Fractured carbonate rocks; moderate to high transmissivity; heads 20–50 m higher than in overlying tuff aquifer	Regional Carbonate Aquifer

3 PERMEABILITY OF THE UNSATURATED ZONE

From a performance-based perspective, knowledge of unsaturated zone (UZ) permeability at YM is important only insofar as it affects the following three factors: (i) the spatial and temporal distribution of water reaching repository drifts, (ii) the amount of that water that could potentially drip onto a waste cannister, and (iii) the radionuclide transport pathways from the repository to the SZ. All three of these factors depend, in a complex manner, not only on the intrinsic permeability of rock matrix and fracture networks, but also on deep percolation flux and fracture/matrix moisture retention properties. Section 3.1 of this chapter contains a discussion of the complex processes that lead to the division of percolation fluxes into three distinct flow regimes—matrix flow, distributed seepage along fracture-matrix interfaces, and preferential fracture flow—and the implications of each for repository performance. UZ permeability data come from measurements of rock matrix saturated hydraulic conductivity and bulk air permeability estimates, the sources of which are discussed in section 3.2. The use of permeability data by DOE is discussed in section 3.3, and key uncertainties are identified in section 3.4.

3.1 SYSTEM DESCRIPTION AND IMPORTANCE

At YM, the relationships between saturation and capillary pressure within the interconnected pores of the rock matrix and fracture networks play a vital role in determining the distribution of percolation fluxes throughout the mountain. These pressure-saturation relationships, referred to as "moisture retention properties," are functions of the distributions of matrix pore sizes or fracture apertures. Because average pore sizes in rock matrix are generally much smaller than fracture apertures, capillary suction results in imbibition of water from fractures into rock matrix. Imbibition continues until either an equilibrium is reached or the fractures run dry. Because of the complex interaction between percolation rate and fracture/matrix hydraulic properties, percolation fluxes through the UZ at YM are logically divided into three distinct flow regimes: (i) matrix flow, (ii) distributed seepage at fracture matrix interfaces, and (iii) preferential fracture flow paths. As discussed in the following subsection, these flow regimes are operative over various temporal and spatial scales.

It is also important to understand how the juxtaposition of differing hydrostratigraphic units and heterogeneities within a particular unit may affect the distribution of flow. An excellent, peer-reviewed discussion and model of how such characteristics can lead to lateral diversion and focusing of flow in the UZ at YM is provided by Pruess (1999). Brief discussions of the effect of stratigraphic juxtaposition and heterogeneity on permeable pathways are also provided in following subsections.

3.1.1 Flow Regimes in the Unsaturated Zone

Matrix flow only. Where percolation fluxes are significantly lower than matrix saturated hydraulic conductivity, flow through the UZ may occur entirely within rock matrix. Such conditions may exist during current climate conditions in the PTn unit where matrix saturated hydraulic conductivities are on the order of tens of millimeters per year (Flint, 1998). This type of flow may also occur in the Calico Hills nonwelded vitric (CHnv) unit, beneath the repository horizon, where matrix saturated hydraulic conductivities are also on the order of tens of millimeters per year (Flint, 1998). Data emerging from tracer and infiltration studies at the Busted Butte site, though presently unpublished, reveal that water in the CHnv unit is quickly imbibed from fractures. Anisotropy of matrix permeability in the CHnv also results in rapid horizontal spreading of injection pulses within this zone.

Rock matrix in the UZ at YM tends to imbibe fracture water and has relatively low saturated hydraulic conductivity. As a result, percolation fluxes within rock matrix at depths below the near-surface dryout zone do not likely exhibit significant spatial or temporal variability within a particular stratigraphic layer. Exceptions to this postulate may include zones of high intralayer heterogeneity of moisture retention properties, such as in the Calico Hills formation where the degree of zeolitic alteration is spatially variable. Intralayer heterogeneity is discussed further in section 3.1.3.

Distributed seepage along fracture-matrix interfaces. As percolation fluxes approach or just begin to exceed matrix hydraulic conductivity, matrix saturations and capillary pressures increase, causing reduced imbibition rates. At high enough matrix capillary pressures, seepage can occur along a narrow zone at the fracture-matrix interface. Percolation fluxes that greatly exceed matrix hydraulic conductivity may be accommodated as "film flow" within a narrow interval along the fracture-matrix interface but still essentially within the matrix (Tokunaga and Wan, 1997).

There are several lines of evidence for ubiquitous seepage along the fracture-matrix interface throughout the TSw unit, which includes the proposed repository horizon. First, recent monitoring of matrix saturations in the East-West Cross-Drift (ECRB) show the rock mass is wetter and moisture is more uniformly distributed than previously thought.[1] Second, deposits of hydrogenic secondary minerals (primarily calcite and opal) are found ubiquitously throughout the Exploratory Studies Facility (ESF) (Paces et al., 1998a,b). The hydrogenic source of these deposits implies seepage of mineral-bearing water at the fracture-matrix interfaces. Marshall et al.[2] made a preliminary attempt to estimate seepage rates at locations of observed secondary mineralization, but it is not yet clear whether such estimates can be used to interpret the fraction of percolation flux that occurs via this flow regime.

The spatial and temporal variability of this flow regime is probably greater than that of matrix flow, but less than that of focused flow paths. Insight into the spatial distribution of interface seepage is gained from the number of observed mineral coatings per 0.6-m × 30-m area, centered on 100-m intervals, from the detailed line survey data (Paces et al., 1998b). Although secondary mineralization is not observed in most fractures, the frequency of secondary mineral observations (i.e., coatings on fracture surfaces and deposits in lithophysal cavities) exceeds unity over 5-m intervals, approximately the length of a waste package (WP). Geochronology using ^{14}C, $^{230}Th/U$, and U-Pb dating methods provide limited insight into the temporal variability of this interface seepage. Results suggest a slow and relatively constant rate of mineral deposition, on the order of 1–5 mm per million years (Paces et al., 1997, 1998a). This evidence suggests the flux rate depositing these minerals has remained relatively uniform over the last 10 million years. It is not clear, however, whether the temporal resolution of such dating methods is sufficient for assessing variability over the postulated 100-kyr cycle of climate change.

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[1] Unpublished research. Reported in U.S. Geological Survey Yucca Mountain Branch progress report. July 1999.

[2] Marshall, B.D., L.A. Neymark, J.B. Paces, Z.E. Peterman, and J.F. Whelan. Seepage flux conceptualized from secondary calcite in lithophysal cavities in the Topopah Spring Tuff, Yucca Mountain, Nevada. *Proceedings of the Society for Mining, Metallurgy, and Exploration, Inc. Annual Meeting 2000*. Accepted for publication. 2000.

These lines of evidence are consistent with a conceptual model of a spatially and temporally uniform fraction of total percolation flux that is fairly ubiquitous throughout the interconnected fracture network of the TSw. Efforts should be focused on attempting to bound the fraction of total deep percolation flux that occurs as distributed fracture-matrix interface seepage, and the potential for such seepage to result in dripping on waste packages. Monitoring flux through the matrix of the PTn units would provide useful data for evaluating and bounding this fraction of percolation flux. For flow paths below the repository, assessments should be made regarding the implications for radionuclide transport.

Preferential fracture flow paths. At percolation fluxes that significantly exceed matrix saturated hydraulic conductivity, localized zones of saturation begin to occur in fractures, narrowest apertures first, until localized preferential flow pathways, or "flow fingers," form within the fracture network that are sufficient to accommodate the percolation rate. This type of flow, in addition to film flow, certainly must occur in the TCw unit following heavy precipitation. Evidence for preferential fracture flow also exists within the TSw, where wet streaks in fractures were observed during excavation of Niches 3566 and 3560 (Wang et al., 1999). Ventilation of the ESF and ECRB, however, causes such wet fractures to dry out quickly. It could well be the case that such preferential fracture flow paths are quite ubiquitous but are drying out in advance of excavation due to ventilation in the ESF and ECRB. It is our understanding that DOE plans to allow a section of the ECRB to return to ambient conditions and conduct tests that would identify seeps and preferential flow paths that might result in dripping during present climate conditions. Such tests should be supported by data to prove that conditions have indeed returned to ambient.

3.1.2 Effects of Stratigraphic and Structural Juxtaposition

Because several layers with differing fracture densities and differing moisture retention properties are encountered by downward-percolating water, the distribution of water between fractures and matrix can vary greatly between layers. Some layers within the UZ at YM—the PTn and the CHn, for example—are nonwelded and relatively unfractured, with flow occurring almost entirely in the matrix. These layers are juxtaposed against layers moderately to densely welded—the TCw or the TSw, for example. Figure 3-1 illustrates several conceptual models that may result from the complex interplay between percolation rates and differences in matrix or fracture properties across stratigraphic units. Basically, contrasts in layer properties can result in two types of flow barrier effects: permeability barriers and capillary barriers.

Permeability barriers occur when the vertical hydraulic conductivity of an underlying layer is lower than the percolation flux received from the overlying layer. Perched water may or may not occur at permeability barriers, depending on the ease with which water can divert laterally around the barrier. The eastward dip of the strata at YM causes water to divert laterally eastward along permeability barriers. This situation is illustrated in figure 3-1, which demonstrates a conceptual model where water diverts laterally across the top of the PTn unit until reaching a high permeability zone along the Ghost Dance fault (GDF). This conceptual model is likely to occur under future climate scenarios when percolation fluxes are expected to significantly exceed the hydraulic conductivity of the PTn unit.

