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**A Measurement System for Systematic Hydrological Characterization of Unsaturated
Fractured Welded Tuff in a Mined Underground Tunnel**

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ABSTRACT

A field investigation of unsaturated flow through a lithophysal unit of fractured welded tuff containing lithophysal cavities has been initiated. To characterize flow in this spatially heterogeneous medium, a systematic approach has been developed to perform tests in boreholes drilled at regular intervals in an underground tunnel (drift). In this paper, we describe the test equipment system that has been built for this purpose. Since the field-scale measurements, of liquid flow in the unsaturated, fractured rocks, require continuous testing for periods of days to weeks, the control of test equipment has been fully automated, allowing operation with no human presence at the field site. Preliminary results from the first set of tests are described. These tests give insight into the role of the matrix (perhaps also lithophysal cavities) as potential storage during the initial transient flow prior to the breakthrough of water at the drift crown, as well as the role of connected fractures that provide the subsequent quasi-steady flow. These tests also reveal the impact of evaporation on seepage into the drift.

INTRODUCTION

The possibility that certain locations in unsaturated, fractured geological environments may serve as possible disposal sites for high-level radioactive waste has in recent years spurred much

research towards understanding of flow and transport phenomena in these settings. Water flow in unsaturated fractured rock is complex because it is affected by both the matrix and fracture properties, and the coupling between them, which in turn, is dependent on the degree of saturation. The intrinsic complexity of the flow processes, and the difficulty in interpreting and correlating measurements to flow and transport parameters, call for experiments executed under well-controlled conditions that are more easily attainable in the laboratory. On the other hand, because of the significant role of spatial scaling in flow phenomena, *in-situ* measurements are also indispensable. In this paper, we describe an experimental system for field investigations of flow and transport in partially saturated, fractured welded volcanic tuff. The *in-situ* measurements were designed to specifically address the issue of spatial variability.

Field investigations of flow and transport through thick unsaturated zones have been carried out using both the soil physics approach and from modeling geochemical constraints. The soil physics approach relies upon making measurements, such as moisture potential or permeability, and applying a model such as Darcy's law to predict transport. *Andraski* [1997] used thermocouple psychrometers and neutron log data to interpret infiltration in arid soils used to store low-level radioactive wastes. This type of approach has been found to be inadequate in highly heterogeneous formations. Stochastic approaches, such as the heterogeneity index used by *Stagnitti* [1999] to model percolation experiments, have attempted to work around the difficulties of a heterogeneous system.

Geochemical constraints used to study transport include natural radioactive isotopic dating, anthropogenically introduced chemicals and radioactive isotopes as environmental tracers, and

basic soil chemistry. Soil chloride concentration has long been used to estimate infiltration rates. *Scanlon* [1991] used chloride concentration to study moisture flux in desert soils, whereas *Fabryka-Martin et al.* [1998] looked at chloride concentration in boreholes drilled from the Exploratory Studies Facility at Yucca, Mountain, Nevada, to estimate infiltration rates in the deep vadose zone. *Izbicki et al.* [1995] and *Nativ et al.* [2000] have looked at percolation in desert areas using $\delta^{18}\text{O}$ and δD water composition under washes in the Mojave Desert, California, and in the Negev desert, Israel, respectively. Both these studies have also looked at chloride concentrations to infer information about soil water flux rates.

The soil-physics approach is limited in heterogeneous fractured rock, where continuum approximations fail to model hydrological processes. The geochemical- constraint methodology often presents conflicting data not easily explained by the current conceptual understanding of flow and transport. *Wolfsberg et al.* [1998] used ^{36}Cl and ^3H isotopes introduced into the atmosphere during nuclear tests as a tracer to infer that a component of infiltration at Yucca Mountain, NV is extremely rapid, on the order of meters per year. This contrasts with the net estimates of several millimeters per year presented by *Fabryka-Martin et al.* [1998] based on chloride concentrations. Likewise, the work of *Andraski* [1997] fails to explain observations of rapid transport of tritium [*Prudic et al.*, 1997] from a nearby low-level radioactive waste site in Beatty, Nevada through several hundred meters of fluvial deposits.

