The Impact of Episodic Nonequilibrium Fracture-Matrix Flow on Geological Repository Performance

T.A. Buscheck
J.J. Nitao
D.A. Chestnut

This paper was prepared for the FOCUS '91 Conference on Nuclear Waste Packaging
Las Vegas, Nevada
September 29-October 2, 1991

October 29, 1991

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.
DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.
THE IMPACT OF EPISODIC NONEQUILIBRIUM FRACTURE-MATRIX FLOW ON GEOLOGICAL REPOSITORY PERFORMANCE

Thomas A. Buscheck, John J. Nitao, and Dwayne A. Chesnut

Earth Sciences Department, Lawrence Livermore National Laboratory
P.O. Box 808, L-206, Livermore, CA 94550

(510) 423-9390, (510) 423-0297, (510) 423-5053

ABSTRACT

Adequate representation of fracture-matrix interaction during episodic infiltration events is crucial in making valid hydrological predictions of repository performance at Yucca Mountain. Various approximations have been applied to represent fracture-matrix flow interaction, including the Equivalent Continuum Model (ECM), which assumes capillary equilibrium between fractures and matrix, and the Fracture-Matrix Model (FMM), which accounts for nonequilibrium fracture-matrix flow. We analyze the relative impact of matrix imbibition on episodic nonequilibrium fracture-matrix flow for the eight major hydrostratigraphic units in the unsaturated zone at Yucca Mountain. Comparisons are made between ECM and FMM predictions to determine the applicability of the ECM. The implications of nonequilibrium fracture-matrix flow on radionuclide transport are also discussed.

INTRODUCTION

The Yucca Mountain Site Characterization Project (YMSCP) of the U.S. Department of Energy (DOE) is investigating the suitability of the fractured, tuffaceous rocks occurring in the unsaturated zone at Yucca Mountain, Nevada, for nuclear waste storage. Adequate representation of fracture-matrix interaction during episodic infiltration events is crucial in making valid hydrological predictions of repository performance under nominal and perturbed conditions. Various approximations have been applied to represent fracture-matrix flow interaction. The Equivalent Continuum Model (ECM) is a zeroth order approximation (Klavetter and Peters 1988) which assumes instantaneous capillary equilibrium between the fracture and matrix. Under this assumption, the fracture and matrix properties can be pore-volume-averaged into an equivalent (or effective) continuum. In the dual porosity approach, effectively a first order approximation, mass transfer between fracture and matrix is represented by a mass transfer coefficient, implying quasi-steady-state flow. The dual porosity approach has been applied to model single phase flow in fractured reservoirs (Barrenblatt et al. 1960; Warren and Root 1963).

The second order approximation (Buscheck and Nitao 1988; Nitao and Buscheck 1989; Nitao, 1991) explicitly accounts for the fracture and matrix porosities using the Fracture-Matrix Model (FMM). The FMM work has involved numerical modeling using the V-TOUGH code (Nitao 1989a), which is a modified version of the TOUGH code (Pruess 1987), as well as the development of analytical and semi-analytical models (Nitao 1989b). Recent calculations also used the NUF (Nonisothermal Unsaturated Flow and Transport) code, which has recently been developed at LLNL. This report describes the modeling of nonequilibrium fracture-matrix flow at Yucca Mountain. The relative importance of matrix imbibition is analyzed for the eight major hydrostratigraphic units in the unsaturated zone. We also address the question of what sequencing of infiltration events gives rise to episodic behavior vs behavior which may be time-aggregated. The implications of nonequilibrium fracture-matrix flow for radionuclide transport are also discussed.

Background and Available Data

Yucca Mountain consists of a series of variably fractured, nonwelded to densely welded tuff units with an eastward tilt of about 5 to 30 deg (Montazer and Wilson 1984). The thickness of the unsaturated zone varies from 500 to 750 m. The potential repository location is in Topopah Spring (TSW2) moderately to densely welded tuff, which is about 350 m below the ground surface and 225 m above the water table (Klavetter and Peters 1986). Montazer and Wilson (1984) report the absence of perennial streams at Yucca Mountain. Therefore, recharge due to rainfall or snowmelt occurs episodically.

The matrix properties of the hydrostratigraphic units at Yucca Mountain are summarized in Table 1 (Klavetter and Peters 1986). The units generally fall into two categories: (1) the welded tuffs (TCw, TSW1, TSW2, and TSW3) and the nonwelded zeolitized unit (CHnz), all of which have low matrix permeability, \( k_m \), and low-to-medium matrix porosity, \( \phi_m \), and (2) nonwelded vitric tuffs of high \( k_m \) and \( \phi_m \). The \( k_m \) of the nonwelded vitric tuffs is 4 to 5 orders of magnitude greater than those of the welded tuffs and the CHnz. Because of the small matrix pore size of all of the units, water in the matrix pores is held under high suction potential, causing the capillary fringe to extend from the water table to the ground surface (Fig. 1). Because of the low capillarity of all fractures except those with very small apertures, most fractures will be drained of water under ambient
Buscheck and Nitao (1991) modeled infiltration in Yucca Mountain using a one-dimensional steady-state ECM. On the basis of that model, the observed range in saturation at the repository horizon corresponds to a range in recharge flux of approximately -0.005 to 0.05 mm/yr. Figure 1 shows the vertical liquid saturation distribution from the water table (z = 568 m) to the ground surface (z = 0 m) for zero recharge flux, which corresponds to gravity-capillary equilibrium. Because of the relatively small capillarity of the high-\(k_m\) PTn and CHnv units, the high capillary suction potential of their neighboring units causes them to be nearly drained to near-residual saturation. Figure 1 also includes recharge fluxes of 0.045 and 0.132 mm/yr, resulting in saturations at the repository horizon of 85 and 95 percent, respectively. Because of the relatively small \(k_m\) of the TSw2 and TSw3, the saturation profile within those units is quite sensitive to variations in recharge flux. Because of its large \(k_m\), the CHnv can sustain the steady-state flux at small saturations. The saturation profiles in the CHnv and PPw are less sensitive to variations in the steady-state recharge flux.

