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ESTIMATES OF THE HYDROLOGIC IMPACT OF DRILLING WATER ON CORE SAMPLES TAKEN FROM PARTIALLY SATURATED DENSELY WELDED TUFF

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ESTIMATES OF THE HYDROLOGIC IMPACT OF DRILLING WATER ON CORE SAMPLES TAKEN FROM PARTIALLY SATURATED DENSELY WELDED TUFF

Thomas A. Buscheck and John J. Nitao

<u>Abstract</u>

The use of drilling water may perturb near field hydrology around the waste package environment test so that the results are not indicative of native saturation conditions. The purpose of this work is to determine the extent to which drill water might be expected to be imbibed by core samples taken from densely welded tuff. In a related experimental study conducted in G-Tunnel, drill water imbibition by the core samples was observed to be minimal. Calculations were carried out with the TOUGH code with the intent of corroborating the imbibition observations. Due to the absence of hydrologic data pertaining directly to G-Tunnel welded tuff, it was necessary to apply data from a similar formation. Because the moisture retention curve was not available for imbibition conditions, the drainage curve was applied to the model. The poor agreement between the observed and calculated imbibition data is attributed primarily to the inappropriateness of the drainage curve. Also significant is the value of absolute permeability (k) assumed in the model. Provided that the semi-log plot of the drainage and imbibition moisture retention curves are parallel within the saturation range of interest, a simple relationship exists between the moisture retention curve, k, and porosity

(ϕ) which are assumed in the model and their actual values. If k and ϕ are known, we define the hysteresis factor λ to be the ratio of the imbibition and drainage suction pressures for any saturation within the range of interest. If k and ϕ are unknown, λ also accounts for the uncertainties in their values. After conducting a laboratory imbibition experiment, we found that $\lambda = 0.025$ yields very good agreement between the calculated and observed resaturation data. When $\lambda = 0.025$ is applied to the model of drill water imbibition by the core samples, the calculated and observed imbibition penetration depths are seen to compare reasonably well. Both the experimental and modeling studies show that drill water imbibition by the core has a minimal effect on its saturation state.

Introduction

The Nevada Nuclear Waste Storage Investigations (NNWSI) Project is studying the feasibility of constructing and operating a high-level nuclear waste repository in the tuffaceous rocks underlying Yucca Mountain, Nevada. The NNWSI project has assigned Lawrence Livermore National Laboratory (LLNL) the task of designing and assessing the expected performance of waste packages in the repository environment.

The reliable assessment of the waste package performance requires, among other things, accurate characterization of the thermal and hydrologic properties of the near field geologic environment. Various in situ tests will be conducted within the Topopah Spring member of the Paintbrush Tuff at Yucca Mountain to investigate the rock mass response to the heat load generated by emplaced electrical heaters representing waste packages. Of particular importance is the hydrothermal response of the variably saturated, fractured rock mass to heating, cooling, and possible future groundwater recharge events. Geophysical monitoring of the near field rock mass response to the simulated heat load will require the drilling of numerous instrument boreholes in the vicinity of the heater borehole. The use of water as a drilling fluid may perturb the near field hydrology so that the results of the tests are not indicative of native saturation conditions.

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The calculations reported herein were carried out in conjunction with experiments conducted by Daily and Ramirez (1987). The purpose of both studies is to determine the extent to which drill water might be expected to penetrate the matrix of core samples taken from densely welded tuff.

Experiment Description

The experiment described in Daily and Ramirez (1987) was part of a suite of "heater" experiments which are preliminary to those described in the Test Plan: <u>Prototype Engineered Barrier Design Testing</u> contained in the Nevada Waste Management Program Quality Assurance Program Plan (Lawrence Livermore National Laboratory, 1987). These experiments were conducted in the G-Tunnel complex at the Department of Energy, Nevada Test Site, Nye County, Nevada in a welded ash flow tuff formation of the Grouse Canyon member of the Belted Range tuff. This formation was chosen because it has bulk, thermal, and mechanical properties similar to those of Topopah Spring tuff found in the proposed repository horizon at Yucca Mountain.

