LBL-33627
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Presented at the International High Level Radioactive Waste Management Conference, Las Vegas, NV, April 26–30, 1993, and to be published in the Proceedings

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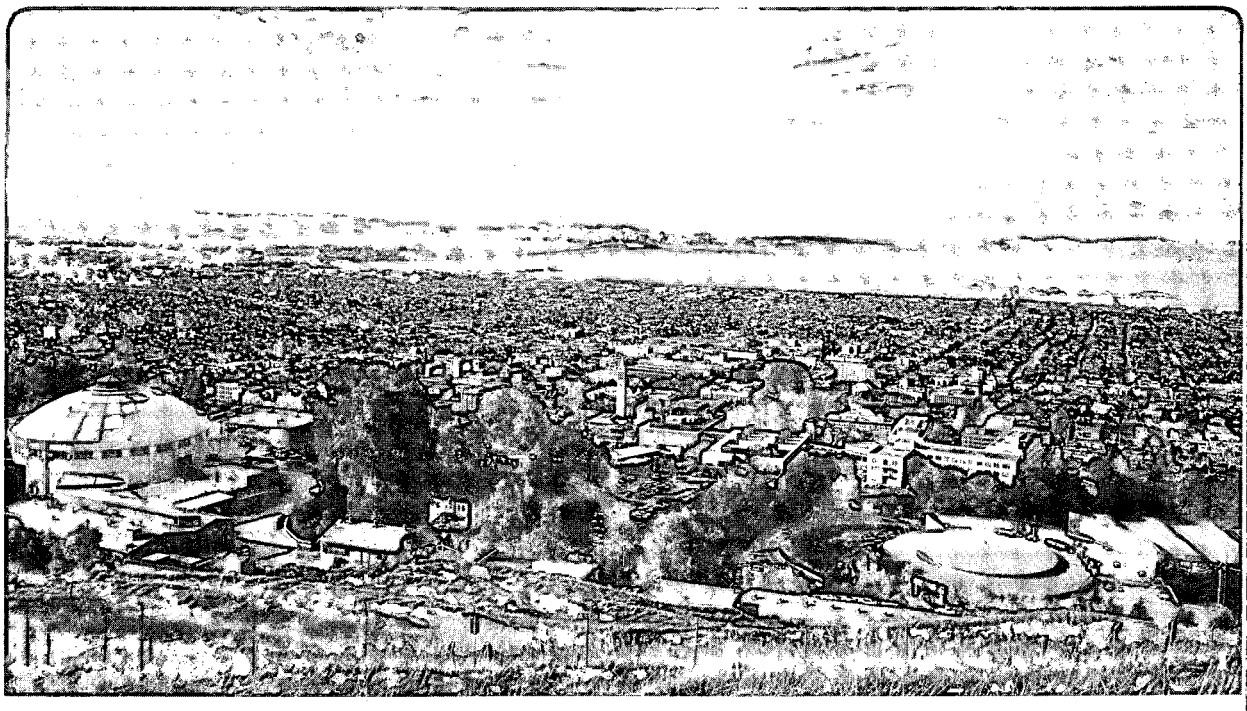
January 1993



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This work was supported by the Director, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project Office, Regulatory and Site Evaluation Division, through U.S. Department of Energy Contract No. DE-AC03-76SF00098.

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GEOHYDROLOGIC DATA AND MODELS OF RAINIER MESA AND THEIR IMPLICATIONS TO YUCCA MOUNTAIN

