encl. to 8/4/88 ltr.
from Osiensky to Pohle
Communication # 191

A SUMMARY OF GROUNDWATER TESTING METHODOLOGIES APPLICABLE TO UNSATURATED FRACTURED ROCK AT YUCCA MOUNTAIN

by

Williams & Associates, Inc.
P.O. Box 48
Viola, Idaho 83872

and

Water, Waste and Land, Inc.
Creekside Two Building
2629 Redwing Road, Suite 200
Fort Collins, Colorado 80526

March, 1988
Revised August, 1988

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

Introduction

Characterization of the Yucca Mountain high-level waste repository site will require the determination of hydraulic properties for the volcanic tuff above, below and within the repository unit (Topopah Spring member of the Paintbrush tuff). In addition, the total water potential under natural conditions must be measured in order to determine the magnitude of downward flux and the resulting natural recharge through the mountain. A detailed literature review was conducted to assess the availability and acceptability of methodologies for characterization of unsaturated tuff at the Yucca Mountain repository site. This literature review is divided into four parts: 1) determination of total water potential (sum of matric potential, osmotic potential and gravitational potential), 2) determination of water content, 3) determination of hydrogeologic parameters for the various geologic units, and 4) methods for collecting water samples. The methods discussed will be those that have some possibility of being adaptable to fractured tuff. *In situ* methods must be used for measuring the total water potential or water content of the tuff under natural conditions.

Determination of Soil Water and Matric Potential

The measurement of total water potential is important for the determination of the direction and magnitude of flow in the rock matrix. Methods that potentially are applicable to the conditions that exist within Yucca Mountain are discussed below.

METHOD: Soil moisture blocks

PARAMETER(S) MEASURED: Matric potential

DESCRIPTION OF METHODOLOGY: Soil moisture blocks consist generally of blocks of gypsum, nylon or ceramic material. The principle of operation of these blocks is that water under negative pressure (i.e., suction or tension) within the block is allowed to equilibrate with the water under negative pressure in the material of interest. The electrical resistivity between two contacts in the block is a measure of water content or of matric potential. According to Gardner (1965), the blocks can be calibrated to measure matric potential more accurately than to measure water content. The calibration procedure for matric potential is described by Bouyoucas (1960). It should be noted that when calibrating for matric potential it is not necessary to calibrate the block in the material that is to be tested. However, such calibration is necessary when calibrating for water content.

ACCURACY/DEVELOPMENT STATE: Soil moisture blocks are not suitable for measuring water content in certain soil water solutions which contain salts because the presence of the salts will change the electrical conductivity irrespective of the water content. Generally blocks are used for soil water pressures less (more negative) than -.8 atmospheres; they are not suitable for high water content.

YUCCA MOUNTAIN APPLICABILITY: It is doubtful that blocks made of ceramic, gypsum or nylon materials available currently could be placed in contact with fractured tuff in such a way as to achieve sufficient transfer of water from the moisture block to the tuff matrix. Present types of moisture blocks therefore are not recommended for use in Yucca Mountain.

COMMENTS: If DOE proposes to use this method for measuring the matric potential in the fractured tuff the data will have a high degree of uncertainty associated with them.

REFERENCES:

Bouyoucas, G.J., 1960, Measuring Soil Moisture Tension. Agriculture Engineering, Michigan, 41, 40-41.

Gardner, W.H., 1965, Water Content in Methods of Soil Analyses, C.A. Black (ed), Agronomy No. 9, 82-125, Amer. Soc. Agron., Madison, WI.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, D.C., NUREG/CR-4655.

METHOD: Absorber method

PARAMETER(S) MEASURED: Matric potential

DESCRIPTION OF METHODOLOGY: The assumption upon which the absorber method is based is that porous materials in liquid or vapor contact with filter paper will exchange water with the paper until the matric potential of both systems are the same. The method is very simple in that the filter paper is placed in contact with the soil or rock for sufficient time for equilibration to occur. The matric potential of the filter paper is then determined using thermocouple psychrometer techniques.

ACCURACY/DEVELOPMENT STATE: Since first introduced in 1937, several enhancements to this measuring technique have been suggested. Current limitations include the difficulty of conducting the measurements in boreholes and the inaccuracies in measuring the matric potential of the filter paper.

YUCCA MOUNTAIN APPLICABILITY: This method may be very useful during site characterization at Yucca Mountain because it is relatively simple and easy to use. For optimum efficiency, a device that would allow downhole measurements to be conducted must be developed. The long equilibration times and the method used to measure the matric potential of the filter paper may limit the usefulness of this technique but it is recommended for investigation.

COMMENTS: Rasmussen and Evans (1987) indicate that they are working on a device to estimate in situ matric potentials with filter papers. These authors indicate also that they have had relatively good success using this method in rocks where the presssure is less than -2 bars.

REFERENCES:

Al-Khafaf, S. and Hanks, R.J., 1974, Evaluation of the Filter Paper Method for Estimating Soil Water Potential. Soil Sci., 114(4):194-199.

Fawcett, R.G. and Collis-George, N., 1967, A Filter Paper Method for Determining the Moisture Characteristics of Soil. Aust. J. Exp. Agri. Amin. Husb., 7:162-167.

Gardner, R., 1937, A Method of Measuring Capillary Tension of Soil Moisture Over a Wide Moisture Range. Soil Science, 43:238-277.

Hamblin, A.P., 1981, Filter-Paper Method for Routine Measurement of Field Water Potential. J. of Hydrology, vol. 53, p. 355-360.

McQueen, I.S. and Miller, R.F., 1968, Calibration and Evaluation of a Wide-Range Gravimetric Method for Measuring Moisture Stress. Soil Sci. Soc. Am. Proc., 106:225-231.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. NUREG/CR-4655, p. 103.

METHOD: Thermocouple psychrometer

PARAMETER(S) MEASURED: Total water potential

DESCRIPTION OF METHODOLOGY: A thermocouple psychrometer is an electronic instrument which measures the relative humidity of air. The total potential, ϕ_t, (matric potential, gravitational potential and osmotic potential) can be estimated with

$$\phi_t = \frac{R\ T}{M_w \ell n(P/P_o)}$$

where R is the gas constant, T is the absolute temperature, M_w is the molecular weight of water, P is the actual vapor pressure, and P_o is the saturated vapor pressure. The psychrometer contains a small thermocouple with measuring and reference junctions. The measuring junction is wet and the reference junction remains dry. As water evaporates from the measuring junction, it cools relative to the reference junction. The temperature difference creates a voltage which is proportional to the magnitude of the difference in temperature. Cooling at the wet junction is proportional to the product of the evaporation rate and the latent heat of vaporization. Two measurement methods normally are utilized with thermocouple psychrometers. In the 'psychrometric' method, the measuring junction is cooled relative to ambient temperature which causes the surface to become wet through condensation. After the measuring junction is wetted, the temperatures of the measuring and reference junctions are measured. The amount of temperature depression at the measuring electrode relative to the reference electrode is a function of the relative humidity of the air surrounding the measuring junction. The 'dew point' method also has been developed for making psychrometer measurements. The instruments used with this method contain circuitry which controls the temperature of the wetted measuring electrode so that it remains equal to the dew point corresponding to the ambient relative humidity. Under these conditions, water does not condense on or evaporate from the measuring electrode. The effective range of this instrument is about -2 to -50 bars of pressure. Under wet conditions (0 to -2 bars) the inability of the instrument to measure temperature differences is attributed to very slow evaporation which does not significantly lower the temperature at the measuring electrode. At the dry extreme (less than about -50 bars pressure), the instrument fails, apparently because insufficient moisture exists in the air to keep the measuring electrode wet.

ACCURACY/DEVELOPMENT STATE: This method has been used extensively in the past for the measurement of total water potential in unsaturated porous media. According to Rasmussen and Evans (1987), substantial differences were noted between pairs of psychrometers placed to measure essentially the same pressures. Although uncertainty in the absolute magnitude of the results was noted, the temporal variation in pressure measurements could be followed fairly closely.

YUCCA MOUNTAIN APPLICABILITY: These methods may be suitable for obtaining measurements of *in situ total* water potential at Yucca Mountain. However, because of the uncertainty with respect to the magnitude of the pressure measurements, these instruments may be best for obtaining a long term record of relative changes in pressure.

COMMENTS: Detailed calibration processes are required for thermocouple psychrometers. These calibration requirements vary among the units available commercially. These devices are recommended for use in Yucca Mountain.

REFERENCES:

Briscoe, R., 1979, Effective Use of Thermocouple Psychrometers in Measurement of Water Potential. Presented at Annual Meeting of Agronomy Society of America, Fort Collins, CO, Aug. 3.

Brown, R.W. and Johnston, R.S., 1976, Extended Field Use of Screen Covered Thermocouple Psychrometer. Agronomy J., 68:995-996.

Campbell, E.C., Campbell, G.S., and Barlow, W.K., 1973, A Dewpoint Hygrometer for Water Potential Measurement. Agr. Meteorology, vol. 12, p. 113-121.

Daniel, D.E., Hamilton, J.M., and Olson, R.E., 1981, Suitability of Thermocouple Psychrometers for Studying Moisture Movement in Unsaturated Soils. Permeability and Groundwater Contaminant Transport, ASTM, STP-746, Philadelphia.

Merrill, S.D. and Rawlins, S.L., 1972, Field Measurement of Soil Water Potential with Thermocouple Psychrometer. Soil Sci. Soc. Am. Proc., vol. 13, p. 102-109.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 82.

METHOD: Pressure plate outflow method

PARAMETER(S) MEASURED: Soil-water diffusivity

DESCRIPTION OF METHODOLOGY: Gardner (1956) developed a method for estimating the soil water diffusivity using the rate of outflow from a soil sample that is held on a porous plate. The sample is subjected to an instantaneous pressure change (Bouwer and Jackson, 1974). Standard equipment is used to measure the water characteristic relation. Bouwer and Jackson suggest that, in principle, diffusivity [given by $D(\theta)=K\ dh/d\theta$], hydraulic conductivity [$K(\theta)$], and hydraulic head [$h(\theta)$] are obtainable as functions of water content [θ]from one set of experimental operations. The following equation was developed by Gardner (1956):

$$\ln(Q_o-Q_t) = \ln(8Q_o/\pi^2) - (\pi/2L)^2Dt$$

where: Q_o is the total quantity of outflow at infinite time,
Q_t is the quantity of outflow at time t,
L is the length of the sample,
D is obtained from the slope of the straight line portion of a plot of $\ln(Q_o-Q_t)$ vs. t
t is time

The pressure plate outflow method was modified by Miller and Elrick (1958) and Rijtema (1959) to account for the impedance of the porous plate. Gardner (1962) showed that, for certain boundary conditions, the diffusivity can be calculated from the water content and instantaneous outflow for a sample of length L.