The limitations of both the soil physics approach and the geochemical constraints methodology have led others to try innovative *in-situ* experiments that could provide a better understanding of infiltration processes through heterogeneous unsaturated media. For example, *Shimajima et al.*

[2000] looked at the seepage discharge in a tunnel to understand mechanisms of infiltration in a fractured sedimentary formation. This work aimed to separate components of matrix and fracture flow. *Dahan et al.* [1998] developed a measurement system to collect water in compartmentalized sample locations within a 25 cm diameter core-drilled borehole in a fractured chalk infiltration experiment. At the Hell's Half Acre Lava Field, southeastern Idaho, *Podgorney et al.* [2000] conducted ponded infiltration tests above a ledge overhanging a partially collapsed lava tube with drip sensors and collection pans to characterize flow through individual fractures in near-surface basalts.

Work conducted by *Wang et al.* [1999] investigated mechanisms of seepage through volcanic tuffs, within Yucca Mountain, Nevada. Their approach of conducting air-permeability and liquid seepage studies along with dye tracers serves as a starting point for the current work, which seeks to develop a systematic testing methodology for investigating water percolation through a highly heterogeneous system at Yucca Mountain. The geological features of the mountain include a lithophysal unit (the lower lithophysal unit in the Topopah Springs welded unit). This unit, located approximately 300 m below the ground surface, is being considered as the proposed national storage location for high-level nuclear waste. The unit is traversed by a 5 m diameter tunnel (East-West Cross Drift) in the 8 km long Exploratory Studies Facility (ESF) at Yucca Mountain. The lithophysal unit has many fractures that are less than 1 meter in length and lithophysal cavities ranging in size from 15 to 100 cm. Both the fracture and lithophysal cavity size and spacing vary significantly along the drift walls over an 800-meter stretch within the same unit, indicating that hydrological characteristics at one particular location are not likely representative of the entire lower lithophysal unit. Therefore, systematic testing at regular

intervals along the drift, unbiased by knowledge of specific features, is needed to gain an understanding not only of the hydrological characteristics, but also the associated heterogeneities of this unit.

To facilitate a systematic characterization of the lower lithophysal unit at Yucca Mountain for understanding flow and transport of radionuclides, we have designed an array of instruments to evaluate fracture permeability, effective porosity, and characteristics of water seepage into a drift. In this paper, we describe this custom-built equipment system and present initial results from the ongoing systematic characterization of the welded tuff in the East-West Cross Drift.

TEST SYSTEM DESIGN AND FUNCTION

Testing Overview

For systematic characterization, tests will be performed in 20-meter long boreholes at regularly spaced locations along the drift, shown schematically in Figure 1. Air-injection and liquid-release tests will be performed in low-angled boreholes inclined at 15° from the drift-axis. These low-angled boreholes are drilled from the crown (top) of the 5 m diameter East-West Cross Drift; the spacing of adjacent boreholes from collar (start of hole) to collar is 30 meters. The pressure response to air-injection tests will give a measure of fracture permeability. The liquid-release tests into these low-angle boreholes are intended for determining (1) the ability of the open drift to act as a capillary barrier that diverts water around itself [Phillip, 1989], and (2) the potential of water to seep into the drift. The latter is of particular importance because the current design of the potential repository at Yucca Mountain calls for emplacement of waste canisters in 5 m diameter drifts. Consequently water seepage into the drifts is relevant to corrosion of waste

canisters and subsequent release of radionuclides. Figure 1 also shows two other groups of boreholes along the tunnel. One configuration consists of near-vertical boreholes drilled from the crown of the drift, while the other consists of pairs of parallel horizontal boreholes, spaced at 3 m intervals and drilled from the side of the drift. The former are intended for air injection tests to determine the effect of drift excavation on fracture properties, and the latter are for gas tracer tests to determine the effective porosity. These two categories of boreholes drilled along the Cross Drift have a systematic group-to-group separation of 90 meters. In this paper, we focus on measurements only in the low-angle boreholes.

Two criteria govern the design of the equipment system: automation and mobility. The underground facility for our field experiments is typically open only eight hours per day for four days every week, but for our field-scale measurements involving liquid flow in unsaturated rocks, we require continuous testing for periods of weeks to months. It is therefore essential that control of test equipment be fully automated and allow remote intervention if necessary with no human presence at the field site. The second criterion of mobility is achieved by designing all equipment needed for the systematic characterization as a complete unit to fit on flatbed rail cars. This allows for equipment to be efficiently transported from one test station to another along the tunnel.

