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To Phil, Thanks for your encouragements for me (Poor English?)
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UNSATURATED ZONE HYDROLOGIC PRINCIPLES APPLIED TO YUCCA MOUNTAIN AND BEATTY SITES

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ABSTRACT

Physical principles govern the movement of water and/or the transport of mass and energy through porous media. These principles may be cautiously applied to fractured rock in the vadose zone. In this paper, these principles are reviewed and briefly presented. The understanding and documenting of hydrogeologic processes, such as infiltration, recharge, redistribution, evaporation, and storage of water through site-specific data, are essential and necessary for confident characterization of the vadose zone in sites such as Yucca Mountain and Beatty, Nye County, Nevada. Much research by many investigators has firmly established the principles that govern the flow of water through the matrix of geologic materials under laboratory and field conditions. At the present time, no measurement techniques have been demonstrated for confidently documenting the hydrology of fractured rocks such as the welded tuffs of Yucca Mountain. Recently a great deal of work has been published either to model or study the role of fractures within the unsaturated welded and unwelded tuff; however, most of the work has been hypothetical in nature and there are no laboratory or field data to support the results published.

INTRODUCTION

During the last ten years, the problem of flow of water and transport of dissolved solutes in the thick unsaturated (vadose) geologic media of the arid zone have received much attention, mainly because of the possibility of finding suitable media for permanent disposal of large quantities of radioactive waste. The National Academy of Sciences[1] (1966) was first to suggest the disposal of high-level nuclear waste in the unsaturated zones of desert environments. A persuasive case for unsaturated-zone disposal was presented by Winograd[2,3] (1974, 1981) that promoted the thick unsaturated zones as likely having no effective processes which dissolve and transport radionuclides to deep water tables or to the land surface in very arid climatic regions.

The vadose (unsaturated) zone of the earth's crust is known to be hydrologically complex and involves infiltration, evaporation, soil moisture storage, ground-water recharge, as well as soil-forming processes. Thus, the vadose zone represents the conduit through which liquid and gaseous constituents are attenuated and transformed as they are exchanged in both directions between the land surface and the regional ground-water table.

The purpose of this paper is to review the physical principles and assumptions that are made governing the movement of water, mass, and energy through porous media as they may relate to the Yucca Mountain and Beatty nuclear waste repository sites in Nevada.

HISTORICAL BACKGROUND AND ASSUMPTIONS

Henry Darcy's[4] classic study (1856) has been widely accepted and used as the basis for describing flow of water through saturated porous materials. Buckingham[5] (1907) provided the physical basis for the presently-accepted conceptual picture of water movement through unsaturated porous media, and Richards[6] (1928) went on to formulate the concept of capillary potential. He also described a device for matric potential measurements, the tensiometer, and presented graphs of the matrix potential as a function of water content. In 1931[7], he published his classic paper which contains, among other things, precise values for hydraulic conductivity, including the hysteresis of the capillary potential function. Childs and Collis-George[8] (1950), Kirkham and Powers[9] (1972), Gardner[10] (1972), Sposito and Jury[11] (1985), Nielsen, et al.[12] (1986), and many others have firmly established the physical principles that govern the flow of water and dissolved chemicals through the matrix of unconsolidated porous materials under laboratory and field conditions.

The mathematical/physical approach to study and describe the flow of water and mass involves (1) the selection of relationships between the mass flux and the appropriate driving forces, and (2) the combination of these flux equations and the mass balance equation. Partial-differential equations are then developed which, in principle, may be solved and used to predict the behavior of the flow within a particular system. In developing the flow equation of water and mass, numerous assumptions are made to simplify the process of flow of water and mass through porous earth material. Most experts in this field of research agree on the following simplified assumptions that:

1) isothermal conditions prevail;
2) the porous matrix is a rigid system;
3) the chemical concentration of solutes in the liquid phase is negligible;
4) the gas phase is at constant atmospheric pressure;
5) the liquid phase displays a constant macroscopic average density;
6) the storage of water in the gas phase is negligible;
7) the volumetric flux of liquid water is proportional to the hydraulic gradient (i.e., Darcy's law is valid);
8) the coefficient of proportionality in the Darcy equation (the hydraulic conductivity) is independent of the hydraulic gradient and position, but may depend on other variables such as water content and temperature;
9) the water density of the gaseous phase is a function of the liquid water pressure;
10) the diffusion flux of the gaseous phase of water is proportional to the gradient of the water vapor density (i.e., Fick's law is valid);
11) the porous medium is directionally isotropic with respect to Darcy flow and vapor diffusion; and
12) the coefficient of proportionality in Fick's law (the diffusivity of water vapor) is independent of the vapor density gradient and position; it may depend on other factors such as gas-phase pressure, volumetric air content, temperature, and air-filled pore-space geometry.

TRANSPORT OF WATER AND SOLUTE

If it is further assumed that there is a defined relationship (single-value function) between the water content and the pressure head of the system; thus, Richards' equation for water flow can be written as:

$$C(h)\frac{\delta h}{\delta t} = \frac{\delta}{\delta x}\left[K_x(h)\frac{\delta h}{\delta x}\right] + \frac{\delta}{\delta y}\left[K_y(h)\frac{\delta h}{\delta y}\right] + \frac{\delta}{\delta y}\left[K_z(h)\frac{\delta h}{\delta z}\right] + \frac{\delta K_z(h)}{\delta z} \qquad (1)$$

In this parabolic partial differential equation, which is central to any porous media flow system, z is vertical and positive upward. The water capacity, C(cm^{-1}), is defined as the slope of the water characteristic curve (h(θ) function):

$$C = \delta\theta/\delta h \qquad (2)$$

where θ is volumetric water content (cm^3cm^{-3}).

In equation (1), the letters x, y, and z refer to the directions of the Cartesian axes and to distances in these directions (all of dimension cm). K_x, K_y, and K_z are the hydraulic conductivity function in direction x, y, and z, respectively. Note that the hydraulic conductivity of the unsaturated system is a function of the pressure head, h, or the volumetric water content, θ.

Equation (1) is the fundamental equation that governs the flow of water through the porous matrix under isothermal and isobaric conditions. The corresponding equation governing transient, one-dimensional solute transport through the matrix of earth material and porous rocks may be written, only in the z direction, as:

$$\frac{\delta(S+\theta c)}{\delta t} = \frac{\delta}{\delta z}\left[\theta D_s(\overline{V})\frac{\delta c}{\delta z}\right] - \frac{\delta(Vc)}{\delta z} \qquad (3)$$

where c is the solute concentration of the liquid phase; S is the amount of solute adsorbed by the porous matrix per unit volume of the earth material; V is the Darcy water velocity; $D_s(\overline{V})$ is the solute dispersion coefficient; and $\overline{V}$ (= V/θ) is the pore water velocity. The dispersion coefficient $D_s(\overline{V})$ of equation (3) is assumed to be a function of pore water velocity, $\overline{V}$.

The adsorption isotherms which express relationships between quantities of solute sorbed by the porous matrix, S, and corresponding concentration in the liquid phase, c, are commonly used to evaluate the rate-of-sorption term ∂S/∂t. Thus, equation (3) could be modified to:

$$\frac{\delta c}{\delta t} = \overline{D}\frac{\delta^2 c}{\delta z^2} - A\frac{\delta c}{\delta z} \qquad (4)$$

where

$$\overline{D} = \frac{D_s(\overline{V})}{R(c)} \qquad (4a)$$

$$A = \frac{\overline{A}}{R(c)} \qquad (4b)$$

$$\overline{A} = \frac{V}{\theta} - \frac{D_s(\overline{V})}{\theta}\frac{\delta\theta}{\delta z} - \frac{\delta D_s(\overline{V})}{\delta z} \qquad (4c)$$

$$R(c) = 1.0 + \frac{\rho k(c)}{\theta} \qquad (4d)$$

and k(c) is the solute distribution function measured from adsorption isotherms and ρ is the matrix bulk density. For noninteracting solutes (i.e., $k(c) = 0$), the retardation factor $R(c)$ equals unity; whereas, for interacting solutes having a linear isotherm, where $k(c)$ is a constant, $R(c)$ becomes a constant.