Gardner developed the following equation:

$$D(\theta) = - \frac{4L^2}{2(\theta-\theta_f)} \frac{d\theta}{dt}$$

where: θ_f is the water content of the sample at final equilibrium
t is the time.

This method is known as the one-step method; the water content-diffusivity relation is obtained over a range of water contents with one pressure step.

ACCURACY/DEVELOPMENT STATE: The accuracy of the pressure plate outflow method has been questioned by Jackson et al. (1963). In addition, a detailed description of procedures and experimental details is presented by Klute (1965).

YUCCA MOUNTAIN APPLICABILITY: This method has not been evaluated for conditions at the Yucca Mountain site. This method is recommended to be evaluated by the DOE during the Yucca Mountain characterization activities.

COMMENTS: Elrick (1963) showed that an excessively long time is required to reach equilibrium at high water contents.

REFERENCES:

Bouwer, H., and Jackson, R.D., 1974, Determining Soil Properties, in Drainage for Agriculture. Edited by Jan Van Schilfgaarde, American Society of Agronomy, Inc., Madison, Wisconsin.

Elrick, D.E., 1963, Unsaturated Flow Properties of Soils. Aust. J. Soil Res., 1:1-8.

Gardner, W.R., 1956, Calculation of Capillary Conductivity from Pressure Plate Outflow Data. Soil Sci. Soc. Amer. Proc. 20:317-320.

Gardner, W.R., 1962, Note on the Separation and Solution of Diffusion Type Equations. Soil Sc. Soc. Amer. Proc. 26:404.

Jackson, R.D., van Bavel, C.H.M., and Reginato, R.J., 1963, Examination of the Pressure-Plate Outflow Method for Measuring Capillary Conductivity. Soil Sci. 96:249-256.

Klute, A., 1965, Laboratory Measurement of Hydraulic Conductivity of Unsaturated Soil, in Methods of Soil Analysis, Part 1. edited by C.A. Black, Agronomy 9:253-261.

Miller, E.E., and Elrick, D.E., 1958, Dynamic Determination of Capillary Conductivity Extended for Non-Negligible Membrane Impedance. Soil Sci. Soc. Amer. Proc. 22:483-486.

Rijtema, P.E., 1959, Calculation of Capillary Conductivity from Pressure Plate Outflow Data with Non-Negligible Membrane Impedance. Neth. J. Agr. Sci. 7:209-215.

METHOD: Tensiometer

PARAMETER(S) MEASURED: Matric potential, unsaturated zone sample collection

DESCRIPTION OF METHODOLOGY: The standard tensiometer consists of a porous, ceramic cup connected by a tube to a device which is capable of measuring negative pressure. The cup and tube are filled with water and sealed. After insertion in a borehole at the desired location in an unsaturated medium, water flows out of the cup in response to the matric potential of the medium. At equilibrium, the negative pressure measured is equal to the matric potential of the medium. Because the cup is permeable to dissolved constituents in the matrix fluid, the osmotic potential is not included in the potential measured. The device is usable only in a pressure range of 0 to -0.8 bars. Under certain conditions, these devices have been modified and used to collect water samples in the unsaturated zone (pressure vacuum lysimeters). When used in this manner, a vacuum pump is connected to the tube and cup and the cup is evacuated. This lowers the pressure in the cup relative to the surrounding media. Water flows from the soil into the cup where it remains until pumped out. Only relatively wet (0 to -0.5 bars pressure) soils can be sampled in this manner.

ACCURACY/DEVELOPMENT STATE: Tensiometers have been used for a number of years, particularly in the agricultural industry to support irrigation scheduling and other aspects of soil water monitoring. When properly calibrated and maintained, these instruments can provide fairly accurate measurements of matric potential.

YUCCA MOUNTAIN APPLICABILITY: It is unlikely that these instruments can be used at Yucca Mountain, because most of the pressures in the tuffs in Yucca Mountain are considerably less than -1.0 atmosphere. However, it may be possible to use tensiometers for measuring matric potential in some of the alluvial materials in the vicinity of Yucca Mountain.

COMMENTS: None

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 98.

METHOD: Osmotic tensiometer

PARAMETER(S) MEASURED: Matric potential

DESCRIPTION OF METHODOLOGY: This instrument is a modification of the standard tensiometer. It is capable of measuring potentials in the range of 0 to -15 bars pressure. Communication between the device and soil water is achieved through a semi-permeable membrane. The tensiometer initially is filled with an aqueous solution of large organic molecules, and positive hydrostatic pressures are maintained within the device at all times. The osmotic potential created by the organic solution in the tensiometer partially offsets the matric potential of the surrounding soil moisture. This reduces the amount of liquid which must flow through the membrane during equilibration. These devices are designed so that the membrane is nearly impermeable to the organic solution but remains very permeable to the soil water solution. Therefore, the device does not measure the osmotic potential of the soil water.

ACCURACY/DEVELOPMENT STATE: This device has been reported in the literature for a number of years; however, it does not appear to be used to the extent that the standard tensiometer is used. Various organic solutions have been used in the past and it does not appear that a standard device is available. Therefore, it may be necessary to design and build similar but different devices for installation in different locations.

YUCCA MOUNTAIN APPLICABILITY: This method is not applicable for Yucca Mountain. Development of a device for use at Yucca Mountain cannot be dismissed. However, it is deemed unlikely that this will be accomplished because similar data probably can be obtained by other methods.

COMMENTS: Rasmussen and Evans (1987) report on the development of a prototype osmotic tensiometer designed specifically for measuring matric potential in fractured rock with low water content (large negative pressure).

REFERENCES:

Peck, A.J. and Rabbidge, R.M., 1966, Soil Water Potential: Direct Measurement by a New Technique. Science, vol. 151, p. 1385-1386.

Peck, A.J. and Rabbidge, R.M., 1969, Design and Performance of an Osmotic Tensiometer for Measuring Capillary Potential. Soil Sci. Soc. Am. Proc., vol. 33, p. 196-202.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 100.

METHOD: Heat dissipation probe

PARAMETER(S) MEASURED: Matric potential

DESCRIPTION OF METHODOLOGY: The rate of heat conduction in a partially saturated porous medium (in which the solid matrix has low heat conductivity) is dependent primarily on the water content of the medium. Air is a poor conductor of heat compared to water; as water is replaced with air when a porous medium desaturates, its thermal conductivity decreases. If heat is applied to the midpoint of a block of a porous medium, the rate of heat dissipation within the block is related to the difference in temperature of the midpoint before and after heating. The temperature difference can be used as an index of the water content. If the properties of the porous medium do not change with time, an empirical relationship between the matric potential and temperature difference can be obtained. Output voltage of the probe is proportional to the matric potential. Calibration results of output voltage versus applied pressure (matric potential) are collected for each sensor.

ACCURACY/DEVELOPMENT STATE: Various probes are used for specific matric potentials.

YUCCA MOUNTAIN APPLICABILITY: The USGS and its contractors currently are using heat dissipation probes to monitor matric potential in borehole USW UZ-1.

COMMENTS: Thermocouple psychrometers are being used to monitor matric potential. Thamir and McBride (1985) list two primary limitations of the use of heat dissipation probes in deep boreholes in Yucca Mountain. These limitations are: 1) long lead wires have an uncertain effect on the reliability of the instrument readings, and 2) it is not possible to recalibrate the instruments after installation. These are serious handicaps but the present use will determine whether they are worth further use.

REFERENCES:

Montażer, P., Weeks, E.P., Thamir, F., Yard, S.N., and Hofrichter, P.B., 1985, Monitoring the Vadose Zone in Fractured Tuff, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Dublin, OH, p. 439-469.

Phene, C.J., Hoffman, G.J., and Rawlins, S.L., 1971, Measuring Soil Matric Potential In-Situ by Sensing Heat Dissipation Within a Porous Body: I Theory and Sensor Construction. in Soil Sci. Soc. Amer. Proc., vol. 35, p. 27-33.

Thamir, F., and McBride, C.M., 1985, Measurements of Matric and Water Potentials in Unsaturated Tuff at Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose (Unsaturated) Zone, National Water Well Association, Dublin, OH, p. 470-487.

Determination of Water Content and Matrix Porosity

Any of the methods described to measure the matric potential can be used to determine the water content if the relationship between water content and matric potential is known for the material of interest. Because of this fact, overlap in the discussions of the methods available for determining water content and matric potential is unavoidable. Methods available to determine water content and porosity are discussed below.

METHOD: Induction log

PARAMETER(S) MEASURED: Water content

DESCRIPTION OF METHODOLOGY: Induction logging is based on the principle of electromagnetic coupling between the logging sonde and the rocks to be investigated. Focused induction logging systems are composed of transmitter-receiver coil pairs. The number of coils and spacing of these coils determine the depth of investigation, the borehole response and the resolution of the instrument. A regulated alternating current is produced in the transmitter coils which induces eddy currents by electromagnetic induction in the formations surrounding the coil system. The eddy currents induced in the formation have a magnetic field which induces voltages in the receiver coil. These voltages are related to the conductivity of the formation. The reciprocal of the conductivity is the resistivity. Knowledge of resistivity and porosity allows water saturation to be estimated.

ACCURACY/DEVELOPMENT STATE: Induction logging is used in the oil industry. The technology is mature in the oil industry. The accuracy of the measurement is limited above 200 ohm-m. Borehole effects on the induction curve are small except when highly conductive, salty fluids are present in large boreholes. Focusing of the signal minimizes the effects of the borehole, invaded zone, and adjacent beds.

YUCCA MOUNTAIN APPLICABILITY: Induction logs recorded in wells USW UZ-1 and USW UZ-6 were used to locate zones of high moisture. The data obtained from the logs were reported to have excellent contrast; resistivities ranged from 10 to 50 ohm-m from high moisture zones and 90 to 220 ohm-m for low moisture zones. Induction logs are recommended for use in Yucca Mountain.

COMMENTS: None

REFERENCES:

Palaz, I., 1985, Application of Geophysical Logs to Estimate Moisture-Content Profiles in Unsaturated Tuff, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 424-438.