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ABSTRACT

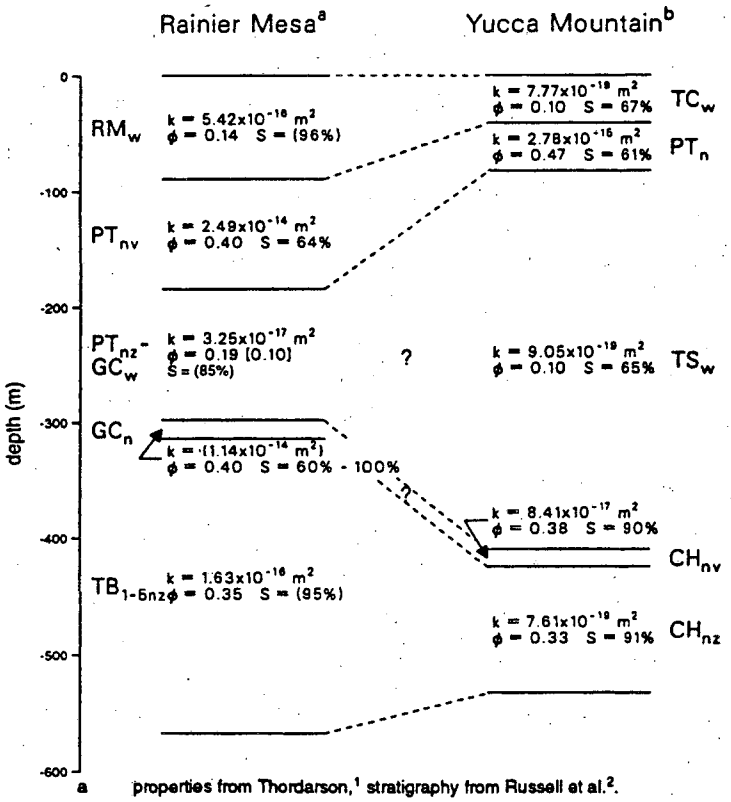
The geohydrologic data collected at Rainier Mesa provide the only extensive observations in tunnels presently available on flow and transport in tuff units similar to those of a potential nuclear waste repository at Yucca Mountain. This information can, therefore, be of great value in planning the Exploratory Studies Facility (ESF) testing in underground drifts at Yucca Mountain. In this paper, we compare the geohydrologic characteristics of tuff units of these two sites and summarize the hydrochemical data indicating the presence of nearly meteoric water in Rainier Mesa tunnels. A simple analytic model is used to evaluate the possibility of propagating transient pulses of water along fractures or faults through the Paintbrush nonwelded tuff unit to reach the tunnel beds below. The results suggest that fast flow could occur without significant mixing between meteoric fracture water and matrix pore water. The implications of these findings on planning for the ESF Calico Hills study at Yucca Mountain are discussed.

INTRODUCTION

Over three decades, the data collected by the Defense Nuclear Agency, U. S. Geological Survey,[1] and Desert Research Institute[2] indicate that perched water zones exist in some tuff units above the water table and fracture flows occur as localized seeps along some of the tunnels below Rainier Mesa. While Rainier Mesa is higher in elevation and has a wetter climate than the present conditions at Yucca Mountain, the Rainier Mesa tunnels may be used[3,4] to support Yucca Mountain characterization and assessment studies. Rainier Mesa and Yucca Mountain both have thick sequences of alternating welded and nonwelded tuffs. Under high infiltration conditions, fracture flows are generally assumed to occur in the highly fractured welded units. The nonwelded units are usually modeled as porous media. We review hydrological and geochemical information to examine if a porous medium model is adequate to account for potential fast movement of water from the surface to the tunnels at Rainier Mesa. We then discuss the possibilities of propagating transient pulses of water along fast flow paths.

GEOHYDROLOGIC COMPARISON

The lithology of alternating welded and nonwelded tuffs at Rainier Mesa is similar to that at Yucca Mountain, Figure 1,