Another conceptual model for a permeability barrier at YM, also illustrated in figure 3-1, is the formation of perched water at the base of the TSw caused by a permeability barrier across the Calico Hills nonwelded zeolitic (CHnz) unit. In this situation, down-dip lateral diversion on top the CHnz leads to pooling at the layer offset along GDF. Depending on the percolation flux, vertical buildup of water continues until

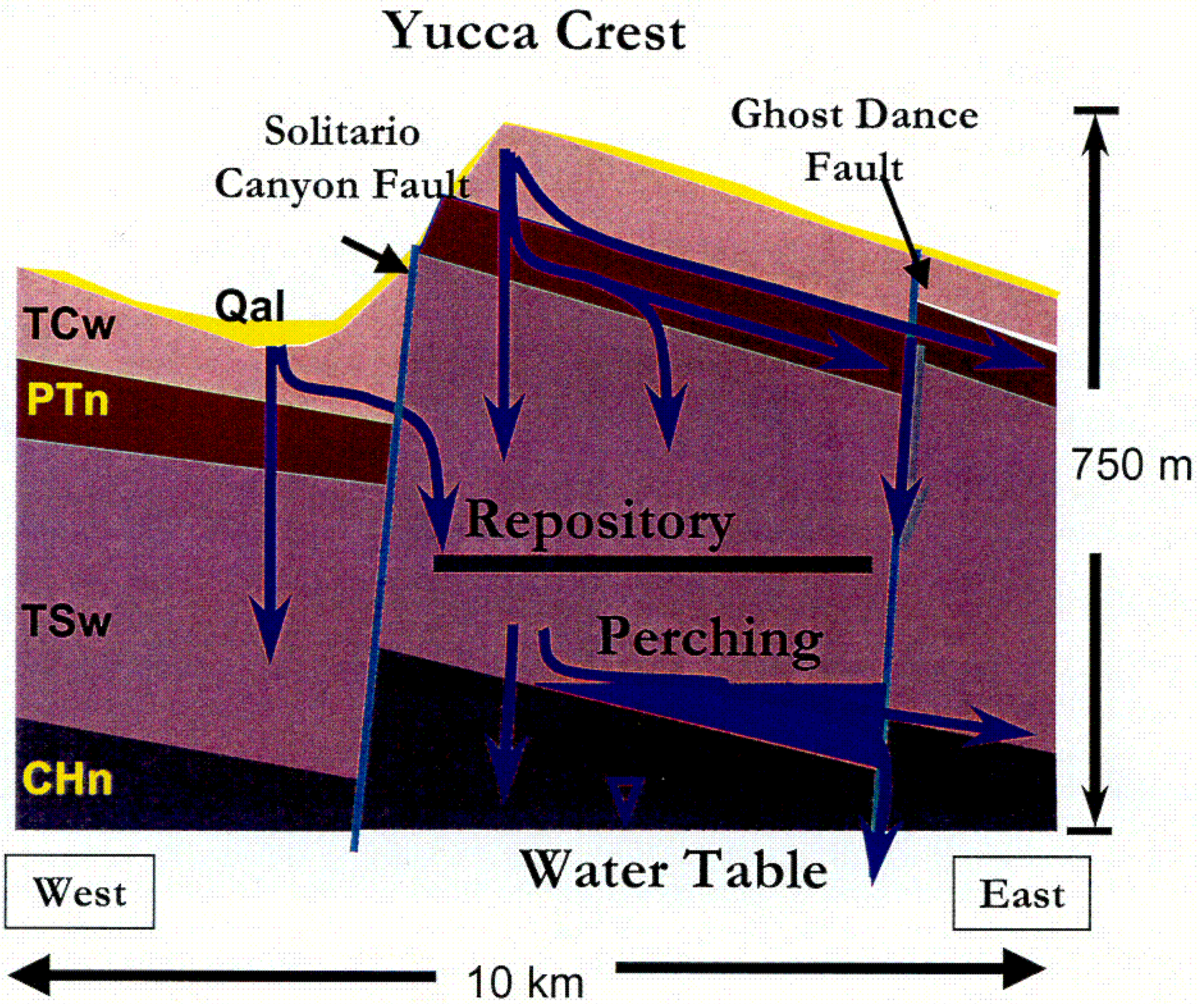

Figure 3-1. Schematic illustration of the various conceptual models for the downward percolation of water from the surface of Yucca Mountain to the water table

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either hydraulic head is high enough to push the water through the barrier or the water spills over the layer offset and continues flowing down dip.

Capillary barriers occur when water is held in overlying layers by higher capillary suction due to differences in moisture retention properties between unsaturated layers. Capillary barriers can also result in the down-dip lateral diversion of water and zones of high saturation. These barriers do not, however, result in the formation of perched water. Lateral diversion due to a capillary barrier is illustrated in figure 3-1 along the base of the PTn unit. In this scenario, the saturated hydraulic conductivity of the fracture network in the TSw is more than enough to accommodate the percolation flux reaching the base of the PTn. However, the PTn matrix is assumed to have greater capillary suction than the TSw fracture network. Such a system behaves akin to a wet sponge on a sloping bed of coarse gravel: the capillary attraction of the PTn (the sponge) holds onto the water and diverts the water down dip. Several investigators, however, have proposed that capillary diversion is of limited effectiveness in shielding the repository from downward percolation fluxes (e.g., Gauthier et al., 1992; Pruess, 1999) perhaps due to heterogeneity or the episodic nature of infiltration at the surface.

3.1.3 Effects of Heterogeneity

The extent of lateral diversion of water atop or within the PTn and CHn units may be controlled substantially by heterogeneities. For example, although the Calico Hills Formation has been divided into CHnv and CHnz for purposes of this discussion, these are not discrete, parallel layers. Rather, the distinction is made somewhat arbitrarily by degree of zeolitic alteration. For example, evaluations of the distribution of zeolites have been conducted by Carey et al. (1997) using a threshold of 20 percent by weight zeolites to distinguish the units. Another evaluation by the NRC (1998) used a smaller threshold value of 2.5 percent. Results of these evaluations show that the model area covered by zeolitic layers changes significantly when different threshold values are used. As such, the results of models based on assigned permeabilities to discrete CHnz and CHnv zones depend entirely on the choice of threshold.

Heterogeneities within permeability or capillary barriers in the PTn layer are of particular importance to repository performance because of their potential effect on the distribution of flow that might reach the repository for various climate scenarios (i.e., percolation fluxes). The DOE Site-Scale UZ Flow Model presently does not include effects of heterogeneity within this unit (Bodvarsson et al., 1997). The scale at which heterogeneities must be considered, depends largely on the problem at hand. For assessing lateral diversion across permeability and capillary barriers, for example, it may be sufficient to average hydraulic properties over scales of tens of meters and still incorporate the important effects of heterogeneity in the model. For models used to assess dripping into repository drifts, however, it may be necessary to incorporate hydraulic property variability at much finer scales. For example, small increases in fracture apertures can significantly reduce the moisture retention capacity of a fracture. As such, fracture aperture variability significantly controls the effectiveness of fracture-drift intersections as capillary barriers and, hence, the percolation threshold at which dripping may occur. Because fracture apertures vary over scales of several millimeters to a few centimeters, averaging of properties for scales greater than a few centimeters may smooth or mask important effects.

Incorporating heterogeneity into models is among the most difficult problems encountered by hydrologic modelers. Often there are insufficient data on which to base assumptions regarding spatial distribution of model parameters. Another problem is the increased computational difficulties imposed by the need for refined model grids, particularly in areas with highly contrasting material properties. For models used to support risk-based performance assessments, it is often necessary to make conservative bounding assumptions in cases where model limitations preclude incorporation of heterogeneity. Ongoing investigations by the Center for Nuclear Waste Regulatory Analyses (CNWRA) staff are focused on assessing whether heterogeneity is adequately addressed in DOE models used in repository performance predictions.

3.2 REVIEW OF AVAILABLE DATA

Estimates of permeability along flow paths through the UZ at YM include laboratory rock-core studies, *in situ* pneumatic injection and pumping tests, and passive monitoring of barometric signal attenuation. A review of available data sources is contained in the following subsections.

3.2.1 Rock Matrix Permeability

Rock matrix permeabilities and moisture retention properties have been exhaustively studied throughout the UZ at YM (e.g., Peters et al., 1984; Anderson, 1991, 1994; Flint et al., 1996; Flint, 1998). The division of the UZ into the major hydrostratigraphic units depicted in table 2-1 is based, primarily, on the observations reported in these studies. The matrix permeabilities reported by Flint (1998), for virtually every stratigraphic unit in the UZ at YM, provide an excellent basis for initial model parameter estimates. Additionally, the large number of samples analyzed in this study provides a sound understanding of variability of matrix permeability within each stratigraphic unit.

3.2.2 Pneumatic Injection and Pumping Tests

Surface-based pneumatic testing. Air injection tests have been used to estimate formation permeabilities on the scale of tens of meters. Because permeability is an intrinsic property, the bulk permeability of a dry fracture network to air should be the same as that of a saturated fracture network to water. To support this concept, Rasmussen et al. (1993) showed a strong correlation between permeabilities obtained by both water and air injection tests conducted in boreholes completed in unsaturated, fractured tuffs.