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

METHOD: Dielectric log

PARAMETER(S) MEASURED: Water content

DESCRIPTION OF METHODOLOGY: Conventional resistivity and conductivity methods operate within the frequency range from 35 Hz to 20 kHz. The dielectric log operates at frequencies in the gigaHertz range to measure phase shift and attenuation rate of an electromagnetic wave traveling in formations. The phase shift is converted to propagation time, which is related to dielectric permittivity. The value of dielectric constant for water at high frequencies is significantly higher than those for gas, oil, and matrix materials, and is almost independent of the salinity of the water. The dielectric constant value of reservoir rock therefore increases with the increase of formation water volume.

The bulk volume water from the dielectric tool measurement can be compared to the total porosity, which is measured by neutron and density logs or core analysis. The comparison provides an estimate of the water saturation and does not require the knowledge of water resistivities or formation resistivities. The dielectric logging tool consists of three parts: transmitter, receiver, and phase detector.

ACCURACY/DEVELOPMENT STATE: In the oil industry, dielectric logging is used mainly to locate watered out zones and to give a quantitative interpretation of current water saturation of oil bearing strata. In general, the depth of investigation (into borehole walls) of dielectric logging is 0.4 to 0.5 m. Dielectric logging by means of the phase-shift measurement has good vertical resolution. The dielectric constant of the rock matrix must be known to determine the water saturation. Consequently, to achieve high accuracy, the dielectric constant should be determined by measuring the core whenever the core is available.

YUCCA MOUNTAIN APPLICABILITY: The USGS has used geophysical logs together with borehole cuttings to estimate water content profiles for unsaturated fractured tuff (Palaz, 1985). Water content was calculated from dielectric logs using a modified form of an empirical equation. The modified equation is as follows (Geng et al., 1983):

$$\Sigma^{c} = 1.67 + (2.44\ Sw_v - 0.39) + 1.77\ V_{sh}$$

where:

Σ = dielectric constant readings from log,
c = dielectric cementation factor,
Sw_v = water content of tuff,
V_{sh} = volumetric fraction of shale in the tuff.

According to Palaz (1985), the volumetric fraction of shale was set equal to zero based on the assumption that the contribution of clay minerals to the dielectric-constant values was insignificant for the Yucca Mountain tuffs.

Palaz (1985) notes also that the dielectric cementation factor, c, for volcanic tuff was unknown; however, the best agreement between the water-content profiles derived from drill cuttings and calculated water content values for boreholes USW UZ-1 and USW UZ-6 was obtained with "c" values between 0.1 and 0.13. Induction logs and epithermal neutron logs were used to check the moisture profile derived from the dielectric logs. Palaz (1985) considered the correlation of these logs to be excellent. This logging method is recommended for Yucca Mountain.

COMMENTS: None

REFERENCES:

Delano, J.M, and Wharton, R.P., 1984, An EPT Interpretation Procedure and Application in Freshwater, Shaly Oil Sands. Journal of Petroleum Technology, vol. 36, no. 11.

Geng, X., Tinzu, Y., Da, L., and Shutang, Z., 1983, Dielectric Log. A Logging Method for Determining Oil Saturation. Journal of Petroleum Technology, p. 1797-1805.

Palaz, I., 1985, Application of Geophysical Logs to Estimate Moisture-Content Profiles in Unsaturated Tuff, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 424-438.

Shen, L.C., 1985, A Laboratory Technique for Measuring Dielectric Properties of Core Samples at Ultra-High Frequencies. Society of Petroleum Engineers Journal, vol. 25, no. 4.

Timur, A., 1982, Advances in Well Logging. Journal of Petroleum Technology, vol. 34, no. 6.

METHOD: Gamma ray attenuation

PARAMETER(S) MEASURED: Water content, bulk density, matrix porosity

DESCRIPTION OF METHODOLOGY: This procedure can be used to determine the bulk density of a sample if the water content is known. The measured bulk density can be used to estimate matrix porosity assuming that the particle density of the sample is known. This technique most often is used to determine water content after the bulk density has been determined by other methods. Regardless of the parameter(s) desired, the procedures followed are similar. A mono-energetic, gamma radiation beam is passed through a sample of the material being tested. The water content, θ, is estimated with the relationship

$$\theta = \frac{-\ln(I/I_0) - xu_s\rho_s}{xu_w\rho_w}$$

in which I is the measured intensity of the gamma beam after attenuation by the sample, I_o is the intensity of the gamma source, x represents the thickness of the sample at the point where the gamma beam is passed, u is the mass attenuation coefficient, the subscripts s and w represent the sample and water, respectively, ρ_W is the density of water and ρ_S is the dry bulk density of the sample. The intensity, I, is defined as the number of gamma photons counted during a given time interval.

ACCURACY/DEVELOPMENT STATE: This technique is well established and has been used by numerous investigators.

YUCCA MOUNTAIN APPLICABILITY: Gamma ray attenuation probably can be used to estimate the water content of core samples collected at Yucca Mountain. The standard problems associated with collection of core samples (i.e., effects of heat on *in situ* water content) may limit actual use of this method.

COMMENTS: This technique is useful particularly in determining water content at many locations (e.g., along the centerline of a long core sample) very rapidly if the dry bulk density is known.

REFERENCES:

Davidson, J.M., Biggar, J.W., and Nielsen, D.R., 1963, Gamma-Radiation Attenuation for Measuring Bulk Density and Transient Water Flow in Porous Materials. J. Geophy. Res., vol. 68, p. 4777-4783.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 181.

METHOD: Neutron-neutron log

PARAMETER(S) MEASURED: Water content

DESCRIPTION OF METHODOLOGY: The downhole neutron-neutron logging tool consists of three main components: 1) a probe containing a source of high energy neutrons, 2) a detector of low energy (epithermal) neutrons, and 3) a scaler or ratemeter to monitor the low energy neutrons. The basic operation of the tool consists of the measurement of the number of high energy neutrons slowed and returned to the detector. In theory, the number of neutrons that return to the detector is a measure primarily of the hydrogen atom density of the soil, which in most soils, also is a measure of the water content. The tool's range of influence from the borehole generally is inversely proportional to the volume wetness of the soil. In general, the tool must be calibrated for the soil used.

Detection of epithermal neutrons reduces greatly the perturbing influences of the thermal neutron absorption characteristics of formation matrices and water salinity; the presence of hydrogen in a formation determines, for all practical purposes, the ability of the formation to slow down fast neutrons.

ACCURACY/DEVELOPMENT STATE: Although this technique has been available for over 20 years, it has been limited for several reasons. The two primary difficulties are the borehole geometry traditionally used for neutron logging, and the limited range of influence of the instrument. The radius of investigation for neutron-moisture probes has been shown to decrease with increasing water content when all other factors such as source-detector spacing, borehole diameter, and rock density are held constant.

YUCCA MOUNTAIN APPLICABILITY: Field calibration of neutron-moisture tools at Yucca Mountain have: 1) showed good correlation between neutron-moisture counts and water content for sections of uncased boreholes in nonwelded and bedded tuff and 2) showed that bulk density variations produce significant effects on the calibration curves. A study in the alluvial material at the Nevada Test Site indicated that the neutron moisture gauge can be extended for use in steel cased boreholes up to 15 cm in diameter with excellent results (Hammermeister, et al., 1985). The method is recommended for use in Yucca Mountain.

COMMENTS: High-energy neutrons are emitted from a plutonium-beryllium or plutonium-americium source mounted in the sonde. These neutrons collide with nuclei of the formation materials; with each collision, the neutron loses some of its energy. Collisions with heavy nuclei slow the neutron very little; collisions with hydrogen cause rapid slowing of the neutrons. Successive collisions with other nuclei slow the neutrons to thermal velocities until they are captured by nuclei of atoms of chlorine, hydrogen, silicon, etc. The capturing nuclei emit high-energy gamma rays which are counted by a detector in the sonde. Where hydrogen concentration is high around the neutron source most of the neutrons are captured.

REFERENCES:

Hammermeister, D.P., Kneiblher, C.R., and Klenke, J., 1985, Borehole-Calibration Methods Used in Cased and Uncased Test Holes to Determine Moisture Profiles in the Unsaturated Zone, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 542-563.

Keys,W.S., and McCary, C.M., 1976, Application of Borehole Geophysics to Water Resources. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter E1, 126 p.

Tyler, S., 1985, Moisture Monitoring in Large Diameter Boreholes. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 97-106.

METHOD: Gravimetric method

PARAMETER(S) MEASURED: Matrix porosity

DESCRIPTION OF METHODOLOGY: The volume of a regularly shaped sample is determined and the sample is oven dried and weighed. The bulk density, ρ_b, can be calculated as

$$\rho_b = W_d/V_s$$

where: W_d is the weight of the oven dried sample and V_s is the sample volume. Porosity, n, is estimated by

$$n = 1 - (\rho_b/\rho_s)$$

where: ρ_s represents the particle density of the sample.

ACCURACY/DEVELOPMENT STATE: This method of determination of porosity is widely used and accepted.

YUCCA MOUNTAIN APPLICABILITY: This method is recommended for measurement of matrix porosity at Yucca Mountain. Core samples would be required because most of the rocks at the site are consolidated.

COMMENTS: An estimate of the particle density is required to determine porosity. The method provides an estimate of the bulk density of the sample.

REFERENCES:

Brady, N.C., 1974, The Nature and Properties of Soils. 8th edition, McMillian Publishing Co., New York, NY 10022, p. 50.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 48.

METHOD: Water saturation method

PARAMETER(S) MEASURED: Effective matrix porosity (interconnected porosity)

DESCRIPTION OF METHODOLOGY: The volume of a regularly shaped sample, such as a cylindrical core, is determined. The sample is oven dried and weighed. The sample then is de-gassed in a vacuum chamber and saturated with water. After saturation, the sample again is weighed to determine the weight of water added from which the water volume can be estimated. Assuming full saturation, the effective matrix porosity, n_e, can be estimated from

$$n_e = \frac{V_w}{V_s}$$

where: V represents a volume with the subscript w denoting water and the s subscript denoting the entire sample.

ACCURACY/DEVELOPMENT STATE: This method is well established and often is used to estimate porosity of rocks as well as soils.

YUCCA MOUNTAIN APPLICABILITY: This procedure can be used reliably for samples from Yucca Mountain. Rasmussen and Evans (1987) used this method for tuffaceous rock samples and achieved good agreement with other methods.