A schematic of the systematic testing equipment system is shown in Figure 2. The function of the equipment is to distribute water at a specified rate along a specified length of borehole and to capture any water that makes its way from the borehole through the rock formation as seepage

into the drift. The key components of the system are the packer assembly, the water supply hardware, and the seepage capture system.

Packer Assembly

The packer assembly uses inflatable rubber packer units to seal off sections of borehole, so that released water cannot reach these sections, and isolates each borehole into three nonsealed 2 m sections into which water can be introduced. Water is released into these unsealed sections or zones by one of two means. One method uses a single release point close to the rubber sealing section at the far (upper) end of the unsealed zone. The other method uses multiple orifices along the unsealed section to enable water to be released at many points along the entire unsealed section. The packer assembly has an additional feature in that it can let water out of the unsealed sections as return flow through a drain hole at the lowest point in the zone should the delivery rate prove to be too high for all the water to completely enter the formation. Because of the small-angle incline of the borehole, the vertical distance from the outermost unsealed section to the drift crown is about 1 meter while the vertical distance between the second and innermost sections and the crown are on the order of 2.5 and 5 meters respectively.

The three sealing sections of the packer assembly use 3-meter long, 0.64 cm thick, 5-cm diameter soft inflatable rubber tubing supported and clamped at each end onto a stainless steel core for an overall uninflated diameter of 6.3 cm. The rubber is inflated with compressed air. The relatively long packers (3 m) are intended to provide effective sealing even in rock where the size of lithopysal cavities can reach 1 m.

Of the three water-delivery sections, also made of 5 cm diameter stainless tubing, two lie between the three rubberized sections in the borehole and the third lies beyond the furthest rubber section into the borehole. Tubing resides inside each of the delivery sections for single point injection, for multipoint injection at six evenly spaced locations, and for drainage of overflow. One additional tube from each delivery section connects it to a pressure transducer located outside the hole, so as to measure air pressure in each zone.

In keeping with the design requirements of the testing site, the sections of packer assembly are shipped as separate parts and assembled at the site. O-rings at the connections between sections ensure that the annuli left around the water delivery sections are sealed from atmospheric conditions inside the hollow, open packer core. The packer inflation, water supply, and water drain tubing from all sections runs through the core of the packer assembly to the outside of the borehole, where it hooks into the water supply system.

Water Supply System

Each delivery section in the borehole is supplied by its own water supply system. The water supply components control the amount of water delivered to a section and also measure the total quantity of water supplied to that section over time. In addition, the components also measure, over time, the quantity of any return flow through the drain port from the delivery section. Each supply system makes use of twin vertical cylindrical bottles to supply and measure the water that is delivered. The bottles are 1.5 meters tall and 20 cm in diameter, providing a balance between volume resolution, supply volume and mobility. One bottle can fill while the other is pumped so that the supply and measurement system can run without interruption. Differential pressure

transducers are located at the base of each bottle. These account for changes in atmospheric pressure and are used to measure the head of water in each bottle, which, when multiplied by the known area of a bottle, yields the current water quantity residing in the bottle. One of two sizes of electronically controlled gear pumps pump water from the bottom of the active supply bottle and up to the packer assembly for water delivery. The two different size pumps are used to provide a range of 10 ml/min to 2000 ml/min supply rate. The crossover from the small pump to the large pump is at about 300 ml/min. Valves enable either bottle to supply either pump and either pump to supply either the single-point delivery tube or the multipoint delivery tube. Another valve to each bottle directs any return flow to run back into the inactive bottle so that this flow can be measured. One more valve at each bottle supplies each with refill water from the tunnel water supply when needed. All the valves are pneumatically actuated via air lines controlled by solenoids. Electronic relays under computer control operate the solenoids. Voltage signals delivered by digital-to-analogue converters under computer control govern the pumps, and an analogue-to-digital converter with a multiplexor converts the transducers' current-loop output to digital format, which is recorded by the same computer used for valve and pump control.