A 5.8 meter long, 6 cm diameter borehole was cored 2° above horizontal into the rib of the small diameter heater alcove of the Rock Mechanics Incline. This hole was drilled using standard coring procedures except that the drill water contained a methylene chloride dye which stains the rock a dark blue on contact. Because this hole was drilled above any preexisting holes in the vicinity, this drilling activity represents the first time that the borehole wall and core were exposed to non-native saturation conditions. Six pieces of core were examined, and the observed depth of dye penetration was assumed to be indicative of the depth to which drill water imbibed into the rock matrix. In most of the samples the depth of dye penetration was observed to range from approximately 0.2 to 1.0 mm with an average of about 0.3 mm. In one highly broken piece of core, containing many pumice inclusions and lythophysal cavities, the depth of dye penetration ranged up to 7 mm.

Modeling Approach

When this investigation was first conceived, the goal was simply to corroborate the imbibition penetration observations of Daily and Ramirez (1987) with numerical calculations of matrix imbibition. Owing to limitations in the available data required to model this process as well as uncertainties in the applicable initial and boundary conditions, it was necessary to broaden the scope of the numerical modeling of this experiment to include parameter sensitivity and to recognize that conclusive corroboration between the experimental and numerical data was not possible.

For this investigation all numerical calculations were carried out using LLNL's version of the TOUGH code (Nitao, 1987; Buscheck and Nitao, 1987). TOUGH is a multidimensional numerical simulator capable of modeling the coupled transport of water, vapor, air, heat, and aqueous phase constituents in fractured porous media. It is a member of the Mulkom family of multiphase, multicomponent codes developed at Lawrence Berkeley Laboratory by Preuss (1985). The acronym "TOUGH" stands for "transport of unsaturated groundwater and heat". TOUGH has seen previous use in studies of high-level nuclear waste isolation in partially saturated geological media (Preuss, Tsang, and Wang, 1984).

The TOUGH simulator accounts for liquid and gaseous phase fluid flow under pressure, viscous, and gravity forces according to Darcy's law, with interference between phases represented by relative permeability versus saturation curves for the respective phases. The combined effects of capillarity and phase adsorption are accounted for in the suction pressure (or matric potential) versus saturation curves (also called the moisture retention curve). Vapor pressure lowering due to capillarity is accounted for using Kelvin's equation (Edlefsen and Anderson, 1943). In addition to binary diffusion in the gas phase, the effect of Knudsen diffusion, which is also called the Klinkenberg effect (Klinkenberg, 1941), may also be included. Hysteresis is not presently accounted for in either the moisture retention or relative permeability curves. An efficient equation-of-state table-look-up algorithm accurately determines the thermophysical properties of liquid water and vapor based on

experimentally determined steam tables (International Committee, 1967). Air is treated as an ideal gas and air dissolution in water is represented by Henry's law. Heat transport mechanisms include conduction, with thermal conductivity dependent on water saturation, and convection, including both sensible and latent heat. Dispersive heat transfer is not presently considered.

The governing mass- and energy-balance continuum equations are discretized in space using the "integral finite difference" method (Edwards, 1972; Narasimhan and Witherspoon, 1976). Time is discretized in a fully implicit manner. Due to the strongly coupled, highly nonlinear interdependence of mass and heat flow, TOUGH performs a completely simultaneous solution of the discretized governing equations, taking all coupling terms into account. The nonlinearities are handled by Newton/Raphson iteration and in LLNL's version of TOUGH the solution matrix is inverted using a block banded Gaussian elimination scheme (Nitao, 1987; Buscheck and Nitao, 1987). Additional details of the TOUGH code can be found in Preuss (1986) and Preuss, Tsang, and Wang (1985).