Saturation values obtained from the Reference Information Base (RIB) are also included in Fig. 1 (DOE 1990). While zero recharge flux results in a saturation of about 10 percent for the PTn and CHnv, the RIB reports mean saturation values of 61 and 91 percent, respectively. Obviously, significant recharge fluxes (i.e., much greater than those shown in Fig. 1) are able to reach the high-\(k_m\) units without affecting the saturation of the neighboring low-\(k_m\) units. Nonequilibrium fracture flow through the TCw, TSw1, TSw2, and TSw3 is a likely explanation for the inconsistency between the measured saturation data and the saturation profile predicted by the one-dimensional, steady-state ECM. Moreover, bomb-pulse \(^3\)H measurements reported by Norris (1989) are consistent with nonequilibrium fracture flow from the ground surface to considerable depths. The discrepancy between the apparent near-zero recharge flux to the low-\(k_m\) units and the apparent large flux to the high-\(k_m\) units can also be partially resolved by mechanisms that remove water from the vadose zone. These mechanisms may include vapor flow (Thorstenson et al. 1989) as well as lateral liquid flow along high-\(k_m\) units such as the PTn and CHnv. The capacity of these mechanisms may be considerably in excess of what is currently required to provide a net zero flux at the repository horizon.

### Matrix-Dominated vs Fracture-Dominated Flow

Nitao (1991) found that the flow behavior of a two-dimensional, unsaturated fracture-matrix system is characterized by a critical flux, \(q_f^*\), given by

\[
q_f^* = \frac{\phi_m(S_i - S_d)D_m}{1}\tag{1}
\]

where \(\phi_m\) is matrix porosity, \(S_i\) is the maximum matrix saturation, \(S_d\) is the initial matrix saturation, and \(D_m\) is the matrix imbibition diffusivity constant. If the flux \(q_f\) into the fracture satisfies \(q_f > q_f^*\), the flow field is fracture-dominated, whereas if \(q_f < q_f^*\), the flow field is matrix-dominated and the system behaves as a single equivalent porous medium with capillary equilibrium between fracture and matrix. If the fracture entrance is ponded, the critical fracture hydraulic conductivity \(K_f^*\), or corresponding critical aperture \(b^*\) from the "cubic" law, controls the flow behavior instead of the critical flux. Rocks with fracture aperture \(b\) sufficiently large such that \(b^* > b^*\) have fracture-dominated flow, while rocks with fracture aperture sufficiently small such that \(b^* < b^*\) will be matrix-dominated.

When the flow into a fracture is small enough, most of the water is imbibed by the matrix near the inlet before it moves a
significant distance along the fracture (Nita 1991). The wetting front in the fracture lags behind the front in the matrix, and the speed of the wetting front is dominated by matrix properties. This condition corresponds to matrix-dominated flow. The ECM is satisfactory for this case.

Fracture-Dominated Flow Periods

Fracture-dominated flow occurs at higher fluxes. The wetting front in the fracture moves ahead of the front in the matrix, and matrix flow is primarily perpendicular to the fracture plane. Under these conditions, the speed of the wetting front in the fracture is governed by the competition between the driving forces in the fracture (gravity and fracture capillarity) and capillary imbibition into the matrix. Nita and Buscheck (1989) found that fracture-dominated flow can be classified into three physically interpretable flow periods, corresponding to the degree to which matrix interaction retards the speed of the wetting front in the fracture, with minimal retardation occurring during flow period I, intermediate retardation during flow period II, and maximal retardation during flow period III.

The three fracture-dominated flow regions have both spatial and temporal significance. Figure 2 shows the longitudinal penetration of the wetting front in the fracture vs time for the three flow periods. The three diagrams in Fig. 2 depict how the flow periods are related to spatial flow regions. The three straight line segments are asymptotes identified theoretically by Nita (1989b) and confirmed through numerical simulations by Nita and Buscheck (1989). In the numerical simulations we found that the transitions between the flow periods occur more gradually than depicted by the straight line segments.

The matrix in flow region I has imibed less than one fracture pore volume (Fig. 2). Consequently, during flow period I, matrix imbibition has not yet significantly retarded the speed of the wetting front in the fracture. Therefore, the speed of the wetting front is dominated by the driving forces in the fracture: fracture capillarity, the imposed boundary flux or pressure, and gravity. For ponded conditions at the inlet to vertical fractures, flow period I is dominated by gravity, and the wetting front moves linearly in time.

In flow region II, the matrix has imbibed more than one fracture pore volume (Fig. 2). Consequently, during flow period II, matrix imbibition significantly retards the speed of the wetting front in the fracture. Whereas the lack of retardation resulted in the wetting front moving linearly in time during flow period I, during flow period II, matrix imbibition retards the speed of the wetting front, causing it to move as \( t^{1/2} \). Although flow region II controls the speed of the wetting front during flow period II, flow region I still remains downstream of flow region II (Fig. 2).