Air-Injection System

The water supply system includes an air injection system for determining the air permeability of each delivery zone. Incorporated into the single-point delivery tubes are valves that allow water to drain from these tubes and valves that allow introduction of air into each zone. Mass-flow controllers can deliver air at constant-mass flux through the single point injection line. Dedicated absolute-pressure transducers for each zone enable air pressure measurements during air

injection and thus allow calculation of air permeability. The mass flow controllers are computer controlled, and air flow rates are recorded by the data acquisition system.

Seepage Capture System

The equipment for seepage capture system at each zone consists of a horizontally mounted V-shaped PVC curtain, which captures seepage from the rock under the release zone and funnels it into twin collection bottles designed similarly to the supply bottles. Figure 2 shows the arrangement of the capture curtains relative to the packer system. A valve at the bottom of each bottle allows drainage into the tunnel drain. Another valve at the top of each determines whether collected water can enter. This configuration thereby allows drainage of one bottle without interruption of seepage collection and measurement in the other. The collection system also utilizes differential pressure transducers to obtain head and therefore quantity of water in the bottles. As with the supply system, the collection system is serviced by the computerized control and recording system.

Control and Recording System

In addition to continuous recording of all transducer outputs, the computer for the supply and collection systems enables the processes for both to be manually or automatically controlled. The computer incorporates secure remote-control capability so that the systems can be started and controlled from any networked computer.

Automation Program

The automation program takes two basic parameters from the operator, that of pump rate and that of water delivery zone selection. All other aspects of control are performed automatically.

Pumping starts from bottle A while bottle B collects return water, until the water content read by the bottle A transducer indicates that this bottle is nearly empty. At this point bottle B is filled to a preset limit (as read by the transducer) if it is not at this limit already. When bottle B is filled, pumping is switched from bottle A to bottle B. Bottle A is now able to collect any return flow.

While filling from the main water supply, bottles are not able to collect return flow. Because filling is a rapid event, this pause in collection does not adversely affect data collection. If filling does not occur rapidly enough to prepare the second bottle before the first one runs dry, the pump is switched to the second bottle even before it is completely full when a lower limit is passed (as read by the transducer of the first bottle). Conversely, if complete filling from return flow occurs before the other bottle has a chance to completely empty the pump will switch to the full bottle so as avoid an overflow condition. To obtain a smooth record of all the water delivered to a zone, the water content of a bottle being emptied is subtracted from the water content at the start of that bottle's emptying. This value is in turn added to the total recorded when the last bottle switch occurred. A similar arrangement works for the return-water record.

System Fail-safes

To avoid over-filling of the bottles or running the pumps dry, in the event of a failure in the automatic control system or inadvertent use of the controls on manual setting, the system employs float switches at the top and bottom of the bottles as a backup to the automation. When triggered the bottom float switches force the pumps on these to stay off even if requested to

operate by a user or automation system. The top float switches interrupt the electrical current to the fill valves when triggered. In the event of a computer shutdown such as during a power failure, all the relays and pump controls are turned off so that the system defaults to a stand-by mode.

PRELIMINARY EXPERIMENTAL RESULTS

Air-Injection Tests

The first set of field measurements deploying the systematic equipment and testing control system were carried out in May 2000 in a low-angle borehole (LA#2) located 1,726 meters from the start of the East-West Cross Drift. The packers were set such that the three zones for fluid injection lay at average vertical distances of 1.58 m, 2.84 m and 4.10 m above the drift crown. A constant flow rate of air (200 Standard Liters Per Minute) maintained by mass flow controllers was introduced into each of the three isolated borehole zones, in turn. The pressure responses as a function of time, to the air injection into the three zones, are shown in Figure 3. The local permeability, averaged over the zone length, was evaluated from the steady-state pressure response in the injection borehole by means of an analytical solution *LeCain*, [1995]; *Guzman et al.*, [1996]; *Cook*, [2000]. yielding estimated permeabilities of, respectively, $2.5 \times 10^{-11} \text{ m}^2$, $2.6 \times 10^{-11} \text{ m}^2$, and $1.1 \times 10^{-11} \text{ m}^2$, for the three zones. These rather large values indicate that at a scale of two meters, the fractures (and/or lithophysal cavities) are well connected. These large values are to be contrasted to the saturated matrix permeability value of $2.3 \times 10^{-17} \text{ m}^2$ based on the geometric mean of 453 core samples from surface-based boreholes, (Flint, 1998).

