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THE IMPLICATIONS OF EPISODIC NONEQUILIBRIUM FRACTURE-MATRIX FLOW ON SITE SUITABILITY AND TOTAL SYSTEM PERFORMANCE

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ABSTRACT

We apply our work on fracture- and matrix-dominated flow to develop a conceptual model of hydrological flow processes in the unsaturated zone at Yucca Mountain. The possibility of fracture-dominated flow is discussed, and various deductions are made on its impact on natural and total system performance, site characterization activities, and site suitability determination.

INTRODUCTION

The unsaturated zone at Yucca Mountain in southwest Nevada is being considered as a potential repository site for storage of high-level nuclear waste. 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. [1] The thickness of the unsaturated zone varies from 500 to 750 m. The potential repository location is in Topopah Spring moderately to densely welded tuff, which is about 350 m below the ground surface and 225 m above the water table. Predicting the movement of water in the unsaturated zone is important for evaluating radionuclide migration, waste package corrosion, and waste form dissolution. From a performance perspective, fractures can have higher flow velocities and are of potentially greater concern than matrix flow. We have, therefore, investigated the possibility of infiltration in fractures and identified conditions when it is likely to occur. We explore the ramifications of our conceptual models on evaluation of the Yucca Mountain site. Our discussion will emphasize the need to look at total system performance in determining site suitability, especially in light of the potential for episodic infiltration events.

ROLE OF THE NATURAL SYSTEM IN MEETING REGULATORY REQUIREMENTS

The ultimate goal of evaluating the total system performance of a potential repository is to provide a technical basis for answering the question: Is the level of risk resulting from storage of nuclear waste at the repository acceptable with regard to its possible impact on public health and safety? We focus the discussion by addressing this question in the context of federal regulations. The Nuclear Waste Policy Act (NWPA), [2] requires that a site for a high level waste (HLW) repository must first undergo a *site characterization* stage by the Department of Energy (DOE) before construction can ever begin. At the conclusion of this stage, DOE must obtain approval from the Nuclear Regulatory Commission (NRC) in the form of a license application described in 10 CFR 60. [3] The application must demonstrate to the NRC that guidelines and requirements in 10 CFR 60 have been met. Specific requirements for the repository and site are:

Criterion 1: Containment of HLW in waste packages will be "substantially complete" for a "containment period" to be determined by the Commission that is not less than 300 years nor more than 1,000 years after permanent closure of the geologic repository. *(sec. 60.113(a)(1))*

Criterion 2: A limit is placed on the release rate from the engineered barrier system (EBS) after the containment period calculated as a specified fraction of the inventory remaining at 1,000 years after permanent closure. *(sec. 60.113(a)(1))*

Criterion 3: Ground water travel time (GWTT): "The geologic repository shall be located so that pre-waste-emplacement groundwater travel time along the fastest path of likely radionuclide travel from the disturbed zone to the accessible environment shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission." *(sec.*

60.113(a)(2))

Criterion 4: The release of radionuclides to the accessible environment must meet Environmental Protection Agency (EPA) standards. *(sec. 60.112)*

The EPA standards in Criterion 4 are described in 40 CFR 191 [4] which (1) places limits on the cumulative releases of individual radionuclides to the accessible environment for the first 10,000 years after disposal *(sec. 191.13)*, and (2) sets a limit on the annual dose to any member of the public in the accessible environment during the first 1,000 years after disposal *(sec. 191.15)*.

In 10 CFR 60 the *waste package* is defined to be the "waste form and any containers, shielding, packing and other absorbent materials immediately surrounding an individual waste container." The *engineered barrier system* (EBS) is defined as "the waste packages and the underground facility" with the *underground facility* defined as "the underground structure, including openings and backfill materials, but excluding shafts, boreholes, and their seals." The *controlled area* means "a surface location ... extending horizontally no more than 10 kilometers in any direction from the outer boundary of the underground facility, and the underlying subsurface, which area has been committed to use as a geologic repository ... " In 40 CFR 191 the EPA has a more restrictive definition of the controlled area. It is defined to be "a controlled surface location, to be identified by passive institutional controls, that encompasses no more than 100 square kilometers and extends horizontally no more than five kilometers in any direction from the outer boundary of the original location of the radioactive wastes in a disposal system; and ... the subsurface underlying such a surface location."

Essentially, the above performance requirements limits either flux of radionuclides across a specified outer boundary of a particular system: the waste package, the EBS, or the controlled area. (The GWTT criterion is not a flux limit and is not directly related to containment or the release of radionuclides.) As part of the controlled area, the natural system is only one of several systems. From a regulatory context, the natural system is inseparable from the other components of the repository system, and man-made systems must be viewed as being equally important. In the Federal Register, [5] the NRC has said, "The Commission considers both engineered and natural barriers to be important ... " *(p. 28203)* The EPA in 40 CFR 191 has stated that "disposal systems shall use different types of barriers to isolate the wastes from the accessible environment. Both engineered and natural barriers shall be included." *(sec. 191.14)*

The natural system is particularly important because it largely controls the environment of the EBS and waste package systems, and it forms the barrier around the EBS. According to regulatory requirements, favorable attributes of a natural system are (1) a lack of mechanisms to transport radionuclides to the accessible environment (for Criterion 4); (2) capacity to retard radionuclide transport to the accessible environment (for Criteria 3 and 4); (3) a favorable environment for the waste packages and the EBS (for Criteria 1 and 2) that slows breakdown of WP's and other barriers, limits dissolution rate of waste form, and allows for robust, redundant engineering solutions.

Thus, steps in evaluation of the natural system include (1) determining the likelihood and distribution of liquid and gaseous fluxes and their effectiveness in transporting radionuclides, (2) determining the amount that radionuclides will be retarded as they travel through the natural system, and (3) determining whether the behavior of the natural system is suitable for the design of an effective and reliable EBS. ("Human intrusion" into the repository, that is, the likelihood that humans in the future will drill wells or excavate Yucca Mountain for mineralogical exploration or exploitation, is also an issue but is outside the scope of our discussion.)

Because 10 CFR 60 was written for a generic geologic repository, the NRC may make modifications depending on the particular characteristics of a site. In the Federal Register [5] the NRC has said that ". . . the Commission may approve or specify a radioactive release rate or a pre-waste-emplacement groundwater travel time that differs from the normal values, provided that the EPA standard as it relates to anticipated processes and events, is satisfied. Appropriate values will be determined in the course of the licensing process in a manner sensitive to the particular case, using principles set out in the performance objectives, without having to have recourse to the exemption provisions of the regulations" *(p. 28197)*. For example, 10 CFR 60 states that the travel time "shall be at least 1,000 years or such other travel time as may be approved or specified by the Commission." It also states that "on a case-by-case basis, the Commission may approve or specify some other radionuclide release rate, designed containment period or pre-waste-emplacement groundwater travel time, provided that the overall system performance objective, as it relates to anticipated processes and events, is satisfied" *(sec. 60.113(b))*.

The text in 10 CFR 60 then goes on to list some factors that the Commission may take into account in its decision. It also states that other requirements may be necessary in addition to those already given. In light of NRC's past statements, [5] the intention of these and similar clauses appears to be not for the relaxation of requirements but to allow flexibility for tightening them based on the characteristics of a particular site. However, it should be pointed out that evaluation of the license application will be based on scientific judgement concerning the acceptable level of uncertainties involved in performance analyses. One can conceive of situations in which a subsystem is demonstrated to be so robust that the acceptable level of uncertainties associated with the other subsystems can be lowered as long as the total system uncertainty is acceptable. Second, regulations may be found to be inappropriate as a result of scientific investigation either because they contain tacit assumptions that are not applicable to conditions at a particular site or are inconsistent with new scientific facts.

NATURAL SYSTEM, EBS, AND TOTAL SYSTEM PERFORMANCE

The natural system and the EBS are closely linked together for providing total system performance. A major task in the licensing process is to estimate the probability distribution of the cumulative mass of radionuclides passing through the outer boundaries of the waste package, EBS, and the controlled area. The interdependence between the three systems is evident in Criteria 1 and 2. This section discusses how this relationship also holds for Criterion 3. The probability of radionuclides traveling to the accessible environment can be broken down into the following categories:

Category 1. Probability distribution of certain events or processes that affect the breakdown of man-made, or engineered, barrier systems (EBS) subject to the conditional probability of events leading to breakdown

Category 2. Probability distribution of release from the EBS subject to the conditional probability of various events or processes leading to events which, in turn, lead to the probability distribution in Category 1.

Category 3. Probability distribution of events that lead to transport of radionuclides from the EBS to the accessible environment (these events are not necessarily statistically independent of events or processes in Categories 1 and 2)

We see that the identification of events in Category 1 depends on processes that affect Category 2. Therefore the characterization task depends on the EBS and on the degree of uncertainty with which we need to quantify events in Category 1, which depends on Category 2. Conversely, the design of the EBS must be based on the effect of the natural system on the EBS, especially any conditions that could reduce the effectiveness of the EBS.

The term *site characterization* appears in the NWPA as the stage immediately preceding the application for NRC approval. It is defined in 10 CFR 60 as primarily meaning data collection. But because 10 CFR 60 requires (1) subsystem performance analyses of both the natural and EBS systems, and (2) total system analyses, more than data collection is needed to meet licensing requirements. Prelicensing activities will include all technical investigations pertinent to the site supporting the license application, including not only data collection but analyses based on the data collected.

We draw the following conclusions (1) The identification of what attributes of the natural system needs to be characterized and to what degree largely depends on what form the EBS will take including its interaction with the natural system, and the extent of natural system characterization will depend on the contribution of the EBS to overall performance. (2) The design of the EBS depends on site specific characteristics of the natural system. (3) The site chararacterization stage of the natural system cannot be effectively performed without considering the EBS.