It is apparent from equation (4) that the transport of solutes in the matrix of porous media is dependent on the water content, θ, and Darcy velocity, V, both of which are variable under most field conditions. Due to the nonlinearity of equations (1) and (4), numerical solutions utilizing digital computers are widely used.

During the last two decades, numerous analytical and numerical solutions of equations (1), (3), and (4) have been developed to the point that, at present, certainly no scarcity exists in one- or multi-dimensional models. An extensive review and model inventory of unsaturated and partially saturated flow models is given by Narasimhan and Witherspoon[13] (1976), van der Heijde, et al.[14] (1985), Nielsen, et al.[12] (1986), Evans[15] (1983) and Evans and Nicholson[16] (1987).

TRANSPORT OF WATER AND HEAT

The published literature on simultaneous movement of water heat in soil and other geologic porous media is extensive. Attempts to study and model this process have ranged from an almost totally empirical approach to the state-of-the-art theory. Philip and deVries[17] (1957) proposed a theoretical model based on the following assumptions:

1. All processes are single-valued, i.e., hysteresis is not present in relationships such as the water content-pressure potential characteristic function of the porous media.
2. The effects of any matrix and volumetric changes of the porous media are negligible, and the effect of temperature on the water movement can be treated independently of matrix or volumetric changes.
3. Dynamic equilibrium between the phases of water in the pores can exist on a microscopic scale within the pores when the transport of water as a whole is not a steady-state process.
4. Dissolved chemical (solutes) and other contaminants.

Fick's law of diffusion, modified for water vapor in porous media as reported by Rollins, et al.[18] (1954), is given as:

$$V_f' = -D_o A \, \alpha v \nabla \rho \qquad (5)$$

where V_f (gm/cm^2/sec) is the vapor flux, D_o (cm^2/sec) is the diffusion coefficient of water vapor in the air, A (cm^3/cm^3) is the volumetric air content, α is Penman's tortuosity factor (≈ 0.66), $v = P/(P-p)$ is the mass flow factor in which P is the total gas pressure (mm Hg) and p is the partial vapor pressure in the pores of the rock matrix (or soil), and $\nabla \rho$ (gm/cm^3/cm) is the vapor concentration gradient. The movement of water vapor through porous materials under nonisothermal conditions involves a diffusion process coupled with evaporation and condensation in small localized areas. This process is similar to the evaporation of droplets in a small space or area. The increase of liquid water due to condensation in regions of lower temperature leads to a net difference in water potential which would create a liquid water flow toward the warm region. Childs and Collis-George[8] (1950) showed that Darcy's law was experimentally valid and applicable to flow in unsaturated porous media, such as soils. Following Edlefsen and Anderson[19] (1943), we can write the relationship:

$$\rho = \rho_o \psi = \rho_o \exp\left(\frac{hg}{RT}\right) \qquad (6)$$

where ρ is the density of water vapor, gm/cm^3, ρ_0 is the density of saturated water vapor, gm/cm^3, ψ is the relative humidity, g is the acceleration due to gravity, cm/sec^2, R is the gas constant of water vapor, erg/gm/C°, h is the pressure potential head, cm of H_2O, and T is the absolute temperature, in degrees Kelvin. Hence,

$$\nabla\rho=\psi\frac{\delta\rho_o}{\delta T}\nabla T+\rho_o\frac{\delta\psi}{\delta\theta}\nabla\theta \tag{7}$$