In flow region III, matrix imbibition has fully saturated the matrix between neighboring fractures. Consequently, the interference of the wetting zones between neighboring fractures has reduced the imbibition rate. The movement of the front is again linear in time (but substantially reduced relative to flow period I) and is the same as that predicted by the ECM. The reduction in the wetting front velocity (relative to flow period I) is related to the ratio of the initially unsaturated porosity in the fracture and matrix divided by the initially unsaturated porosity of the fracture. In Fig. 3, this reduction is represented by a log shift in the curve of wetting front penetration vs time, with the log of the time shift, \( \delta \log t_0 \), given by

![Fig. 2. The asymptotic dimensionless fracture front penetration, \( h(t)/K_f t_b \), is plotted against dimensionless time, \( t/t_b \), for the three flow periods. The relationship between flow periods and flow regions is depicted in the insets.](image-url)
\[
\Delta \log t = \log \left( \frac{B + b(1 - S_i)C_m}{b} \right)
\]

where \( \phi_m \) is matrix porosity, \( S_i \) is initial matrix saturation, \( b \) is fracture aperture, and \( B \) is fracture spacing. Although interference between neighboring fractures has reduced the rate of matrix imbibition, because the entire matrix porosity is affecting the speed of the wetting front, the matrix effectively maximally retards the speed of the wetting front in the fracture. Although flow region III controls the speed of the wetting front during flow period III, flow region II and I exist downstream of flow region III (Fig. 2).

The performance of Yucca Mountain as a repository site depends greatly on whether it can prevent liquid pulses along fractures from (1) reaching waste packages (WPs), which would presumably accelerate their failure, and (2) transporting radionuclides to the water table. The capability of Yucca Mountain to prevent these failure modes is critically dependent on the degree to which matrix imbibition retards the speed of the wetting front in the fracture. Figure 3 summarizes how the flow regions relate to physical retardation of fracture flow.

The impact of physical retardation on fracture flow is best understood by considering the two most extreme (i.e., asymptotic) examples of fracture-matrix interaction. The first example occurs when the matrix is impermeable, resulting in no interaction between the fracture and matrix. In this case, there is no transfer of liquid from the fracture to the matrix. Therefore, all of the water entering the top of the fracture (such as may occur in washes during rainstorms) remains in the fracture, resulting in the greatest possible velocity of the wetting front in the fracture. Without fracture-matrix interaction, the matrix cannot play a role in retarding the rate of fracture flow. This situation corresponds to flow region I (Fig. 3).

The second extreme example of fracture-dominated flow pertains when \( k_m \) is extremely large, resulting in nearly instantaneous equilibration between the fracture and matrix. As soon as the flow in the fracture reaches a given level, imbibition into the matrix occurs so quickly that \( 0 < \phi_m \) entire matrix porosity lying between flowing fractures is saturated to 100 percent. In this extreme mode, matrix imbibition retards the speed of the wetting front in the fracture to the maximum possible extent. If a wetting front starting from the ground surface were to reach the water table, Yucca Mountain would have to be entirely filled to 100 percent saturation. Incidentally, the ECM incorporates only this extreme mode of fracture-matrix interaction (Fig. 3). It should be obvious why the ECM always tends to overpredict groundwater travel time, \( GWTT \). The ECM assumes the most favorable possible degree of matrix interaction and thereby the greatest possible degree of fracture flow retardation irrespective of whether it is physically valid to do so.

Flow in Yucca Mountain will generally lie between these two extreme examples. The extent to which matrix imbibition retards the speed of the wetting front in the fracture will always lie between "no retardation" and "maximal retardation".

**Overview of Fracture-Matrix Flow at Yucca Mountain**

With regard to the degree of fracture-matrix interaction at Yucca Mountain, we found that the major hydrostratigraphic units generally fall into two extreme categories: (1) high-\( k_m \) units, which give rise to a very large degree of fracture-matrix interaction and can thereby significantly retard fracture flow, and (2) very low \( k_m \) units, which give rise to much less fracture-matrix interaction and thereby have much less capacity to retard fracture flow. Accordingly, because of their very small \( k_m \), fracture flow will be greatest in the welded TCE, TSW1, TSW2, and TSW3 units (as well as in the CHZ1). The

\[\text{Fig. 3. Similar to Fig. 2, showing the relationship between the flow periods and the degree of fracture flow retardation. Note that the ECM corresponds to maximal fracture flow retardation.}\]
low \( k_m \) results in fracture-dominated flow period II for small- to medium-aperture fractures and fracture-dominated flow period I for large-aperture fractures. The large \( k_m \) of the PTn and CHv results in either (1) matrix-dominated flow for small to medium aperture fractures, (2) fracture-dominated flow period III for large-aperture fractures, or (3) fracture-dominated flow period II for very-large-aperture fractures. These estimates may change as matrix imbibition data become available. However, the fundamental distinction between the impact of the low-\( k_m \) and high-\( k_m \) units on fracture flow still holds.

Because fracture-dominated flow periods I and II result in the greatest penetration of wetting fronts in fractures, hydrological performance assessment will be very sensitive to the vertical connectivity of fracture networks in the low-\( k_m \) units. The high \( k_m \) of the vitric nonwelded tuffs may result in substantial lateral matrix flow. The interaction of this lateral flow with vertically contiguous faults is a critical hydrological performance issue. Therefore, hydrological performance assessment will need to focus on whether (or how) fracture networks in the welded units facilitate fracture-dominated flow periods I and II and the interaction of lateral matrix flow within the vitric nonwelded units with vertically contiguous faults.