THE POSSIBILITY OF EPISODIC FRACTURE FLOW

The GWTT regulation of 10 CFR 60 requires that we identify pre-emplacement fast flow paths for liquid water and likelihood of their occurence. The dose and release limits in 10 CFR 60 and 40 CFR 191 require the identification and evaluation of all possible pathways of liquid water flow that can transport radionuclides to the accessible environment. They also include the evaluation of the effectiveness of liquid water as a transport mechanism of radionuclides from the EBS and waste packages and the effect of water on their degradation. If the repository site were in a saturated zone, the flow of water would occur predominantly in the fractures. In an unsaturated site the amount of fracture flow is limited by the availability of water for flow. In areas subject to low spatially and temporally uniform infiltration fluxes, flow in the unsaturated fractured porous rock occurs primarily in the matrix instead of in fractures because water is preferentially held in the matrix by capillary forces. This flow is very slow, especially in the welded tuffs, because of their low matrix permeability.

It has been recognized by the Yucca Mountain Site Characterization Project and its predecessor organizations that the potential for flow of water in fractures and faults is a major candidate for the fastest pathway and needs to be investigated as part of site characterization activities. [6] The possibility of infiltration by fracture flow is not new and was hypothesized in an early conceptual model of Yucca Mountain by Montazer and Wilson. [1] One way to investigate the possibility of fracture flow is by using numerical models. Many hydrological analyses of Yucca Mountain have used low, areally uniform infiltration fluxes of not greater than 1.0 mm/yr. In this section we will point out several reasons why the use of low infiltration fluxes may not always be valid. Most analyses have used the equivalent continuum model (ECM) or similar models which are valid under low fluxes that are so low that the fracture and matrix are in capillary equilibrium. Such models cannot predict transient fracture flow that occurs before equilibration occurs. Significant fracture flow occurs in these models only when the matrix is nearly saturated; therefore, they severely underpredict the amount of fracture flow during episodic conditions.

A discrete fracture model is needed predict transisent fracture flow. Travis et al. [7] used such a model to numerically simulate the movement of a finite slug of water down a fracture for a single layered system. Wang and Narasimhan [8] used the MINC dual porosity model to ascertain the validity of the equivalent continuum model under low infiltration fluxes. The only detailed analysis of Yucca Mountain, including the various units and surface conditions resulting in sustained fracture-dominated flow conditions appears to be that of Buscheck et al. [9] Nitao [10] has given a detailed theoretical analysis of the conditions under which fast "fracture-dominated" flow occurs (as opposed to "matrix-dominated" flow).

In later sections we present some field evidence that supports the hypothesis of fast fracture flow. What are possible sources for this flow if the evidence is correct? Why is such flow not predicted by most of the previous hydrological simulation analyses? These analyses have typically used areally and temporally uniform net infiltration rates of around 0.1 to 1.0 mm/yr. There are various reasons why this assumption may not be valid. (1) Precipitation at Yucca Mountain does not fall uniformly on the ground surface but is strongly affected by surface topography. [11] (2) Surface infiltration from precipitation at Yucca Mountain is not uniform in space but depends on runoff patterns and surface soil type. [11] It is not uncommon, even in semi-arid areas where the concentration of surface runoff is not as severe, for recharge to occur only over localized drainage areas. [12] (3) Subsurface infiltration is not uniform in space but is higher where there are high-permeability pathways. (4) Precipitation at Yucca Mountain is infrequent but occurs as short intense thunderstorms, often leading to short-lived flash floods in nearby washes. [11] (5) Traditional estimates of net infiltration using evapotranspiration rates were meant for aquifer recharge and agricultural irrigation. They give only areally averaged values and do not account for higher infiltration in areas of concentrated runoff, nor do they take into account water quickly flowing through the evapotranspiration zone in higher-permeability pathways such as fractures.

We draw the following conclusions. (1) Previous hydrologic analyses have assumed areally uniform, constant in time, low flux rates that do not exceed 1 mm/yr. (2) Infiltration rates may be higher in some areas because of surface runoff, variation in soil type, and surface exposure of fractures. (3) Infiltration may also be higher because infrequent, but intense, precipitation events could result in fracture flow through the evapotranspiration zone. (4) Because of the low fluxes assumed, most analyses have been able to use the ECM approach. At higher fluxes this model severely underpredicts fast fracture flow. (5) Characterization should examine the possibility of localized high-recharge areas as potential sources of fast fracture flow.

POSSIBLE EVIDENCE SUPPORTING FRACTURE FLOW

Field evidence supports the occurrence of long-distance, relatively rapid flow (presumably through fractures) in the vadose zone at Yucca Mountain and environs. This includes:

1. Detection of chlorine-36 at a depth of 450 - 500 feet, as well as tritium at similar depths. [13]

2. Loss of polymer-based drilling fluid while drilling borehole USW G-1; a subsequent air-drilled borehole (USW UZ-1) located about 1000 ft laterally and updip from USW G-1 produced water (by swabbing) containing drilling polymer. [14] This indicates that water movement occurred over a significant distance in less than three years. If the drilling fluid had imbibed into the matrix it almost certainly could not have been swabbed into the borehole; hence, it

seems likely that it was still in the fractures. This shows that imbibition may be very slow (perhaps retarded by polymer) that colloid-size particles can be transported long distances in fractures, and that at least some fracture networks are not continuous all the way to the water table. Otherwise, all the fluid would have drained away during the three year interval between drilling the two wells.

3. Recent unpublished results by Dick Luckey and Gary Patterson of the USGS, obtained from analysis of barometric response in the C-well complex indicate that the pneumatic diffusivity from the surface to the water table in this area is very high – converting to air permeability gives a value of more than 40 darcys. Corroborating values of pneumatic diffusivity are quoted in a paper by Nilson et al. [15] for the Nevada Test Site. Such high values of permeability can only be explained by the existence of connected pathways of large-aperture fractures. For example, if the fractures are idealized as regularly spaced and smooth-walled, then a 1 mm aperture fracture would have to occur every meter in order to provide permeabilities of a few tens of darcys.

4. Stable isotope signatures (carbon-13 and oxygen-18 ratios) for Trench 14 were reported by Quade and Cerling, [16] and compared to pedogenic soil carbonates and known spring deposits in the Amargosa Valley and Devil's Hole. The Trench 14 data are consistent with modern calcite deposited in soils from Pinyon-Juniper vegetation zones. Szabo and Kyser [17] reported similar measurements for calcite filling fractures in cores taken from Yucca Mountain tuffs; the isotope signatures of these samples are for all practical purposes the same as those of the Trench 14 calcite. If we accept that this similarity in stable isotope ratios indicates the same origin, then we can rule out the possibility of upwelling water as the source of the fracture-filling calcites. However, if we accept the pedogenic origin of Trench 14 deposits, then the deposits in the fractures must also be derived from percolating meteoric water, and fracture flow must have occurred to depths below the present water table.

DIFFERENCES BETWEEN UNSATURATED AND SATURATED SYSTEMS

Yucca Mountain is unique from other repository programs in the world because the site is in the unsaturated zone instead of the saturated zone. The United States is one of the few industrialized countries that has large regions with thick unsaturated zones allowing the siting of a repository to be located several hundred meters above the water table. Confusion can result when attempting to translate saturated zone concepts to an unsaturated site. We point out some of the differences between saturated and unsaturated sites, especially in light of the possibility of episodic flow events.

The hydraulic flow velocity in the host aquifer of a saturated repository site may vary spatially because of the heterogeneity of the formation, but changes in time are slow because flow is usually driven by a large-scale mean regional gradient relatively insensitive to changes in recharge flux. Because of the usually great depth of these sites below the water table, any changes in flux caused by water table fluctuations are minor. Under such steady-state conditions it makes sense to subdivide the total system into a "near-field" subsystem embedded within and driven by a "far-field" flow system. High thermal fluxes can enhance radionuclide transport around the waste packages by locally increasing hydraulic velocities. Buoyancy driven currents induced by the waste heat could carry radionuclide large distances. Heat from the waste can also damage the sorbing and sealing properties of clay backfill materials. Thus, a decision appears to have been made for most, if not all, saturated sites to use only waste that has been long enough out of core that its heat output has been significantly reduced. Under low heat output conditions the area around the repository that has been physically or chemically is believed to be small.

To analyze the performance of a repository in unsaturated fractured rock, we must, of course, deal with distinctly different flow behavior than in a saturated site. The relative scarcity of free water in an arid climate, such as at Yucca Mountain, creates a favorable EBS and waste package environment and reduces the likelihood of radionuclide transport. However, beyond a certain point, hydrological conditions are potentially more sensitive to changes at surface recharge points if there are connected high-conductivity flow paths from the surface to the repository. Unsaturated zone flow can be more variable in time and have a nonlinear dependence on the far-field flux conditions. At low fluxes, flow occurs in the matrix, while under high flux conditions, fast fracture flow begins. (A nonlinear system is not necessarily bad. In fact, most systems of any practical use are nonlinear.)

In an unsaturated system, the borderline between the near-field and the far-field is not as clear-cut as in the saturated zone. Simulations indicate that waste heat could induce thermally driven convection currents at Yucca Mountain that could result in condensation fluxes greater than estimated mean infiltration rates. Boiling of pore water near the waste package could lead to significant condensate fluxes all the way to the water table.

By analogy with saturated repository sites, we might conclude that disturbed zone effects are necessarily bad. Such an assumption appears to be made in 10 CFR 60 where the GWTT requirement refers to the time it takes for water to travel from the "disturbed zone" to the accessible environment. The *disturbed zone* is defined in 10 CFR 60 as the "portion of the controlled area the physical or chemical properties of which have changed as a result of underground facility construction or as a result of heat generated by the emplaced radioactive wastes such that the resultant change of properties may have a significant effect on the performance of the geologic repository." (For further discussion on the disturbed zone and its characterization see the paper by D. A. Chesnut in these proceedings [18]). The NRC appears to view the disturbed zone as a region of possibly reduced performance. [5] However, we point out that in an unsaturated environment, waste heat will dry the host rock which benefits performance by (1) removing water as a possible transport mechanism, and (2) providing a favorable environment that will reduce the likelihood of waste package container corrosion. Performance under pre-emplacement conditions is not necessarily representative of post-waste emplacement conditions, which could be better or worse.