Water-Release Tests

The design of our equipment for three completely independent systems allows water-release tests to be performed in all three zones of the borehole LA#2 simultaneously. The multipoint mode of injection was used so that water was evenly spread along each 2 m zone. Figure 4 shows the cumulative volume of water supplied to the rock (left y axis) and the cumulative volume of water that seeped through the drift crown and collected in the seepage collection system (right y axis) as a function of time. Data for zones 1, 2 and 3 are displayed in Figures 4a, 4b, and 4c respectively. Understandably, the time for the initial arrival of seepage water increased with the vertical distance between the borehole section into which water was introduced and the drift crown. Thus, the time recorded by the data acquisition system for the first arrival of water into the seepage collection cylinders are 22.9 hours, 150 hours for zones 1 and 2 respectively. Water release continued for a period of about nine days in zone 1, and for about 16 days in zone 2. For zone 3, due to the experimental problem of interface between the software control and the valves controlling the water supply system, the release of water was interrupted for two periods over a total duration of 34 days of testing. The periods where no water was supplied were (1) two days between May 30 and June 1, and (2) 11 days between June 3 and June 14. The experimental problem was corrected on June 14, and the first sign of seepage water being collected in the seepage bottles for zone 3 was recorded by the data acquisition system to be at midnight June 26, 2000. (The apparent non-zero readings before this are noise.) Unfortunately, other testing activities in the underground tunnel necessitated the termination of water release in zone 3 as well as monitoring of data only about 8 hours after the first onset of seepage. For the tests in zones 1 and 2, however, we were able to resume the steady release of water until the rates of seepage reached "steady state," and to collect monitoring data long past the termination of water

release into these borehole sections. We observed that seepage to the drift ceased within hours of (for zone 1) and less than a day after (for zone 2) the turnoff of water supply. Through the duration of each test, the cumulative volumes of water introduced into the boreholes were 335 liters for zone 1 and 665 liter for zone 2, while the cumulative volumes of water recorded by the seepage collection bottles from water released in these two borehole zones are 49 liters and 14 liters respectively.

Very prominent in the cumulative volume of seepage water data in Figure 4b are the step-like structures, indicating two different slopes and therefore different rates of seepage. The periods of larger slope in Figure 4b can be correlated to evenings and weekends when the underground tunnels were closed for access and the ventilation system was not in operation. Data in Figure 4a for zone 1 also give different slopes for seepage water volume versus time, depending on whether ventilation is on or off. The step-like signature in Figure 4a is more obscure than that in Figure 4b because of the higher rate of seepage here. The fact that water that has seeped into the drift has evaporated and is therefore not recorded by our data acquisition places uncertainty on the seepage data. This is because even when the ventilation is not in operation in the evenings and on weekends, the relative humidity in the underground tunnels is still far below 100%. As a result, while data in Figures 4a and 4b gives a measure of the extra amount of water continually lost to evaporation due to active ventilation, it does not provide information on the amount of water lost to evaporation in the absence of active ventilation. As a result of these initial results, we incorporated into the system measurements of relative humidity and evaporation potential (from an open pan) in the tunnel space between the drift crown and the seepage collection PVC curtain enclosure. Preliminary data from the modified testing system indicate that perhaps 10 to

20% of seepage water could have been lost to evaporation in the evenings and weekends when the active ventilation was off.

Despite the uncertainty associated with evaporation measurements, this first test in the systematic characterization gives insight to unsaturated flow in the lower lithophysal unit of the fractured welded tuff. Figure 4b shows that the cumulative volumes of water introduced into the three borehole zones at the time of initiation of recorded seepage were on the orders of 37 liters, 270 liters, and 1071 liters, respectively. It is anticipated that fractures will dominate any steady state liquid flow component while cavities and matrix contribute to the initial storage. Thus the cumulative volume of water introduced into the rock mass until the onset of seepage provides an estimate of the storage porosity. Lithophysal cavities, fractures and matrix contribute to the overall porosity of the lower lithophysal rock. Observations along the drift wall indicate a mean lithophysal cavity porosity of 0.125. Gas tracer measurements indicate the fracture porosity is on the order of 0.003 to 0.01. Both the cavities and the fractures are expected to be essentially dry at ambient conditions. The laboratory measurements from 453 samples from surface-based boreholes give the mean matrix porosity of 0.13 and a mean saturation of 0.78 (Flint, L.E. 1998), hence the matrix contribution to actual porosity available for liquid storage during systematic testing is about 0.03. We hypothesize that for the systematic tests, when seepage is initially recorded, the flow can be assumed to have reached, along fast paths, the wall of a cylinder which has roughly the diameter equal to the distance between release zone and the drift ceiling. The assumption of the cylindrical volume for the flow plume is based on field observations (Robert Trautz, personal communication) where water traced with colored dye was released into rock mass, and subsequent mine out of the rock in the flow paths suggested the shape of the flow