Modeling Drill Water Imbibition by Core Samples of Welded Tuff

The calculations of drill water imbibition into core samples of welded tuff carried out in this study require a number of assumptions regarding the relevant hydrologic properties, initial and boundary conditions. The exact nature of the hydrologic conditions imposed on the core samples during drilling is very difficult to assess. Because the drill water was free to drain out of the collar of the slightly inclined borehole, it was assumed that the annular space surrounding the core is filled with water at a pressure of 1.0 atmosphere. Due to the high suction pressures prevalent at native saturation conditions in this experiment, a variation of several atmospheres in the drill water pressure has a negligible impact on the rate of imbibition by the core. For the formation of interest, Zimmerman and Blanford (1986) reported an initial saturation greater than 60 percent and a porosity ranging from 15 to 46 percent. For our calculations we have assumed a porosity of 20 percent and an initial saturation of 65 percent. Based on the drilling

rates observed during this experiment, Wilder (personal communication, 1987) estimated that any given section of core was in contact with drill water for no more than one hour.

There are no published data for the characteristic curves (relative permeability and suction pressure versus saturation) for the welded tuff in the Grouse Canyon member. The only available data for absolute permeability were measured with air (Board, et. al., 1987). Because no attempt was made to isolate the effect of Knudsen diffusion (slip flow) in their gas permeability measurements, their values for absolute permeability are likely to be greater than values which would have been obtained with water. Russo and Reda (1987) report that the effect of Knudsen diffusion can result in gas permeability being an order of magnitude greater than water permeability measured in the same sample. Because our imbibition calculations are much more sensitive to water permeability than gas permeability, we decided that the gas permeability data of Board and others (1987) was not applicable to our calculations.

Zimmerman and others (1984) determined that the welded tuffs in G-Tunnel have similar bulk, thermal, and mechanical properties to those of Topopah Spring welded tuff found in the repository horizon at Yucca Mountain. Accordingly, we decided to use the absolute permeability and characteristic curve data obtained by Peters and others (1984) for sample G4-6 which was cored at a depth of 1158 within the repository horizon at Yucca Mountain. The characteristic curves were obtained by applying the curve-fitting method developed by van Genuchten (1980) to the data. Peters and others (1984) express their characteristic curves as functions of suction pressure. The input requirements of TOUGH make it necessary to re-express the characteristic curves in terms of saturation (see Figures 1 and 2).

It is important to recognize the conditions underwhich Peters and others (1984) obtained their moisture retention data. Starting with a fully saturated sample, they desaturated it in small incremental steps by placing it in a microwave oven for 30 seconds, removing and allowing the sample to cool before weighing it and measuring the suction pressure with a thermocouple psychrometer. The microwave enabled the samples to be

dried more uniformly than drying in a conventional thermal oven. Assuming that the mass of pore vapor which re-condenses during cooling is negligible in comparison with that which leaves the sample, this process is effectively one of drying (i.e. drainage). Because data was not obtained under wetting (i.e. imbibition) conditions, it is not possible to construct hysteretic moisture retention curves which apply to imbibition as well as drainage. Therefore, we decided to use the drainage curve in our first attempt to model the in situ imbibition experiment. Table 1 and Figures 1 and 2 summarize the hydrologic parameters used in our calculations.

For our calculations the core is represented with a one-dimensional radially-symmetric finite difference mesh with a radius of 3.0 cm. Because drill water penetration was never observed to be more than 1.0 mm in any of the core samples, very fine spatial resolution in the numerical mesh is required close to the surface of the core. Table 2 lists the grid spacing used in the model, progressing from the core surface to the centerline. Notice that a very fine mesh of 0.05 mm is used from the surface to a depth of 0.5 mm, followed by a grid spacing of 0.1 mm to a depth of 1.0 mm into the core. The core has a porosity of 20 percent with an initial uniform saturation of 65 percent. The drill water surrounding the core is represented with a boundary block having 100 percent porosity which is fully saturated at a constant pressure of 1.0 atmosphere. Drill water imbibition by the core is assumed to occur under isothermal conditions. All fluid properties are determined from their state values at an assumed ambient temperature of 23°C. Any heat build up which would result from dissipating the mechanical energy of drilling is neglected.