Some thought is required for the interpretation of the GWTT requirement in an unsaturated environment. The concept of GWTT is more meaningful in a saturated system, where flow is more or less uniform in time and insensitive to recharge. For an unsaturated zone, the type of flow, fracture-dominated or matrix-dominated, from the repository to the water table (which is one segment of a possible pathway to the accessible environment, the next leg being from the water table to the accessible environment via the saturated zone), as well as the magnitude of flow, depends on the amount of available water at the repository level. The amount of water is in turn a function of how much water has percolated from the surface. Thus, the GWTT in an unsaturated site can be more sensitive to changes in the amount of water infiltrating from above, especially during intense storm events. We propose that the GWTT regulation be interpreted with regards to the unsaturated zone that it applies to how fast water existing under pre-emplacement conditions can travel from the repository level to the water table, not with respect to how fast *any* amount of water travels. The amount of water at the repository level is equal to percolation from above the repository under pre-emplacement conditions. (*Groundwater* defined in 10 CFR 60 is all water below the ground surface. Here, we assume that the term water refers only to the liquid phase.) Under this interpretation, in order to determine the amount of water existing at the repository *characterization and analysis must examine not only hydrological conditions below the repository but hydrological conditions above the repository as well, including at the ground surface.* Important aspects of percolation that should be investigated are (1) climatic conditions, distribution of precipitation, (2) surface runoff patterns, evapotranspiration flux, (3) hydraulic properties and flow processes occuring at the units above the repository including gas and water vapor flux, estimation of flow at repository levels, and (4) the potential for non-welded units as barriers to fracture flow. Simulations presented in a later section indicate that the units above the potential repository level have a greater potential to attenuate fast fracture percolation than those below.

The determination and characterization of *pre-emplacement conditions* and their effect on GWTT are more difficult because of the episodic nature of fracture flow events. Should pre-emplacement conditions be based on observations over a certain length of time during the characterization stage before emplacement begins? How long should this time be? Fracture flow can vary not only temporally but spatially as well. Thus, it is conceivable that fracture flow is much heavier in some localized areas than at other locations. Should pre-emplacment conditions refer to conditions only in areas where the waste is to be emplaced? If so, repository layout could take advantage of fracture flow characterization to avoid areas with potential for fracture flow. How sensitive is performance to larger infiltration events caused by climatic changes?

We conclude the following. (1) The concept of near-field and far-field in an unsaturated sytem is not as clear-cut as in a saturated system. (2) Hydrologic conditions at the repository level may vary in time and have high spatial variability, more so than in a saturated system. (This, in itself, is not of concern if the expected repository performance within its range of uncertainty meets regulatory requirements.) (3) For unsaturated systems, the disturbed zone has been viewed as a region of possible decreased performance for saturated sites because of thermal effects from waste heat; in the unsaturated zone, it may be possible to use heat so that the disturbed zone is an area of increased performance. Thus, there may be reasons why we may want to increase the size of the disturbed zone instead of reducing it. (4) It makes sense that the GWTT in the unsaturated zone should refer only to the movement of water which exists under pre-emplacement conditions but not to unlimited amounts of water. (5) Characterization of pre-emplacement conditions for GWTT is complicated by the possibility of episodic fracture flow. (6) Pre-emplacement hydrologic conditions are not necessarily indicative of performance under post-emplacment conditions.

CONDITIONS FOR FRACTURE FLOW

An important step in developing conceptual models of fast fracture-dominated flow events is to understand under what conditions fracture-dominated flow occurs and to obtain a basic understanding of these conditions. Another important, related question is under what conditions is the equivalent continuum model (ECM) valid.

The ECM approach is only valid under sufficiently low fluid fluxes [8,19] and not valid under sufficiently large, localized, episodic fluxes. The condition for failure of the ECM model and the condition for "fracture-dominated" flow can be shown to be identical. [10] Moreover, for an idealized fracture-matrix system, the condition for fracture-dominated flow to occur is that the specific flux q_f into the fracture (per width of the portion of the fracture that is flowing) must be much greater than the critical specific flux q_f^* given by $q_f^* = \phi(S_s - S_i)D_m$, where ϕ is matrix porosity, S_s maximum matrix saturation (one minus the air entrapment gas saturation), S_i initial matrix saturation, and D_m, matrix diffusivity coefficient, which is a function of S_i. Conversely, matrix-dominated flow, which is when the ECM model is valid, occurs if q_f is much smaller than to q_f^*.

Under ponded conditions at the fracture entrance, fracture-dominated flow occurs if the hydraulic conductivity K_f of the fracture is much greater than the critical fracture conductivity K_f^*, given by $K_f^* = \pi q_f^*/2b\beta$, where b is fracture half-aperture and β is the cosine of the angle of inclination of the fracture from vertical. Matrix-dominated flow occurs if K_f is much smaller than K_f^*.

The matrix diffusivity coefficient D_m is indicative of the capillary sorbing strength of the porous medium and is defined by the relation for the instantaneous one-dimensional flux, $q_I = \phi(S_s - S_i)\sqrt{D_m/\pi t}$, for imbibition into a core with one end at saturated conditions. The value of D_m can easily be determined from imbibition experiments. Its value depends on the initial saturation S_i of the matrix. (In porous media the permeability varies roughly as the square of the pore diameter, $K_m \sim d^2$, while the dependence of the mean capillary pressure is $p_{cm} \sim d^{-1}$. The imbibition diffusivity is related to the pore diameter by $D_m \sim K_m p_{cm} \sim d$. Hence, in general, high permeability corresponds to high matrix diffusivity, and therefore high matrix sorption.)

How does the critical flow behavior between the fracture- and matrix-dominated flow, leading to a highly non-linear dependence on the inlet flux, arise? We give a qualitative explanation, which, although not rigorous, is more general than the idealizations made in our mathematical analyses. At high fluxes fracture flow is faster than matrix flow; this forces the streamlines of capillary imbibition into the matrix to be orthogonal to the fracture. This restriction of streamlines causes the imbibition flux to be locally equivalent to that of a one-dimensional problem, which results in a $t^{-1/2}$ time dependence in the decaying imbibition flux. This decay is so fast that there is enough flow left over in the fracture for the fracture front to propagate at a rate faster than the matrix front. However, at low fluxes, fracture flow is not fast enough to overtake the flow in the matrix, and matrix streamlines are not forced to be orthogonal to the fracture, thus resulting in a higher matrix imbibition flux, which reduces the amount of water left for fracture front propagation. The net outcome is that the speed of the fracture front is reduced to less than that of the matrix front. A similar explanation holds for a fracture under ponded entrance conditions except that fracture hydraulic conductivity controls the available amount of water instead of inlet flux.

Assuming that the fracture conductivity obeys a cubic law, [20] $K_f = (2b)^2\rho g/12\mu$, where μ is dynamic viscosity, g gravitational acceleration, and ρ the density of water, the condition for fracture-dominated flow becomes $b^3 \gg b^{*3}$ and for matrix-dominated flow $b^3 \ll b^{*3}$, where the critical aperture is given by $b^* = (6\mu q_f^*/\pi\rho g\beta)^{1/3}$. The cubic law is not always valid for actual fractures but is useful for illustrative purposes. Table 1 shows the type of flow expected in the various units at Yucca Mountain for fractures with cubic law apertures based on the critical apertures computed in Nitao. [10] Parameter values that were used are those in Table 1 of the paper by Buscheck et al. [9] with values from Klavetter and Peters. [22]

The above analysis has interesting implications. Under episodic conditions, fast fracture flow occurs only in fractures with sufficiently large apertures. Thus, in terms of fracture connectivity, we are interested in the connectivity of networks of large-aperture fractures. Second, matrix that is sufficiently fractured with small-aperture fractures will act as an equivalent single continuum. Thus, we may be able to consider the system as consisting of large-aperture fractures embedded in an equivalent continuum of the matrix and small-aperture fractures.

Effect of Lithological Layers

The introduction of lithological layers, or, more generally, of variations in matrix properties, can have a major effect on the propagation of fracture flow. Spatial variability in matrix properties and aperture which occur primarily longitudinal to the fracture is averaged by imbibition occurring over an imbibition length scale which, for a homogeneous matrix, is $L_f = K_f \pi ba/\phi(S_s - S_i)D_m$. [10] If the length scale of property variations is much less than the imbibition length scale and the variations are statistically stationary, then averaged matrix and fracture properties can be used in the formulas of the previous section.

The behavior in the presence of larger scale variations from lithological layering can lead to major changes in fracture flow behavior. Consider a fracture penetrating three layers with the top layer (layer 1) having a much lower permeability than the second layer (layer 2), and the bottom layer (layer 3) having the same permeability as layer 1. Suppose the fracture half-aperture b is much larger than the critical half-aperture b_1^* for layer 1, so that fracture flow occurs in this layer. As a downward propagating liquid front in the fracture enters layer 2, the total matrix imbibition for the two layers is much less than that for a system consisting of layer 2 matrix only. Thus, the critical half-aperture is smaller than that calculated using layer 2 properties. From asymptotic solutions for a two layered system, this intermediate-stage critical half-aperture for flow from layer 1 to layer 2 can be shown to be the harmonic mean $b_{1,2}^* = \sqrt{b_1^* b_2^*}$ where b_1^* and b_2^* are the critical half-apertures for units 1 and 2 considered separately. As the fracture front proceeds further into layer 2 the net imbibition increases and the fracture front slows down. The critical half-aperture then approaches that of layer 2 alone, i.e., b_2^*. If the permeability of layer 2 is large enough that $b_2^3 \ll b_2^{*3}$, then the flow becomes matrix-dominated. At early stages of matrix-dominated flow, the matrix imbibition front in layer 2 is semiradial and emanates from the point where the fracture penetrates the top of the layer. As imbibition continues, the imbibition front hits the low permeability barrier created by layer 3, and imbibition is confined to a front moving in the transverse direction to the fracture. We saw in the previous section that imbibition from transverse flow allows fracture-dominated flow to occur, and therefore the system becomes fracture-dominated as the front passes through layer 2.