plume was roughly spherical underneath the release point. The plume volume for the three zones is obtained by substituting the heights of the three zones from drift ceiling (1.58 m, 2.84 m and 4.10 m, respectively) for the cylinder diameters, and applying the liquid release zone of ~ 2 meters to the cylinder length. An estimate of the effective porosity for the establishment of fast paths is obtained by dividing the volume of water introduced (37 liters, 270 liters, and 1071 liters, respectively) by the cylinder volume. The simple calculations give respectively the liquid storage porosity of 0.009, 0.02, and 0.04 for the three zones. The values of these rough estimates (when compared to the available porosity contribution from fractures, cavities, and matrix) are consistent with the conceptual model that until the first arrival of recorded seepage, water is being imbibed and stored in the matrix pores. Once seepage is initiated, flow is likely through the least resistive fast paths with weak capillary suction. The latter occupies a far smaller fraction of pore space, which probably accounts for the observation that seepage water ceased within hours of water-release termination in the borehole. These rough estimates also suggest that the cavities participate little in the initial storage during the transient flow period.

CONCLUSION

A field investigation of the unsaturated flow through a lithophysal unit of fractured welded tuff has been initiated. To characterize flow in the spatially heterogeneous medium a systematic approach has been chosen to perform tests in boreholes drilled at regular intervals in an underground tunnel. In this paper, we have described the customized test equipment system that has been built for this purpose and presented preliminary results from field tests. Since field-scale measurements involving liquid flow in unsaturated rocks require continuous testing for periods of days to weeks, the control of test equipment has been fully automated, allowing the

equipment to be operated remotely with no human presence at the field site. Field observations reveal the impact of evaporation to the determination of seepage into the drift. As the less than 100% humidity conditions and tunnel ventilation are field boundary conditions that cannot be avoided, our equipment system has been modified to incorporate monitoring of humidity and evaporation potential into the liquid flow and seepage measurements. The uncertainty on the seepage data due to evaporation notwithstanding, the first test gives insight to the role of matrix and lithophysal cavities as storage during the initial transient flow prior to the breakthrough of water at the drift crown, and the role of connected fractures that provide the subsequent quasi-steady flow.

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REFERENCES:

Andraski, B. J. 1997. Soil-water movement under natural-site and waste-site conditions: a multiple-year field study in the Mojave Desert, Nevada, *Water Resour Res.* 33(8): 1901–1916.

Cook, P. 2000. *In situ* pneumatic testing at Yucca Mountain. *International Journal of Rock Mechanics and Mining Sciences* 37: 357–367.

Dahan, O., R. Nativ, E. Adar, B. Berkowitz. 1998. A measurement system to determine water flux and solute transport through fractures in the unsaturated zone, *Ground Water*, 36(3): 444–449.

Fabryka-Martin, J. T., S. T. Winters, A. V. Wolfsberg, L. E. Wolfsberg, J. L. Roach. 1998. Using chloride to trace water movement in the unsaturated zone at Yucca Mountain. High-Level Radioactive Waste Management Conference, Amer. Nucl. Soc., La Grange Park, Illinois.

Guzman, A. G., A. M. Geddis, M. J. Henrich, C. F. Lohrstorfer, and S. P. Neuman. 1996. Summary of air permeability data from single-hole injection tests in unsaturated fractured tuffs at the Apache Leap Research Site; Results of steady-state interpretation, *U.S. Nuclear Regulatory Commission Report NUREG/CR-6360*. Nuclear Regulatory Commission, Washington DC.