The U.S. Geological Survey (USGS) conducted 194 single-hole air injection tests using a straddle packer assembly in four vertical boreholes (UE-25 UZ#16, USW SD-12, USW NRG-6 and USW NRG-7a) that penetrated the TCw, PTn, TSw, and Calico Hills Formation (LeCain, 1997). Permeability values estimated for the TCw and TSw units in these tests showed considerable variability, as summarized in tables 3-1 and 3-2. These estimates are 3–6 orders of magnitude larger than laboratory estimates of matrix permeabilities for the TCw and TSw units obtained from cores—an indication that bulk permeability is dominated by fracture networks in the welded tuff units.

Results from tests in the PTn interval reported by LeCain (1997), shown in table 3-3, come only from borehole NRG-7a. In contrast to the welded units, the difference between the laboratory- and air injection-based estimates from the PTn unit was much smaller, suggesting predominantly matrix flow at the scale of measurement. The air-injection permeability estimates for the PTn also suggest less spatial variability, at least in the vertical dimension, but tests in more than one borehole would be needed to draw a statistically meaningful conclusion.

Table 3-1. Permeability estimated from single-hole air injection tests in Tiva Canyon Tuff (adapted from LeCain, 1997)

Borehole	No. of Test Intervals	Minimum [m^2]	Maximum [m^2]	Arithmetic Mean [m^2]	Geometric Mean [m^2]
UZ-16	4	1.5×10^{-12}	27.0×10^{-12}	12.3×10^{-12}	7.6×10^{-12}
SD-12	11	0.8×10^{-12}	38.0×10^{-12}	7.0×10^{-12}	3.4×10^{-12}
NRG-6	4	0.3×10^{-12}	28.0×10^{-12}	11.2×10^{-12}	4.1×10^{-12}
NRG-7a	4*	0.2×10^{-12}	54.0×10^{-12}	26.6×10^{-12}	8.4×10^{-12}
*Does not include the nonwelded crystal-poor vitric test intervals.					

Table 3-2. Permeability estimated from single-hole air injection tests in Topopah Spring Tuff (adapted from LeCain, 1997)

Borehole	No. of Test Intervals	Minimum [m^2]	Maximum [m^2]	Arithmetic Mean [m^2]	Geometric Mean [m^2]
UZ-16	54	0.02×10^{-12}	9.5×10^{-12}	1.8×10^{-12}	0.9×10^{-12}
SD-12	27	0.12×10^{-12}	33.0×10^{-12}	4.7×10^{-12}	1.7×10^{-12}
NRG-6	34	0.08×10^{-12}	24.0×10^{-12}	2.1×10^{-12}	0.8×10^{-12}
NRG-7a	38	0.04×10^{-12}	2.4×10^{-12}	0.4×10^{-12}	0.3×10^{-12}

Table 3-3. Permeability estimated from single-hole air injection tests in Paintbrush Group (adapted from LeCain, 1997)

Borehole	No. of Test Intervals	Minimum [m^2]	Maximum [m^2]	Arithmetic Mean [m^2]	Geometric Mean [m^2]
NRG-7a	18*	0.12×10^{-12}	3.0×10^{-12}	0.5×10^{-12}	0.3×10^{-12}
* Includes two test intervals from the crystal-poor nonwelded vitric zone of the Tiva Canyon Tuff.					

Underground pneumatic testing in ESF alcoves. Air injection and tracer testing were also conducted by USGS in ESF alcoves within the upper TCw unit, at the Bow Ridge fault (BRF), and at the upper PTn contact (LeCain, 1998). These tests are representative of scales of several to a few tens of meters.

In the Upper Tiva Canyon Alcove, 27 tests, conducted in three boreholes tapping the crystal-poor upper lithophysal zone of the Tiva Canyon tuff, yielded permeability values ranging from 0.2×10^{-12} m^2 to 85×10^{-12} m^2 with an arithmetic mean of 28.6×10^{-12} m^2 and a geometric mean of 16.0×10^{-12} m^2

(LeCain, 1998). Some tested sections of boreholes showed no pressure response, which LeCain (1998) attributed to either improperly seated packers or permeability higher than the maximum range of test equipment. As in the surface-based testing, these permeability estimates are several orders of magnitude higher than the laboratory based matrix permeabilities for TCw rocks. Interestingly, during attempted cross-hole tests, no pneumatic response between injection and monitoring intervals could be detected between the three boreholes. This could be an indication that the permeability of the rock surrounding the alcove is extremely high, allowing high flow rates to occur under undetectable pneumatic head gradients.

In the BRF Alcove, two 26-m long, horizontal, parallel boreholes, spaced 3 m apart, were drilled across the BRF. The following lithologies were penetrated: the crystal-poor middle and lower lithophysal zones of the TCw unit; a 2.7 m-wide-fault zone; and the pre-Rainier Mesa bedded tuffs from the upper TCw unit. Both single- and cross-hole tests were performed. From these results reported by LeCain (1998), permeabilities in the fault zone do not significantly differ from those on either side of the fault. Additionally, the range of estimates obtained from the BRF Alcove are of similar magnitude to those obtained from the surface tests and from the Upper Tiva Canyon Alcove. Permeability estimates for the fault zone from cross-hole tests were about twice as great as those from the single-hole tests. It should be noted, however, that the presence of discrete permeable fractures and the close proximity of injection and monitored intervals calls into question the applicability of the spherical flow model used to interpret the data. The type-curve fits of the model to the data were not shown by LeCain (1998).

In the Upper PTn Contact Alcove, 29 single-hole pneumatic injection tests were conducted in two horizontal boreholes penetrating several subzones of the TCw. The two 30-m boreholes are perpendicular and intersect at about 9 m penetration depth. According to LeCain (1998), the degree of welding appears to decrease and porosity seems to increase with penetration depth. Single-hole air injection tests were conducted at 1-m intervals, except for the tests at the ends of the holes that had lengths of 3.2–5.0 m. The results reported by LeCain (1998) are summarized in table 3-4 and seem to indicate higher permeability values of the less-welded, vitric intervals.

More recently, several cross-hole pneumatic injection tests were conducted in the Northern GDF Alcove to test pneumatic properties across the fault (LeCain et al., 1999). Three horizontal boreholes were drilled to form a triangular pattern. The tests yielded estimates of permeability and porosity in three zones (foot wall, fault zone, and hanging wall) using both analytical type-curve methods and numerical methods. Similar permeability estimates were obtained from both methods. Fault zone permeability was found to be slightly higher than that of the adjacent formations. A summary of results is provided in table 3-5.

Numerous cross-hole pneumatic injection tests were also conducted in Niches 3650 and 3566 of the ESF. The tests revealed increases in permeability near the excavated surface following excavation of the niche (Wang et al., 1998). Wang et al. attributed the increase to reduced *in situ* stress around the niches allowing fractures to open. Another plausible explanation, however, is that connectivity of the fracture system is increased, simply due to the presence of the niche. In other words, the niche acts as a high-permeability boundary close to the boreholes. Conclusions regarding increased permeability following drift excavation have led DOE researchers to assert that increased permeability and porosity can suppress drift seepage (U.S. Department of Energy, 1999).The DOE postulate is that increased permeability surrounding the drift promotes lateral diversion while increased porosity requires more water to fill the fracture volume before seepage occurs. This assertion seems to completely ignore the fact that the postulated increased fracture apertures would change moisture retention properties in a manner that could actually increase dripping into the drift.

Table 3-4. Permeability estimated from single-hole air injection tests in the Upper Paintbrush Contact Alcove (data from LeCain, 1998)

Geologic Zone	No. of Test Intervals	Minimum [m^2]	Maximum [m^2]	Arithmetic Mean [m^2]	Geometric Mean [m^2]
Tpcplnc*	6	0.02×10^{-12}	2.0×10^{-12}	0.7×10^{-12}	0.3×10^{-12}
Tpcpv1† and Tpcpv2‡	12	0.4×10^{-12}	57.0×10^{-12}	16.5×10^{-12}	7.0×10^{-12}
Tpcplnh§	11	0.1×10^{-12}	12.0×10^{-12}	3.7×10^{-12}	2.1×10^{-12}

* Tiva Canyon Tuff crystal-poor lower nonlithophysal columnar subzone
† Tiva Canyon Tuff crystal-poor vitric subzone 1
‡ Tiva Canyon Tuff crystal-poor vitric subzone 2
§ Tiva Canyon Tuff crystal-poor lower nonlithophysal hackly subzone

Table 3-5. Permeability estimated from cross-hole air injection tests in the Ghost Dance Fault Alcove (data from LeCain et al., 1999)

	Type-Curve Analysis		Numerical Inverse Analysis	
Geologic Zone	Permeability [m^2]	Porosity	Permeability [m^2]	Porosity
Footwall	8.7×10^{-12}	0.04	10.0×10^{-12}	0.07
Fault zone	18.1×10^{-12}	0.13	20.0×10^{-12}	0.20
Hanging wall	5.0×10^{-12}	0.04	5.0×10^{-12}	0.05

Cross-hole pneumatic injection tests were conducted in 31 boreholes drilled in the Thermomechanical Alcove of the ESF to characterize the rock for the single-heater test (Tsang et al., 1996). Pressure responses in the monitored boreholes varied considerably with direction and location, yet pressure responses were detected in most boreholes implying that on a scale of a few meters, the fracture system is well connected (Tsang and Birkholzer, 1999).