**Spatial and Temporal Variability of Recharge Flux**

The analyses of Niatz and Buscheck (1989), Niata (1991), and Buscheck and Niato (1991) indicate the need to account for the areal variability and episodic nature of recharge flux. An important question is what sequencing of infiltration events gives rise to episodic behavior vs behavior that may be time-aggregated. Buscheck and Niata (1988) found that, because of matrix imbibition, little additional penetration of a liquid pulse in a fracture occurs after a ponded source of water is removed. Because fracture flow will not persist for long (usually for only a few hours) following the removal of the infiltration source, the episodic nature of recharge flux will probably be seen with little attenuation to considerable depth. For welded tuffs, the dimensionless liquid saturation, \( S_\ast \), of the matrix wetting zone decays to within 10 percent of native saturation conditions in a few months, where \( S_\ast \) is defined as

\[
S_\ast = \frac{S - S_1}{1 - S_1},
\]

where \( S_1 \) is the initial matrix saturation. For the CHv it takes over 10 yr. For episodic infiltration events separated by a few days, the cumulative wetting front movement in the low-\( k_m \) units is nearly the same as would occur had all events occurred consecutively. For the CHv, events can be separated by a year without affecting the cumulative wetting front movement.

As previously mentioned, the high suction potential of the matrix results in the fractures being drained of water under conditions of low recharge flux. Similarly, the high suction potential of the matrix will result in the WP borehole being drained of water under low recharge flux. This is the basis of one of the primary hydrological performance attributes of the WP emplacement configurations: a capillary barrier exists between the WP and the borehole wall, so no pore water should contact the WP. As long as rock around the WP remains partially saturated and the capillary barrier is intact (no WP contact with the borehole walls or sloughing of rock into the boreholes), there is no mechanism other than fracture flow to allow water to contact the WPs. Therefore, on the basis of the observation that fracture flow is insignificant after removal of an infiltration source, the key consideration determining whether water will contact the WP is the intensity and duration of the maximum possible infiltration episode, i.e., an event or a group of events that effectively act as a single event.

**MODELING FRACTURE-MATRIX FLOW**

Given that fracture flow along preferential flow paths provides the most likely means of transporting radionuclides to the water table, there are two major hydrological attributes of Yucca Mountain that will tend to physically retard the vertical movement of radionuclides. The first is the "disconnectedness" of preferential flow paths, i.e., the degree to which these paths are discontinuous. Because of the small \( k_m \), fracture-to-matrix-to-fracture flow will be tremendously impeded by matrix flow in the welded units (and the CHv). The high \( k_m \) of the CHv and PTn will result in fracture-to-matrix-to-fracture flow being less impeded by matrix flow for small- to medium-aperture fractures, but more impeded for large-aperture fractures. The second major attribute consists of flow features that laterally divert or attenuate fracture flow. Lateral attenuation is particularly important for relatively large-scale, vertically connected fracture networks. In addition to lateral attenuation due to matrix imbibition, flow branching from major fracture pathways into tributary fractures will have a lateral dispersive effect on fracture flow. Lateral dispersion within fracture networks will enhance the impact of matrix imbibition on fracture flow.

Before analyzing the impact of fracture connectedness and dispersivity, it is crucial to understand the time and length scales of vertical fracture flow vs lateral matrix flow. Therefore, in this report we focus on the impact of lateral attenuation due to matrix imbibition by considering vertical fractures that extend from the ground surface to the water table. We will investigate the effects of fracture connectedness and dispersivity in future studies.

An important objective of this study was to demonstrate the domain of applicability of the ECM in modeling episodic nonequilibrium flow at Yucca Mountain. Therefore, we conducted parallel calculations using the ECM properties. Comparisons of the calculations are listed in table form. We present two suites of calculations, in which a ponded boundary condition is maintained either at (1) the ground surface until the wetting front has broken through to the repository horizon, or (2) the repository horizon until the wetting front has broken through to the water table. The relative impact of matrix imbibition is examined for the eight major hydrostratigraphic units between the ground surface and the water table.

**Numerical Models, Physical Data, and Assumptions**

We consider a two-dimensional system of vertical, parallel, uniformly spaced fractures extending continuously from the ground surface to the water table. Because of symmetry, we can consider an infinite periodic two-dimensional system extending from the no-flow boundary at the midplane of the fracture to the no-flow boundary at the midplane of the matrix block. Liquid enters the top of the fracture under a constant pressure due to ponding. In the first suite of calculations, the top of the fracture represents the floor of a drift at the repository horizon. This situation is applicable to the "human intrusion drilling scenario" being considered by the YMEC. In this scenario, once an exploratory drilling operation has penetrated a drift, circulation of drilling fluid is lost, thereby introducing enough fluid to maintain a ponded condition for a limited period. In the second suite of calculations, the top of the fracture represents either the ground surface or the base of the alluvium (e.g., within a wash or the streambed of an ephemeral stream).

Using the matrix property data listed in Table 1 (Klaver et al. 1984), we modeled the eight major hydrostratigraphic units in the unsaturated zone. It is important to note that characteristic curve data are not available for imbibition. Applying the characteristic curves determined by Peters and coworkers (1984) with the use of an oven psychrometer to imbibition calculations for Grouse Canyon
densely welded tuff, Buscheck and Nita (1987, 1988) found that a reasonable match between modeled and observed data was obtained if \( k_m \) was reduced by a factor of 40. This discrepancy could be attributed to uncertainty concerning \( k_m \) or to capillary hysteresis. Using data for the welded tuff TSw (Lin and Daily 1990), we obtained a reasonable match between modeled and observed imbibition data after applying a similar reduction in \( k_m \). In order to approximately account for what is an apparent capillary hysteresis effect, we decided to apply this \( k_m \) reduction factor to all of the units listed in Table 1.