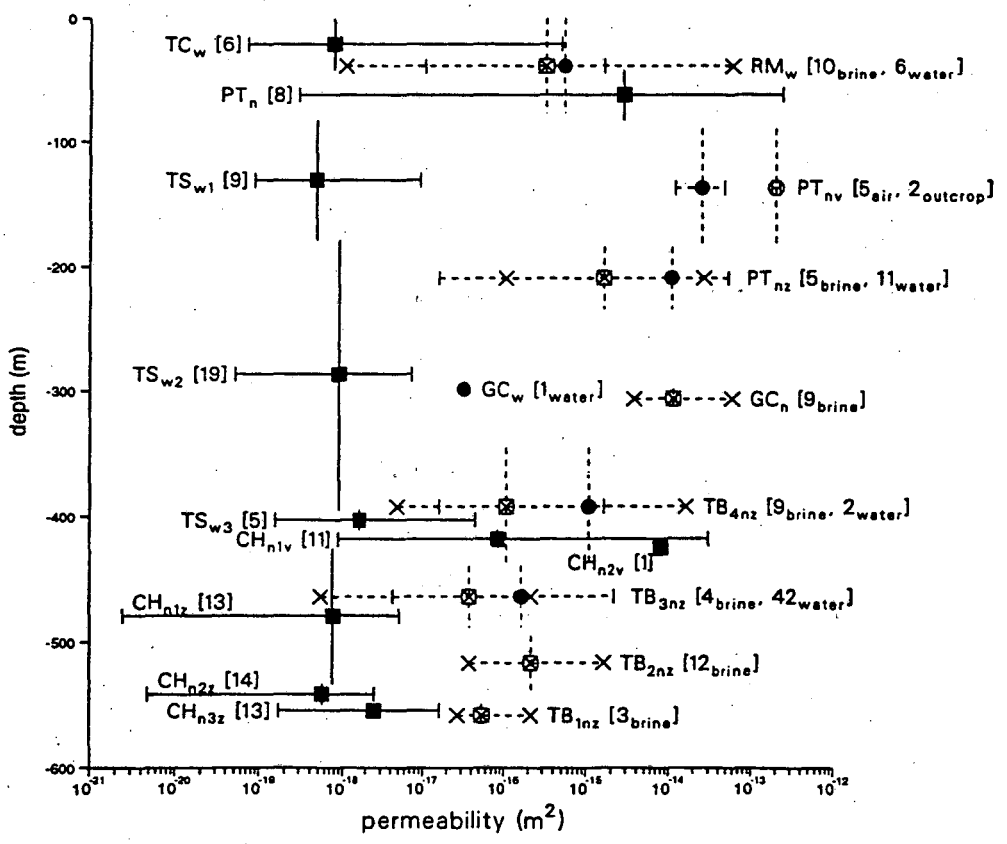
a properties from Thordarson,[1] stratigraphy from Russell et al.[2].
b from RIB4.4,[5] Peters et al.,[5] Wang and Narasimhan.[7,8]
( ) mean calculated with welded, vitric, and zeolitized cores from U12n tunnel.[9]
[ ] measured by L. Myer (personal communication, 1991) for Grouse Canyon welded tuff.
{ } measured with brine instead of fresh water.[1]

Figure 1. Comparison of hydrogeologic stratigraphic sections of Rainier Mesa and Yucca Mountain (RM: Rainier Mesa; PT: Paintbrush; GC: Grouse Canyon; TB: Tunnel Bed; TC: Tiva Canyon; TS: Topopah Spring; CH: Calico Hills; w: welded; n: nonwelded; v: vitric; z: zeolitized).

although the relative thicknesses of the tuff units differ. Below the caprocks of welded tuff, Rainier Mesa has a thick (144.8 m) nonwelded unit of Paintbrush tuff with the upper part is vitric (friable) conditions (PT_{nv}) and the lower 50 m is zeolitized (PT_{nz}). Only the main tuff units in the unsaturated zones are included in Figure 1. In the simplified hydrologic stratigraphy, we combine welded and zeolitized units but keep the vitric tuffs as separated units. The zeolitic Tunnel Bed (TB) tuffs at Rainier Mesa span a similar range of mineralogical compositions to those in the Calico Hills (CH) nonwelded tuff at Yucca Mountain.[3] The water table is located about 1000 m below the ground surface at Rainier Mesa and over 500 m at Yucca Mountain.

There are two principal differences between Rainier Mesa and Yucca Mountain which affect their hydrologic settings. First, the present infiltration at Rainier Mesa probably exceeds that at Yucca Mountain. Infiltration in the U12n tunnel catchment has been estimated to be 23.7 ± 8.0 mm/yr, which is approximately 8% of precipitation of 320 mm/yr.[2] The corresponding value at Yucca Mountain was estimated to be 0.5 – 4.5 mm/yr, 0.3 – 3% of precipitation of 150 mm/yr.[10] Second, the reported matrix permeabilities[1] of the tuffs at Rainier Mesa appear to be a few orders of magnitude greater than those of corresponding units at Yucca Mountain.[6] The tuffs at the two sites have the same origins, share similar mineralogies, and have similar porosities. There is no obvious reason why their permeabilities should be so different. It could be an artifact of the methods used to determine permeabilities. For any unit the values for the permeabilities of individual cores range over several orders of magnitude. These ranges of permeability are compared for Rainier Mesa and Yucca Mountain in Figure 2. From this figure it appears as if the differences are real.