Fig. 1 is a computer simulation showing fracture flow coming down a low permeability layer. As it hits the lower high permeability unit it becomes matrix-dominated. In this manner, the vertical extent of fracture pulses is attenuated by *high* matrix permeability units.

At sufficiently low permeabilities capillarity is the main driving force for fluid movement in the matrix. At higher permeabilities, such as for non-welded vitric tuff, gravity effects become noticeable. Gravity causes flow into the matrix to be no longer transverse to the fracture compared to the case with capillarity alone. The resulting increase in imbibition makes it harder for fracture-dominated flow to occur and increases the critical half-aperture.

APPLICATION OF AN ANALYTICAL SOLUTION TO GWTT

We have developed a simple analytical model to estimate the movement of water under fracture-dominated conditions. [21] Consider a parallel fracture system with fractures spaced a distance $2a$ apart and with ponded conditions at the entrances. Here, $t_b = \pi(b\phi_f \Delta S_f)^2/\phi^2(S_s - S_i)^2 D_m$ is the matrix-fracture *interaction response time*, the time it takes for matrix suction to significantly affect fracture flow, and $t_a = \pi a^2/D_m$ is the *fracture interference time*, the time it takes for the matrix fronts from adjacent fractures to interfere with each other. The variable ϕ_f is the porosity in the fracture, with the fracture considered as a porous medium, and ΔS_f is the mean increase in fracture saturation in the fracture front.

It is convenient to define three flow periods. In Flow Period I ($t \ll t_b$), flow is not strongly influenced by matrix imbibition, and the fracture front travels approximately as if there were no matrix contribution. In Flow Period II ($t_b \ll t \ll t_a$), matrix imbibition retards fracture flow, and the fracture front velocity continuously decreases as $t^{-1/2}$. In Flow Period III ($t_a \ll t$), interference of the matrix imbibition front with the lateral boundary causes the fracture and matrix fronts to stabilize to a steady profile with the two fronts asymptoting to a constant rate; the matrix becomes nearly saturated except around the head of the fracture front. Values of t_b and t_a were calculated by Nitao [10] and show that for the welded tuffs the duration of Flow Period I is very short except for large apertures and t_a is large unless the fractures are very close together. Hence, most of the welded tuffs at Yucca Mountain fall within Flow Period II unless fracture flow occurs for a very long time.

Approximate expressions for the distance $h(t)$ from the entrance traveled by the fracture front is given in the different flow periods by [21]

$$h(t) \sim \frac{2}{3}K_f\beta\ (t/(\phi_f\Delta S_f)), \qquad t \ll t_b \qquad (1)$$

$$h(t) \sim \frac{K_f b\beta}{\phi(S_s - S_i)}\sqrt{\pi t/D_m}, \qquad t_b \ll t \ll t_a \ (2)$$

$$h(t) \sim \frac{K_f b\beta}{b + a\phi(S_s - S_i)}\ (t/\phi_f\Delta S_f), \qquad t_a \ll \ (3)$$

Using the solution for Flow Period II, we can easily calculate the travel time T of flow in a fracture at ponded conditions through a given unit of thickness L,

$$T \sim \frac{D_m}{\pi}\left[\frac{L\phi(S_s - S_i)}{K_f b\beta}\right]^2 \qquad (4)$$

Tables 2, 3, and 4 show the calculated travel time through the various units for different assumed fracture apertures using parameters given in Table 1 of the paper by Buscheck et al. [9].

If enough water is available for surface ponding, a 1000 μm fracture would allow a wetting front to penetrate the units in less than one day, except for the PTn, which could take 12 days. A fracture with aperture of 100 μm would require surface ponding lasting over thousands of days with most of the attenuation occuring in the PTn. Fracture flow occurs in all of the units except the CHn1z and PTn. A fracture with 10 μm aperture is matrix dominated except for the TSw3 and requires tens of thousands of years to reach the water table. These tables illustrate the strong dependence on the fracture aperture.

From the above relationship we can see the dependence of travel time on various hydrological parameters.

$$T \sim L^2, \quad T \sim b^{-6}, \quad T \sim K_m, \quad T \sim \beta^{-2} \quad (5)$$

$$T \sim \phi, \qquad T \sim (1-\gamma)^{1/n}(S_s - S_i) \qquad (6)$$

where we assumed a cubic law type of dependence for K_f, n is a characteristic curve parameter ranging from from 1.56 to 6.87 depending on the unit [22], K_m is matrix saturated hydraulic conductivity, and γ is the normalized initial saturation given by $\gamma = (S_i - S_r)/(S_s - S_r)$. The relations for T assume an approximate expression derived by Nitao [10] for D_m using a result using Zimmerman and Bodvarsson. [23]

Clearly, the travel time is most strongly dependent on the fracture aperture. For example, a two-fold increase in aperture results in a decrease in travel time by a factor of 1/64. This strong dependence on aperture is seen in Tables 2-4.

FIELD SATURATIONS ARE CONSISTENT WITH EPISODIC FRACTURE FLOW

Numerical simulations of vertical percolation through Yucca Mountain driven by a constant infiltration flux predicts a saturation vs depth profile which is not consistent with measured values. [9] In the unsaturated zone, the saturation profile is determined by the interaction of gravity, capillarity, infiltration flux, evapotranspiration, and gaseous advection and diffusion fluxes. For each several values of net infiltration fluxes the model was run until a steady-state was attained. Effect of evapotranspiration and surface driven gaseous advection currents were neglected. Comparisons of computed saturation profiles with measured saturation values [24] (ranges are shown as error bars in Fig. 2) show that computed saturation is too high in the welded units unless the flux is kept at less than or equal to around 0.045 mm/yr. At such low fluxes, the units are close to capillary equilibrium with each other, and the model correctly predicts that the nonwelded vitric tuffs are drier than the fine-pore welded tuffs because of the larger pore sizes of the nonwelded tuffs. However, the measured values in the nonwelded vitric units are much higher than model values and are in considerable capillary disequilibrium with the adjacent units if we use the capillary pressure curves of Klavetter and Peters. [22] Direct field measurements of capillary suction potential using psychrometers at well USW UZ-7 on Yucca Mountain also indicated that the nonwelded vitric PTn unit is too wet to be in capillary equilibrium with the adjacent TSw1 welded tuff unit. [25]

A possible explanation is that episodic infiltration pulses in fractures, perhaps originating from washes during flash floods, are passing through the welded units, which, because of their low matrix permeability, imbibe very little water over the relatively short time period of the pulses. As pulses reach the nonwelded vitric unit, the higher permeability matrix absorbs most of the water in the pulse retarding the fracture pulses.

This explains the relatively high saturation in the nonwelded vitric tuffs. But several questions arise. What maintains the capillary disequilibrium of the nonwelded vitric and welded units between pulses? Why doesn't water in the nonwelded vitric unit move into into the neighboring welded units resulting in eventual equilibrium? Several explanations exist. Water imbibing from the matrix of the nonwelded vitric tuff to the welded tuffs may dry between pulses by air flow in fractures which carry water vapor to the surface. [26] If the welded units are more fractured than the nonwelded vitric, the welded units would dry more readily maintaining the lower suction of the welded units relative to the nonwelded vitric units. (The welded units also don't imbibe as much water nor can they hold as much water because of their lower porosity.) Heterogeneous "bedded tuffs" [27] lying between the major nonwelded vitric and welded units may also be preventing equilibrium by acting as capillary barriers to flow.

Why don't the nonwelded vitric units eventually saturate? Water may be flowing laterally away from the area because the units have a tilt towards the east. Water vapor transport by air flow may also be contributing to net removal of water from nonwelded vitric units.

NUMERICAL SIMULATIONS OF GWTT FOR FLOW IN FRACTURE PATHWAYS

Buscheck et. al. [9] simulated the flow through a purely hypothetical highly conductive vertical fracture or fault at Yucca Mountain extending continuously from the ground surface to the water table. This could represent a conductive fault or a connected fracture pathway within a network of fractures. A ponded source was applied to the entrance of the fracture at the ground surface. In order to test the capacity of the natural system to the extreme, the source was left on until the front in the fracture reaches the water table, at which time the run is terminated. The initial saturation of the system was determined by running the model at 0.045 mm/yr until steady state was reached. Matrix properties from Klavetter and Peters [22], were used for the eight major hydrostratigraphic units in the unsaturated zone. Matrix permeability in each unit was multiplied by a factor of 1/40 for reasons discussed in Buscheck et al. [9] (this factor was not used in the calculations for Tables 2, 3, and 4)

The model fracture has a uniform aperture of 100 μm. 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. 5(a)). Because of its large K_m, the PTn matrix dominates the propagation of the wetting front through it (Fig. 5(b)). Since matrix flow is dominated by imbibition, "transverse matrix flow" (TMF) results in the PTn, as is evident in Fig.5(c). In other words, gravity has not yet significantly added to the vertical (or lateral) component of 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 completely penetrated the PTn (Fig. 5(d)). 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 begins to be evident in the lower PTn. 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. 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 is forced by the low permeability of its confining layers to become transverse to the fracture, and it therefore undergoes a transition from matrix-dominated flow to fracture-dominated flow period II, facilitating the penetration of the wetting front through the PTn and into the TSw1. The low K_m of the TSw1 promotes fracture-dominated flow period II in this layer. At t = 68 yr, fracture-dominated flow period II continues to prevail in the PTn, with fracture-dominated flow period II continuing in the TSw1. At t = 68 yr, the wetting front has penetrated into the top of the TSw2, reaching the repository horizon at t = 70 yr.