Using equation (6) to determine the relation $\frac{\delta\psi}{\delta\theta}$ we get

$$\nabla\rho=\psi\frac{\delta\rho_o}{\delta T}\nabla T+\frac{g\rho}{RT}\frac{\delta h}{\delta\theta}\nabla\theta \tag{8}$$

From equation (8) and Darcy's law, we obtain the general equation for vapor flux under nonisothermal conditions

$$\frac{V_f}{\rho_l}=-D_o A\alpha v\psi\frac{\delta\rho_o}{\delta T}\frac{1}{\rho_l}\nabla T - D_o A\alpha v\frac{g\rho}{RT}\frac{\delta h}{\delta\theta}\frac{1}{\rho_l}\nabla\theta \tag{9}$$

or

$$\frac{V_f}{\rho_l}=-D_v(T)\nabla T-D_v(\theta)\nabla\theta \tag{10}$$

in which $D_v(T)=D_o A\alpha v\psi\frac{\delta\rho_o}{\delta T}\frac{1}{\rho_l}$ is the nonisothermal water vapor diffusivity, and

$$D_v(\theta)=D_o A\alpha v\frac{g\rho}{RT}\frac{\delta h}{\delta\theta}$$

is the isothermal water vapor diffusivity in cm^2/sec.

Similarly, since liquid flow of water also is influenced by temperature gradients and knowing that pressure potential (soil-water suction), h, is dependent on both content and temperature, it follows that

$$\frac{\delta h}{\delta T}=\frac{h}{\sigma}\frac{d\sigma}{dT}=\gamma h \tag{11}$$

where σ is the water surface tension, in dyne/cm, and γ is the temperature coefficient of surface tension, in C^{o-1}. Darcy's law and using equation (11), can be written as

$$\frac{q}{\rho_l}=-K\gamma h\nabla T-K\left(\frac{\delta h}{\delta\theta}\right)\nabla\theta-Ki \tag{12}$$

where i is the unit vector in positive z direction and q is Darcy's flux (cm/sec). It is clear that the above equation is of the form

$$\frac{q}{\rho_l}=-D_l(T)\nabla T-D_l(\theta)\nabla\theta-Ki \tag{13}$$

It should be mentioned that the value of γ can be taken as a constant equal to -2.1×10^{-3} C^{o-1} for a temperature range of 5C° and 40C°.

Combining equations (13) and (10) and applying the continuity requirement leads to the general differential equation describing moisture movement due to temperature gradients in the form,

$$\frac{\delta\theta}{\delta t}=\nabla\cdot(D_T\nabla T)+\nabla\cdot(D_\theta\nabla\theta)+\frac{\delta K}{\delta z}\ . \tag{14}$$

where $D_T = D_V(T) + D_l\ (T)$ is the total nonisothermal moisture diffusivity (cm^2/sec/C°), and $D_\theta = D_V(\theta) + D\ (\theta)$ is the total moisture diffusivity in cm^2/sec.

Philip and deVries[17] (1957) proposed the following equation for the conduction of heat in soil, which can be used for other porous geologic materials:

$$\overline{C}\frac{\delta T}{\delta t} = \nabla \cdot (\lambda \nabla T) - L\nabla \cdot (D_v(\theta)\nabla(\theta) \tag{15}$$

where L is the latent heat of vaporization of water (cal/gm), λ is the thermal conductivity of the porous media, including the thermal distillation effect (cal/sec/cm/C°) and $\overline{C}$ is the volumetric heat capacity of soil (cal/cm^3/C°). The second term on the right-hand side of equation (15) represents the distillation effects inducted by the moisture gradient in soil. This equation is of the diffusion type involving θ-dependent diffusivity as well as gradients of both θ and T. It should be mentioned that equations (14) and (15) are the best mathematical formulas used to describe moisture and heat transport in soil as a rigid porous medium (no swelling upon wetting). These equations are nonlinear second-order parabolic partial differential equations; and since exact solutions are very difficult and sometimes impossible to obtain, numerical methods are used to develop the simulated theoretical results.