Data on fracture properties in Yucca Mountain is sparse. For a range of fracture spacings listed in Table 2, Buscheck and Nita (1991) calculated the hydraulic aperture on the basis of the cubic law (Witherspoon et al. 1980) and the bulk permeability measurements reported by Montazer and coworkers (1985) and Thordarson (1983). Note that for this calculation, we conservatively assumed all fractures to be parallel. We considered fracture apertures, \( b \), of 10, 50, 100, 200, 400, and 1000 \( \mu \)m.

Ponded Conditions at the Repository Horizon

Before conducting the episodic infiltration calculations, it was necessary to initialize the saturation and pressure fields in the model. For the reference case, a steady-state recharge flux of 0.045 mm/yr was used, resulting in a repository saturation of 85 percent (Fig. 1), which lies at the upper end of the range of measured saturations at the repository horizon (DOE 1990). The saturation at the water table is fixed at 100 percent.

For the episodic infiltration calculations, a ponded upper boundary is maintained at the repository horizon (at \( p_w = 1 \) atm, where \( p_w \) is the fracture entrance pressure), until the wetting front breaks through to the water table, located 225 m below the repository. Figure 4(a) is a contour plot of dimensionless liquid saturation, \( S_a \) [Eq. (3)], 2 h into this episodic event. Notice how the wetting front in the fracture has already penetrated 35 m and that matrix imbibition is primarily perpendicular to the fracture plane. The ECM predicts a very different saturation distribution for this case (Fig. 4(b)), with the wetting front only penetrating 0.56 m after 2 h. By assuming capillary equilibrium between fractures and matrix, the ECM allows instantaneous mass transfer from the fracture to the entire initially unsaturated matrix porosity, resulting in maximal retardation of the wetting front in the fracture.

The impact of matrix flow on the wetting front movement is illustrated by comparing portions of the the groundwater travel time, GWTT, for wetting front penetration through (1) the low-\( k_m \) welded units, TSw2 and TSw3, and (2) the high-\( k_m \) nonwelded vitric unit CHnv (column 2 of Table 3). For the reference case (\( b = 100 \mu \)m and \( b = 3.0 \) m), it takes only 4.5 h for the wetting front to penetrate the TSw2 and TSw3, but an additional 83 days to penetrate the CHnv. Figure 5(a) shows \( S_a \) at \( t = 8 \) h, shortly after the front has reached the CHnv. Flow in the CHnv is dominated by the matrix and so is laterally diverted as quickly as it enters the CHnv. After 20 days, the wetting zones from neighboring fractures start to interfere [Fig. 5(b)]. Because of the dominance of matrix flow, the wetting front does not penetrate the CHnv and enter the CHnz until entirely saturating the CHnv [Fig. 5(c)]. Because of the small \( k_m \) of the CHnz and the very high initial saturation of the PPw, it takes only an additional 3.4 days for the wetting front to penetrate those units and reach the water table [Fig. 5(d)].

Tables 3 through 5 illustrate the impact of matrix flow by comparing GWTT for the case of no matrix flow (column 1) with the case of fracture-matrix interaction (column 2). Column 3 lists the "retardation" ratio, \( R_m \), defined as the ratio of the GWTT with matrix interaction to the GWTT without matrix interaction. In other words, \( R_m \) is the factor by which GWTT is delayed by virtue of matrix interaction. By definition, for flow period 1, \( R_m \leq 2 \). Therefore, in the reference case, as the wetting front penetrates the TSw2 and TSw3, a transition occurs from flow period 1 to II (Table 3). As the wetting zones in the CHnv begin to interfere, flow in this layer changes from matrix-dominated flow to fracture-dominated flow region III. Fracture-dominated flow period II persists in the CHnz and PPw. For \( b = 1000 \mu \)m (Table 4), the large fracture conductivity dominates flow, with flow period I persisting in all but the CHnv, where flow period II prevails (Fig. 6). Notice that it only takes 70 s for the wetting front to reach the CHnv, another 30 s to penetrate the CHnv, and a total of only 345 s to reach the water table (Table 4).

Tables 3 through 5, column 4, list \( R_m \) predicted by the ECM. Effectively, the ECM provides instantaneous matrix interaction over all of the matrix porosity lying between wetting fractures. The GWTT is overpredicted by the ECM for the TSw2, TSw3, CHnz, and PPw. Only for the CHnv (and only for \( b \leq 100 \mu \)m) is the ECM sufficiently accurate (Table 3).

While it was necessary for the wetting zones in the CHnv of the reference case (\( b = 3.0 \) m) to interfere prior to re-establishing
fracture-dominated flow, for wider fracture spacing fracture-dominated flow is eventually re-established by virtue of the small thickness of the CHnv and decaying matrix imbibition flux. Eventually, the total flux into the matrix declines to the point that the fracture flux is sufficient to penetrate through to the CHnv. For \( b = 100 \mu \text{m} \) and \( B = 30 \text{ m} \), this point occurs after the wetting zone has spread 6.08 m laterally in the CHnv (Fig. 7(a)). Because the wetting zone width is much less than the fracture spacing \((b = 3 \text{ m}), \) increasing \( B \) to \( 30 \text{ m} \) does not affect the GWT through these units. However, increasing \( B \) does significantly affect GWT through the CHnv. Because of the lack of interference with the neighboring fractures, it takes 241 days for the wetting front to penetrate the CHnv [Fig. 7(a)], while for \( B = 3 \text{ m} \) it takes only 83 days [Fig. 5(d)].