Wetting front movement in an underlying low K_m unit, such as TSw2, is dominated by the amount of water available to support fracture flow, i.e., the net flux that is not imbibed by the overlying high K_m unit, such as PTn. The impact on fracture flow through and below the potential repository horizon, i.e., in the CHnv and CHnz, is that wetting front movement in those units may be largely governed by a flux-limiting fracture-matrix interaction that is occurring hundreds of meters above (within the PTn). Therefore, an adequate prediction of flow conditions in the CHnv and CHnz units under either the current or future climate conditions at Yucca Mountain requires a comprehensive quantitative understanding of fracture-matrix flow in the overlying PTn. The need for understanding the features and processes that will govern fracture-matrix flow in the Calico Hills units is particularly crucial to correctly analyzing the impact of a shift to pluvial climatic conditions.

The theory of Nitao and Buscheck [21] can be used to compare the time required to penetrate the PTn and CHnv, defined in Eq. (4). The ratio of T for these two units is given by

$$\frac{T_1}{T_2} \sim \left(\frac{L_1}{L_2}\right)^2 \frac{D_{m1}}{D_{m2}} \tag{7}$$

Equation (7) holds where TMF conditions prevail. Because of the small T for the CHnv, 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 CHnv, $T_{PTn}/T_{CHnv} \approx 76$. Given $T_{CHnv} = 290$ days, then $T_{PTn} \approx 60$ 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.

For a 1000 μm 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. At $t = 2400$ s, the wetting front has penetrated the PTn and entered the TSw1. Because of their lower K_m, it only takes 1200 s for the wetting front to penetrate the TSw1 and TSw2. The wetting front reaches the repository horizon only 1 h after the start of the ponded event. For this example, flow period I occurs in the TCw while flow in the PTn undergoes a transition from matrix-dominated flow to fracture-dominated flow period II. Because flow period I dominates in the TSw1 and TSw2, it only takes 1200 s for the wetting front to penetrate 275 m through those units, roughly the time it would take for a fracture which did not interact with the neighboring matrix. From our conceptual model we clearly see why the 1000 μm case has a significantly different breakthrough time.

Implications Concerning Site Suitability

We also ran simulations for a ponded source at the repository instead of at the ground surface. It takes 70 yr for a wetting front starting at the ground surface to travel 350 m along a 100 μm fracture and reach the repository, while for ponded conditions at the repository it only takes 290 days for the front to travel 225 m from the repository to the water table (where the CHnv is present).

The CHnv unit does not extend throughout the repository site. Where the CHnv is absent, it only takes 52 h for a wetting front to travel from the repository to the water table. Therefore, 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, most of Yucca Mountain's capacity to attenuate and retard liquid pulses (by virtue of imbibition into the matrix) lies above the repository. Therefore, if there are connected, extensive fracture pathways, site suitability depends strongly upon flow attributes 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 determine what flow phenomena cause measured saturations in the CHnv that greatly exceeding values consistent with zero or low recharge flux.

We make the following observations: (1) More of the favorable attributes of the site lie above than below the repository with regard to preventing episodic fracture flow from reaching the water table. (2) Fracture flow stops quickly after the ponded source is turned off; therefore, a continous source of water must be present for fracture flow to propagate. [28] (3) If the nonwelded vitric units are laterally extensive, a single pulse from the surface flowing in a small-aperture fracture is easily attenuated. A ponded condition would have to last on the order of years to reach the water table (4) Flow in a single connected fracture with sufficiently large aperture can reach the water table in days. (5) Determing the capacity and duration of surface sources of flow into fractures is needed for predicting infiltration in addition to the conductivity and connectivity of fractures.

NATURAL BARRIERS TO FRACTURE FLOW AND GWTT

Much larger apertures are required for fracture flow to occur in nonwelded vitric units than in welded units. The larger pore-size of nonwelded vitric units results in larger matrix diffusivity D_m, and hence, a larger critical aperture. Moreover, in nonwelded vitric units the speed of fracture flow is greatly reduced, again because of their higher matrix diffusivity. Analytical theory and numerical simulations both show that a nonwelded vitric unit can be a barrier to fracture flow if it does not contain large-aperture fractures in direct communication with fractures from the unit above. The probability of such fractures may be decreased if the nonwelded vitric tuffs has a smaller density of fractures.

Since nonwelded vitric units are effective barriers only until they saturate, the capacities of the units, including their thickness and lateral extent, are important. A simplified geological description of Yucca Mountain has been used in many analyses, including this paper. The unsaturated zone is often viewed as a simple "layer cake" of the major pyroclastic-flow tuffs TCw, PTn, TSw1, TSw2, TSw3, CHn1v, CHn1z, etc. However, between these units there exist heterogeneous "bedded tuffs" consisting of reworked (1) pyroclastic-surge, (2) porous pyroclastic-fall, and (3) diagenetically altered pyroclastic-flow tuffs. [27] The pyroclastic-fall tuffs are estimated to have permeabilities several orders of magnitude larger than the other types and are potential barriers to fracture flow. They are also expected to be less fractured. The thickness of the pyroclastic-fall tuffs is highly variable, consistent with their origin. Instead of contiguous layers it may be possible that some of the pyroclastic-fall tuff actually consist of bodies of limited extent between the more prevalent pyroclastic-flow tuffs with the size of the bodies determining how fast they saturate. The bedded tuff zones consist of alternating layers of material of different grades of coarseness, possibly forming capillary barriers between the major units.

We conclude the following (1) Nonwelded vitric high permeability units can act as barriers to fast fracture flow as long as they do not have large-aperture fractures directly fed by fractures in the unit above. (2) The nonwelded vitric barriers do not fail until they become nearly saturated. (3) The bedded tuff zones between the major units may act as capillary barriers that cause infiltration to pond, and some of the pyroclastic-fall members may be absorbent buffers that stop fracture flow.

IMPLICATIONS OF EPISODIC FRACTURE FLOW FOR TRANSPORT

Aqueous transport of radionuclides and geochemical species can occur either under locally fracture-dominated or matrix-dominated flow conditions. The type of flow has a major impact on the relative amount of geochemical interaction with the matrix and fractures. The water chemistry affects the corrosion rates of the waste packages, dissolution rates and solubilities of waste components, and chemosorption properties on the rock. The hydrogeochemistry depends on what routes water percolates on its way to the repository and on its contact time with the minerals in different geological units.

In transport under matrix-dominated flow conditions, the concentration field of a species is dispersed because of heterogeneities in matrix permeability, while in fracture-dominated flow, dispersion depends on the geometric properties of the fracture network. In both instances, dispersion is a multiphase process but the flow fields are quite different in character.

Movement
of chemical species in matrix-dominated flow is retarded by chemical sorption properties of the matrix. Movement under fracture-dominated flow, on the other hand, is retarded by chemosorption onto fracture surfaces, which, because of geochemical alteration from previous episodic events, could be different from the matrix. Additional retarding mechanisms in transport within fractures are liquid advection and diffusion transporting the species from the fracture into the matrix. Radionuclides moving through the fractures will be carried into the matrix by liquid advection driven by capillary forces. The concentration of radionuclides in the fracture is not reduced in this process, but the movement of the advective liquid front itself is retarded. This type of retardation could be termed "physical, or advective, retardation" as opposed to "chemical retardation."

Diffusion through the liquid phase into the matrix is an important retarding mechanism only when it is comparable to or stronger than advective flux. Diffusion into the matrix dominates if the matrix diffusivity coefficient for imbibition is much smaller than the apparent coefficient of aqueous diffusion of the solute. Diffusion, unlike advection, retards transport by reducing concentration in the fracture stream. [29] In Fig. 6 we show a conservative solute undergoing transport by a liquid front advancing within a single fracture driven by gravity. The fracture is initially dry. Important parameter values for the matrix and fracture are given in Table 5. The matrix values are typical of TSw2 tuff and the fracture conductivity corresponds to a cubic law aperture of 100 μm. (The tortuosity factor, τ for liquid diffusion was based on the Millington formula [30] given by $\tau = S^{7/3}\phi^{1/3}$) A constant concentration source is kept at the entrance to the fracture. The relative effect of the retarding processes is seen by turning some of them off. Curve A is the case in which matrix imbibition and matrix diffusive transport have been turned off. Curve B is with matrix imbibition but matrix diffusion turned off, and Curve C is with both matrix imbibition and diffusion present. (The overshoot above a relative concentration of unity is a numerical artifact.)

Because of the small storativity of the fracture, liquid diffusion from the fracture to the matrix is an important retarding mechanism for fracture transport, even though it is a relatively slow process. Conversely, "back-diffusion" can also occur: a clean pulse of water flowing down a fracture will be contaminated by radionuclides diffusing out of the matrix. A possible release scenario to consider is radionuclides transported by liquid diffusion from the waste package through the matrix resulting in a slowly expanding plume of radionuclides in the matrix. Radionuclides will then diffuse into the fracture each time a liquid pulse passes through fractures that intersect the plume domain.

In an earlier section we saw that nonwelded vitric units could be buffers to fracture flow because of their tendency to have matrix-dominated conditions. Fracture flow percolating from above is absorbed in these units. Under high rainfall conditions some of these units above the repository could eventually fill and feed fractures in the unit below them. Therefore, the water reaching the repository could be more closely in chemical equilibrium with the nonwelded vitric unit. On the other hand, if flow passes through these units in large-aperture fractures, the water would be closer to that of meteoric water or with the mineralogy in the fractures. Thus, under episodic scenarios, the geochemistry of the water in contact with the waste package is different from that of water extracted from the matrix.

We conclude the following. (1) A sequence of infiltration events will not necessarily give rise to cumulative vertical transport of a chemical solute. (2) Flow behavior can have a major impact on what to study and what data to collect. (3) Geochemistry of the water reaching the repository through episodic events will not be the same as in water extracted in the matrix. (4) The choice of conceptual model of infiltration has a strong effect on interpretation of data, such as those from isotope studies.