COMMENTS: The difference between the matrix porosity and the effective porosity determined using this method is an indication of the isolated pores.

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 47.

METHOD: Paraffin method

PARAMETER(S) MEASURED: Matrix porosity

DESCRIPTION OF METHODOLOGY: This procedure is used to obtain an estimate of the total porosity of samples of rock material. A sample is oven dried at a temperature of 104°C and weighed daily to determine the moisture loss. Once all water has been evaporated from the sample, the sample is cooled to room temperature and dipped into molten paraffin. After the paraffin has cooled and solidified, the coated sample is weighed again to determine the weight of paraffin added. The coated sample then is suspended in water from a thread and its weight determined to give an estimate of its buoyancy. The porosity, n, is estimated by

$$n = 1 - (\rho_b/\rho_s)$$

where: ρ_s is the particle or solid density and ρ_b is the bulk density:

$$\rho_b = \frac{\rho_w W_d}{W_d - W_w + W_p(1 - (\rho_w/\rho_p))}$$

where: ρ represents density, the subscripts p and w refer to paraffin and water, respectively, and W represents weights with subscripts d, w, and p referring to the oven dry sample, water, and paraffin, respectively.

ACCURACY/DEVELOPMENT STATE: This procedure has been used to estimate rock porosities by many researchers in the past. The method appears to provide reasonable results when compared to other methods.

YUCCA MOUNTAIN APPLICABILITY: This method for estimating matrix porosity can be used with samples from Yucca Mountain. Rasmussen and Evans (1987) used this method for estimating total porosity of tuffaceous materials and achieved good agreement with other methods.

COMMENTS: An advantage of the method is that irregularly shaped samples can be used. Although the method provides an estimate of the bulk density of the rock, particle density must be known to calculate the porosity.

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 46.

Hydrologic Parameters

Water content, matric potential and unsaturated hydraulic conductivity have physical significance in that they can be related to physical characteristics of the soil, at least in a qualitative manner. As mentioned previously, relationships exist among these three parameters. Such relationships have been published by Brooks and Corey (1964), Van Genuchten (1978), Mualem (1976) and many others. The Brooks and Corey relationships have been well accepted for more than 20 years. The relationships are not convenient to use in some cases because discontinuities of slope exist at the transition between complete saturation and low water content. Three empirical parameters must be determined by laboratory methods. The following sections relate various hydrologic parameters.

METHOD: Van Genuchten and Mualem methods

PARAMETER(S) MEASURED: Pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: The Van Genuchten and Mualem equations have become widely accepted over the past few years and have been used with good success by Peters et al. (1984) with material from various units of Yucca Mountain. The preferred method to obtain values for the hydrologic parameters needed for both equations is to conduct laboratory tests on core samples of the porous material. The data needed consist of water content and matric potential data over the range of water content of interest. The parameters may be determined graphically or by means of computer programs, by best fit procedures.

ACCURACY/DEVELOPMENT STATE: The Van Genuchten (1980) and Mualem (1976) equations currently are the most widely used methods for determining the relationships between water content, matric potential and unsaturated hydraulic conductivity.

YUCCA MOUNTAIN APPLICABILITY: It is possible to calculate the relationship between water content, or matric potential, and unsaturated hydraulic conductivity. However, it usually is necessary to measure the saturated hydraulic conductivity as most of these methods do not reproduce the measured saturated hydraulic conductivity values accurately. These methods should be investigated for use in Yucca Mountain.

COMMENTS: The Guelph permeameter (Reynolds and Elrich, 1985) can be used to obtain the various hydrologic parameters used in the Van Genuchten and Mualem equations. At the present time, it is the only practical means for measuring these parameters in situ in a field situation. It is unknown whether sufficient contact between the porous tip of the Guelph permeameter and fractured tuff can be attained to make its use possible at Yucca Mountain. It also is unknown whether the permeameter is suitable at the large negative pressures that exist in Yucca Mountain.

Rasmussen and Evans (1987) mention several types of pressure cells used to measure saturated and unsaturated hydraulic conductivity. They also present a comparison of the hydrologic parameters calculated by the Brooks and Corey, Van Genuchten, and Mualem methods. The comparison appears to be fairly good in most cases but some wide discrepancies exist.

REFERENCES:

Brooks, R.H. and Corey, A.T., 1964, Hydraulic Properties of Porous Media. Hydrology paper (3), Civil Engineering Dept. Colorado State University, Fort Collins, CO.

Mualem, Y., 1976, A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media. Water Resour. Res., 12(3):513-522.

Peters, R.R., Klavatter, E.A., Hall, I.J., Blair, S.C., Heller, P.R., and Gee, G.W., 1984, Fracture and Matrix Hydrologic Characteristics of Tuffaceous Material from Yucca Mountain, Nye County, Nevada. Sandia Report SAND84-1471.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

Reynolds, W.D. and Elrick, D.E., 1985, Measurement of Field-Saturated Hydraulic Conductivity, Sorptivity and the Conductivity-Pressure Head Relationship using the "Guelph Permeameter". Proceedings NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, OH, p. 9-33.

Van Genuchten, M.Th., 1980, A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Am. J., (44):892-898.

METHOD: Brooks method

PARAMETER(S) MEASURED: Pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: A sample with a known initial water content is placed in contact with a capillary barrier (pressure plate or pressure membrane). A carefully metered quantity of water is added to the sample. After allowing time for the water content to equilibrate and the pressure to stabilize, the pressure is measured. Assuming a uniform moisture content, the new water content of the sample can be calculated based on the amount of fluid added. This process is repeated at several incremental values of water content until the pressure approaches zero (zero gage pressure).

ACCURACY/DEVELOPMENT STATE: This is an accepted procedure for determination of the pressure-saturation function in porous media.

YUCCA MOUNTAIN APPLICABILITY: The applicability of this method to Yucca Mountain is unknown and it is not recommended. While this method could probably be used at Yucca Mountain, it is anticipated that other methods more suitable to the tight nature of the rocks which exist at the site will be used to obtain pressure-saturation relationships.

COMMENTS: This method provides the pressure-saturation function only for the imbibition cycle.

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 45.

METHOD: Guelph permeameter

PARAMETER(S) MEASURED: Hydraulic conductivity, sorptivity, and hydraulic conductivity/pressure head relationship

DESCRIPTION OF METHODOLOGY: The Guelph Permeameter (GP) method measures the steady-state liquid recharge necessary to maintain a constant depth of liquid in an uncased well in the unsaturated zone. The permeameter operates by maintaining the liquid level at a given height in the wellbore. The flow rate at steady state for a given head in the wellbore is recorded. Analysis of the data for the conductivity, sorptivity, and conductivity/pressure head relationship can be performed using two separate methods. The Richards method uses two or more successively ponded H-levels in one well and their corresponding steady state flow values. The Laplace and Gardner Analysis use only one head and one flow rate.

ACCURACY/DEVELOPMENT STATE: The present permeameter design has a practical measurement range of saturated hydraulic conductivity of about 10^{-4} to 10^{-8} m/s. The method has been developed only recently and it is not known if the equipment has been tested in a fractured tuffaceous material. The equipment is available commercially.

YUCCA MOUNTAIN APPLICABILITY: The limitation on the practical measurement range of the saturated hydraulic conductivity reduces the applicability of the Guelph pemeameter for Yucca Mountain. There may be locations in alluvial deposits where it would be of use.

COMMENTS: The theory used to evaluate the experimental data obtained from the Guelph permeameter is based on a single porosity system. Use of the equipment is practical only for the measurement of the matrix hydrogeologic parameters.

REFERENCES:

Reynolds, W.D. and Elrick, D.E., 1985, Measurement of Field-Saturated Hydraulic Conductivity, Sorptivity and the Conductivity-Pressure Head Relationship using the "Guelph Permeameter". Proceedings NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, OH, p. 9-33.

METHOD: Long column

PARAMETER(S) MEASURED: Pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: A long column is filled with sample material. A constant head boundary, usually zero gage pressure, is applied to the bottom of the column. The porous medium in the column is allowed to come to equilibrium. Saturation or water content is determined at various elevations along the column by the gravimetric method, or gamma attenuation. The capillary pressure under equilibrium conditions is a function of the elevation above the lower boundary of the column. In general, this method can be used only on unconsolidated materials in the laboratory. A long time period may be necessary to reach equilibrium.

ACCURACY/DEVELOPMENT STATE: The theory underlying this approach is well accepted and has been used in soils investigations for a number of years (it is surmised that this was the first method used to obtain pressure saturation relationships). Accurate results can be obtained provided that equilibrium is reached, although the measurement range generally is limited due to physical constraints (column length).

YUCCA MOUNTAIN APPLICABILITY: It is unlikely that this method can be used to investigate porous media at Yucca Mountain and it is not recommended for use.

COMMENTS: None

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 42.

METHOD: Centrifuge

PARAMETER(S) MEASURED: Pressure-saturation relationship, unsaturated zone water sample collection

DESCRIPTION OF METHODOLOGY: When used to determine pressure-saturation data points, a short column of initially saturated material is placed with its long axis horizontal in a centrifuge. The centrifuge is run at some fixed angular velocity which imposes a centrifugal force on the sample. In some cases this procedure is used to obtain an estimate of the residual saturation. Under these conditions, the outer end of the sample is covered by a porous plug so that when equilibrium conditions are achieved, an arbitrarily large negative pressure will exist within the sample. The water content determined for the large negative pressure is assumed to be equal to the residual water content. In other cases, the porous plug at the outer end of the sample is omitted. Under these conditions, a range of pressures exist across the sample. The water content can be determined using gamma attenuation during rotation; the pressure at the measurement location can be calculated. During rotation at high angular velocity, water forced from the samples can be collected for chemical analysis.

ACCURACY/DEVELOPMENT STATE: The centrifuge method has been used by researchers in soil physics for a number of years (a report issued in 1907 describes one such use). In general, the method probably is most useful in evaluation of soil materials.

YUCCA MOUNTAIN APPLICABILITY: The centrifuge method may be used to obtain water samples from core samples collected during site characterization. However, because of the tight nature of most of the rocks and the expected low saturations, other methods of obtaining water samples may be more successful. There may be situations where this device would be useful in working with samples from Yucca Mountain.

COMMENTS: Under normal conditions, this method is used to obtain the pressure-saturation relationship for the drainage cycle although methods have been devised by which the relationship can also be determined for imbibition.

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 43.