For \( B = 30 \text{ m} \), even after the wetting front has penetrated through the CHnv, the large lateral matrix flow into this layer continues to significantly retard the speed of the wetting front as it penetrates the CHnv and PPw. Consequently, it takes an additional 49 days for the wetting front to reach the water table [Fig. 7(b)]. For \( B = 3 \text{ m}, \) since the CHnv becomes fully saturated, lateral matrix flow into it ceases and it no longer retards the speed of the wetting front. Consequently, it takes only an additional 3.4 days for the wetting front to travel from the base of the CHnv to the water table. A three-dimensional map of the major hydrostratigraphic units at Yucca Mountain (Ortiz et al. 1985) indicates that the CHnv is not areally extensive over the repository block. Therefore, we repeated the episodic flow calculations for situations in which the CHnv is absent. For \( b = 100 \mu \text{m} \) and \( B = 30 \text{ m}, \) the absence of the highly attenuating CHnv results in the wetting front taking only 52 h to reach the water table [Fig. 7(c)]. Obviously, the presence (or absence) of the high-\( k_\text{CHnv} \) CHnv unit has a profound effect on fracture-matrix flow below the repository.

For 1000-\( \mu \text{m} \) fractures, the presence (or absence) of the CHnv only minimally impacts fracture-matrix flow below the repository. For the case in which \( \nu = 1000 \mu \text{m} \) and \( B = 30 \text{ m}, \) the wetting front
Figure 8 is a log-log plot of the information in Table 6. Notice that the slopes of all of these curves (except the Chnz) vary from -3 for small \( b \) to -1 for large \( b \). For the Chnz, the transition to a slope of -1 occurs for \( b > 1000 \mu m \). Therefore, the sensitivity of the lateral penetration of the wetting zone in the matrix varies from \( b^{-3} \) for small \( b \) to \( b^{-1} \) for large \( b \). This sensitivity is better understood in light of the analysis of Nita and Buscheck (1989), who found that the lateral penetration, \( d_m \), of the wetting zone in the matrix is dependent on the matrix wetting diffusivity, \( D_m \):

\[
d_m \sim \frac{2(D_m - \Delta \rho)}{\mu}
\]

During flow period I, the wetting front penetration, \( h(t) \), is linearly dependent on the saturated hydraulic conductivity of the fracture, \( K_f \):

\[
h(t) \sim K_f t
\]

where \( K_f \sim b^2 \). If it takes \( t = t^* \) for the wetting front in the fracture to vertically penetrate the entire thickness of a hydrostratigraphic unit, \( L \), then

\[
L = h(t^*) \sim b^2 t^*
\]

We now define \( d_m^* \) to be the maximum lateral penetration of the imbibition front in the matrix during the time it takes the wetting front to vertically penetrate a given hydrostratigraphic unit (i.e., for \( t = t^* \)), such that

\[
d_m^* \sim \frac{2(D_m - \Delta \rho)}{\mu}
\]

Substituting into Eq. (4), we get

\[
d_m^* \sim \frac{2(D_m - \Delta \rho)}{\mu} b
\]

In order to model more complex fracture network geometries, it is useful to quantify the length scales of lateral matrix flow for the respective hydrostratigraphic zones at Yucca Mountain. For this purpose, Buscheck and Nita (1991) conducted a suite of calculations for fracture apertures ranging from 10 to 1000 \( \mu m \) and for fracture spacings sufficiently large to preclude any interference between neighboring fractures. At the point at which the wetting front in the fracture just reaches the bottom of a given unit, the maximum lateral penetration of the wetting zone into the matrix in that unit is listed in Table 6. Table 6 can be used as an upper bound on the required spacing between wetting fractures in order for the ECM to be valid for this idealized system of fractures. Notice that for all but the Chnz (and for \( b > 100 \mu m \)), the necessary spacing is on the order of millimeters to centimeters.

**Table 6**

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>10 ( \mu m ) fracture</th>
<th>50 ( \mu m ) fracture</th>
<th>100 ( \mu m ) fracture</th>
<th>200 ( \mu m ) fracture</th>
<th>400 ( \mu m ) fracture</th>
<th>1000 ( \mu m ) fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSW2</td>
<td>4.15</td>
<td>3.54x10^2</td>
<td>6.26x10^2</td>
<td>2.33x10^2</td>
<td>1.08x10^2</td>
<td>4.48x10^2</td>
</tr>
<tr>
<td>TSW3</td>
<td>0.90</td>
<td>5.45x10^0</td>
<td>9.85x10^0</td>
<td>3.59x10^0</td>
<td>1.61x10^0</td>
<td>6.92x10^0</td>
</tr>
<tr>
<td>CHnz</td>
<td>5.92x10^2</td>
<td>47.3</td>
<td>6.08</td>
<td>0.80</td>
<td>0.11</td>
<td>6.74x10^0</td>
</tr>
<tr>
<td>Chnz</td>
<td>68.7</td>
<td>0.55</td>
<td>6.72x10^0</td>
<td>9.27x10^0</td>
<td>2.06x10^0</td>
<td>1.01x10^0</td>
</tr>
<tr>
<td>PPW</td>
<td>700.</td>
<td>5.90</td>
<td>0.71</td>
<td>9.02x10^0</td>
<td>1.32x10^0</td>
<td>5.31x10^0</td>
</tr>
</tbody>
</table>

**Fig. 8.** Log-log plot of the maximum width of the wetting zone vs fracture aperture for the five major hydrostratigraphic units between the repository horizon and the water table.
yielding a \( b^{-1} \) dependence of lateral matrix penetration during flow period I. This dependence is consistent with the observation concerning large \( b \) in Fig. 8. Notice that during flow period I, \( d_m^* \) scales as \( \sqrt{L} \).