SIMULTANEOUS TRANSPORT OF WATER, HEAT, AND SOLUTES

Under natural conditions, especially where thick unsaturated zones of geologic earth materials are encountered, water heat and dissolved chemicals (solutes) are transported simultaneously through these earth materials. For the field problems encountered at most waste disposal sites, the movement of water and contaminants should be investigated under nonisothermal conditions. Conceptually, the equations listed above could be solved simultaneously by numerical methods, and digital computers could be utilized to provide solutions to many field problems. At the present time, many published papers deal with solutions to these equations under many varieties of boundary and initial conditions. However, the lack of field and laboratory data is evident from surveying the literature (Nielsen, et al.[12] [1986]).

TRANSPORT OF WATER VAPOR

In the development of the previous equations for water, heat and solutes transport through porous matrix, the viscous flow of the gas phase was ignored. Water flow through a rigid porous media which is characterized by very low permeability and low water content, such as may be found in arid climates in the southwestern part of the U.S., demands the study of the gas-phase displacement and transport. Recently, Green and Evans[20] (1987) studied the diffusive and convective processes by which vapor can be transported through geologic media. They pointed out that diffusion, pressure diffusion, forced diffusion, and thermal diffusion may be the four major contributing processes to a multicomponent system. They also stated that, in the near field surrounding high-level radioactive waste, the large temperature gradient and the electrical field may be important in causing diffusion of gaseous elements. Weeks, et al.[21] (1982) used Fick's law in combination with the porous media continuity equation to determine the diffusion parameter of unsaturated zones of alluvium material in the southern high plains, using atmospheric fluorocarbons.

Most of the published work in this area of vapor flow considers the process of ordinary (concentration) diffusion to be the main contributing factor for diffusion of vapor through porous geologic media. Weeks[22] (1987), Kemper, et al.[23] (1986), and Montazer and Wilson[24] (1984) reported air flow from unsaturated-zone geologic media in Idaho and Nevada. Weeks[22] (1987) reported substantial airflow from wells tapping the unsaturated fractured tuffs near the crest of Yucca Mountain, Nevada. He concluded that the convective gas diffusion process plays a large role as a means of transporting gaseous phase within porous/fractured tuff, and this process may have an important role with respect to the conduction of heat and gaseous radionuclide transport from a repository within the unsaturated fractured rocks. He suggested that more studies are needed to understand the process of gas transport under field conditions, especially within the thick porous/fractured geologic media.

FRACTURE FLOW

In developing the previous flow equations, it is assumed that water conductivity and other hydraulic parameters are defined on the macroscopic scale and that there is local equilibrium on what is termed "Darcy's scale" within the porous media of interest. However, in porous/fractured rock, the previous assumption may not be valid for the application of the unsaturated flow theory. Although the geometry of a single fracture in a rock type such as tuff can be described and accurately studied in terms of shape, radius, roughness, and aperture, it is unlikely that hydrogeologic variables needed for the unsaturated fracture flow characterization can be evaluated with the same ease and accuracy. During the last five to seven years, because of the interest in locating a high-level radioactive waste repository within unsaturated fractured tuff, many works have been published. Most of these deal with computer modeling of fracture flow under saturated/unsaturated conditions. For example, work published by Peters, et al.[25] (1984), Klavetter, et al.[26] (1985), Travis, et al.[27] (1984), Pruess, et al.[28] (1986), and many others have assumed that unsaturated fractures would behave hydraulically as porous media with respect to the conductivity function, water-capacity function and the void ratio-water content function which are necessary to characterize such fractured unsaturated media. To date, no such data have been measured or evaluation experimentally to promote the application of an unsaturated porous media theory on fractured unsaturated media such as tuff. However, it is shown that when the bulk volume of the fractured rocks is drained, liquid water will still be found on the fracture walls held by the adsorption forces as a film (Philip[29], 1978).