SPATIAL VARIABILITY OF FRACTURE FLOW

Experience has shown that the spatial distribution of flow in many fractured systems is highly variable and is due to variation in fracture conductivities and the poor connectivity of fracture networks. A particularly interesting example is the Stripa infiltration test. [31] Dripping water was collected along the entire ceiling of the tunnel complex, at every 2 square meters, infiltrating from fractures. It was found that 50% of the flux occurs over 3% of the flow area, and that very little flow (less than the measurable limit) occurs over 70% of the flow area.

Since the Stripa site is saturated (i.e., the site is below the water table) and the rock matrix has very low porosity, it is not an exact analog for Yucca Mountain. An unsaturated site with fracture geometry similar to Stripa but with more porous rock and time-varying infiltration may be even more heterogeneous because matrix imbibition can extinguish some of the fracture flow. Spatially localized infiltration in unsaturated fractured tuff occurs at the G-tunnel Complex in the Nevada Test Site.

Spatial variability has an important impact on repository performance and analysis. Given a certain net flux over the a repository, it is important to know the spatial distribution of flux. If the variability is high, most of the waste packages will be exposed to very low fluxes while there will be a few with large fluxes. Large fluxes will subject waste packages to a more hostile environment and provide more rapid aqueous transport of radionuclides if they are mobilized. If these conditions lead to early failure and release of radionuclides from even a small number of waste packages, the controlled release requirements could be violated which shows that extreme conditions are more important than average ones. Also, it may be that failure of only a few waste packages could lead to mass release rates that are small relative to the total inventory of the repository. Thus, what are often viewed as "far-field" phenomena (e.g., the temporal and spatial distribution of infiltration at the ground surface above the repository) have an important impact on the "near-field" environment (This shows why in an unsaturated system the distinction between the far-field and near-field is not clear-cut as in a saturated system). Clearly, flow variability also impacts repository design, especially with regard to drainage of infiltrating water.

Heterogeneity in fluid displacement processes in porous media often leads to a log-normal breakthrough curve for the percentage of injected fluid that leaves the system as a function of time. [18, 32] The log-standard deviation σ can be obtained by either (1) calculation from the distribution of permeability values derived from flow measurements on cores (for non-fractured systems), or (2) fitting actual large-scale breakthrough curves.

In the idealized theory, σ from cores is identical to the value of σ determined by fitting breakthrough data to the theoretical equation. In reality, the value characterizing the breakthrough curve is affected by phenomena other than the variation of permeability, which also introduces, heterogeneity into the flow behavior. However, the σ values are often approximately equal, and, more important, the functional form for the breakthrough curve given by the theory is often consistent with the observed shape of the breakthrough curve. If any change is required, it is a (generally) slight adjustment in the value of σ, not a revision of the functional relationships.

Stripa data show that the spatial distribution of flux within a fractured non-porous medium (granite) is log-normal (see Fig. 3). Stripa may be the only direct experimental measurement of the spatial variability of the flow of water crossing a plane parallel to the ground surface. Similar measurements in other mines would be useful to determine whether log-normality is commonly observed and to provide a range of values for specific geologic settings.

The approach of characterizing flow and transport heterogeneity with a single parameter, σ, has been tested (1) in a number of field cases, (2) by comparison with detailed computer models for unfractured porous media, and (3)in a partial test for a fractured non-porous rock mass using Stripa data (as shown in Fig. 3). It needs to be tested in a much wider variety of media and for different flow regimes, most specifically in fractured *porous* media to determine its potential applicability to Yucca Mountain. A test strategy should include experiments and measurements similar to Stripa (measurement of the spatial distribution of water inflow, conducting large-scale tracer tests from the surface down) to determine the spatial and temporal variability of flow and transport in any location where underground access exists.

Another possible approach, which needs more analysis to determine its feasibility, is to conduct unsaturated zone pressure transient tests and gas-phase tracer tests in the various horizons of interest at Yucca Mountain. Similar tests have been conducted at the Nevada Test Site for the containment program, [15] and should be analyzed to see if this approach is feasible for Yucca Mountain. Of particular interest are large-scale gaseous tracer tests and direct down-hole measurement of gas-pressure response to barometric pressure fluctuations at the surface. Properly designed tests for Yucca Mountain should be able to quantify lateral and vertical continuity of fracture networks.

For illustrative purposes, Fig. 4 plots a hypothetical distribution of fluxes for Yucca Mountain the Stripa value of σ and a nominal infiltration rate of 0.5 mm/yr, assuming no flow occurs through 70% of any horizontal plane. If the distribution is viewed probabilistically, given any positive flux there is always a finite probability that a larger flux can occur, but this probability decreases with increasing flux. If this model is conceptually correct, how is the GWTT criterion to be viewed in the absence of a single well-defined flow velocity with which to compute travel time? One possibility is to place a limit on the probability of a certain amount of flux of water passing through the accessible environment, as is done in the regulations for radionuclide release from the EBS.

CONSTRUCTIVE USE OF HEAT

A knowledge of natural system processes can be incorporated into engineered systems to reduce total system uncertainty arising from possible episodic fracture flow. The functions of the EBS are (1) to improve overall system performance, (2) to compensate for uncertainty in how the natural system will behave, and (3) to protect the waste or other components from known unfavorable aspects of the natural system.

Technically, the EBS may include the engineered use of certain processes to provide a favorable environment such as using decay heat to keep the waste packages dry. [33] Whereas in a saturated zone repository, waste heat may be detrimental to performance, the opposite could be true for an unsaturated zone site. Repository scale computer simulations indicate that together with a proper scheduling of the age of the waste and drift emplacement of the waste packages, heat given off by the waste could keep the waste package dry for thousands of years (see Buscheck and Nitao, [34] these proceedings).

The heat output of a nominal waste package holding spent fuel rods is expected to be around 3 kW at 10 years from core. The output goes down to 1.4 kW at 60 years from core and 0.2 kW at 1000 years. The nominal areal heat load of 60 kW/acre over the entire repository is quite small and works out to an initial loading of 15 watts per square meter for a 10 year spent fuel waste. But because of the relatively low thermal conductivity of the rock and the concentration of the waste, there is sufficient heating for significant boiling of water in the rock to occur. The porosity at the repository horizon is expected to be around 10%. Approximately 40 to 90% of this porosity is occupied by water. The permeability of this rock is very low, on the order of microdarcies, which means that water vapor from boiling does not readily move in the matrix. If there is a fracture nearby, the vapor moves to the fracture, where it is forced away from the waste package by higher gas pressure in the boiling zone caused by vapor production (see Fig. 7).

As vapor in the fractures driven beyond the region of the rock with temperatures above boiling, it condenses and either imbibes into the rock or flows downward by gravity in fractures. The analysis used in Buscheck and Nitao (these proceedings) and Nitao [35] used an equivalent continuum approach which overestimates imbibition into the rock and underestimates gravity drainage by fractures, and, therefore, underestimates the amount of drying of the rock.

Much information about the effect of waste heat on the surrounding rock was obtained by the experiments conducted by LLNL at the G-tunnel complex at the Nevada Test Site. There, a half-scale electric heater was emplaced into a horizontal borehole and turned on for 120 days. [36] The region of rock dried by the heater extended out to 1 meter from the centerline of the heater. Comparison with the computer model indicated that imbibition of fracture water into the matrix was small, and evidence pointed to almost complete drainage of condensed water down fractures and away from the heater.

Draining fractures were actually observed a meter away from the heater in the heater borehole. The computer model accurately predicted the dried-out zone but did not accurately predict fracture drainage because of its use of the ECM. [37] We are working to replace the ECM with one that will include disequilibrium fracture flow. Pruess et al. [38] hypothesized that a heat pipe effect in the fractures might keep the area around the waste package near the boiling isotherm because of two-phase refluxing in the fractures. This effect was not observed in the test. A different type of heat pipe effect takes place where vapor is driven outward through fractures and refluxing to the waste package occurs in the matrix. [38, 35] This was not observed because the test period was not long enough for this heat pipe to establish itself.

Another type of heat pipe was seen, however. Temperature contours around the heater were asymmetric, with those above the heater closer to the heater than those below. This observation was ascribed to a *gravity-driven heat pipe* above the heater caused by flow of condensed water in the fractures driven by gravity. This heat-pipe is not a closed loop; the thermal signature indicated that water is laterally shed beyond the sides of the heater through fractures in the rock.

A large scale heater test of relatively long duration would go a long way toward answering the following questions: (1) Is the fracturing extensive enough to reliably drain condensate water? (2) To what extent will convective gas phase movement contribute to cooling of the rock? (3) Can the age of waste be scheduled to create a uniform heating environment? (4) How likely is it for condensate water to drip onto cooler waste packages? (5) How can we optimize the constructive use of heat, e.g., should we tailor the heat loads so that areas between drifts are below boiling to allow for drainage? (6) Should we enhance drainage pathways by using boreholes and other means?

We conclude the following. (1) Drainage of condensate water in fractures was observed in the field test. (2) An advantage of fractures is that they provide the host rock with free drainage paths, especially during the thermal drying period. (3) Drying by waste heat is an important consideration which could tremendously reduce uncertainties associated with episodic fracture flow events. (4) Heater tests of larger scale and longer duration will reduce uncertainties regarding the constructive use of heat by testing our theories of mass and heat flow at different spatial and temporal scales.

CONCLUSIONS

We have described conceptual models of episodic fracture flow at Yucca Mountain based on a combination of mathematical analyses, computer simulation, laboratory and field experiments, and preliminary field evidence. Our work prepares the way for quantitative models that can be incorporated into performance models. We also described the implications of our conceptual view of episodic fracture flow for site suitability, characterization, and licensing. We conclude the following.

1. The possibility of episodic fracture flow has not been adequately addressed by previous analyses because of the use of the ECM which do not allow for fast fracture flow. Low, areally uniform surface infiltration fluxes have been used to justify the use of such models, but they do not account for the high spatial and temporal variability of infiltration from the surface.

2. The concept of pre-emplacement GWTT as a regulatory criterion must be reexamined in light of (a) the spatially- and time-varying nature of episodic fracture flow events, which depends on flow conditions, not just below, but above the repository; and (b) the dominant effects of hydrologic flow driven by repository heat.