Huang et al. (1999) performed simultaneous inversions of the pressure data obtained by Tsang et al. (1996) for the cross-hole tests. The inversion of the pressure data was used to develop maps of permeability distribution within the tested rock mass. The method of Huang et al. (1999) for estimating permeability distributions works well if one can presume air-filled porosity to be a fixed parameter. One concern regarding this approach is that heterogeneity patterns predicted using this trial and error approach are likely nonunique, and no statistical measure of uncertainty is obtained.

3.2.3 Passive Monitoring of Barometric Signal Attenuation

Monitoring of ambient pressure fluctuations at depth, induced by barometric pressure changes at the surface, can be used to estimate intrinsic vertical diffusivity through the UZ. Such data have been used to estimate vertical permeability of major hydrogeologic units, properties of faults and fracture zones, flow of gas and water vapor through the deep UZ, and the effects of the ESF construction (Rousseau et al., 1997a). Researchers have used both the AIRK computer code (Weeks, 1978) and the UZ site-scale model to simulate the barometric pressure propagation through several stratigraphic units (Ahlers et al., 1999). Observations show that the barometric fluctuations propagate through the TSw and TCw units with minimal signal lag and attenuation, indicative of the high permeability fracture pathways. Significant amplitude attenuation and phase lag of the barometric signal occurred through the PTn unit, reflecting the reduced permeability and high storage capacity of this unit. The degree of signal attenuation in the PTn appears to vary spatially across the YM site (Rousseau et al., 1997b; Patterson et al., 1996; Ahlers et al., 1999). The primary cause of the lateral variation in barometric signal has been linked to the thickness of the Paintbrush unit, but the variability in matrix saturation and the presence of fractures can also cause significant variability.

The permeability estimates obtained from passive monitoring were somewhat larger than the values reported by LeCain (1997) from surface-based pneumatic injection tests. Permeability estimates obtained using this approach require assumptions regarding the porosity for the major hydrostratigraphic units. Thus permeability estimates are only as good as the estimates of formation porosity, which are highly uncertain in units where flow occurs primarily in fractures.

3.3 U.S. DEPARTMENT OF ENERGY MODELING APPROACH

DOE developed both a 3D Site-Scale UZ Flow Model (Bodvarsson et al., 1997) and a drift-scale model (Birkholzer et al., 1999) to support the Total System Performance Assessment-Viability Assessment (TSPA-VA) (U.S. Department of Energy, 1998). Both models used the multi-phase mass and energy transport code, TOUGH2 (Pruess, 1991). CNWRA staff performed a critical review of these models (Winterle et al., 1999a). It is expected that similar, but refined, approaches will be used for future TSPA analyses to support a LA for a repository at YM.

In the Site-Scale UZ Flow Model used for the TSPA-VA, different permeabilities are assigned to the fractures and rock matrix of each stratigraphic unit. Available data were used to constrain permeability estimates. Intrinsic permeability values assigned to the matrix and fracture system were refined through one-dimensional (1D) model calibrations to match rock-matrix saturations observed in the rock core samples. As mentioned earlier in this report, it is becoming increasingly clear, however, that *in situ* rock-matrix saturations are wetter and more uniformly distributed than previously thought. As such, when reviewing the UZ models to support the LA, NRC should verify that model calibrations based on matrix saturation are consistent with the more recent *in situ* monitoring data.

Matrix and fracture properties within any single hydrostratigraphic layer in the Site-Scale UZ Flow Model were assumed homogenous for the TSPA-VA (Bodvarsson et al., 1997). As discussed in section 3.1, this could be a serious flaw in the model because intra-layer heterogeneities, especially in the nonwelded units, are likely to profoundly affect the spatial and temporal distribution of flow in the UZ.

Moisture retention properties in both the site-scale and drift-scale models are based on the van Genuchten (1980) model. A wealth of data are available as a basis for assigning moisture retention properties to rock matrix. For fracture networks, however, there is really no sound basis for estimating values for moisture retention parameters, or even for assuming that the van Genuchten model is applicable to fracture networks.

The drift-scale UZ model was used to provide estimates of water seepage into repository drifts for the TSPA-VA. A major concern of the CNWRA staff regarding the drift-scale model is the applicability of the 3D continuum approach to model flow in a fractures. Because calculations of drift seepage are extremely important to repository performance assessments, NRC and CNWRA staff will focus close attention to review of drift-scale modeling put forth by DOE to support a repository LA.

3.4 REVIEW OF UNCERTAINTY IN PERMEABILITY

Without question, the effect of heterogeneity is the key remaining uncertainty in assessing the permeable pathways through the UZ. Heterogeneity within the PTn unit likely controls the spatial and temporal distribution of flow reaching the repository. Heterogeneity on the scale of a single fracture intersecting a drift has important implications for the quantity of water that might drip onto waste canisters. The heterogenous distribution of zeolitically altered zones within the CHn unit is a controlling factor for radionuclide transport paths from the repository to the water table. Such heterogeneities are not explicitly accounted for in the UZ flow models reviewed by NRC/CNWRA staff to date.

Constructing and calibrating 3D UZ flow models that incorporate heterogeneity at appropriate scales can be extremely difficult and results are likely to be either non-unique or biased by underlying assumptions. The DOE should not, however, be required to prove their UZ flow models produce accurate results. Rather, the impetus should be placed on determining whether DOE has demonstrated that the models used as the basis for TSPA abstractions produce reasonably conservative bounds on the factors important to repository performance. Based on information made available by DOE to date, such a demonstration remains to be made for three UZ issues identified by NRC as important to performance: (i) the spatial and temporal distribution of flow reaching the repository, (ii) the quantity and chemistry of water contacting waste canisters, and (iii) SZ flow paths from the repository to the water table. Carefully designed TSPA importance analyses may be useful in this regard.

Although DOE efforts to characterize the UZ at YM continue on several fronts, there presently exist no reasonable quantitative estimates of uncertainties in the spatial distribution of UZ fracture network permeabilities and moisture retention properties. Given the complexities involved in obtaining estimates of permeability at a variety of scales, and the lack of available technologies for estimating fracture-network moisture retention properties at the mountain scale, DOE should be encouraged to rely on conservative bounding assumptions regarding ranges of parameter values for permeability and moisture retention properties in the UZ. For example, NRC has suggested that the issue of quantity and quality of water contacting waste could be partially resolved by conservatively assuming that all percolation flux that intersects a WP footprint will drip onto the WP (Nuclear Regulatory Commission, 1999).

4 PERMEABILITY OF SATURATED ZONE

An assessment of the distribution of permeability in the saturated zone (SZ) downgradient from YM is needed to reliably bound receptor locations and contaminant arrival times, should a release occur. In prevailing conceptual models, the SZ flow path from YM to the 20 km compliance boundary passes through two distinctly different flow systems: a volcanic tuff aquifer and an alluvial/valley-fill aquifer. For reasons discussed in the following sections, it is believed that of the tuff and alluvial aquifer systems, the alluvial aquifer is expected to play a more important role as a natural barrier to radionuclide migration through groundwater.

4.1 SYSTEM DESCRIPTION AND IMPORTANCE

The SZ directly beneath YM consists of volcanic tuffs of varying degrees of welding and fracturing. In the volcanic tuff aquifer, the majority of groundwater flow is expected in rock fractures, which can be highly permeable, but occupy a small fraction of total porosity. With such conditions, groundwater pore velocities are relatively high and exposed mineral surfaces available for cation sorption are relatively small. As a result, the tuff aquifer will probably not act as an effective natural barrier to radionuclide migration, unless a significant amount of matrix diffusion occurs. Matrix diffusion is the diffusive migration of flowing solutes from high-permeability zones into the more-or-less stagnant waters in adjacent low-permeability zones. The matrix diffusion conceptual model is suited to the tuff aquifer because interconnected networks of fractures and faults are high-permeability zones that dissect low-permeability rock matrix.

In a recent CNWRA report (Winterle et al., 1999b), it was demonstrated using the Total-system Performance Assessment Code (Mohanty and McCartin, 1998) that inclusion of matrix diffusion in performance assessments can result in noticeably lower predicted doses at the 20 km receptor location over a 10 ky compliance period. The efficacy of matrix diffusion as a natural attenuation mechanism is largely determined by the ratio of the time scale for advection through the flow system to the time scale for diffusion into the low-permeability rock matrix: the greater this ratio, the greater the effect of matrix diffusion as a natural attenuation mechanism. The fracture/fault network permeability in the tuff aquifer is a controlling factor in the time scale for advection through the flow system. A controlling factor in the time scale for diffusion into the rock matrix is the effective thickness of the matrix blocks or slabs surrounded by flowing fractures. Thus, both the overall transmissivity of the tuff aquifer and the effective spacing between transmissive zones can be important to performance of a repository at YM.

Regardless of whether the tuff aquifer is effective as a natural barrier, the distribution of permeable zones within the volcanic tuff flow system determines where groundwater that has passed beneath YM will enter the alluvial flow system. For example, it has been postulated that the predominance of north- and south-striking fractures and faults could result in horizontally anisotropic transmissivity in the tuff aquifer (Luckey et al., 1996; Ferrill et al., 1999; Winterle and LaFemina, 1999). Such anisotropy could lead flow in a more southerly direction than would occur for flow in the direction of the hydraulic gradient. If such is the case, groundwater flow would exit the tuff aquifer much closer to the proposed 20 km compliance point, thereby diminishing the barrier capacity of the alluvial aquifer. The potential for channelization of flow along faults is another factor that must be considered in assessing flow paths through the volcanic tuff aquifer.