FIELD CHARACTERIZATION

The ultimate objectives of the application of flow and transport theory to the field situations under consideration are the successful understanding, characterization, and management of the earth materials/water regime as they apply to waste disposal. Our opinion of the validity of the previously-listed 12 simplifying assumptions for unsaturated flow of water through the geologic materials found at Beatty and Yucca Mountain is shown in table 1. Most of these assumptions are probably valid for the flow of water through the matrix of the porous rocks, with some uncertainties related to the nonisothermal and nonhomogenity of the field condition. However, most of these assumptions are probably invalid for the unsaturated flow through fractures.

It follows, therefore, that flow models based on the simplifying assumptions are not likely to confidently characterize the fractured rock vadose-zone environment in the absence of appropriate site-specific data. Field validation through surface-based studies using boreholes for sampling and monitoring seems necessary for any confident model depictions, and processes of flow and transport remain uncertain without site-specific databases.

Table 2 lists most of the drilling methods that may be utilized to establish boreholes for sampling and installation of monitoring equipment. Some of these drilling methods can be used to drill into or through the unconsolidated and consolidated stratigraphic units of Yucca Mountain vadose zone. However, for establishing liquid and gas phase samples and monitoring in-situ hydrogeologic parameters, only the drilling techniques which do not add water-based fluids seem potentially useful. However, the odex-reverse circulation and vacuum-reverse circulation drilling methods have major disadvantages. The odex-reverse circulation method is limited in usefulness for some purposes by the shallow depth of penetration,

Table 1. The probable validity or invalidity of the 12 simplifying assumptions for unsaturated flow of water through different geological materials.

Unsaturated zone assumption number (as noted in text)	Yucca Mountain Site				Beatty Site
	Welded Tuff[1] (many fractures)		Bedded Tuff[2] (fractured)		(Alluvium)
	Matrix Water	Fracture Water	Matrix Water	Fracture Water	Primarily Matrix Water
1	V(?)[3]	I[3]	V(?)	I	I
2	V	I	V(?)	I	V
3	V	I	V(?)	I	V(?)
4	V(?)	I	V(?)	I	V
5	V(?)	I	V(?)	I	V
6	V	I	V	I	V(?)
7	V	I	V	I	V
8	V	I	V	I	V(?)
9	V	I	V	I	V
10	V	I	V	I	V
11	V(?)	I	V(?)	I	V(?)
12	V(?)	I	V	I	V

[1] The welded tuff is representative of the Tiva Canyon and Topopah Spring stratigraphic unit.

[2] The bedded tuff is representative of the Paintbrush nonwelded, Calico Hills, and Crater Flat stratigraphic units.

[3] I = Probably invalid assumption V = Probably valid assumption

Table 2. Drilling methods for vadose zone in unconsolidated and consolidated media.

Drilling Method	Unconsolidated	Consolidated	Depth	Fluids Added	Hole Size	Casing Needed
Auger	Yes	No	Very limited	No	Small to large	No
Dual-Wall Reverse Circulation	Yes	Yes	1500-2500'(?)	Air	Small	No
Conventional/Air Foam Rotary	Yes	Yes	Unlimited	Yes	Small to large	No
Cable-Tool (Percussion)	Yes	Yes	Unlimited[1]	Yes	Small to large	Yes[2]
Odex-Reverse Circulation	Yes	Yes	Limited to 450'[3]	Air	6"[3]	Yes
Vacuum-Reverse Circulation	Yes	Yes	1750'[3]	Air	17"[3]	No

[1] Hole size reduction may be needed.

[2] Normally used in unconsolidated media.

[3] Yucca Mountain DOE experience.

the casing, as well as cost and slowness in consolidated rock environments. The vacuum-reverse circulation method is limited in usefulness by slow drilling, inability to pass through saturation, and large hole diameter/hole instability in fractured rock. In addition, it has proven to be extremely costly.