3. The different types of flow behavior discussed in this paper can have a major impact on what to study and what data to collect – the site characterization stage is not simply data collection but the development of conceptual models which will lead to quantitative models. These models cannot be fully

developed in advance – they must be refined as data becomes available.

4. Site characterization efforts will be not be fully utilized and focused unless objectives are broadened beyond meeting GWTT requirements to include consideration of EBS design concepts and the aspects of the natural system favorable to meeting release limits at the EBS and waste package boundaries.

5. Determination of site suitability by examining only the natural system may be difficult (e.g., because of the possibility of episodic fracture flow) because of the inherent heterogeneity and large scale of natural systems which limits the degree of characterization and the ability to test for performance. But, extensive and intensive controlled performance tests of the EBS can be used to decrease total system uncertainty.

6. Reliance on the natural system alone without considering the contribution of the EBS and engineering techniques, such as waste heat, may substantially underestimate total system performance.

Acknowledgments

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Table 1: Flow Type in Yucca Mountain Units as Function of Fracture Aperture

Unit	Fracture Aperture (μm) 10	100	300	1000
TCw	m	f	f	f
PTn	m	m	m	f
TSw1	m	f	f	f
TSw1	m	f	f	f
TSw2	m	f	f	f
TSw3	f	f	f	f
CHn1v	m	m	f	f
CHn1z	m	f	f	f

m = matrix-dominated flow
f = fracture-dominated flow
(fracture conductivity is
calculated from cubic law)

Table 2: Flow Properties of Fractures with 10 micron Aperture

Unit	Flow Type	I.U.T.T. (days)	Amt. of Water (liters)
TCw	m	500 K	36 K
PTn	m	5 M	360 K
TSw1	m	14 M	1 M
TSw2	m	31 M	2 M
TSw3	f	130 K	9 K
CHn1v	m	21 K	1.5 K
CHn1z	m	9 M	64 K

1. m = matrix-dominated flow
2. f = fracture-dominated flow
3. I.U.T.T. = individual unit travel time = travel time of water in a vertical fracture running through the entire respective unit with ponded conditions at the top of the unit
4. Amt. of Water = amount of water needed to traverse the unit for a 1 meter wide fracture assuming that the front fully fills the fracture
5. fracture conductivity calculated from cubic law
6. matrix diffusivity is computed from hydrological parameters in Klavetter and Peters [22] without the permeability adjustment used by Buscheck et al. [9]

Table 3: Flow Properties of Fractures with 100 micron Aperture

Unit	Flow Type	I.U.T.T. (days)	Amt. of Water (liters)
TCw	f	1.7	120
PTn	m	5 K	360 K
TSw1	f	140	10 K
TSw2	f	300	21 K
TSw3	f	0.1	9
CHn1v	m	20	1.5 K
Chn1z	f	80	5.5 K

Table 4: Flow Properties of Fractures with 1000 micron Aperture

Unit	Flow Type	I.U.T.T. (days)	Amt. of Water (liters)
TCw	f	<1	0.1
PTn	f	12	36 K
TSw1	f	<1	10
TSw2	f	<1	20
TSw3	f	<1	0.01
CHn1v	f	<1	60
Chn1z	f	<1	6

Table 5: Parameters used in Transport Calculation

Property	Symbol	Value
matrix conductivity	K_m	4.66×10^{-13} m/s
matrix porosity	ϕ_m	0.11
matrix van Genuchten parameters		
	m	0.4438
	α	5.67×10^{-1} m^{-1}
fracture volumetric aperture	2b	100 μm
fracture conductivity	K_f	8.17×10^{-3} m/s
porosity of fracture	ϕ_f	0.90
fracture van Genuchten parameters		
	m	0.7636
	α	12.9 m^{-1}
molecular diffusion coeff.	D	1.9×10^{-9} m^2/s

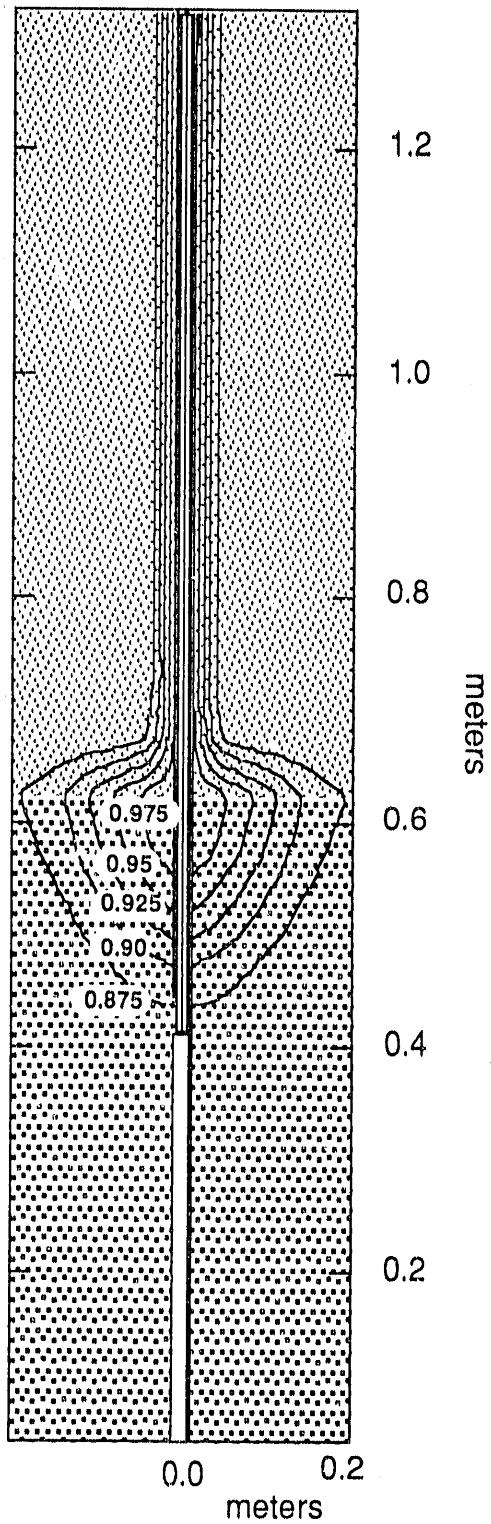

Figure 1: Saturation Contours showing Simulation of Transition from Fracture- to Matrix-Dominated Flow at an Interface between Low to High Permeability Layers

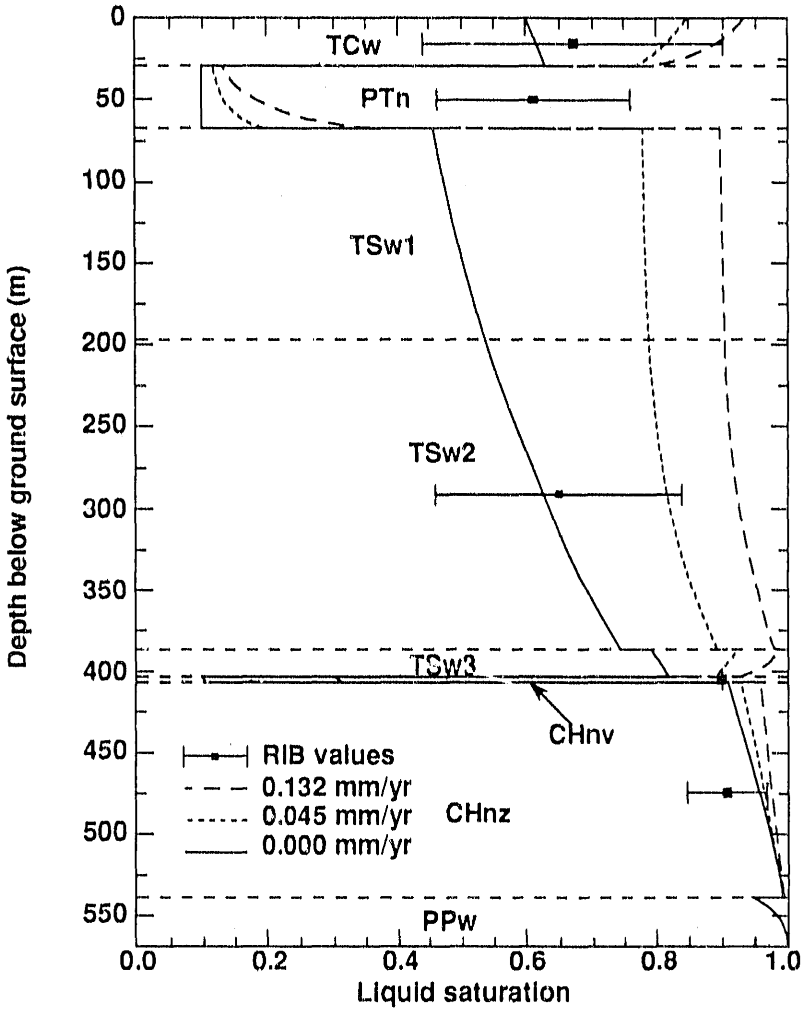

Figure 2: Vertical Saturation Profiles at Yucca Mountain at Various Fluxes: Comparison with Measured Values