At some point downgradient from YM, groundwater exits the volcanic tuff aquifer system and enters an alluvial aquifer system of valley-fill sediments composed of clays, sands, gravels, and cobbles. Much less is known about the alluvial aquifer system, owing to a paucity of monitoring wells along the alluvial aquifer portion of the projected flow paths away from YM. However, this situation is changing. The DOE is funding Nye County to install several new boreholes in the vicinity of Fortymile Wash and along U.S. Highway 95 near the 20 km compliance boundary. Meanwhile, it is generally thought that flow in the alluvial aquifer system is accommodated by a larger fraction of the total porosity, resulting in much slower pore velocities than in the tuff aquifer. Additionally, the larger mineral-surface to volume ratio in the alluvial sediments translates into greater capacity for sorption of cationic radionuclides. Matrix diffusion may also be an operative attenuation mechanism in the alluvial aquifer, as solutes can diffuse into the pore spaces within large cobbles or clay lenses where low permeability results in minimal advective mass transfer. If these predicted qualities of the alluvial aquifer system can be demonstrated through data collected in the planned Nye County boreholes, the alluvial aquifer system may be established as a significant part of the natural barrier system. Planning is currently underway to construct an Alluvial Testing Complex, which will consist of several wells, optimally located and spaced for conducting cross-hole hydraulic and tracer testing.

The volcanic tuff and alluvial aquifers are underlain by a regional-scale aquifer system that consists mainly of Paleozoic carbonates (e.g., Winograd and Thordarson, 1975). It is generally believed that groundwater flow paths from YM to the proposed compliance boundary are hydraulically isolated from this regional aquifer by thick sequences of low-permeability, volcanic and sedimentary materials. Because the regional carbonate aquifer is a highly productive and valuable source of groundwater, it is important to evaluate how well it is isolated from any threat of exposure, should a release of contaminants occur at YM. A strong upward hydraulic gradient has been observed across this confining unit in several wells penetrating the tuff aquifer (e.g., Luckey et al., 1996). This upward gradient could produce upwelling from the carbonate aquifer into the volcanic tuff aquifer, perhaps along faults. Farrell et al. (1999, chapter 4) point out existing hydrochemical evidence for such an upwelling. Bredehoeft (1997) modeled the strong, in-phase, Earth-tide response in the carbonate interval of Well UE-25 p#1; he estimated an admittedly tenuous upper bound of 365,000 m^3/yr for upward discharge from the carbonate aquifer along major faults in the area. Such upwelling could possibly serve as a dilution mechanism for contaminants migrating in the volcanic aquifer system. Additionally, as Bredehoeft (1997) observed, the gradient across this confining unit protects the regional aquifer system from potential contamination from the overlying tuff aquifer.

From the preceding discussion, the aspects of permeability important for assessing repository performance are

- Bulk aquifer transmissivity along transport pathways, which can be used to estimate groundwater fluxes and, if effective porosity estimates are available, groundwater travel times

- Effective spacing between flow zones in the tuff aquifer, which affects the efficacy of matrix diffusion in the natural attenuation of dissolved contaminants

- Heterogeneity and structural controls on flow, which may cause flow channelization and affect the direction of groundwater flow

- Permeability of the lower volcanic confining unit that isolates the tuff and alluvial aquifers from the regional carbonate aquifer

In the following section, available data for each of these topics are summarized, and an assessment is made of the understanding of these topics to support an LA for a repository at YM.

4.2 REVIEW OF AVAILABLE DATA

Data for the SZ near YM are available from numerous sources. Water-level measurements from wells tapping the tuff aquifer are reported by Graves (1998) and Graves et al. (1997) along with summaries of lithologic and borehole-construction data. Luckey et al. (1996) did an excellent job of summarizing existing SZ data and developed conceptual models of site-scale hydrology. Luckey et al. (1996) categorized the tuff aquifer into four main hydrostratigraphic units that have become familiar terms in the lexicon of YM hydrology.

- The upper volcanic aquifer is formed by the highly fractured, densely welded TSw.
- The upper volcanic confining unit consists mainly of the nonwelded CHn, but also includes the basal vitrophyre of the TSw above the CHn and the upper nonwelded part of the Prow Pass Tuff below the CHn.
- The lower volcanic aquifer contains most of the Prow Pass Tuff, Bullfrog Tuff, and Tram Tuff.
- The lower volcanic confining unit is composed of the Lithic Ridge Tuff and older flows and tuffs that separate the Lithic Ridge Tuff from the underlying regional Paleozoic carbonate aquifer.

Since the efforts of Luckey et al. (1996), additional hydraulic and tracer tests have been conducted at the C-Holes Complex (e.g., Geldon et al., 1997, 1998). CNWRA recently conducted an independent review and analysis of available data from the C-Holes Complex (Winterle and La Femina, 1999). In the past year, several new wells have been completed in both the tuff and alluvial aquifers, and a second round of tracer tests at the C-Holes was finished. Much of the newer data, however, is still either unavailable or considered preliminary.

Figure 4-1shows a map of the YM area that will be referred to often in the following discussions of available data. The map indicates locations of wells and contains an overlay of water-table elevation contours that represent the most recent CNWRA interpretation. It should be noted that the well identifications on figure 4-1 have been abbreviated to improve readability. For example, Well UE-25 b#1 is listed simply as b#1; Well USW H-4 as H-4, and so on.

4.2.1 Bulk Aquifer Transmissivity of Transport Pathways

Single-well hydrologic tests have been performed in numerous wells penetrating the tuff aquifer. Summaries of single-well test results are contained in reports by Geldon (1993) and Luckey et al. (1996). Multiple-well, or cross-hole, hydrologic testing has also been conducted. One early cross-hole test was conducted by pumping Well UE-25 b#1 while Well UE-25 a#1 was used as an observation well 110 m away (Lobemeyer et al., 1983). The most intensive multiple-well testing has been done at the C-Holes Complex

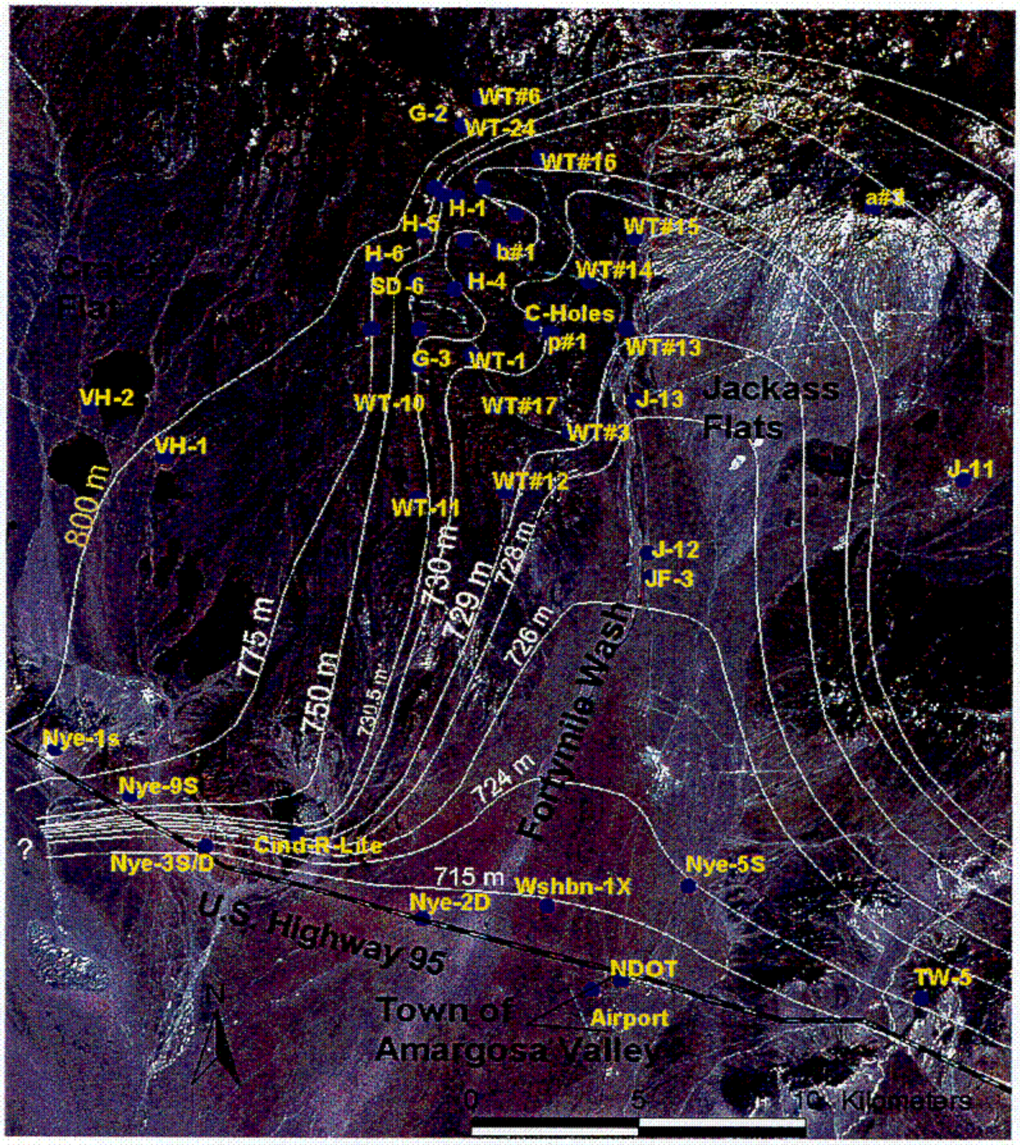

Figure 4-1. Satellite image of the proposed Yucca Mountain repository compliance area. White lines represent hydraulic head contours in the uppermost aquifer inferred from water levels in the wells shown as blue circles. The proposed 20 km compliance boundary lies close to U.S. Highway 95.