Figure 3 is a plot of liquid saturation versus radial distance from the core centerline after 1.0 hour of exposure to the drill water. The imbibition front has penetrated more than 1.0 cm into the core, far in excess of the 0.3 mm average penetration observed in the samples. Owing to the lack of hydrologic data which is directly applicable to welded tuff in G-tunnel, the pronounced discrepancy between the observed and calculated depth of the imbibition front could be the result of the inappropriateness of any or all of the hydrologic data used. However it should be noted that, in addition to the assumption concerning the applicability of the Yucca Mountain data, there is no available moisture retention data for imbibition conditions for the welded tuff found either at G-tunnel or Yucca Mountain. Consequently, it was decided to test the applicability of the drainage curve to modeling an imbibition process.

The effect of hysteresis on moisture retention curves is well known to the field of soil physics (Hillel, 1982; Marshall and Holmes, 1981). Hysteretic moisture retention behavior has been attributed to various causes, including (1) the "inkbottle" effect, (2) the contact-angle effect, (3) entrapped air, and (4) swelling, shrinking, or aging phenomena, depending on the saturation history of the sample (Hillel and Mottes, 1966). Whatever its causes, the net effect of hysteresis is that for a given suction pressure, the liquid saturation is greater during drainage than it is during imbibition. Owing to experimental difficulties, moisture retention data obtained for imbibition conditions are seldom published. Consequently, although it is known to affect moisture retention, hysteresis is typically neglected in the analysis of partially saturated flow.

Although there is little data with which to quantify them, hysteretic moisture retention curves are typically depicted as shown in Figure 4 (taken from Bear, 1979). A notable feature is that the boundary drainage curve and the boundary imbibition curve envelope a family of scanning curves from above and below, respectively. If a process involves either monotonic drainage (starting from saturated conditions) or imbibition (starting from irreducible saturation), then the process will follow one of these boundary curves. These two boundary curves tend to converge as they approach either the irreducible or 100 percent saturation. Within some intermediate saturation range, these curves are often depicted as being parallel to each other when plotted on a semi-log scale. Because (1) the initial saturation in the core samples was only 65 percent and (2) the imbibition front never penetrated more than 1.0 mm into the sample, the prevailing suction pressures for this experiment are characteristic of intermediate saturations for the welded tuff samples. Therefore, if we make the assumption that within the saturation range encountered in this experiment the semi-log plot of the imbibition and

drainage moisture retention curves are parallel, then for a given saturation, the ratio of the imbibition and drainage suction pressures is a constant which we will call the hysteresis factor λ . During the imbibition experiment, the prevailing suction pressures are simply those given by the drainage curve multiplied by λ where 0. $\leq \lambda \leq 1$. (see Appendix for further details).

In order to determine λ for this experiment, it was necessary to conduct an imbibition experiment under controlled conditions in the laboratory using a 10 cm long, 2.5 cm diameter piece of welded tuff obtained from the region of interest. Because the sample had been stored in the laboratory for an extended period of time, its saturation state was considered to be uniform and in equilibrium with the ambient relative humidity of the room. After obtaining the initial weight of the sample, it was submerged in a bucket of water. For the first eight hours, the sample was weighed hourly by removing it from the water, towel drying it, and weighing it. Because the entire weighing procedure involved the sample being out of the water for less than two minutes, the periodic hiatus from the fully saturated boundary condition was considered to be negligible. The experiment continued for approximately one week with bi-daily weight measurements. In order to obtain a fully saturated weight, the sample spent the final two days of the experiment in a pressure vessel at 100 psig. At the end of the experiment, the sample was weighed, then placed in a vacuum oven to obtain its dry weight. Given the initial, wet, and dry weights of the sample as well as the sample weight over time, we calculated its porosity and saturation (averaged over the sample) as a function of time of submersion (see Figure 5).