METHOD: Pressure cell

PARAMETER(S) MEASURED: Pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: Samples of a porous medium are placed in direct contact with another saturated porous medium, often termed a capillary barrier or semi-permeable barrier. The barrier usually is constructed of porous ceramic material (pressure plate) or a pressure membrane (porous plastic). The material used in construction of the barrier must have an air entry pressure (negative pressure) which is large enough to prevent desaturation of the barrier while allowing relatively large negative pressures to be applied to the sample. The sample is placed on one side of the barrier, usually in a vessel surrounded by the non-wetting fluid. The wetting phase is on the opposite side of the barrier such that its pressure can be controlled. The pressure at the surface of the barrier which is in contact with the sample is set at a specified level, either by changing the pressure of the wetting fluid or typically by changing the non-wetting phase pressure maintained in the sample chamber. When the sample has reached equilibrium at the set pressure, the water content of the sample is determined. Repeating this process at several pressure settings allows a functional relationship between pressure and saturation to be determined. Pressure plates with various desaturation pressures (-1 bar, -5 bars, -15 bars, etc.) are available commercially.

ACCURACY/DEVELOPMENT STATE: This method for determining pressure-saturation data has been used extensively in the agricultural and petroleum industries. The experimental apparatus is readily available from commercial suppliers and procedures have been well established for conducting the experiments.

YUCCA MOUNTAIN APPLICABILITY: This method probably could be used to determine the pressure-saturation function for samples of matrix material collected during the Yucca Mountain characterization program. However, usually it is used with materials that have lower matric potentials (less negative) than samples from Yucca Mountain.

COMMENTS: This method can be used to obtain the pressure-saturation relationships for both the wetting (imbibition) and drying (drainage) cycles in porous media.

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 44-45.

METHOD: Mercury infusion or intrusion (mercury porosimetry)

PARAMETER(S) MEASURED: Pore size distribution, pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: Small samples of rock are placed in a mercury filled pycnometer. The pressure within the chamber is increased in a stepwise manner and the volume of mercury intruded into the sample is recorded for each pressure increment. The radius of pores, r, into which mercury is intruded can be estimated by

$$r = 2\ T \cos(\alpha)/P$$

where: T represents surface tension, α is the contact angle of mercury, and P represents the applied pressure.

ACCURACY/DEVELOPMENT STATE: This technique has been used by a number of investigators to develop pressure-saturation functions for various soil and rock materials.

YUCCA MOUNTAIN APPLICABILITY: This method is suitable for use at Yucca Mountain and has been used by DOE researchers for developing the pressure-saturation relationships of the matrix materials for the various hydrologic units at Yucca Mountain.

COMMENTS: Through the use of pressures up to about 140 bars, it is possible to evaluate pores with radii greater than about 0.1 um.

REFERENCES:

Klavetter, E.A. and Peters, R.R., 1987, An Evaluation of Mercury Porosimetry in Calculating Hydrogeologic Properties of Tuffs from Yucca Mountain, Nevada. Sandia National Laboratories, SAND86-0286.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

METHOD: Nitrogen gas adsorption

PARAMETER(S) MEASURED: Pore size distribution, pressure-saturation relationship

DESCRIPTION OF METHODOLOGY: The sample is held at a constant temperature equal to that of liquid nitrogen (76.8^{o} K) while nitrogen gas is sorbed onto and desorbed from the particle surfaces at various pressures. The sample is placed in a flask of known weight and volume, and weighed. The flask containing the sample is then degassed to a pressure of about $1x10^{-7}$ bars. An adsorption isotherm is developed by sorbing nitrogen in a quasi-liquid state onto the surface of the sample at different pressures. The quantities and volumes of gas used during the process are estimated with the ideal gas law. After a pressure of -1 bar is reached, a desorption isotherm is determined by desorbing the nitrogen gas by reducing the pressure in the flask. Again, the ideal gas law is used to determine quantities and volumes. The total quantity of gas sorbed (or desorbed) at any pressure can be used to estimate the pore radius, r, with Kelvin's equation:

$$\ell n(p/p_0) = \frac{2\ T \cos(\alpha)}{r\ R\ t}$$

where: p is the vapor pressure of the system, p_0 is the saturated vapor pressure, T is the surface tension, α is the contact angle of liquid and solid, R is the gas constant, and t is the temperature of the system. The desorption data in the range of 1.0 to 0.5 p/p_0 are used to determine the pore size distribution for the sample. When coupled with water characteristics, these data can be used to develop the pressure-saturation relationship.

ACCURACY/DEVELOPMENT STATE: This method appears to be well developed and accepted by the research community. Information supplied by Rasmussen and Evans (1987) indicates that accuracy may be a function of sample size.

YUCCA MOUNTAIN APPLICABILITY: This method probably can be used at the Yucca Mountain site to determine pore size distributions and pressure-saturation functions of the rock matrix. Rasmussen and Evans (1987) used the procedure coupled with mercury infusion to develop a fairly complete description of the pore size distributions for tuffaceous and granitic materials.

COMMENTS: It appears that this method is most suitable for determination of pore size radii in the range of 0.0001 to 0.1 um.

REFERENCES:

Gregg, S.J. and Sing, K.S.W., 1967, Absorption, Surface Area, and Porosity. Academic Press, London.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655, p. 53.

METHOD: Richards permeameter

PARAMETER(S) MEASURED: Rock permeability to wetting fluid (water) and relative permeability

DESCRIPTION OF METHODOLOGY: The Richards permeameter consists of a column with capillary barriers at the ends. The sample is placed between the two capillary barriers and tensiometer rings are installed at two or more locations along the length of the sample. Pressure on the inflow and outflow ends of the column are adjusted to compensate for the head loss through the barriers such that the pressure gradient in the wetting fluid is reduced to zero. By using air vents, the pressure in the non-wetting phase is maintained at atmospheric pressure and the flow occurs in response to gravity only. Pressure readings are taken at the tensiometer rings after the zero pressure gradient has been established across the column; the outflow rate is measured at the same time. The permeability can be calculated with Darcy's law. If desired, the water content can be measured using gamma attenuation. By changing the pressures of the inflow and outflow ends in increments while maintaining the zero pressure gradient, a functional relationship between capillary pressure and permeability can be obtained. Variations of this approach allow both rock cores and undisturbed soil samples to be tested in this manner.

ACCURACY/DEVELOPMENT STATE: This device was invented by L.A. Richards in 1931 and has been used successfully by many investigators. However, like most methods it probably is most suitable to materials with relatively high permeabilities.

YUCCA MOUNTAIN APPLICABILITY: The applicability of this method to Yucca Mountain is questionable. This method probably can be applied to tuff samples obtained from Yucca Mountain. However, it probably will be difficult to establish a zero pressure gradient across a sample because of the low permeabilities of most of the rocks. It is not recommended for use with samples from Yucca Mountain.

COMMENTS:

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 114.

Richards, L.A., 1981, Capillary Conduction of Liquids Through Porous Mediums. Physics 1.

METHOD: Long column permeameter

PARAMETER(S) MEASURED: Rock permeability to water

DESCRIPTION OF METHODOLOGY: The sample is placed in a long column and a constant head boundary similar to a water table (0 gage pressure) is maintained at the lower end of the column. An inflow rate at the top of the column is set and the system is allowed to come to dynamic equilibrium. In a sufficiently long column, flow in the upper part of the column occurs in response to gravity only (unit gradient); pressure and saturation essentially are constant. Under these conditions, the flux, q, is equal to the hydraulic conductivity. Water saturation can be estimated using gamma attenuation during the experiment, if desired. The existence of heterogeneities in the sample will preclude the establishment of a uniform pressure and saturation distribution anywhere in the column.

ACCURACY/DEVELOPMENT STATE: This method was first suggested in 1950 and has been used in many laboratory experiments.

YUCCA MOUNTAIN APPLICABILITY: It is unlikely that this technique can be applied to samples collected at Yucca Mountain. Extremely long times would be required to allow the system to reach dynamic equilibrium. It is not recommended for use with samples from Yucca Mountain.

COMMENTS:

REFERENCES:

Childs, E.C., and Collis-George, N., 1950, The Permeability of Porous Materials. Proc. Royal Society, London, vol. 201.

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 141.

METHOD: Short column permeameter

PARAMETER(S) MEASURED: Rock permeability to water

DESCRIPTION OF METHODOLOGY: This method is similar to the long column permeameter except that a large negative pressure is applied to the lower end of the column rather than using a "water table" or zero pressure boundary. Through the use of capillary barriers (either pressure plates or pressure membranes) and a vacuum pump, the large negative pressure boundary is applied to the lower end of the column while fluid is applied at a known rate at the upper end of the column. This allows a uniform pressure (and water content) distribution to be developed in the upper end of the column so that the flow occurs in response to a unit gradient. Under these conditions, the hydraulic conductivity of the material is equal to the flux. Maintaining the negative pressure at the base of the column is difficult, however.

ACCURACY/DEVELOPMENT STATE: This method has been used by many researchers in the past and is well accepted. However, difficulties in maintaining the large negative pressure at the bottom of the column can lead to inaccuracies in results obtained.

YUCCA MOUNTAIN APPLICABILITY: The applicability of this technique to Yucca Mountain is questionable. Theoretically it is possible that this technique could be applied to samples collected at Yucca Mountain; however, the low permeabilities of the rocks will make measurements extremely difficult. It is not recommended to be used with samples from Yucca Mountain.

COMMENTS: It is likely that in some of the hydrogeologic units within Yucca Mountain, the flow rates of interest are beyond the range of negative pressure that can be imposed by a vacuum pump.

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 142.

METHOD: Stationary-liquid air permeameter

PARAMETER(S) MEASURED: Rock permeability to air as a function of saturation

DESCRIPTION OF METHODOLOGY: A cylindrical sample is confined laterally by a rubber sleeve which fits inside an outer cylinder. Air pressure is used between the sleeve and the outer cylinder to ensure that the sleeve maintains contact with the sample. The fluid in the sample is in static equilibrium and air flows in an upward direction through the sample. The pressure gradient which causes the air flow is adjusted so that it is exactly equal to the pressure gradient caused by the weight of the static liquid. This ensures that uniform negative pressure and saturation distributions are established during the measurement of rock permeability to air. Usually a soap-film flow meter is used to measure the very small flux required for the measurement. This process is repeated at several saturations to develop the rock permeability to air versus saturation function.

ACCURACY/DEVELOPMENT STATE: This is a well established technique for developing relative permeability curves for the non-wetting phase.