The dual-wall reverse circulation drilling method is capable of drilling exclusively with air in fractured tuff and semi-consolidated bedded tuffs. This method, using small-diameter bits, can probably be successfully used at Yucca Mountain for developing well-controlled samples of water and rock, as well as establishing monitoring systems or devices (see table 3) for temporal variations of in-situ moisture and pressure potential. Our experience with this method, using only air as a drilling medium, suggests that this technique has potential to markedly improve upon the existing quantity and quality of vadose- zone hydrologic data. This method may be capable of establishing boreholes that penetrate as deep as the regional ground-water table at Yucca Mountain. This method can be employed for horizontal or inclined surface-based drilling as well, and this is of interest in that flow in fractures or faults might be better evaluated by horizontal or inclined boreholes. One disadvantage of this drilling technique is high air pressure which may invade the more permeable fractures.

Given that there is likely a drilling technique which allows for reasonably nondisruptive full penetration of the Yucca Mountain vadose zone, there are still major challenges associated with developing useful in-situ liquid and vapor-phase samples, and establishing monitoring for fracture and rock matrix hydrologic conditions. Table 3 lists the state-of-the-art monitoring and sampling field methods for the unsaturated (vadose) zone. Promising techniques for measuring Yucca Mountain vadose-zone water potential (pressure potential) are the heat-dissipation probes and the thermocouple psychrometer. Both methods measure the water potential of the vadose moisture based on the vapor pressure within the pores. However, problems associated with field installation and calibration tend to impact the absolute accuracy of field measurements. The neutron and gamma-ray loggers are used mainly to evaluate the moisture content (in-situ) of the media. The gas sampler tube, double-valve purge sample pump, and the thief sampler system methods may be used to sample the liquid or gaseous phase from boreholes in

Table 3. Field monitoring and sampling field methods for the vadose zone.

State-of-the-Art Monitoring and Sampling Field Methods	The known utility of method to monitor liquid and gaseous phases within vadose zone tuff			
	Liquid Phase		Gaseous Phase	
	Matrix Water	Fracture Water	Water Vapor	Others
Tensiometer	?	?	No	No
Heat-dissipation probe	Yes	?	Yes	?
Thermocouple psychrometer	Yes	?	Yes	?
Gas sampler tube	No	No	Yes	Yes
Double-valve purge sample pump	Yes*	Yes*	?	?
Thief sampler system	Yes*	Yes*	Yes	Yes
Neutron logger	Yes	?	No	No
Gamma-ray logger	Yes	?	No	No
Resistance blocks	?	?	?	No

* Liquid samples from boreholes.

either the fractured welded tuff or the bedded tuffs (liquid phase sampling requires local fracture saturation in the welded tuff or matrix/fracture saturation in the bedded tuff).

In summary, although we believe the correct combination of drilling, sampling, and monitoring methods exist for the vadose zone of Yucca Mountain, they have not been successfully developed and tested for fracture hydrology in the Yucca Mountain vadose zone to our knowledge.

BEATTY SITE

The low-level radioactive waste burial site is located about ten miles southeast of Beatty, Nye County, Nevada, about 100 miles northwest of Las Vegas. The region is very arid, the average mean annual precipitation is less than three inches a year at Lathrop Wells (about two miles south of the waste-burial site). The mean daily maximum temperature in July is about 37°C. The burial site is underlain by poorly-stratified deposits of gravel, sand, and thick beds of clay sediments. The regional ground-water table is about 255 feet (85 meters) below the land surface. It is known that the valley-fill deposits are about 525 feet (175 meters) thick beneath the site.