During flow period II, the wetting front movement is given by

\[
h(t) = K \sqrt{t}
\]

where \( \sqrt{t} \approx b \). Therefore,

\[
L = h(t^*) = b^3 \sqrt{t^*}
\]

Substituting into Eq. (4), we get

\[
d_m^* \approx \frac{2\sqrt{D_m^*}}{\sqrt{t^*}} \text{ (8)}
\]

yielding a \( b^{-3} \) dependence of lateral matrix penetration during flow period II. This dependence is consistent with the observation for small \( b \) in Fig. 8. Notice that during flow period II, \( d_m^* \) scales linearly with \( L \).

**Ponded Conditions at the Ground Surface**

This section considers a two-dimensional system of vertical, parallel, uniformly spaced fractures extending continuously from the ground surface to the repository. Starting from the ground surface, this model includes the low-\( k_m \) welded TCw, the high-\( k_m \) nonwelded vitric PTn, and the low-\( k_m \) welded TS1w and TS2w (Table 2). A steady-state recharge flux of 0.045 mm/yr was once again used in the reference case (Fig. 1).

Because of the low \( k_m \) of the welded TCw, it only takes 1.5 h for the wetting front in a 100-µm fracture to penetrate it and reach the PTn (Fig. 9(a)). In order to observe the lateral spread of the wetting zone in the PTn without the effect of interference with neighboring fractures, a large fracture spacing was modeled (\( B = 400 \) m). Because of its large \( k_m \), the PTn matrix dominates the propagation of the wetting front through it [Fig. 9(b)]. Since matrix flow is dominated by imbibition, "transverse matrix flow" (TMF) results in the PTn, as is evident in Fig. 9(b). Gravity has not yet significantly contributed to matrix flow in the PTn.

Matrix-dominated TMF conditions continue to prevail during the first 30 yr of this ponded event and the wetting zone in the matrix has vertically penetrated the PTn [Fig. 9(c)]. Because of the dominance of matrix flow, the fracture in the PTn continues to be desaturated; therefore, the vertical migration of the wetting front in the PTn has occurred entirely in the matrix, primarily dominated by imbibition. The effect of gravity on matrix flow is beginning to become evident in the lower PTn [Fig. 9(c)]. Notice that because of the small \( k_m \) of the TCw, lateral matrix flow in this unit is minor.

The effect of gravity on matrix flow in the PTn is very evident at \( t = 62 \) yr [Fig. 9(d)]. As the liquid saturation in the lower PTn builds up, the liquid-phase permeability continues to increase and eventually becomes high enough to facilitate gravity-driven flow. The addition of the driving force of gravity to that of imbibition causes lateral flow in the lower PTn to overtake the lateral flow in the upper PTn (where flow is primarily driven by imbibition). Notice that the matrix continues to dominate flow in the PTn, causing the fracture to remain unsaturated in this unit.

Between \( t = 62 \) and 64 yr, flow in the PTn undergoes a transition from matrix-dominated to fracture-dominated flow period III, facilitating the penetration of the wetting front through the PTn and into the TS1w. The low \( k_m \) of the TS1w promotes fracture-dominated flow period II in this layer. At \( t = 68 \) yr [Fig. 9(e)], fracture-dominated flow period III continues to prevail in the PTn, with fracture-dominated flow period II occurring in the TS1w and upper TS2w. At \( t = 70 \) yr, the wetting front reaches the repository horizon [Fig. 9(f)].
An examination of the wetting front movement through the TS\textsuperscript{w1} and TS\textsuperscript{w2} indicates that wetting front penetration is related to \( r^2 \). This relationship is the result of total matrix imbibition into the PTn declining as \( r^{-1/2} \). Therefore, the net flux available to penetrate the TS\textsuperscript{w1} and TS\textsuperscript{w2} increases as \( r^2 \). This general relationship will hold whenever a unit of very high \( k_m \) overlies a unit of much lower \( k_m \). The wetting front movement in the underlying low-\( k_m \) unit will be dominated by the net flux available for fracture flow, i.e., the net flux that has not been imbibed by the overlying high-\( k_m \) unit. The implication for fracture flow through and below the repository horizon is that wetting front movement in the TS\textsuperscript{w2}, TS\textsuperscript{w3}, CHhv, and CHHz may be largely governed by fracture-matrix interaction that is occurring hundreds of meters above (within the PTn). Therefore, an adequate understanding of fracture-matrix flow in the CHhv and CHHz units under current and future climatic conditions must include a comprehensive quantitative understanding of fracture-matrix flow in the overlying intervals of Yucca Mountain, particularly in the PTn.

The theory of Nisao and Buscheck (1989) can be used to compare the time required to penetrate the PTn and CHhv, defined in Eq. 6 as \( t^* \). The ratio of \( t^* \) for these two units is given by

\[
\frac{t^*_1}{t^*_2} = \frac{k_{m1}}{k_{m2}} \cdot \frac{D_{m1}}{D_{m2}}
\]

Equation (9) holds where TMF conditions prevail. Because of the small \( t^* \) for the CHhv, there was insufficient time for gravity to become significant, so TMF conditions prevailed in this unit. Given the matrix properties of the PTn and the CHhv, \( t_{PTn}/t_{CHhv} = 76 \). Given \( t_{CHhv} = 290 \) days, then \( t_{PTn} = 60 \) yr. However, because the effect of gravity is beginning to invalidate the assumption of TMF conditions in the PTn, we find that it takes 70 yr for the wetting front to penetrate the PTn. Because gravity flow effectively enhances the lateral matrix diffusivity in the PTn, the matrix continues to dominate flow longer than would have occurred had TMF conditions prevailed. Where TMF conditions prevail, eventually there is a transition from matrix- to fracture-dominated flow because the imbibition flux declines as \( r^{-1/2} \). In this example, the effect of gravity causes the matrix flux away from the fracture inlet at the top of the PTn to decline less steeply than a \( r^{-1/2} \) dependency.