YUCCA MOUNTAIN APPLICABILITY: This method, or variations of it, may be useful in determining the permeability of the rock matrix to air or other gases.

COMMENTS: None

REFERENCES:

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, p. 116.

METHOD: Neutron density (compensated neutron log)

PARAMETER(S) MEASURED: Lithology, porosity

DESCRIPTION OF METHODOLOGY: The neutron porosity log measures the rate of decrease of neutron density with distance from a source and converts it to a calibrated porosity value. The rate of decrease primarily is dependent upon the hydrogen content of the formation. Neutron logs measure porosity accurately only to the extent that the hydrogen content defines the liquid-filled porosity. Appropriate corrections must be made for the presence of light hydrocarbons, especially dry gas, and for waters bound within the rock matrix. Perturbations from standard borehole conditions are compensated by means of the dual detector system. The corrected porosity values are derived from the count rate ratio for near- and far-spaced detectors.

The neutron density log responds to the density distribution of neutrons in the formation which have not yet been captured by the formation nuclei. Thus, the spatial distribution of neutrons is affected by the neutron slowing ability and by the thermal neutron capturing ability of the formation.

ACCURACY/DEVELOPMENT STATE: The logs have been used extensively in the petroleum industry. The neutron log provides values of porosity with reasonable accuracy if the rock matrix contains only minute quantities of hydrogen and the pore space is filled with water only. With a two-phase system, neutron derived porosities are too low and indicate only the liquid-filled pore volume fraction. The neutron log by itself therefore is unable to measure porosities in gas saturated intervals.

YUCCA MOUNTAIN APPLICABILITY: This device is applicable at Yucca Mountain.

COMMENTS: None

REFERENCES:

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

METHOD: Natural gamma ray log

PARAMETER(S) MEASURED: Lithology

DESCRIPTION OF METHODOLOGY: Naturally occurring radioactive elements of significant abundance are the uranium series, thorium series, and the potassium-40 isotope. Each element in these series emits gamma rays naturally which are distinctive emitted gamma rays in the borehole. Lithology identification is the primary application of the gamma ray log.

ACCURACY/DEVELOPMENT STATE: The first practical instruments were developed by the oil industry in the late 1930s. The technology is mature.

YUCCA MOUNTAIN APPLICABILITY: The natural gamma ray log may be used at Yucca Mountain to identify the various units.

COMMENTS: None

REFERENCES:

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

METHOD: Gamma-gamma ray log

PARAMETER(S) MEASURED: Lithology, bulk density, porosity

DESCRIPTION OF METHODOLOGY: Density logging is based on the physical phenomenon of gamma ray scattering as a function of the bulk density of an environment irradiated by a gamma ray source. Gamma-gamma logs provide a record of the intensity of radiation from a source in a down-hole probe after it has backscattered and attenuated in the well and surrounding media. The down-hole probe contains a source of gamma photons, such as cobalt-60 or cesium-137, and a sodium iodide detector. A section of the formation adjacent to the wellbore is irradiated by gamma rays. Formation bulk density is obtained from an accurate correlation between the scattered gamma ray intensity at the detectors and instrument calibration data. The scattered gamma ray intensity at the detectors is inversely related to the formation bulk density.

The bulk density measured by the logging instrument is the weighted average of the densities of the matrix and pore fluid. Knowing the densities of the matrix and the pore fluid, and the saturation of the pore fluid, the porosity can be determined.

ACCURACY/DEVELOPMENT STATE: Gamma ray logging has been used in the oil industry for decades. It is a mature technology.

YUCCA MOUNTAIN APPLICABILITY: This device is applicable at Yucca Mountain.

COMMENTS: None

REFERENCES:

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

METHOD: Acoustic logs

PARAMETER(S) MEASURED: Fracture detection and porosity determination

DESCRIPTION OF METHODOLOGY: A displacement temporarily imposed upon an elastic medium produces an oscillating motion after the cause of displacement is removed. This oscillating motion is transmitted through the medium over long distances from the origin of displacement. The vibratory state generated in an elastic medium is called an elastic wave or an acoustic wave. The most important waves in acoustic logging are compressional and shear waves.

The basic measurement in acoustic logging is the specific acoustic time, Δt, which is the time in microseconds required for a compressional wave to traverse one foot of the formation. The acoustic wave pulse is produced in the borehole device by a transducer producing pulses in the form of wave trains of short duration. At some distance along the wellbore, a receiving transducer in the device picks up the wave.

Acoustic amplitude logs can indicate the presence of fractures in rock formations. Both compressional and shear waves are reduced in amplitude while traversing across fractures. The fluids within the open fractures are incapable of conducting shear waves. Attenuation depends upon the angle that a fracture plane makes with the vertically traveling acoustic signals.

Specific acoustic time measurements have been related to porosities of the subsurface formations. The velocity of a compressional wave through a rock formation is influenced both by the rock matrix as well as by the fluids filling the pore space. The radius of investigation is quite shallow.

Wyllie's relationship defining a uniform intergranular porosity in terms of the total formation velocity, rock matrix velocity, and fluid velocity is used to determine the fractional porosity of the rock.

ACCURACY/DEVELOPMENT STATE: The interpretation of the acoustic log is qualitative and empirical. It is largely based upon picking the depths where the amplitude of the arriving shear waves are found to be considerably reduced. Such log-derived information must also be corroborated by observations on cores and drilling records.

YUCCA MOUNTAIN APPLICABILITY: This method is applicable at Yucca Mountain in the deep boreholes to provide qualitative information on the amount of fracturing. The method also would provide porosity data from the boreholes which could be used with other information to determine saturations.

COMMENTS: None

REFERENCES:

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

METHOD: Dry hole resistivity log

PARAMETER MEASURED: Water content

DESCRIPTION OF METHODOLOGY: The purpose of the dry hole resistivity log is to measure the resistivity; thus, indirectly, the water saturation level of formations penetrated by a dry borehole can be measured or estimated. The reasons for the development of a dry hole resistivity logging device are strictly economical. Design, testing, and assembly costs for a resistivity logging tool are much less than for an induction logging tool. Resistivity systems use simple electrical circuits; induction systems require complex transmitting and rewiring costs. Other than the cost factor, the dry hole resistivity log has no advantage over the conventional induction log and, in fact, has the disadvantage that the results are very qualitative and difficult to interpret when compared with the induction log.

ACCURACY/DEVELOPMENT STATE: Dry hole resistivity logging is strictly experimental at the present time. No routine commercial services are available for this type of logging. Attempts have been made to coat the sides of a borehole with a gel mud to keep moisture on the walls so as to facilitate logging the hole with a conventional micro-resistivity logging device. The micro-resistivity tool includes a spring device which forces a wire pad against the side of the hole. In general, the method works poorly. Inversion of the resistivity readings are common, that is, resistive formations appear to be conductive. The method has worked best in less compacted formations, probably because of greater penetration of the gel into the formation. At best, the log yields only qualitative resistivity measurements. Higher resistivity formations can be distinguished from lower resistivity formations but no absolute resistivity measurements can be obtained.

YUCCA MOUNTAIN APPLICABILITY: Application of the dry hole resistivity log to Yucca Mountain is unknown. The method might be useful on an experimental basis in porous portions of tuffs at the Yucca Mountain site. However, the lower cost should not be a determining factor for its use instead of induction logs at Yucca Mountain.

COMMENTS: None

REFERENCES:

Anyermeir, Gary, Personal Communication, BPB Instruments, 1617 Allens Lane, Evansville, Indiana, 47710.

METHOD: Geotomography

PARAMETER MEASURED: Water content

DESCRIPTION OF METHODOLOGY: Geotomography is the geological analogue of CAT scanning in medical technology. Geotomography combines information from a large number of crisscrossing waves to construct three-dimensional images of the materials traversed by the rays. Geotomography can be conducted using either seismic or electromagnetic waves. In geotomography, velocity variations of seismic waves are used to map the formation being scanned. Seismic velocity generally increases with increases in water content. Electromagnetic waves of frequencies between 0.01 hertz and 500 megahertz are used to map absorption of the waves by the rock. The absorption of electromagnetic waves is strongest in the portions of the formation that have the highest water content. Conventional geophysical measurements often cannot distinguish the source of anomalous signals. Geotomographic techniques solve this problem by using many source and receiver locations usually in a large number of boreholes that penetrate the formation to be studied. By recombining mathematically the information from the many source and receiver locations, a three-dimensional picture of internal water content variations can be determined. The more source and receiver positions used, the greater the resolution and accuracy of the three-dimensional image.

ACCURACY/DEVELOPMENT STATE: Delineation of velocity or absorption values that satisfy all the constraints of the methodology requires a complex mathematical procedure and a large computer to solve the equations. Essentially, the technique involves solving a set of simultaneous equations for each unit region of the formation to be studied. The known travel times or amplitudes of all the rays that traverse the formation are on the right side of the equations. A series of terms with associated velocity and absorption parameters is on the left side of the equation. Solving the problem requires finding the values of the parameters that produce the closest fit between the expansions of terms and the observations.

Geotomography is in a developmental state. Because of the analog with medical technology, progress should be swift in this field. Spectacular three-dimensional pictures of the interior of the earth as a whole have been produced, but the algorithms necessary to scale down the procedure to the formation scale are still in development.

YUCCA MOUNTAIN APPLICABILITY: The method should prove very useful during site characterization at Yucca Mountain because no other technique holds the same promise for filling in the gaps between boreholes.

COMMENTS: The Laboratory for Advanced Subsurface Imaging at the University of Arizona, Tucson is the current center for research in electromagnetic geotomography.

REFERENCES:

Bishop, T.N. and others, 1985, Tomographic Determination of Velocity and Depth in Laterally Varying Media. Geophysics, v. 50, pp. 903-923.

Currion, P., 1987, Inverse Problems and Tomography in Acoustics and Seismology. Penn Publishing Company.

Dziewonski, A.M. and Anderson, D.L., 1984, Seismic Tomography of the Earth's Interior. American Scientist, v. 72, pp. 483-494.

Ivansson, S., 1985, A Study of Methods for Tomographic Velocity Estimation in the Presence of Low-Velocity Zones: Geophysics, v. 50, pp. 969-988.

METHOD: Cross-hole radar survey

PARAMETER MEASURED: Water content

DESCRIPTION OF METHODOLOGY: Imaging radars are ground-penetrating radar systems that have been adapted for use in boreholes. In cross-hole radar, tomographic techniques are applied to continuous or pulse radar data collected with the transmitter and receiver placed in two different boreholes.