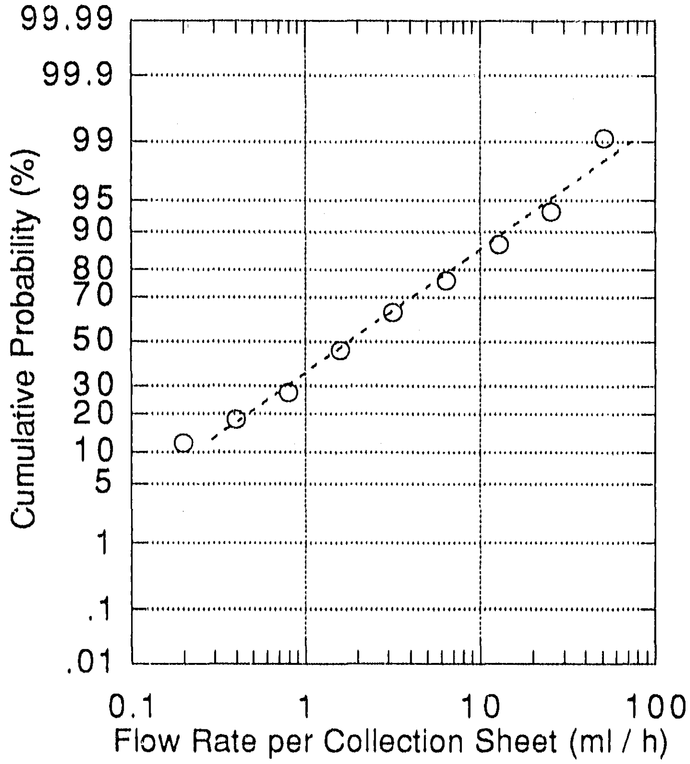

Figure 3: Log-Normal Plot of Percentage of Area Infiltrated vs. Inflow Flux, Stripa Test

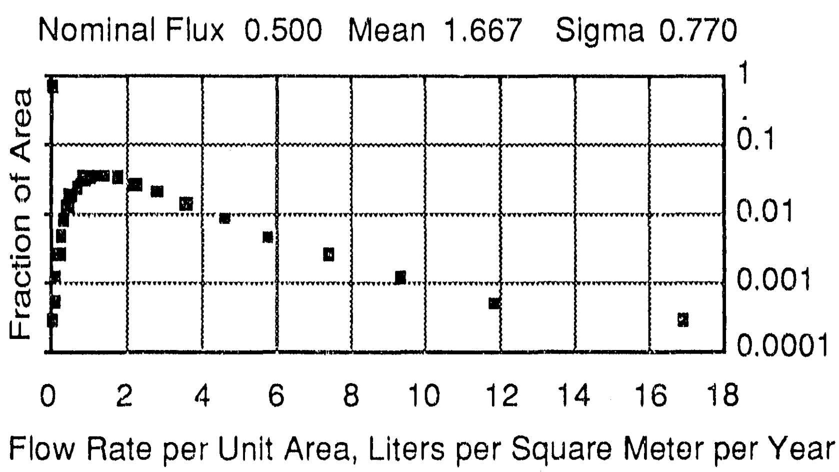

Figure 4: Linear Plot of Percentage of Area Infiltrated vs. Inflow Flux, Stripa Test

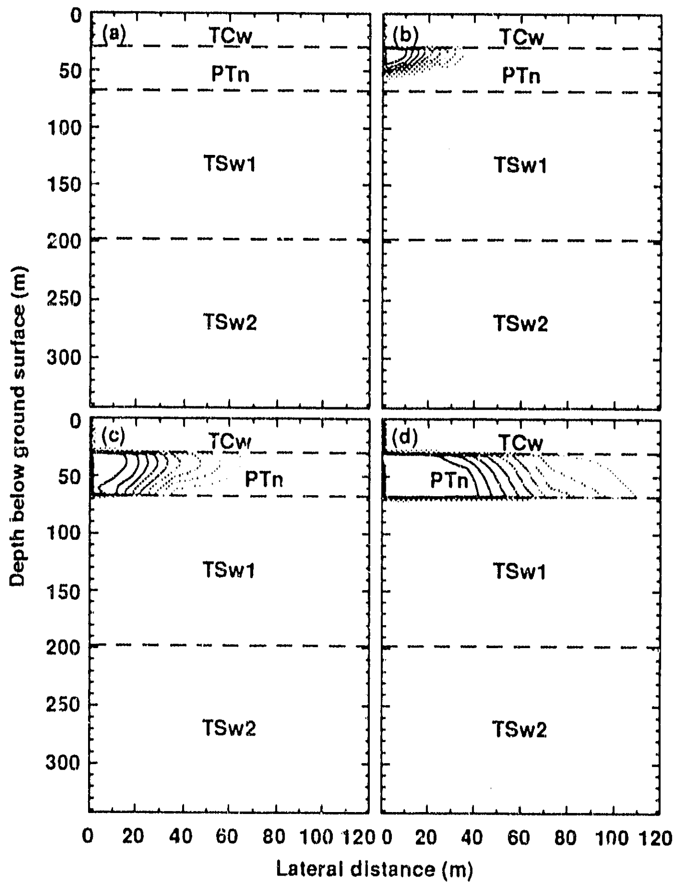

Figure 5: Contours of Dimensionless Change in Liquid Saturation $(S-S_i) / (S_s-S_i)$ for a 100 μm aperture fracture with fracture spacing of 400 m for ponded conditions at the ground surface at (a) t = 1.5 hr, (b) t = 10 yr, (c) t = 30 yr, and (d) t = 62 yr.

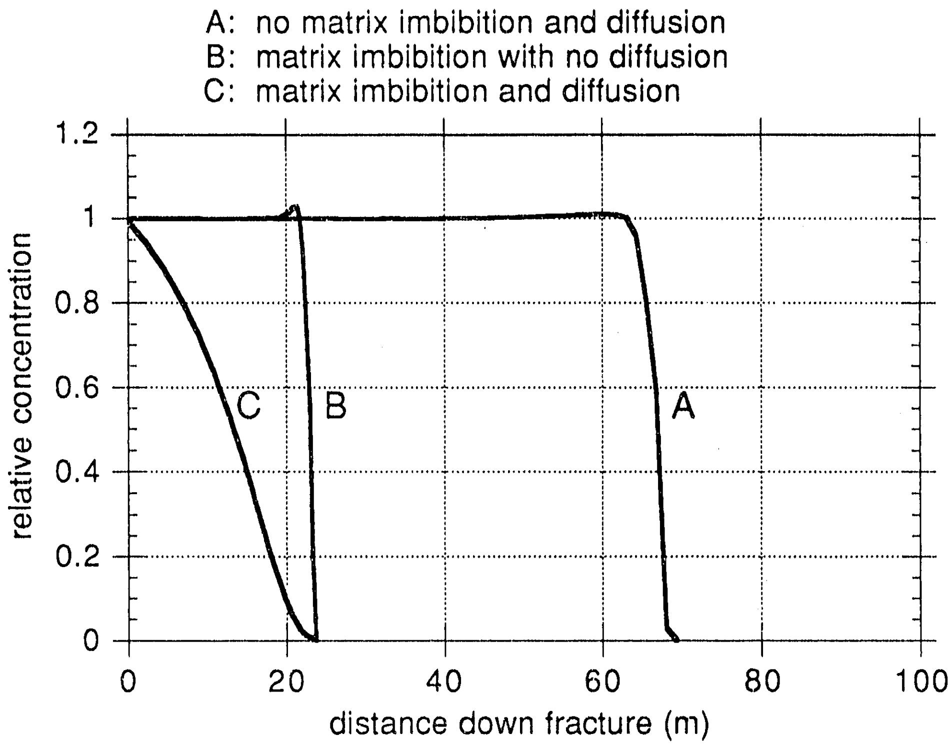

Figure 6: Concentration along Fracture Showing Relative Effect of Retarding Processes

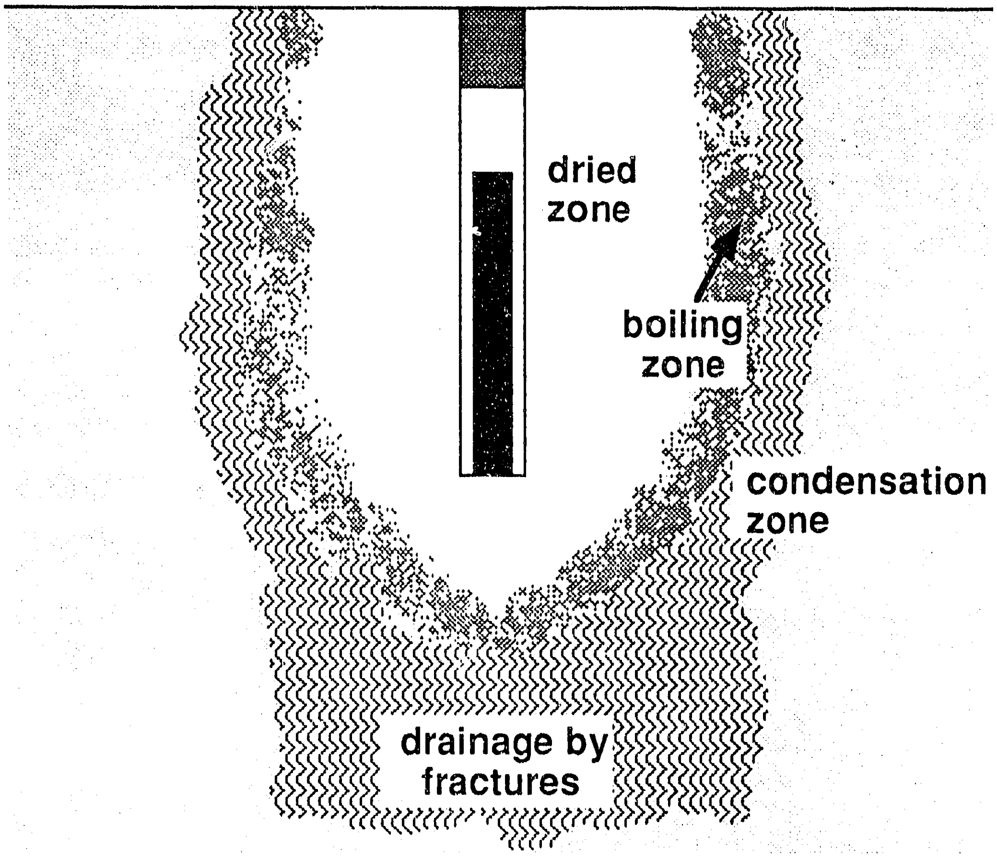

Figure 7: Drying of Area around Waste Package from Waste Heat

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