If the tuff units at Rainier Mesa indeed have matrix permeabilities one to three orders of magnitude greater than those of the corresponding units at Yucca Mountain, then the relatively higher infiltration at Rainier Mesa may be scaled to the lower infiltration and transport at Yucca Mountain for matrix transport at each site. If the values of the permeabilities are actually similar at the two sites, then the infiltration at Rainier Mesa relative to percolation through the matrix is much greater than is expected at Yucca Mountain, except under the most extreme pluvial scenarios under which fracture flow certainly becomes the dominant transport mechanism. To compare the hydrology of these two sites, the differences in permeability values need to be investigated by making new measurements and analyses of permeability on cores from Rainier Mesa using the same methods that have been used on Yucca Mountain samples. The unsaturated characteristic curves (moisture retention and relative permeability) are certainly also needed to determine the transitions between matrix dominated flows and fracture dominated flows.



mean values: Yucca Mountain data in squares; Rainier Mesa data in circles.
number of samples: in [ ] after each unit abbreviation.
Rainier Mesa data measured with brine have x symbol in mean value and permeability range.

Figure 2. Comparison of matrix permeabilities of Rainier Mesa and Yucca Mountain.

HYDROCHEMICAL OBSERVATIONS AT RAINIER MESA

Most of the Rainier Mesa tunnels have been driven in the zeolitized Tunnel Beds 1 through 4. With the exception of the Paintbrush nonwelded, vitric tuff unit, which is considered to be partially saturated (S = 64% or 88%), most of these units are near saturated.[1] Faults and joints are abundant in the zeolitic bedded tuffs of the Tunnel Beds. When intersected by tunnels or drill holes, a fraction of these joints and especially through-going faults have yielded significant amounts of water. For example, $34{,}800 \pm 5{,}300\ m^3/yr$ of water was estimated to be discharged from the U12n tunnel system, based on monitoring the aqueous discharge through the tunnel portal and vapor discharge through the air ventilation system.[2] The flow rates of U12n.03 and U12n.05 drift seeps were approximately 10% of the total portal discharge. An average of 10 seeps are estimated as active flow paths in the U12n tunnel system. The volume $V_o = 3.48\times10^3\ m^3$ corresponds to 10% the infiltration in 1 yr through the U12n catchment basin of area $1.47\times10^6\ m^2$ (side length $W = 1.21\times10^3$ m, assuming a square shape basin). This volume of water is used later in the fast path model for the flow through one seep. For the U12e tunnel system with over $10^4\ m^3/yr$ fluid discharge through the portal, most of the flows came directly from faults, and 50 to 60% of the 110 faults mapped in the drifts yielded most of the water.[1]

The water flowing from these seeps has been observed to be significantly less saline than the pore water in the tuff matrix, with a ratio of 25 to 30 in fluid resistivity values.[1] The average stable isotope signature (^2H, ^{18}O) of U12n.03 and U12n.05 seeps is similar to present-day winter precipitation.[2] The travel time for groundwater in Rainier Mesa is at least 1 yr, based on monitoring of tracer tests,[2] and probably less than 6 yr, based on one tritium sample from U12e tunnel before nuclear tests were conducted in this tunnel.[1] The fallout of ^{36}Cl from testing of nuclear weapons in the Pacific Ocean between 1952 and 1962 was detected in 4 samples from the U12g tunnel.[11]

The chemical compositions of pore waters from the tuff cores of borehole UE12t#3,[12] located above U12t tunnel, are shown as Stiff diagrams in Figure 3, together with the compositions of waters from two near-surface lysimeters above U12n tunnel and that of the U12n.03 seep.[2,13] The composition of the seep water is remarkably similar to those of the pore waters below Tunnel Bed 4 but these are quite different from the compositions of pore waters in Tunnel Bed 4 and above. It is tempting to hypothesize that "fast paths" transport meteoric waters to depths below the tunnels, calcium and magnesium are replaced by sodium in fast ion exchange reactions, and tunnel seeps are hydraulically connected to lower tunnel beds but chemically separated from the neighboring tuff matrix.