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(e.g., Geldon, 1996; Geldon et al., 1997), located about 5 km southeast of the proposed repository center. Several long-term drawdown tests were conducted at the C-Holes, one more than 10 mo long. These tests produced drawdowns in observation wells more than 4 km away and yielded the best available estimates of fault block-scale aquifer properties for the tuffs. An important factor to consider is that analyses of many single-hole pumping tests in the fractured tuffs tend to underestimate aquifer transmissivity by about an order of magnitude (e.g., Geldon et al., 1997; Winterle and La Femina, 1999). This underestimation is likely an artifact resulting from the head losses that occur close to the well bore when flow from a wide aquifer interval must converge into the narrow zones where fractures intersect the well bores. This potential for biased transmissivity estimates from single-well tests must be considered when comparing results to those obtained from multiple-well tests.

From available data, one might infer a general trend of increasing transmissivity in the tuff aquifer from northwest to southeast. The lowest transmissivity values are observed hydraulically upgradient to the north and west of the repository block. For example, north of the repository site, injection tests in Well USW G-2 showed that virtually no water was accepted by the lower volcanic aquifer (Luckey et al., 1996). Transmissivity values for wells on the west side of the repository block, but still east of the Solitario Canyon fault, also have relatively low transmissivity values. Wells USW H-3 and USW H-5, for example, estimated transmissivities of only 1.1 m^2/d (Thordarson et al., 1985) and 36 m^2/d (Robison and Craig, 1991) for the upper volcanic aquifer.

Moving to the east side of the repository block, transmissivities apparently increase as evidenced from transmissivity estimates of ~ 500 m^2/d for Well USW H-4 (Whitfield et al., 1985), ~ 600 m^2/d for Well USW G-4 (Lobemeyer, 1986), and ~ 200 m^2/d for Well USW H-1 [independent CNWRA analysis of data from Rush et al. (1983)]. Still farther east of the repository, within the area of influence of testing at the C-Holes Complex, bulk transmissivity of the tuff aquifer is on the order of 1,000–3,000 m^2/d (Winterle and La Femina, 1999).

About 9 km southeast of the C-Holes Complex, beneath Fortymile Wash, the transmissivity in Well JF-3 was estimated to be 14,000 m^2/d (Plume and La Camera, 1996). This is the largest transmissivity value obtained in the YM area to date. There is also historical evidence of large aquifer productivity at Wells J-12 and J-13 (Thordarson, 1983). For example, roughly 3.4 million cubic meters were extracted over 5 yr in the 1960s, causing a water table decline of less than 1 m at Well J-13 (Young, 1972).

The apparent trend in transmissivity may be due in part to structural control, as stratigraphic layers tend to dip gently in an east-southeast direction. For example, well logs show that beneath the west side of the proposed repository block, the lower volcanic aquifer is only partly below the water table, but it is completely submerged just east of the repository. The area of highest transmissivity, near Well J-F3, coincides with an area where the highly permeable, highly fractured Topopah Spring Tuff (i.e., the upper volcanic aquifer) dips below the water table. The presence of the highly productive upper volcanic aquifer beneath Fortymile Wash may produce a north-south-trending drain. The concept of this aquifer zone acting as a drain is also supported by water level data that indicate hydraulic gradients toward Fortymile Wash from the east and west (figure 4-1). Another factor affecting tuff aquifer transmissivity is the presence of mineral fillings in fractures. For example, although Well USW G-2 fully penetrates the lower volcanic aquifer, Bish and Chipera (1989) report ubiquitous calcite-filled fractures throughout the borehole. As a result, Well USW G-2 has arguably the lowest transmissivity of any well in the repository area.

Another factor to consider regarding transmissivity of the tuff aquifer is the potential for horizontal anisotropy. Fracture data collected from the C-Holes (Geldon, 1996) clearly indicate a preferential north-south strike, even when corrected for bias introduced by borehole orientation (Winterle and La Femina, 1999). Additionally, Ferrill et al. (1999) predicted that the tendency for maximum dilation favors fractures and faults oriented north-northeast. These factors lead to the conjecture that transmissivity in the YM area may be anisotropic. Indeed, analyses of multiple-well drawdown data from the 1996–1997 pumping at the C-Holes (Winterle and La Femina, 1999) supports this hypothesis, predicting maximum directional transmissivity oriented northeast at an azimuth 030. However, the 4:1 anisotropy ratio of maximum to minimum transmissivity predicted by Winterle and La Femina (1999) is poorly constrained due to the limited number of observation wells and inherent uncertainty in pumping test analyses. Ongoing analyses at CNWRA may help to better constrain this estimate.

Hydraulically downgradient from YM, near the proposed 20 km compliance boundary, the uppermost aquifer consists of saturated valley-fill material, often referred to as an alluvial aquifer. The zone of transition where the water table exits the tuff aquifer and enters the alluvial aquifer is at present unclear due to sparse well data south of Well JF-3. Geophysical data suggest that along Fortymile wash, the water table probably exits the tuff aquifer about 1 or 2 km south of Well JF-3.[1] To the west of Fortymile Wash, however, the water table probably remains in the volcanic tuffs much farther to the south, as evidenced by the presence of tuff outcrops that extend south to within 1 km of U.S. Highway 95 (figure 4-1). Given the potential for horizontally anisotropic flow, it is foreseeable that flow from beneath YM could be driven more to the south, askance of the prevailing hydraulic gradient, thus remaining in the tuffs longer than would occur under isotropic conditions.

To date, little is known about the bulk aquifer transmissivity or hydraulic conductivity of the SZ flow paths in the alluvial aquifer. Short-duration tests in Nye County Wells 1S, 3D, and 9S yielded transmissivity estimates ranging from 200–5,000 m^2/d, but these wells apparently produce water from a composite of valley fill and volcanic tuffs. Additionally, these three wells are all west of the Lathrop Wells volcanic cone and do not occur on flow paths from YM. Nye County Wells 2D and Washburn1X are along potential flow paths but are reportedly not highly productive, based on preliminary testing.[2] Nye County Well 5S, on the eastern edge of the potential flow path area, had the lowest productivity of any of the Nye County Wells drilled to date. In fact, 5S was thought to be dry until water slowly rose within the wellbore, stabilizing at about 724 m. Well logs for 5S reveal a thick sequence of clay-rich valley-fill sediments, which may account for the low productivity (Nye County, 1999). Logs from local production wells in Amargosa Valley also indicate the presence of a subsurface clay layer beneath the Lathrop Wells area (along U.S. Highway 95 near Fortymile Wash) at about 110–120 m depth.[3] Water production from most of the local wells is from the water table aquifer in the unconsolidated alluvial sediments that overlie this clay layer. Additional knowledge of the thickness, continuity, and extent of this clay layer is required because SZ flow paths from YM may be

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[1] Farrell, D.A., P. La Femina, A. Armstrong, S. Sandberg, and N. Rogers. Constraining hydrogeologic models using geophysical techniques: Case study Fortymile Wash and Amargosa Desert, Southern Nevada. *Proceedings of the 2000 Symposium on the Application of Geophysics to Engineering and Environmental Problems Conference*. Englewood, CO: Environmental and Engineering Geophysical Society. Submitted for publication. 2000.

[2] U.S. Nuclear Waste Technical Review Board. *Repository Design and the Scientific Program.* Transcript of Summer Meeting. Beatty, NV: U.S. Nuclear Waste Technical Review Board. 1999.

[3] Tom Buqo, consultant to Nye County. Presentation to Nuclear Waste Technical Review Board, July 28–30, 1999.

diverted above, below, or around this low-permeability zone. More quantitative information should be available in the near future as the Nye County drilling and testing program helps fill the data gap south of Well JF-3.

4.2.2 Effective Spacing of Flow Zones in the Tuff Aquifer

As previously mentioned, knowledge of the spacing between flow zones in the tuff aquifer is important for determining whether matrix diffusion makes the tuff aquifer as effective as a natural barrier. Perhaps the best sources of data for this topic are the borehole flow-meter surveys conducted in several boreholes surrounding the proposed repository site. Such a survey was performed by staff at Sandia National Laboratories. Preliminary results of their analysis, which included corrections for borehole and fracture orientations, indicate that the effective distance between flowing fracture zones in the tuff aquifer is lognormally distributed, varying between 2 m and 300 m with an expected value of about 20 m.[4] The Sandia estimates compare favorably with an estimate by Winterle and Murphy (1999) who calculated rates for dissolution of calcite fracture fillings and inferred that effective flow zone spacings in the tuff aquifer must be on the order of tens to hundreds of meters.

4.2.3 Effects of Heterogeneity and Structural Controls on Flow

In this section the primary interest is the potential for focused flow along fault zones in the tuff aquifer. In the alluvial aquifer, preferential flow along buried stream channels or other features is also of interest, but presently there is insufficient data to make any determination regarding preferential flow in the alluvial aquifer.