The core sample in the laboratory imbibition was represented by a one-dimensional radially symmetric finite difference mesh with a radius of 1.25 cm. As was done in modeling the in situ experiment, a very fine numerical mesh is used to provide fine spatial resolution. The model uses the measured values of porosity (8.4 percent) and initial saturation (47 percent which is assumed to be uniform). We also employ the same boundary conditions, characteristic curves, and isothermal assumption which were incorporated in the in situ experiment model. As mentioned,

the purpose of this experiment is to evaluate the hysteresis factor λ by comparing the model predictions with observed imbibition data for different λ . The hysteresis factor can be implemented in the model in one of two ways. The straightforward approach is to simply apply λ according to its definition which is the ratio between the imbibition and drainage suction pressures at a given saturation. Accordingly, we would multiply, by λ , all suction pressures found in the characteristic curve tables which are used as input to the model. We chose a more convenient approach which simply involves multiplying the value of absolute permeability assumed in the model by λ (see Appendix for further details).

Before attempting to evaluate λ we first modeled the laboratory experiment using the drainage moisture retention curve and absolute permeability which were used in modeling the in situ experiment. A comparison with the experimental values (upper curve in Figure 5) indicates that the drainage curve results in significantly overpredicting the rate of imbibition. A review of Figure 4 illustrates why this is so for an intermediate saturation range. For a given saturation, the suction pressure during drainage is greater than it is during imbibition. Consequently, the suction pressure gradient predicted by the drainage curve is greater than that which occurs during imbibition. The large discrepancy observed in Figure 5 indicates the need to implement the hysteresis factor in the model in order to accurately represent the imbibition process.

The evaluation of λ was done by comparing model predictions of the resaturation curve with the observed data for several different λ . After trying several λ , we found that $\lambda = 0.025$ yields the best agreement between the observed and calculated saturation data for the first seven hours of the imbibition experiment (Figure 5). We decided to fit only the early time data in order to stay within an intermediate saturation range where the drainage and imbibition curves are considered to be parallel. Notice that the use of the hysteresis factor yields very good agreement between the calculated and experimental data for the bulk saturation range of 47 to 89 percent (i.e. averaged over the entire sample). In light of the poor agreement obtained with the unmodified

drainage curve, the good agreement between the calculated and experimental data obtained using λ indicates the validity of this approach.

A comment should be made about an implied assumption which was not previously mentioned: the relative permeability curve (as a function of saturation) is effectively nonhysteretic. While we will not attempt to prove why this may be so, this assumption seems plausible due to hysteretic moisture retention behavior primarily arising from physical effects (e.g. the inkbottle and contact angle effects) which would not appear to affect relative permeability.

It should be pointed out that the hysteresis factor does not simply correct for either the moisture retention curve or the absolute permeability in isolation. Peters and others (1984) found that for samples cored from the repository horizon at Yucca Mountain, the matrix permeability varied by one order of magnitude. Because we utilized their data, the absolute permeability used in the model is subject to at least the same range of uncertainty. It is the combination of the mobility of the imbibition front (as is affected by the relative and absolute permeability) as well as its driving force (as is affected by the suction pressure gradient) which control the rate of imbibition. Refering to Equation 4 in the Apppendix, it can be seen that the imbibition rate is inversely proportional to the porosity. Because it was not measured, the value of porosity had to be assumed for the in situ experiment. However, the range of uncertainty for porosity (less than a factor of two) is considerably less than that associated with either permeability or the moisture retention curve. Therefore, our use of λ is a means of effectively accounting for (in lumped fashion) uncertainties in the absolute permeability, porosity, and moisture retention curve. As can be seen in Equation 4 of the Appendix, although we have three unknowns, λ , k, and ϕ , they are related to the observed data (i.e. $\delta S_{ij}/\delta t$) with only one degree of freedom, $\lambda k/\phi$. An important caveat is that this approach is only valid for a process of monotonic imbibition; cyclic processes involving imbibition and drainage result in complex behavior involving the scanning curves (see Figure 4). Such processes require the use of hysteretic moisture retention curves. After

demonstrating (see Figure 5) that this approach yields an accurate prediction of imbibition for our laboratory experiment, we decided to apply it to model the in situ imbibition experiment.