The Beatty site was opened in 1962 for ground burial of low-level radioactive waste (earth containment), and it is commercially operated. Nichols (1987)[30] published on the hydrogeology of the thick unsaturated zone. His data included meteorological parameters, soil moisture and soil-water potential data, and hydraulic properties of representative unsaturated zone sediment samples. He also conducted evaporation studies for about two years on the site. Data from the upper 12 feet of the site show that volumetric soil moisture ranges from 4 to 10 percent and commonly is within the 6 to 8 percent range. The soil-water potential values range from -10 to -70 bars, and the computed unsaturated hydraulic conductivity of representative samples ranges from 10^{-13} to 10^{-4} centimeters per day. He concluded that, for the 18-month soil-moisture monitoring period, "deep percolation does occur" and steady-state downward flow of water at depths greater than 30 feet and beneath the burial trenches would be about 4 cm per 1000 years. However, Goode (1985)[31] reported high concentration of tritium (up to 410 nCi/l) in ground water from two monitoring wells located on the property at the waste-burial site. He also noted high coliform bacteria counts, up to 100 mg/l total organic carbon, 235 pCi/l alpha, 99 pCi/l beta, radium-266 up to 18 pCi/l, and chromium and barium up to 1 mg/l measured in ground-water samples from monitoring wells #301 and #302. This evidence for waste-derived leachate in the underlying saturated-zone ground water strongly argues against a simple calculation of the steady-state water flux within the unsaturated sediments of Beatty site alluvium. Macroscopic structural features in the alluvial sediments, such as fractures, cracks, root holes, and fissures and occasional pulses of recharge from the extreme precipitation events producing runoff probably combine to establish localized downward flow of water through the thick unsaturated zones and the apparent rapid migration of leachate.

YUCCA MOUNTAIN SITE

Currently, the U. S. Department of Energy is studying Yucca Mountain, Nevada, as a prospective site for a high-level radioactive-waste repository. The proposed repository horizon of highly fractured tuff is located in the vadose zone approximately 300 meters above the regional ground-water table.

Yucca Mountain consists of east-dipping lithologic units of alternating welded tuff (forming highly indurated porous rock) and nonwelded bedded tuff. All units are fractured to varying degrees. The hydrologic roles the fractures may play are key to site characterization but, to date, remain undemonstrated by site-specific data. There are five hydrostratigraphic units in which the unsaturated flow and fracture flow hydrologic principles might be applied to develop conceptual flow models to guide site-specific data-collection programs. For example, the uppermost unit can be characterized as discontinuous surficial deposits in contact with underlying units. It is variable in thickness, grain size, cementation, and permeability. The moisture entering such deposits is likely occuring under varying conditions and sometimes is concentrated both in time and space. Matrix unsaturated flow principles may be applied to some of these surficial lithologies, such as alluvium. The uppermost welded tuff, the Tiva Canyon, is highly fractured. It is known that the rock matrix has a low permeability and is locally close to 70% of saturation. We conclude that local fracture flow occurs when there are flux rates greater than about 1 mm/yr. Underlying the Tiva Canyon tuff is the Paintbrush nonwelded bedded tuff unit which is characterized by a lower density of fractures. The porous and moderately indurated nature of this rock unit makes it possible for porous media principles and techniques to be applied in attempts to characterize the hydrology of this zone. However, the role the fractures may play in water movement cannot be ignored. Underlying the bedded tuffs are Topopah Spring welded tuffs which include the proposed repository horizon. This unit is moderately to densely welded and devitrified, contains several lithophsal cavity zones, and is highly fractured. The rock matrix is known to display very small hydraulic conductivities and relatively small porosity values. The fractures must play a major role with regard to any localized flow in time or space that is greater than the smallest values of rock matrix hydraulic conductivities. Porous media unsaturated flow assumptions may not describe the flow conditions within this zone. Site-specific studies which address the hydrologic role of the fractures are needed. The underlying bedded tuff stratigraphic units which are above the ground-water table are known as the Calico Hills and Crater Flat units. Both vitric and devitrified tuff facies occur, the zone may be studied and characterized from a porous media perspective. However, the hydrologic role of the abundant fractures cannot be ignored. Steady-state unsaturated flow conditions might exist within this unit. The water flow through the matrix of this unit might be studied following the well-established principles.

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