ACCURACY/DEVELOPMENT STATE: As of this date all borehole radars have been tested experimentally; the approach has not been applied on a routine basis. Because electromagnetic energy attenuates rapidly in conducting materials, radar is a shallow-penetrating technique. Penetration is rarely more than a few tens of meters. Radar works well in resistive materials, such as dry rocks or clean sand saturated with fresh water; it does not work well in conductive materials, such as clay or rocks with conductive pore fluid.

YUCCA MOUNTAIN APPLICABILITY: The success of the dielectric log in fractured tuff suggests that cross-hole work with radar may be successful at Yucca Mountain to obtain estimates of mean water content between boreholes tens of meters apart.

COMMENTS: None

REFERENCES:

Lytle, R.J., Laine, E.F., Lager, D.L., and Davis, D.T., 1979, Cross-borehole Electromagnetic Probing to Locate High-contrast Anomalies. Geophysics, v. 44, no. 10, pp. 1667-1676.

Rubin, L.A., Griffin, J.N., and Still, W.L., 1976, Subsurface Site Investigation By Electromagnetic Radar. Final Report, NSF (RANN) Grant No. APR75-13414.

METHOD: Fractured rock infiltrometer

PARAMETER(S) MEASURED: Fracture aperture and fracture permeability

DESCRIPTION OF METHODOLOGY: Two methods are used with the fractured rock infiltrometer (FRI). The water intake method utilizes a dual-chambered system to determine water intake rates into individual fracture segments. The FRI is secured to a rock surface containing a fracture trace. Both chambers of the FRI are filled with water and the amount of water which flows into the fracture is recorded. Once the estimates of the intake rates are obtained, a physical model is formulated relating the time-dependent intake rate to parameters characteristic of the fractures of interest.

The air intake method is used to provide information about air permeabilities of fractures, and to augment the water intake investigation by providing a secondary means of determining fracture apertures. The design of the method for air is similar to that for water, except that the exterior and interior chambers are open to each other and are not pressurized separately.

ACCURACY/DEVELOPMENT STATE: Aperture determination using gas intake methods may be preferable to water intake methods when exposed fractures are not vertically inclined or in circumstances when water may not be used. The analytical solution for the water experiment is limited to a horizontal, relatively flat, exposed rock surface; these constraints are included also in FRI experiment procedures. The solution for air experiments is not limited to horizontal rock surfaces.

YUCCA MOUNTAIN APPLICABILITY: The use of the FRI at Yucca Mountain would be limited to the drifts and tunnels or the ground surface but it might be useful at these locations.

COMMENTS: None

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

METHOD: Heat-pulse flowmeter

PARAMETER(S) MEASURED: Fracture permeability

DESCRIPTION OF METHODOLOGY: The heat-pulse flowmeter detects low velocity flows in the fractures of boreholes by measuring the travel time of an induced heat pulse. It is possible to locate zones of outflow which can be correlated with fractures observed in the drill core or by television viewer. The relative permeabilities of the fractures can be compared by observing the amount of outflow.

ACCURACY/DEVELOPMENT STATE:

YUCCA MOUNTAIN APPLICABILITY: The applicability of this device is unknown. The heat-pulse flowmeter can be used for conducting preliminary studies in fractured rock. The technology is experimental and much work is needed before it can be used with confidence.

COMMENTS: The use of the heat pulse flowmeter requires that the borehole be saturated to initiate significant fracture flow. The technology is under investigation currently at the Apache Leap site near Superior, Arizona.

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

METHOD: Borehole television camera

PARAMETER(S) MEASURED: Fracture orientation and aperture

DESCRIPTION OF METHODOLOGY: A television borehole camera is run the length of the borehole. A video recording of the borehole is made for further analysis. The fracture orientations can be determined and the wellbore fracture aperture can be estimated.

ACCURACY/DEVELOPMENT STATE: The television borehole camera has been used at Yucca Mountain with success. The technology has applicability for site characterization of boreholes.

YUCCA MOUNTAIN APPLICABILITY: This device is applicable at Yucca Mountain.

COMMENTS: None

REFERENCES:

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

METHOD: Packer system for fracture permeability

PARAMETER(S) MEASURED: Fracture permeability

DESCRIPTION OF METHODOLOGY: The main injection system consists of four packers and a transducer housing, spaced to create three chambers inside the borehole. The central chamber of the main probe is connected to the transducer through a short piece of steel tubing to reduce system compliance during transient testing. Each of the other chambers is connected to one transducer through plastic tubing. The central chamber can be pressurized with water or air. Pressure in each chamber is sensed by transducers. The central chamber is pressurized with gas or liquid and the pressure response is monitored in adjacent boreholes with monitoring probes (usually a single chamber-double packer assembly).

ACCURACY/DEVELOPMENT STATE: The technology of dual porosity testing in the unsaturated zone is in its infancy. Multichamber, packer injection, testing equipment was developed at the Colorado School of Mines to characterize the in-situ permeability of the fractured rock around a room in unsaturated gneiss. Using steady state tests with less than 0.2 MPa of overpressure, the equipment is capable of detecting zones with permeabilities as low as one nanodarcy. During transient tests, the lower limit of sensitivity is determined by the amount of leakage around the packers.

Nitrogen is used as the injection fluid most often because it is suitable for testing unsaturated fractured rock with very low total water potential. Carbon dioxide and water also have been used as injection fluids to determine the response of the test media to the injection fluid.

Boreholes were tested systematically by the Colorado School of Mines using a sequentially overlapping interval method of sampling. Steady state, pressure fall-off, and pulse tests were used. Individual fractures were selected and cross-hole tested with all three fluids and a variety of testing methods. Analysis of the data revealed that absolute values of permeabilities cannot be determined by single tests. A number of nitrogen injection tests with a wide range of test pressures is required to estimate the permeability.

YUCCA MOUNTAIN APPLICABILITY: The use of the multi-hole packer testing method to determine fracture hydrologic characteristics is applicable at Yucca Mountain.

COMMENTS: None

REFERENCES:

Montazer, P., 1982, Permeability of Unsaturated, Fractured Metamorphic Rocks Near an Underground Opening. Ph.D. Thesis, Colorado School of Mines.

Collection of Water Samples

Methods to obtain representative water samples from the unsaturated zone at Yucca Mountain are very limited. Because of the large negative pressures that exist in Yucca Mountain, it is very difficult to collect sufficient water for chemical analyses. Methods used to condense water vapor yield essentially distilled water which is suitable only for isotopic analyses. These methods do not yield representative water samples for complete chemical analyses. Pressure vacuum lysimeters, and pore-water extraction from cores are the only methods available currently for obtaining water samples from the unsaturated zone.

METHOD: Pore-water extraction

PARAMETER(S) MEASURED: Unsaturated zone water sampling

DESCRIPTION OF METHODOLOGY: Pore-water extraction from core samples may constitute a method to obtain water samples from the unsaturated zone at Yucca Mountain. The method consists of the placement of a segment of core in a commercially available filter press, hydraulic ram, or centrifuge to force water out of the core. Luscynski (1961) describes the use of a filter press to extract pore water. Manheim (1966) describes a core sample squeezer which uses a hydraulic ram to extract pore water.

ACCURACY/DEVELOPMENT STATE: The pore-water extraction technique has been used primarily for the collection of groundwater samples below the water table. The technique was developed to obtain groundwater samples in saturated, low hydraulic conductivity materials. The pore-water extract generally is suitable for standard analytical analyses such as electrical conductivity and titrametric analysis for chloride. The main limitation of the method is the small water sample that is obtained. An additional limitation is that samples cannot be extracted using these methods at a water content below a threshold value of about 11 percent. A vacuum distillation method is available to collect distilled water (from water vapor) for tritium, oxygen and hydrogen isotope analyses from samples with a water content below 11 percent.

YUCCA MOUNTAIN APPLICABILITY: It may be possible to obtain small pore-water samples with pore-water extraction methods; however, the methods cannot be used to collect pore-water samples from tuffs with a water content less than 11 percent.

COMMENTS: None

REFERENCES:

Lusczynski, N.J., 1961, Filter-Press Method of Extracting Water Samples for Chloride Analysis. USGS Water Supply Paper 1544-A.

Manheim, F.T., 1966, A Hydraulic Squeezer for Obtaining Interstitial Water From Consolidated and Unconsolidated Sediment. USGS Professional Paper 550-C, p.. C-256-C-261.

METHOD: Pressure vacuum lysimeter (inverse tensiometer)

PARAMETER(S) MEASURED: Unsaturated zone water sampling

DESCRIPTION OF METHODOLOGY: The pressure vacuum lysimeter consists of a porous ceramic cup capable of holding a vacuum, a small-diameter sample accumulation chamber of PVC pipe, and two sampling tubes leading to the surface. Once the lysimeter is installed, a vacuum is applied to the cup. Moisture in the unsaturated zone moves into the sampler under this gradient. Once the sample is accumulated in the sampler the vacuum is released and a positive pressure is applied to force the sample to the surface through the sampling tube.

ACCURACY/DEVELOPMENT STATE: Pressure vacuum lysimeters have been used for many years to collect water samples from unsaturated soils. Generally, representative water samples can be obtained from soil materials with water pressures greater (less negative) than -1.0 atmospheres. Rasmussen and Evans (1987) have modified the standard methodology by injecting distilled water into the zone around the lysimeter. After the distilled water is allowed to mix with the formation water, a diluted sample is obtained from the lysimeter. This procedure has been demonstrated at an achievable injection pressure.

YUCCA MOUNTAIN APPLICABILITY: It is not likely that pressure vacuum lysimeters will be used at Yucca Mountain due to their pressure limitations of about -1.0 atmospheres. In addition, in deeply-placed lysimeters, positive pressure exceeding about one atmosphere in the sample chamber would drive accumulated water back through the cup rather than to the surface unless the lysimeter is equipped with a pressure chamber and check valve. They are not recommended for use in Yucca Mountain.

COMMENTS: None

REFERENCES:

Grover, B.L., and Lamborn, R.E., 1970, Preparation of Porous Ceramic Cups to Be Used for Extraction of Soil Water Having Low Solute Concentrations. Soil Science Society of America Proceedings, 34(4); p. 706-708.

Parizek, R.R., and Lane, B.E., 1970, Soil Water Sampling Using Pan and Deep Pressure-Vacuum Lysimeters. Journal of Hydrology, vol. 11, p. 1-21.