Using the hysteresis factor obtained from the laboratory experiment, we repeated the imbibition calculations for the in situ experiment. The model is the same as that used for the earlier in situ calculations, except that we multiply the absolute permeability by $\lambda = 0.025$. Figure 6 is a plot of saturation versus radial distance from the centerline after the core has been exposed to drill water for 15, 30, and 60 minutes, respectively. For these three exposure times, the imbibition front has penetrated 0.7, 1.0, and 1.5 mm into the core, respectively. Recall that Daily and Ramirez observed imbibition penetration depths of from 0.2 to 0.7 mm. The estimate of maximum drill water exposure time for an average piece of core made by Wilder (personal communication, 1987) is based on the conservative assumption that the annular space around the core is continuously filled with water. Normal drilling practice rarely fills a horizontal hole with water (Wilder, personal communication, 1987). Recently, Wilder and Ramirez (personal communication, 1987) have observed significant losses in drill water circulation due to the presence of highly conductive fractures. Due to standard drilling practice as well as the (apparently ubiquitous) presence of highly conductive fractures, it is unlikely that the borehole annulus is continuously filled with water during drilling. Consequently, it is likely that the effective exposure time for the core samples examined by Daily and Ramirez (1987) was less than one hour. Therefore, depending on the assumed effective period during which the core is exposed to fully saturated conditions during drilling, the calculated and observed imbibition depths compare reasonably well.

<u>Conclusions</u>

A simple in situ imbibition experiment was conducted to observe the hydrologic impact of drill water on core samples taken from partially saturated, densely welded tuff in G-tunnel at the Nevada Test Site.

Drill water imbibition by the core samples was observed to be minimal (0.2 to 0.7 mm into the core). Calculations were carried out with the TOUGH code with the intent of corroborating the imbibition observations. Due to the absence of hydrologic property data pertaining directly to G-Tunnel welded tuff, it was necessary to utilize data obtained from samples cored from the repository horizon at Yucca Mountain, Nevada. It was noted that because suction pressure versus saturation data was not available for imbibition conditions, it was necessary to use the drainage curve. A complete lack of agreement between the observed and calculated imbibition data was attributed primarily to the inappropriateness of the drainage curve in modeling an imbibition process. It was also recognized that the value of absolute permeability used in the model could also be contributing to the lack of agreement.

Provided that the semi-log plot of the drainage and imbibition moisture retention curves are parallel within the saturation range of interest, a simple relationship exists between the moisture retention curve, porosity, and absolute permeability which are assumed in the model and their actual values. If the absolute permeability and porosity are known, λ simply becomes the ratio of the imbibition and drainage suction pressures at a given saturation. If the absolute permeability and porosity are assumed, the hysteresis factor takes on a broader definition: the ratio of the actual value of $p_c k/\phi$ to the assumed value of $p_c k/\phi$. Although we have three unknowns, λ , k, and ϕ , they are related to the observed data (i.e. $\delta S_u/\delta t$) with only one degree of freedom, $\lambda k/\phi$. Accordingly, a laboratory imbibition experiment was conducted to enable us to evaluate λ . For several λ , the model resaturation predictions are compared with the observed data. After trial and error, we found that $\lambda = 0.025$ yields very good agreement between the calculated and observed resaturation data.

We then applied $\lambda = 0.025$ to the model of the in situ imbibition experiment. For 15, 30, and 60 minutes of exposure with the drill water, the model predicted imbibition penetration depths of 0.7, 1.0, and 1.5 mm, respectively. Depending on the assumed period during which the core is exposed to saturated conditions, the calculated and observed imbibition depths compare reasonably well. However, regardless of

whether drill water has been imbibed 0.2 or 1.5 mm into the core, the overall hydrologic impact on the native saturation state of a 6 cm diameter core sample is still quite small. For a sample initially at 65 percent saturation, an imbibition depth of 1.5 mm only results in the bulk saturation of the sample increasing to 66.8 percent. The issue of the hydrologic impact which instrument boreholes are expected to have on the native saturation state of the fractured tuff in the vicinity of the waste package environment test is beyond the scope of this report. That issue, addressed in a companion study (Buscheck and Nitao, 1987) involves the interaction of fracture flow with imbibition by the welded tuff matrix.