FAST PATH MODEL

To sustain continuous discharge of fresh water into the tunnels, fast flow paths must exist from the ground surface through all tuff units, including the Paintbrush nonwelded vitric tuff unit. Fractures in this vitric tuff have been considered to be closed. The U12p tunnel driven into this unit has not yielded as much water as other tunnels driven into the Tunnel Beds. The Paintbrush also has a high interstitial porosity, is partially saturated, and thus has significant capillary suction. If the matrix permeability of this unit spans the range shown in Figure 2, the infiltration flux of 23.7 mm/yr can pass through this unit under gravity (unit hydraulic gradient) without additional capillary pressure drives. While the flux consideration alone does not refute the porous medium model with matrix flow as the transport mechanism, other hydrological, geochemical and geological data suggest that the simple model with areally uniform flow needs to be reexamined. With porosity ϕ of 0.4, saturation S of 0.64, and thickness of 94.8 m, the amount of interstitial water in a vertical column of 1 m^2 cross-sectional area through this unit is 24.3 m^3. It will take 1,025 yr for the infiltrating meteoric water with 23.7 mm/yr flux to displace the interstitial water in the pores. To account for possibly much shorter travel times (1 to 6 yr), a reduction of the effective water content ϕS by 2 to 3 orders of magnitude is needed. Localized fractures or faults could reduce the effective porosity and form the likely paths for sustaining fast flows.

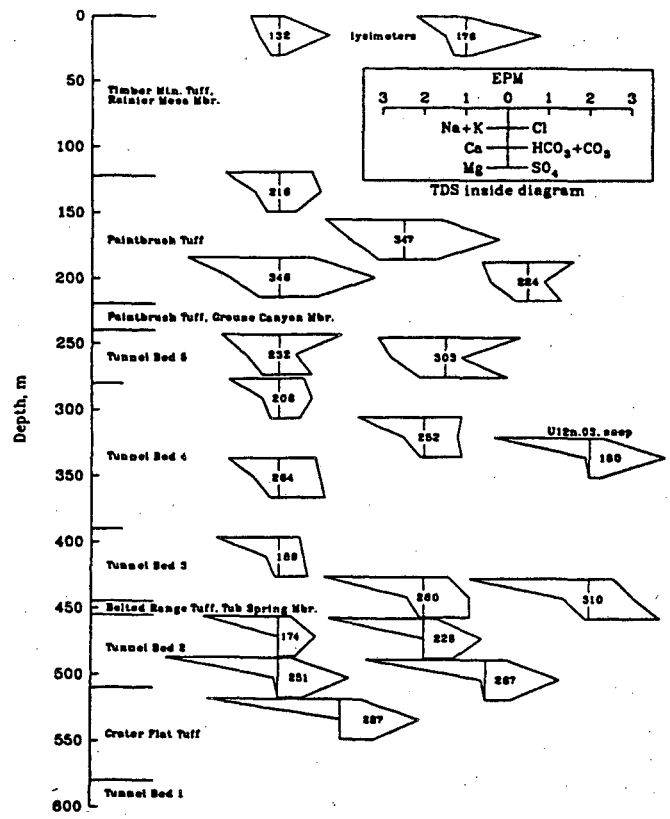


Figure 3. Stiff diagrams for waters from UE12t#3 core, near-surface lysimeters, and seep in U12n.03 (EPM: equivalents per million; TDS = total dissolved solid).