Evidence for preferential flow paths in the tuff aquifer is most readily apparent by examining the water table contours in figure 4-1, especially in the area close to the repository. This evidence was pointed out previously by Lehman and others (Lehman et al., 1992; Lehman and Brown, 1995). They reasoned that radionuclides introduced directly into certain preferential flow zones along interconnected faults could be expected to reach the 20 km compliance boundary within a few years. Such a scenario certainly has not been disproved and, therefore, merits careful consideration. The following paragraphs summarize the most recent CNWRA interpretation of the site-scale hydraulic gradient and what information can be gleaned regarding preferential flow paths from the site-scale water table contour map.

Along the northwest corner of the repository, there are two distinct bends in the water table contours that point upgradient. Such upgradient-pointing bends indicate inward flow toward a zone of lower hydraulic head, possibly caused by a zone of enhanced transmissivity. The southernmost of these bends occurs in the area often referred to as the moderate hydraulic gradient. A possible cause of the moderate hydraulic gradient is a zone of reduced transmissivity along Solitario Canyon fault (SCF), just west of the repository block (e.g., Farrell et al., 1999). Compartmentalization of flow systems on either side of the SCF is also supported by observed differences in well water-level fluctuations (Lehman et al., 1990) and differences in groundwater geochemistry (Farrell et al., 1999). The bend on the north side of the repository is in the area often referred to as the large hydraulic gradient. Possible reasons for the occurrence of the large hydraulic gradient are summarized by Luckey et al. (1996) and Fridrich et al. (1994). Regardless of the causes of the large and moderate hydraulic gradient areas, the two bends in the contour lines may represent zones where water can

[4] Bill Arnold, Sandia National Laboratories. Personal communication to J. Winterle.

preferentially flow from those areas as sources of flow into the area of low hydraulic gradient, east of the proposed repository.

This conceptual model of two flow sources coming from the west side of the repository is also consistent with the observation in figure 4-1 of two ridges of slightly elevated water levels directly opposite each of these postulated sources. Certainly, further investigation is required to validate this conceptual model: confirmatory analysis of geochemical data and structural framework models is necessary to confirm this hypothesis. Present uncertainty notwithstanding, the two ridges within the low hydraulic gradient area form hydrologic divides separating three troughs where the water table contour lines point upgradient. These troughs are possible indications of three southeast-trending zones of preferential flow. Alternatively, the three troughs may represent the resulting geometry of the water table due to the outward spreading of water from the postulated source zones.

If it can be assumed that transmissivity in the tuff aquifer is isotropic (a questionable assumption at best), one can project flow paths leading from the repository using a simple flow-net type of analysis. Such an analysis, shown in figure 4-2, reveals that any vertical seepage reaching the water table beneath the repository footprint would be driven by the prevailing hydraulic gradient into one of three flow zones. The northernmost and southernmost streamtube boundaries in figure 4-2 were selected to coincide with points tangent to the repository boundary. The inner two streamtube boundaries were logically drawn to coincide with the hydrologic divides imposed by the two ridges of elevated water levels. These four streamtube boundaries delineate three streamtubes. Figure 4-2 illustrates the projected paths of these streamtubes to the 20-km boundary, given the present interpretation of the hydraulic gradient and the assumption of horizontally isotropic transmissivity.

The predicted locations at which these streamtubes cross the 20-km boundary are driven to a large extent by the locations of the lowest observed hydraulic heads in that area. The lowest observed heads occur along a line from Nye County Well 2D to the town of Amargosa Valley, and range 705–706 m. Hydraulic heads east and northeast of Amargosa Valley are considerably higher: 724 m at both Wells 5S and TW-5. Heads in eastern Jackass Flats are 733 m at Well J-11, indicating westward flow toward Fortymile Wash from that area. Thus, despite the sparse data from the alluvial portions of the YM flow paths, it is possible to reasonably bound where contaminants might reach the proposed 20 km compliance boundary. Available data suggest that potential locations where SZ transport paths from the repository site might cross the 20-km boundary are contained within a narrow 25° arc extending from Nye Well 5S on the east to a location approximately 7 km west of Amargosa Valley, and directly south of the proposed repository. Note that the streamtubes projected in figure 4-2 cross the proposed 20 km compliance boundary within this arc.

The western limit of the theorized arc would require flow directly south from the repository. Because of the prevailing hydraulic gradient, such a due south flow path could occur only if the permeability of the tuff aquifer exhibits an extraordinarily high horizontal anisotropy ratio. Such a path would also require an assumption that the north-south structurally oriented anisotropy is relatively continuous out to the 20-km boundary. There is little evidence at this time to support this assumption. As previously mentioned, analyses of the C-Holes tests show that the ratio of minimum to maximum directional transmissivity is poorly constrained. The data can support a full range from nearly isotropic conditions to anisotropy ratios as high as 17:1 (Ferrill et al., 1999). East of YM, equipotential lines almost parallel Fortymile Wash, so that a high

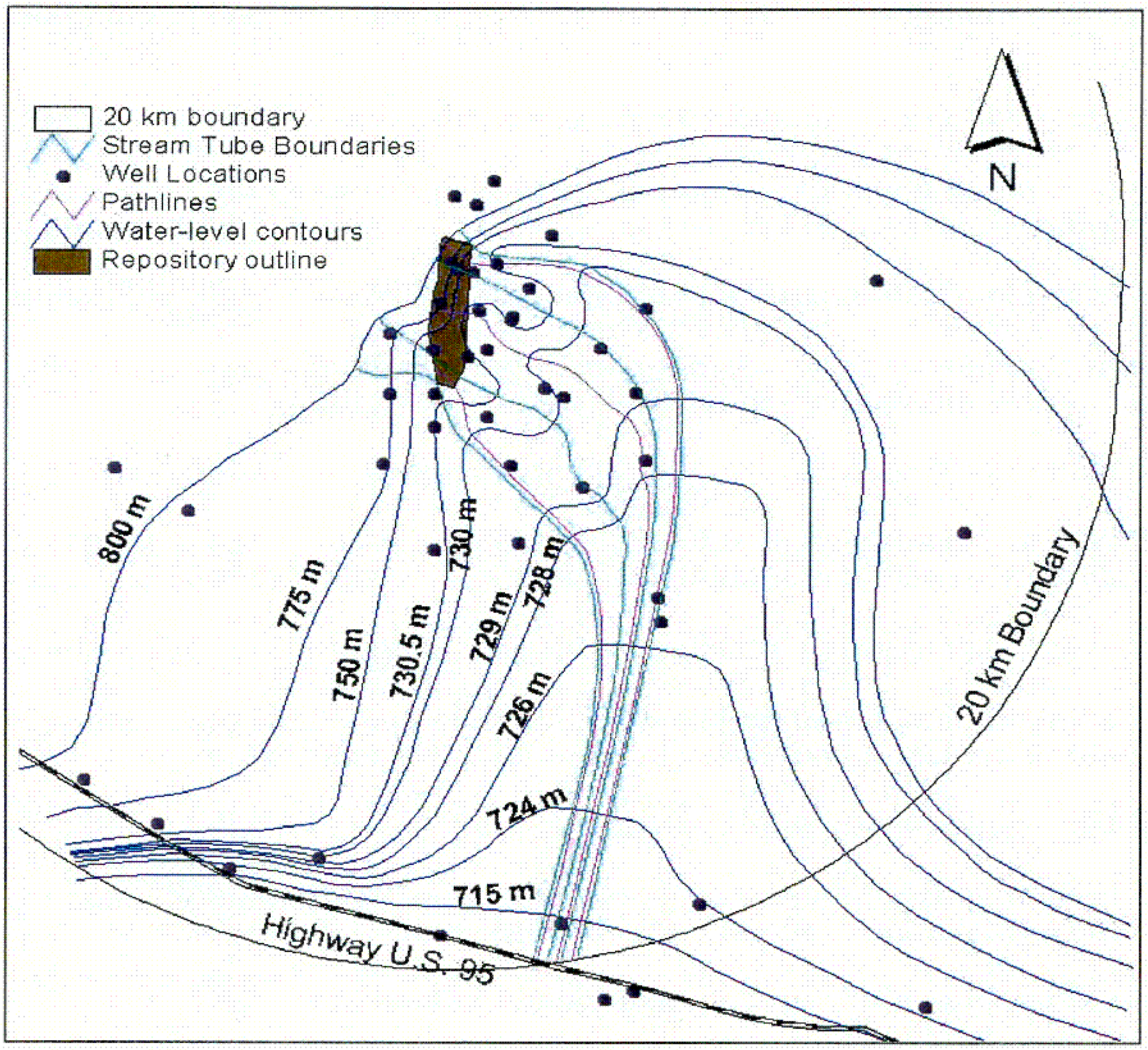

Figure 4-2. Saturated zone groundwater flow paths from Yucca Mountain to the proposed 20 km compliance boundary, assuming isotropic conditions

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degree of anisotropy could produce flow oriented south-southeast.[5] Therefore, the DOE could reasonably conclude that a due south flow path effectively bounds flow in the event of highly anisotropic conditions.