The results of this study clearly demonstrate the need for moisture retention data applicable to imbibition conditions. For processes involving cycling between imbibition and drainage, it is critical that data become available to evaluate hysteretic curves, including scanning curves. At the same time, it will be necessary to develop algorithms in flow and transport codes which can account for highly nonlinear, complex hysteretic behavior in the moisture retention curves. Acknowledgments

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<u>References</u>

- Bear, J., "Hydraulics of Groundwater", McGraw-Hill, New York, 569 pp., 1979.
- Board, M. P., M. L. Wilson, and M. D. Voegel, "Laboratory Determination of Mechanical, Ultrasonic, and Hydraulic Properties of Welded Tuff from Grouse Canyon Heated Block Site", SAN86-7130, Sandia National Laboratory, Albuquerque, N. M., August 1987.
- Buscheck, T. A., and J. J. Nitao, "Fluid Flow Modeling," in Institutional Research and Development, FY86 Annual Report, UCRL-53689-86, Lawrence Livermore National Laboratory, Livermore, CA, pp. 48-49, 1987.
- 4. Buscheck, T. A., and J. J. Nitao, "Estimates of the Hydrologic Impact of Drilling Water on the Saturation Conditions in the Vicinity of the Waste Package Environmend Test at the Yucca Mountain Exploratory Shaft Site", UCID-, Lawrence Livermore National Laboratory, Livermore, CA, 1987 (in preparation).
- Daily, W., and A. Ramirez, "Water Imbibition by In Situ Grouse Canyon Densely Welded Tuff", UCID-, Lawrence Livermore National Laboratory, Livermore, CA, 1987 (in preparation).
- Edlefsen, N. E., and A. B. C. Anderson, "Thermodynamics of Soil Moisture", Hilgardia, Vol. 15, No. 2, pp. 31-298, 1943.

- Edwards, A. L., "TRUMP: A Computer Program for Transient and Steady-State Temperature Distributions in Multi-Dimensional System", National Technical Information Service, UCRL-14754, Rev. II, Springfield, Virginia, 22151, 265 pp., 1969.
- Hillel, D., "Introduction to Soil Physics", Academic Press, Orlando, FLA, 364 pp., 1982.
- Hillel, D., and J. Mottes, "Effect of Plate Impedance, Wetting Method, and Aging on Soil Moisture Retention", Soil Science, Vol. 102, pp. 135-140, 1966.
- International Formulation Committee, "A Formulation of the Thermodynamic Properties of Ordinary Water Substance", IFC Secretariat, Dusseldorf, Germany, 1967.
- Klinkenberg, L. J., "The Permeability of Porous Media to Liquids and Gasses", in: API Drilling and Production Practice, pp. 200-213, 1941.
- 12. Lawrence Livermore National Laboratory, "Test Plan: Prototype Engineered Barrier Design Testing" in the Nevada Waste Management Program Quality Assurance Program Plan, Lawrence Livermore National Laboratory, Livermore, CA, Rev. 0, 033-NNWSI-p11.0, 1987.
- Marshall, T. J., and J. W. Holmes, "Soil Physics", Cambridge University Press, Cambridge, England, 345 pp., 1979.
- 14. Narasimhan, T. N., and P. A. Witherspoon, "An Integrated Finite Difference Method of Analyzing Fluid Flow in Porous Media", Water Resources Research, Vol. 12, No. 1, pp. 57-66, 1976.
- 15. Nitao, J. J., "Numerical Modeling of the Environment of a Nuclear Waste Package Using the Equivalent Continuum Approximation: Horizontal Emplacement", UCID-Laboratory, Livermore, CA, 1987 (in preparation).