We use the simple model shown in Figure 4 to estimate the equivalent apertures of a flow path needed to allow a pulse of meteoric water to flow through the Paintbrush. A finite amount of water with volume V_o is placed on the top boundary $z = 0$ of a partially saturated unit which contains a vertical gap (the "fast" path) imbedded in tuff matrix. We use the sorptivity approximation for the instantaneous flux at the fracture-matrix interfaces.[14] An analytic expression[14] is used to calculate the sorptivity S from the characteristic curve parameters. This simple geometric model has also been used in the literature for different fracture-matrix flux approximation[15] or different boundary conditions.[16,17]

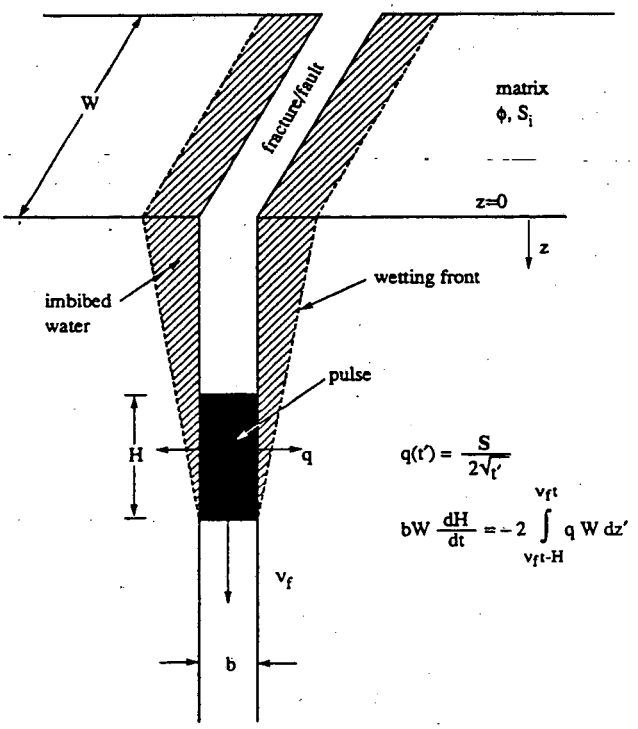


Figure 4. Pulse propagation along a fast flow path.

We assume that all the water of volume V_o at $z = 0$ flows through the inlet and moves down by gravity. As this finite amount of water (a pulse/slug of water) moves along the fast path, part of it is imbibed into the matrix and the remainder stays in the gap. Table 1 summarizes the analytic expression for the change of pulse height H(t) and the parameters used in the following illustrative examples. The capillary scaling factor was estimated from matrix permeability and porosity.[18] For the pore-size distribution index, we use the values of a similar unit PT_n at Yucca Mountain for the sorptivity calculations. The classical cubic law is used to relate the fracture velocity v_f with aperture b. The volume and the pulse height are related by $V(t) = b\,W\,H(t)$. The solution for $H(t) = 0$ determines the time t_D when the pulse along the fast path stops. The depth of penetration is $v_f t_D$ and is inversely proportional to the sorptivity S. The cumulative flux into the matrix can be calculated by integrating the instantaneous flux over time. If we assume a sharp wetting front for the water moving into the matrix, the extent of imbibition into the matrix can be estimated. The derivation of analytic formulas for this simple model and the problems in using this model quantitatively for travel times are discussed in a separate report.[3]

Table 1. Pulse Propagation Analytic Solution

fracture-matrix flux	$q(t') = \frac{S}{2\sqrt{t'}}$ Philip's approximation
solution	$H(t) = \left[\sqrt{H_o} - \frac{S\sqrt{v_f}}{b} t\right]^2$
characteristics model	van Genuchten - Mualem
illustrative examples	PT_{nv}, Rainier Mesa
amount of water in a pulse volume/area	23.7 mm (94.8 mm)
fracture/fault length	W = 1210 m
matrix permeability	2.49×10^{-14} m^2 ($5.96\times10^{-16} - 2.22\times10^{-13}$ m^2)
capillary scaling factor	0.157 m^{-1}
porosity	0.4
pore-size distribution index	2.4 (0.22 – 9.56)
ambient matrix saturation	64% (88%)