Thus far, the Nye County drilling indicates that all flow paths crossing the 20-km boundary within the predicted arc will pass through at least some portion of the saturated valley-fill aquifer. Estimates of the distance any potential flow paths might travel through alluvium remain an important uncertainty. Geophysical data (gravity and electrical sounding) indicate the valley-fill aquifer north of Amargosa Valley is quite thick. For example, a Bouguer anomaly map (Snyder and Carr, 1982) reveals a gravity low at Amargosa Valley that extends to the north-northwest across the wash. This could be caused by a thick valley-fill aquifer beneath Fortymile Wash, extending at least 5 km north of U.S. Highway 95. Additionally, using vertical electric sounding, Oatfield and Czarnecki (1989) estimated that 5 km north of Amargosa Valley the valley fill exceeds a depth of 1,000 m. A recent surface-based magnetic survey by CNWRA staff[6] provides confirmatory evidence of a thick valley-fill sequence in this area.

From the streamtubes predicted in figure 4-2, the volumetric groundwater flow rates within each streamtube can be estimated based on the knowledge of the hydraulic gradient, aquifer transmissivity, and streamtube width. Because the flow within each streamtube should remain constant, a section of the streamtube can be selected where confidence in these parameters is highest. In this situation, confidence is highest just east of the repository block in the vicinity where testing was conducted at the C-Holes. For the three streamtubes shown in figure 4-2, volumetric flow rates are estimated to be 250,000 m^3/yr for the southern streamtube, 300,000 m^3/yr for the center streamtube, and 200,000 m^3/yr for the northern streamtube. To convert these estimates to linear pore velocities, divide the numbers by the product of streamtube width times aquifer thickness, times effective porosity. Assuming an aquifer thickness of 400 m and an effective porosity of 10^{-3}, groundwater pore velocities in the tuff aquifer would be on the order of 500–750 m/yr through areas where the streamtubes are 1-km wide.

Predicted groundwater pore velocities increase as streamtube widths and effective porosities decrease. Thus, these are important parameters for estimating repository performance. Estimated streamtube widths depend entirely on the interpreted shape of the potentiometric contour lines. The present lack of well data between Well JF-3 and Amargosa Valley makes the predicted streamtubes in figure 4-2 highly uncertain in this area. Future wells planned in the Nye County drilling program should help to reduce this uncertainty.

Groundwater geochemistry may also play a role in reducing the uncertainty of the permeable pathways predicted in figure 4-2. For example, average linear groundwater velocities and residence times can be estimated through groundwater dating. Numerous YM groundwater samples have undergone ^{14}C dating, but it is difficult to correct for the significant amounts of "dead" carbon from various sources dissolved in the groundwater. A promising new approach may greatly improve the ^{14}C dating: Thomas (1996) describes the separation of dissolved organic carbon from groundwater using reverse osmosis and ultrafiltration methods. This method could be applied to samples collected at YM to independently estimate the average groundwater residence time at locations within the SZ.

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[5] This conclusion is based on an independent two-dimensional finite element modeling, documented in the Center for Nuclear Waste for Regulatory Analyses scientific notebook 311E.

[6] Farrell et al. Constraining hydrogeologic models using geophysical techniques ... 2000.

4.2.4 Permeability of the Lower Volcanic Confining Unit

Information about the Paleozoic carbonate aquifer in the vicinity of YM is based on only one well: UE-25 p#1. This well, located 2.5 km southeast of YM, verifies the existence of an upward hydraulic gradient from the carbonate aquifer to the volcanic tuff aquifer (Craig and Robison, 1984). Hydraulic heads are about 20 m greater in the isolated carbonate inteval of Well UE-25 p#1 than the heads observed in the overlying tuff aquifer. It should be noted that during the drilling of Well UE-25 p#1, the 20-m increase in head was encountered more than 100 m above the carbonate aquifer, at the base of the Lithic Ridge tuff. Although no other wells in the vicinity penetrate to the carbonate aquifer, several penetrate the Lithic Ridge Tuff and the Older Tuffs that separate the lower volcanic aquifer from the carbonate aquifer. Several of these wells also reveal an upward gradient from deep tuffs to shallower units. For example, in Well USW H-1, hydraulic head in the monitored interval in the Older Tuffs is more than 50 m higher than heads in the lower volcanic aquifer (Graves, 1998).

Additional insight can be gained from observations of heads in the lower interval of Well USW H-3, which monitors the interval from the bottom of the Tram Tuff to about 300 m into the Lithic Ridge Tuff. After inflating the packer that isolates this lower interval in early 1991, heads in the well rose slowly over 5 yr from about 747 m in 1991 to over 760 m in 1996 (Graves et al., 1997; Graves, 1998). Translated to simpler terms, it took 5 yr for the lower confining interval to supply roughly 40 L of water necessary to raise the water level by 13 m in the 6.2-cm diameter observation tube. One could conclude from this that the lower confining unit is an effective hydrologic barrier in the vicinity of Well USW H-3.

In the Nye County wells drilled to date, the depth to the Paleozoic carbonate aquifer system has been greater than anticipated, and yet none have penetrated this regional aquifer. Nye County plans include the drilling of new wells to greater depths and the deepening of some existing wells.

4.3 U.S. DEPARTMENT OF ENERGY MODELING APPROACH

The DOE has evaluated flow and transport in the SZ using a 3D site-scale flow model. Boundary conditions for this 3D site-scale model have been obtained from the Death Valley Regional Groundwater Flow Model (D'Agnese et al., 1997), which is an ongoing, frequently updated project of the USGS. From the site-scale model, streamtubes from beneath the repository to the compliance boundary are developed for use in the TSPA analyses.

In the recent TSPA-VA (U.S. Department of Energy, 1999), six 1D streamtubes were developed to determine the concentration breakthrough curves at receptor locations. Transport distances through each of four hydrostratigraphic units (i.e., middle volcanic aquifer, upper volcanic aquifer, middle volcanic confining unit, and alluvium/valley fill) were determined for each streamtube by particle tracking in the 3D site-scale flow model. The lengths of flowpaths in saturated valley-fill have been assumed to be zero for 10 percent of cases to account for uncertainty. The volumetric flux from the UZ into each streamtube was determined by the Lawrence Berkeley National Laboratory UZ Flow Model (Bodvarsson et al., 1997). This UZ contribution to each streamtube is added to the estimated specific discharge in the SZ for each streamtube. The transport simulations implicitly assume complete mixing of the radionuclide mass into the volumetric groundwater flux specified for each streamtube. A convolution integral method was used to combine radionuclide transport breakthrough curves for each streamtube with the time varying radionuclide source from the UZ. The radionuclide concentrations at the receptor locations were divided by a dilution factor, as suggested by the

Saturated Zone Expert Elicitation (Geomatrix Consultants, Inc., 1998). The TSPA-VA sensitivity analyses were conducted to assess the importance of the dilution factor, the fraction of the flowpath in alluvium, and the method for calculating the final concentration from combined six streamtubes.

The DOE approach seems reasonable based on the available data and allows for incorporation of new data and refinement of SZ flow models. Such updates will be necessary to incorporate new data emerging from the Nye County drilling program in the valley fill south of YM.

4.4 REVIEW OF UNCERTAINTY

Overall, the issue of SZ flow path characterization remains only partly resolved. Flow paths from the proposed repository to a 20-km distance can be bounded reasonably by DOE within a relatively narrow arc. An important remaining uncertainty is where the water table transitions from the tuff aquifer to the overlying valley fill. As such, the lengths of groundwater flowpaths in the valley-fill aquifer have not been determined. Perhaps the greatest remaining uncertainties lie in characterizing heterogeneities, effective porosities, and mineral properties in the saturated alluvium. These factors affect the attenuation of radionuclide migration. Accordingly, additional characterization such as hydraulic and tracer tests are needed in the alluvial aquifer system on a scale large enough to include a statistically representative elementary volume. Limited-scope exploratory drilling and geophysical surveys can also be used, in addition to the Nye County wells, to help fill data gaps. Important data gaps exist northwest of Nye County Well 2D and in the large area between Wells Washburn-1X and JF-3.

In the tuff aquifer, hydraulic properties have been better characterized, and reasonable estimates have been obtained for the effective spacing between flowing fracture zones. Considerable uncertainty remains regarding effective flow porosities. Hydraulic and tracer testing at the C-Holes Complex continues to be interpreted and may result in improved estimates of flow porosity. An additional concern is that preferential fracture and fault orientations in the tuff aquifer may result in aquifer anisotropy, yet transmissivity in DOE flow models has been treated as an isotropic parameter. Confidence in DOE characterization of flow in the tuff aquifer system could be improved by obtaining peer reviews of reports regarding hydraulic and tracer testing at the C-Holes.

Groundwater flow volumes have been estimated with some confidence in areas where well data have permitted hydraulic gradient and transmissivity to be estimated with greater confidence. Much of the potential flow path to a receptor group, however, remains to be characterized. Pore velocity estimates are poorly constrained throughout the entire flow path due to a wide range of estimates regarding effective flow porosities in the fractured tuff aquifer and the paucity of data for the valley-fill aquifer.

Indication of the upward gradient from the carbonate aquifer is not incorporated in current DOE models of the SZ at YM. In the Nye County EWDP wells drilled to date, the depth of valley-fill deposits has been greater than anticipated, and none of the wells have been able to penetrate the deep Paleozoic carbonate aquifer. If it could be demonstrated that the upward gradient from the Paleozoic carbonate aquifer persists at the proposed 20 km compliance point, then treatment of the lower volcanic confining unit as an impermeable model boundary would be a reasonably conservative assumption.

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