For a 1000-\( \mu \)m fracture, it takes only 30 s for the wetting front to penetrate the TCW. Because of the high \( k_m \) of the PTn, the matrix dominates flow for a short period of time, keeping the fracture in the PTn unsaturated. At \( t = 2200 \) s, the fracture in the PTn begins to dominate flow and become saturated [Fig. 10(a)]. The wetting front penetrates the PTn in about 2400s and reaches the repository horizon [Fig. 10(b)] only 1 h after the start of the event.

**SUMMARY OF MODEL RESULTS**

Figure 11 summarizes some of the preceding calculations and illustrates how these results impact site suitability and site characterization. The gray scale represents the saturation distribution, which corresponds to 0.045 mm/yr steady-state recharge flux (Fig. 1). Figure 11 summarizes the 100-\( \mu \)m fracture cases, which were driven by ponded conditions at either the ground surface or the repository. Because the CHhv does not extend over the entire repository area, it is depicted as pinching out roughly in the center of Fig. 11. Notice that it takes about 100 to 10,000 times longer for a wetting front starting at the ground surface to reach the repository than for a wetting front starting at the repository to reach the water table. Obviously, Yucca Mountain's capacity to attenuate and retard liquid pulses (by virtue of matrix interaction) primarily resides above the repository. Therefore, given the existence of vertically extensive fracture pathways, flow attributes that may lead to site suitability primarily reside above the repository. Accordingly, site characterization activities will need to focus on understanding and quantifying how (and to what extent) the PTn is capable of attenuating liquid flow in fractures. At the same time, site characterization will need to address the flow phenomena that may be giving rise to saturations in the CHhv that greatly exceed saturations consistent with zero recharge flux.

As a liquid pulse moves down a fracture, it is continually losing water by imbibition into the adjoining matrix. If a pulse were intense enough to allow water to reach a failed WP, it could dissolve radionuclides and transport them toward the water table. Shortly after the end of the episodic event, liquid in the fracture would be totally imbibed by the matrix along with any dissolved radionuclides. Although subsequent pulses might transport "additional" radionuclides, their capability to further displace radionuclides imbibed by the matrix during earlier events will be limited. This limited capability to further vertically displace radionuclides stems from the fact that

![Fig. 10. FMM-calculated dimensionless liquid saturation, \( S_f \) for a 1000-\( \mu \)m fracture and a fracture spacing of 3.0 m for ponded conditions at the ground surface at (a) \( t = 2200 \) s and (b) \( t = 1 \) h.](image1)

![Fig. 11. Summary of FMM calculations of episodic nonequilibrium fracture-matrix flow for 100-\( \mu \)m fractures, with and without the CHhv.](image2)
the matrix imbibition diffusivity of the low-$k_w$ units is at least as great as the molecular or ionic diffusivities. For the high-$k_w$ units, the matrix imbibition diffusivity is much greater than the molecular diffusivity. Hence, advection by imbibition away from the fracture will tend to dominate molecular diffusion toward the fracture, limiting the re-entrainment of previously imbibed radionuclides by subsequent fracture pulses. If a radionuclide front is not driven to the water table during the course of a single infiltration episode, then subsequent movement of that front will be largely governed by matrix-dominated flow. Vertical movement of radionuclides along fractures is not cumulative for dissolved species in a partially saturated, fractured porous medium. However, vertical movement may be cumulative for radionuclides that are entrained in colloids which can be filtered out on fracture walls.

CONCLUSIONS

Saturation measurements from the RIB (DOE 1990), "bomb-pulse" $^{36}$Cl measurements reported by Norris (1989), and the results of this modeling study are all consistent with episodic fracture flow from the ground surface to considerable depths. With respect to the impact that r-z admission has on nonequilibrium fracture-matrix flow, the major hydrostratigraphic units at Yucca Mountain fall into two general categories: (1) the low-$k_w$ welded and nonwelded zeolitized units (TCW, TSW1, TSW2, TSW3, and CHL2), which are likely to promote fracture-dominated flow, and (2) the high-$k_w$ nonwelded vitric units (PTN and CHNv), which are more likely to promote matrix-dominated flow. The discrepancy between the apparent near-zero recharge flux to the low-$k_w$ units and the apparent large recharge flux to the high-$k_w$ units can also be partially resolved by mechanisms that remove water from the vadose zone. These mechanisms may include vapor flow (Thorstenson et al. 1989) as well as lateral liquid flow along high-$k_w$ units such as the CHNv. For scenarios in which Yucca Mountain is not gradually saturating, the key consideration in analyzing radionuclide transport is the intensity and duration of the maximum possible infiltration episode.

Acknowledgments

The authors acknowledge the helpful review comments of Richard Knapp. We also appreciate the outstanding editorial assistance of Ray Cherniak. This work was supported by the Nearfield Hydrology Task (WBS 12.2.2.2.2) of the Yucca Mountain Site Characterization Project. Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

References


Lin, W., and W. Daily, internal memo, Lawrence Livermore National Laboratory, Livermore, CA (1990).


END

DATE FILMED

01/17/92