Figure 5 shows the depth to which a pulse could penetrate the Paintbrush vitric unit assuming values of matrix permeability that vary from 2.22×10^{-13} m^2 to 5.96×10^{-16} m^2. A lower permeability matrix will allow the pulse to be imbibed less efficiently and penetrate deeper than a higher permeability matrix. With nearly three orders of magnitude variation in permeability, the aperture of the fast path needed to penetrate D = 94.8 m of PT_{nv} varies from approximately 0.5 mm to 1.5 mm. Similarly, the sensitivity of pulse penetration to matrix

liquid saturation is shown in Figure 6. If a matrix has high initial saturation, its capillary force is weaker and its ability to suck water is less than that for a drier matrix. The thickness of matrix adjacent to such a fracture which would imbibe water from the fracture is small, of the order of 0.2 m to 0.6 m (Figure 7) for a permeability of 2.49×10^{-14} m^2 and matrix saturations of 64% and 88%. The volume wetted by a pulse has a wedge shape with the imbibition thickness depending linearly on z. The depth of penetration is set at 94.8 m for the two curves in Figure 7. If the imbibition thickness is indeed small, fast flow could occur without significant mixing between meteoric fracture water and matrix pore water.

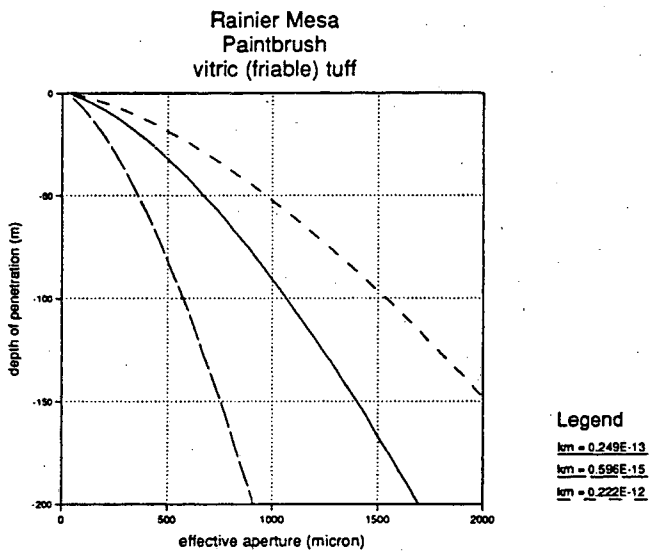


Figure 5. Depth of penetration for a water pulse containing 10% of the total infiltration in the U12n catchment.

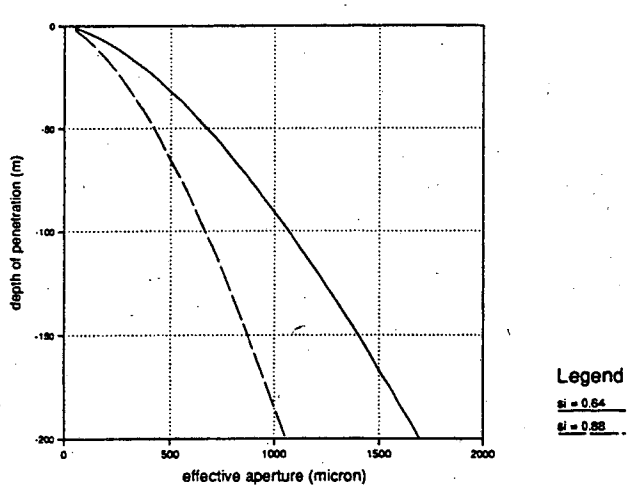


Figure 6. Dependence of penetration depth on matrix saturation.

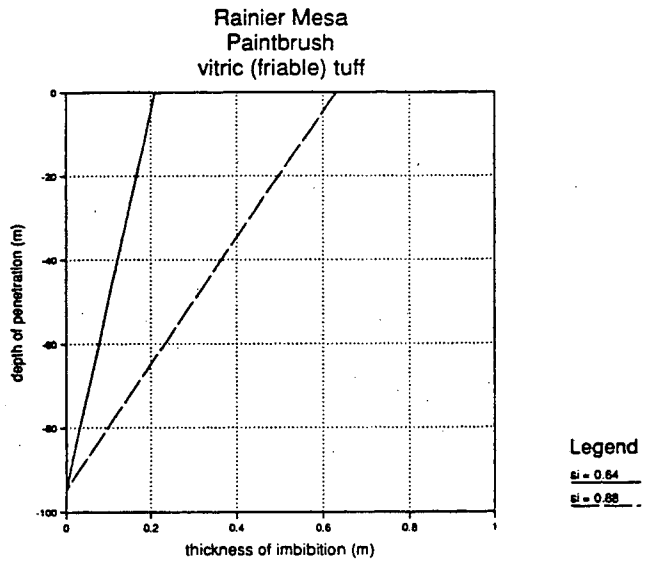


Figure 7. Wetting front imbibed into partially saturated tuff matrix.