- 16. Peters, R. R., E. A. Klavetter, I. J. Hall, S. C. Blair, P. R. Hellers, and G. W. Gee, "Fracture and Matrix Hydrologic Characteristics of Tuffaceous Materials from Yucca Mountain, Nye County, Nevada", SAND84-1471, Sandia National Laboratory, Albuquerque, N. M., December 1984.
- 17. Preuss, K., "TOUGH User's Guide", LBL-20700, Lawrence Berkeley Laboratory, Berkeley, CA, November 1985.
- 18. Preuss, K., Y. W. Tsang, and S. Y. Wang, "Numerical Studies of Fluid and Heat Flow Near High-Level Nuclear Waste Packages Emplaced in Partially Saturated Fractured Tuff", LBL-18552, Lawrence Berkeley Laboratory, University of California, Berkeley, CA, 1984.
- 19. Russo, A. J., and D. C. Reda, "Drying of an Initially Saturated Fractured Volcanic Tuff", SAND87-0293C, Sandia National Laboratory, Albuquerque, N. M., March 1987.
- 20. van Genuchten, M. Th., "A Closed-Form Equation for Predicting the Hydraulic Conductivity of the Unsaturated Soils", Soil Sci. Soc. Am. J., Vol. 44, pp. 892-898, 1980.
- 21. Zimmerman, R. M., and M. B. Blanford, "Expected Thermal and Hydrological Environments for Waste Emplacement Holes Based on G-Tunnel Heater Experiments", Proc. 27th Symposium on Rock Mechanics, Chapter 125, pp. 874-882, 1986.
- 22. Zimmerman, R. M., F. B. Nimick, and M. B. Board, "Geoengineering Characterization of Welded Tuffs from Laboratory and Field Investigations", Proceedings of 1984 Symposium on Scientific Basis for Nuclear Waste Management VIII, Materials Research Society, Boston, MA, 1984.

TABLE 1

Hydrologic Parameters Used to Model In Situ Imbibition Experiment

where

• • ---

φ = porosity
 k = absolute permeability
 C_r = rock compressibility
 S_{wi} = initial water saturation

TABLE 2

Grid Spacing Used to Model the In Situ Imbibition Experiment

(starting from the surface of the core sample)

10 x .05 mm
5 x .10 mm
1 x .40 mm
1 x .60 mm
6 x 1.0 mm
10 x 2.0 mm

Appendix

The conservation equation for the flow of water in a partially saturated porous medium under imbibition conditions takes the form

$$\nabla \cdot \frac{K k_r}{\mu} \nabla (p_g + (p_c)_f) = \phi \frac{\partial S_w}{\partial t}$$
(1)

where

K = absolute permeability

 k_r = relative permeability

 p_s = gas phase pressure

 $(p_c)_I$ = suction pressure under imbibition

$$(p_c)_D$$
 = suction pressure under drainage

 S_w = water saturation

Here, gravity effects are neglected as well as the compressibility of water. A common assumption and one that is applicable to our problem is to neglect variations in gas phase pressure p_g to obtain

$$\nabla \cdot \frac{K k_r}{\mu} \nabla ((p_c)_l) = \phi \frac{\partial S_w}{\partial t}$$
⁽²⁾

If over some saturation interval S_w such that $S_{wir} < S_w < 1.0$ (where S_{wir} is the irreducible water saturation) the suction pressures in the imbibition curve are related to the suction pressures in the drainage curve by a factor λ (which is a constant).

$$(p_c)_I = \lambda(p_c)_D \tag{3}$$

then

$$\nabla \cdot \frac{(\lambda K) k_r}{\mu} \nabla ((p_c)_D) = \phi \frac{\partial S_w}{\partial t}$$
(4)

Thus, the drainage curve can be used under monotonic imbibition by multiplying the absolute permeability K by the constant λ . From the above equations it can be shown that changing the constant λ changes the time scale, but leaves the shape of the saturation curve as a function of space unchanged.







Hysteresis in the moisture retention curve (from Bear 1979).





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