Flint, L. E. 1998. Characterization of hydrogeologic units using matrix properties, Yucca Mountain, Nevada. *Water-Resources Investigations Report 97-4243*. U.S. Geological Survey, Denver, Colorado.

Izbicki, J. A., J. Radyk, and R. L. Michel. 2000. Water movement through a thick unsaturated zone underlying an intermittent stream in the western Mojave Desert, southern California, USA, *J. Hydrol.* 238: 194–217.

LeCain, G. D. 1995. Pneumatic testing in 45-degree-inclined boreholes in ash-flow tuff near Superior, Arizona, *Water Resources Investigations Report 95-4073*, U.S. Geological Survey, Denver, Colorado.

Loll, P., P. Moldrup, P. Schjonning, H. Riley, 1999. Predicting saturated hydraulic conductivity from air permeability: Application in stochastic infiltration modeling, *Water Resour. Res.* 35(8): 2387–2400.

Nativ, R., E. Adar, O. Dahan, and M. Geyh. 1995. Water recharge and solute transport through the vadose zone of fractured chalk under desert conditions. *Water Resour. Res.* 31(2): 253–261

Phillip, J. R. 1989. The seepage exclusion problem for sloping cylinder cavities. *Water Resour. Res.* 25(6); 1447–1448.

Podgorney, R. K., T. Wood, B. Faybishenko, and T. Stoops. 2000. Spatial and temporal instabilities in water flow through variable saturated fractured basalt on a one-meter field scale. In *Dynamics of Fluids in Fractured Rocks, Geophysical Monograph 122*, American Geophysical Union, Washington D.C.

Prudic, D. E., Stonestrom, D. A., R. G. Striegel. 1997. Tritium, deuterium, and oxygen-18 in water collected from unsaturated sediments near a low-level radioactive waste burial site south of Beatty, Nevada, *Water-Resources Investigations Report 97-4062*. U.S. Geological Survey, Denver, Colorado.

Scanlon, B. R. 1991. Evaluation of moisture flux from chloride data in desert soils, *J. of Hydrol.* 128: 137–156.

Shimijima, E., T. Tanake, Y. Hoso, R. Yoshioka, G. B. Davis. 2000. Using short- and long-term transients in seepage discharge and chemistry in a mountain tunnel to quantify fracture and matrix water fluxes, *J. of Hydrol.* 234: 142–161.

Stagnitti, F., L. Li, G. Allinson, I. Phillips, D. Lockington, A. Zeiliger, M. Allinson, J. Lyod-Smith, M. Xie. 1999. A mathematical model for estimating the extent of solute- water-flux heterogeneity in multiple sample percolation experiments, *J. of Hydrol.* 215: 59–69.

Wang, J. S. Y., R. C. Trautz, P. J. Cook, S. Finsterle, A. L. James, J. Birkholzer. 1999. Field tests and model analyses of seepage into drift, *J. Contam. Hydrol.* 38: 323–347.

Wolfsberg, A. V., J. T. Fabryka-Martin, S. S. Levy, 1998. Use of chlorine-36 and other geochemical data to test a groundwater flow model for Yucca Mountain, Nevada. Use of Hydrological Information in Testing Groundwater Flow Models, OECD Proceedings, Borgholm, Sweden.

Figure Captions:

Figure 1. Schematic of borehole configuration in the East-West Cross Drift for systematic characterization of the unsaturated lithophysal unit of the fractured welded tuff at Yucca Mountain.

Figure 2. A schematic of the equipment system: packer assembly, water supply and air injection component, seepage collection component, and data acquisition and control.

Figure 3. Pressure response to constant mass flow of air injection for estimation of fracture permeability.

Figure 4a. Seepage into the drift from release of water in 2 m section of borehole at 1.58 meters above the drift crown.

Figure 4b. Seepage into the drift from release of water in 2 m section of borehole at 2.84 meters above the drift crown.

Figure 4c. Seepage into the drift from release of water in 2 m section of borehole at 4.10 meters above the drift crown.

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Figure 1. Cook

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Figure 2. Cook.

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Figure 3. Cook.

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Figure 4a. Cook.

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Figure 4b. Cook.

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Figure 4c. Cook.