DISCUSSION

The observations at Rainier Mesa have significant implications for the site characterization and performance assessment of a potential nuclear waste repository at Yucca Mountain. Flow of groundwater and the possible transport of radionuclides from the potential repository through the Calico Hills to the underlying aquifer is a key to isolation in the event of the leakage of soluble radionuclides from the canisters. The information from Rainier Mesa indicates that "fast path" fracture flow may pass through the Paintbrush nonwelded vitric unit to reach the Calico Hills, at least under conditions of infiltration similar to those at Rainier Mesa. An important issue is to determine whether or not such flow occurs in the Calico Hills at Yucca Mountain under present conditions. If it does not occur now, then how much larger infiltration rates are needed before fracture flow does occur? The Rainier Mesa data suggest that little mixing of waters in the matrix and fractures occurs. This implies that the retardation of nuclides in water flowing through fractures by absorption into the adjacent zeolitized matrix may also be slight. Finally, how would different repository temperatures affect heterogeneous flow through the Calico Hills?

These important questions can be answered by careful observations and experiments in the Paintbrush, Calico Hills and other tuff units. Combination of hydrological, geochemical, and geophysical investigations is critical to the understanding of heterogeneous flow and transport in fractures and matrix. Initially, further analysis and additional measurements of transport at Rainier Mesa would be helpful in resolving some of the uncertainties concerning groundwater flows observed at the sites. For example, comparative measurements of the permeabilities of cores can resolve the disparity between values of permeabilities at Rainier Mesa and those in the same tuffs at Yucca Mountain, which appear to be several orders of magnitude less in value. In

addition, fractures in Rainier Mesa cores can be examined mineralogically and geochemically, particularly the extent and composition of fracture linings and coatings, and of the alteration in the adjacent matrix, with the purpose of identifying evidence relating to retardation of contaminants in water flowing through fractures. Further, geochemical and isotopic measurements (including ^{36}Cl) can be made to define more precisely travel times and paths at Rainier Mesa. Finally, a thorough hydrological/transport analysis can be made of the observations at Rainier Mesa. In addition to providing a better understanding of the process at the Mesa, this work would constitute a prototype for the analyses that will have to be made of the ESF data from Yucca Mountain. Comparative studies of Rainier Mesa and Yucca Mountain could also be useful to test alternative models for flow and transport through tuff units. If a model could be used to interpret fast flows at high infiltration rates, the predictions for flows at low infiltration cases might be more creditable.

For ESF testing at Yucca Mountain, the radionuclide transport issues can be emphasized by performing sufficient testing in the Calico Hills as a matter of priority. The planning and design of the ESF activities and Study Plans for the Calico Hills should incorporate the knowledge we now have and will still gain from studying Rainier Mesa. The activities should allow for the possibility of fast flows occurring in Calico Hills at Yucca Mountain. The tests should involve the identification of intersections in the Calico Hills of drifts and drillholes with fractures and faults and careful observation and measurement of any existing flow in these discontinuities. Such flows may be small and transient, putting a premium on carefully-controlled development of hydro-chemical characterization procedures. Whether or not such flow now occurs, it will then be necessary to plan experiments in the Calico Hills at sites containing fractures and faults to determine the flow and transport properties of these features for ultimate evaluation of repository performance at Yucca Mountain. One very useful approach is the development of geophysical techniques to locate and characterize fast path features not intersected by drillholes or excavations. The challenge is to characterize the potential fast flow paths and to determine the conditions which activate the fast transport. An integrated, interdisciplinary approach is critical to the success of meeting this challenge.

ACKNOWLEDGEMENTS

We would like to thank G. S. Bodvarsson and K. Pruess for reviewing this paper. Work is performed under the auspices of the Director, Office of Civilian Radioactive Waste Management, Yucca Mountain Site Characterization Project Office, Regulatory and Site Evaluation Division of the U. S. Department of Energy through Contract Number DE-AC03-76SF0098.

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