Rasmussen, T.C., and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

Wagner, G.H., 1962, Use of Porous Ceramic Cups to Sample Soil Water Within the Profile. Soil Science, vol. 94, p. 379-386.

Wengel, R.W., and Griffen, G.F., 1971, Remote Soil-Water Sampling Technique. Soil Science Society of America Proceedings, 35(4), p. 661-664.

Wood, W.W., 1973, A Technique Using Porous Cups for Water Sampling at Any Depth in the Unsaturated Zone. Water Resources Research, 9(2), p. 486-488.

References

Al-Khafaf, S. and Hanks, R.J., 1974, Evaluation of the Filter Paper Method for Estimating Soil Water Potential. Soil Sci., 114(4):194-199.

American Geological Institute, 1974, Glossary of Geology, Washington, D.C.

Anyermeir, Gary, Personal Communication, BPB Instruments, 1617 Allens Lane, Evansville, Indiana, 47710.

Bishop, T.N. and others, 1985, Tomographic Determination of Velocity and Depth in Laterally Varying Media. Geophysics, v. 50, pp. 903-923.

Bouwer, H., and Jackson, R.D., 1974, Determining Soil Properties, in Drainage for Agriculture. Edited by Jan Van Schilfgaarde, American Society of Agronomy, Inc., Madison, Wisconsin.

Bouyoucas, G.J., 1960, Measuring Soil Moisture Tension. Agriculture Engineering, Michigan, 41, 40-41.

Brady, N.C., 1974, The Nature and Properties of Soils. 8th Edition, McMillan Publishing Co., New York, NY 10022, p. 50.

Briscoe, R., 1979, Effective Use of Thermocouple Psychrometers in Measurement of Water Potential. Presented at Annual Meeting of Agronomy Society of America, Fort Collins, CO, Aug. 3.

Brooks, R.H. and Corey, A.T., 1964, Hydraulic Properties of Porous Media. Hydrology paper (3), Civil Engineering Dept. Colorado State University, Fort Collins, CO.

Brown, R.W. and Johnston, R.S., 1976, Extended Field Use of Screen Covered Thermocouple Psychrometer. Agronomy J., 68:995-996.

Campbell, E.C., Campbell, G.S., and Barlow, W.K., 1973, A Dewpoint Hygrometer for Water Potential Measurement. Agr. Meteorology, vol. 12, p. 113-121.

Childs, E.C., and Collis-George, N., 1950, The Permeability of Porous Materials. Proc. Royal Society, London, vol. 201.

Corey, A.T., 1977, Mechanics of Heterogeneous Fluids in Porous Media. Water Resources Publications, Ft. Collins, CO, 259 p.

Currion, P., 1987, Inverse Problems and Tomography in Acoustics and Seismology. Penn Publishing Company.

Daniel, D.E., Hamilton, J.M., and Olson, R.E., 1981, Suitability of Thermocouple Psychrometers for Studying Moisture Movement in Unsaturated Soils. Permeability and Groundwater Contaminant Transport, ASTM, STP-746, Philadelphia.

Davidson, J.M., Biggar, J.W., and Nielsen, D.R., 1963, Gamma-Radiation Attenuation for Measuring Bulk Density and Transient Water Flow in Porous Materials. J. Geophy. Res., vol. 68, p. 4777-4783.

Delano, J.M., and Wharton, R.P., 1984, An EPT Interpretation Procedure and Application in Freshwater, Shaly Oil Sands. Journal of Petroleum Technology, vol. 36, no. 11.

Dresser Atlas, 1982, Well Logging and Interpretation Techniques.

Dziewonski, A.M. and Anderson, D.L., 1984, Seismic Tomography of the Earth's Interior. American Scientist, v. 72, pp. 483-494.

Elrick, D.E., 1963, Unsaturated Flow Properties of Soils. Aust. J. Soil Res., 1:1-8.

Everett, L.G., Wilson, L.G., and Hoyulman, E.W., 1984, Vadose Zone Monitoring for Hazardous Waste Sites. Pollution Technology Review, no. 112, Moyes Data Corporation, Park Ridge, NJ.

Fawcett, R.G. and Collis-George, N., 1967, A Filter Paper Method for Determining the Moisture Characteristics of Soil. Aust. J. Exp. Agri. Amin. Husb., 7:162-167.

Gardner, R., 1937, A Method of Measuring Capillary Tension of Soil Moisture Over a Wide Moisture Range. Soil Science, 43:238-277.

Gardner, W.H., 1965, Water Content in Methods of Soil Analyses, C.A. Black (ed), Agronomy No. 9, 82-125, Amer. Soc. Agron., Madison, WI.

Gardner, W.R., 1956, Calculation of Capillary Conductivity from Pressure Plate Outflow Data. Soil Sci. Soc. Amer. Proc. 20:317-320.

Gardner, W.R., 1962, Note on the Separation and Solution of Diffusion Type Equations. Soil Sc. Soc. Amer. Proc. 26:404.

Geng, X., Tinzu, Y., Da, L., and Shutang, Z., 1983, Dielectric Log. A Logging Method for Determining Oil Saturation. Journal of Petroleum Technology, p. 1797-1805.

Gregg, S.J., and Sing, K.S.W., 1967, Absorption, Surface Area, and Porosity. Academic Press, London.

Grover, B.L., and Lamborn, R.E., 1970, Preparation of Porous Ceramic Cups to Be Used for Extraction of Soil Water Having Low Solute Concentrations. Soil Science Society of America Proceedings, 34(4); p. 706-708.

Hamblin, A.P., 1981, Filter-Paper Method for Routine Measurement of Field Water Potential. J. of Hydrology, vol. 53, p. 355-360.

Hammermeister, D.P., Kneiblher, C.R., and Klenke, J., 1985, Borehole-Calibration Methods Used in Cased and Uncased Test Holes to Determine Moisture Profiles in the Unsaturated Zone, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 542-563.

Hillel, Daniel, 1971, Soil and Water: Physical Principles and Processes. Academic Press, 288 p.

Ivansson, S., 1985, A Study of Methods for Tomographic Velocity Estimation in the Presence of Low-Velocity Zones: Geophysics, v. 50, pp. 969-988.

Jackson, R.D., van Bavel, C.H.M., and Reginato, R.J., 1963, Examination of the Pressure-Plate Outflow Method for Measuring Capillary Conductivity. Soil Sci. 96:249-256.

Keys, W.S., and McCary, C.M., 1976, Application of Borehole Geophysics to Water Resources. U.S. Geological Survey Techniques of Water-Resources Investigations, Book 2, Chapter E1, 126 p.

Klavetter, E.A., and Peters, R.R., 1987, An Evaluation of Mercury Porosimetry in Calculating Hydrogeologic Properties of Tuffs from Yucca Mountain, Nevada. SAND86-0286.

Klute, A., 1965, Laboratory Measurement of Hydraulic Conductivity of Unsaturated Soil, in Methods of Soil Analysis, Part 1. edited by C.A. Black, Agronomy 9:253-261.

Lusczynski, N.J., 1961, Filter-Press Method of Extracting Water Samples for Chloride Analysis. USGS Water Supply Paper 1544-A.

Lytle, R.J., Laine, E.F., Lager, D.L., and Davis, D.T., 1979, Cross-borehole Electromagnetic Probing to Locate High-contrast Anomalies. Geophysics, v. 44, no. 10, pp. 1667-1676.

Manheim, F.T., 1966, A Hydraulic Squeezer for Obtaining Interstitial Water From Consolidated and Unconsolidated Sediment. USGS Professional Paper 550-C, p.. C-256-C-261.

Marshall, T.J., 1959, Relations between Water and Soil. Commonwealth Agricultural Bureau, Farnham Royal, England, p. 99.

McQueen, I.S. and Miller, R.F., 1968, Calibration and Evaluation of a Wide-Range Gravimetric Method for Measuring Moisture Stress. Soil Sci. Soc. Am. Proc., 106:225-231.

Merrill, S.D. and Rawlins, S.L., 1972, Field Measurement of Soil Water Potential with Thermocouple Psychrometer. Soil Sci. Soc. Am. Proc., vol. 13, p. 102-109.

Miller, E.E., and Elrick, D.E., 1958, Dynamic Determination of Capillary Conductivity Extended for Non-Negligible Membrane Impedance. Soil Sci. Soc. Amer. Proc. 22:483-486.

Montazer, P., 1982, Permeability of Unsaturated, Fractured Metamorphic Rocks Near an Underground Opening. Ph.D. Thesis, Colorado School of Mines.

Montazer, P., Weeks, E.P., Thamir, F., Yard, S.N., and Hofrichte, P.B., 1985, Monitoring the Vadose Zone in Fractured Tuff, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p. 439-469.

Mualem, Y., 1976, A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media. Water Resour. Res., 12(3):513-522.

Palaz, I., 1985, Application of Geophysical Logs to Estimate Moisture-Content Profiles in Unsaturated Tuff, Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, Ohio, p.. 424-438.

Parizek, R.R., and Lane, B.E., 1970, Soil Water Sampling Using Pan and Deep Pressure-Vacuum Lysimeters. Journal of Hydrology, vol. 11, p. 1-21.

Peck, A.J. and Rabbidge, R.M., 1966, Soil Water Potential: Direct Measurement by a New Technique. Science, vol. 151, p. 1385-1386.

Peck, A.J. and Rabbidge, R.M., 1969, Design and Performance of an Osmotic Tensiometer for Measuring Capillary Potential. Soil Sci. Soc. Am. Proc., vol. 33, p. 196-202.

Peters, R.R., Klavatter, E.A., Hall, I.J., Blair, S.C., Heller, P.R., and Gee, G.W., 1984, Fracture and Matrix Hydrologic Characteristics of Tuffaceous Material from Yucca Mountain, Nye County, Nevada. Sandia Report SAND84-1471.

Phene, C.J., Hoffman, G.J., and Rawlins, S.L., 1971, Measuring Soil Matric Potential In-Situ by Sensing Heat Dissipation Within a Porous Body: I Theory and Sensor Construction. in Soil Sci. Soc. Amer. Proc., vol. 35, p. 27-33.

Phene, C.J., S.L. Rawlins and G.J. Hoffman, 1971, Measuring Soil Matric Potential In-Situ by Sensing Heat Dissipation Within a Porous Body: II Experimental Results. in Soil Sci. Soc. Amer. Proc., 35, 225-229.

Rasmussen, T.C. and Evans, D.D., 1987, Unsaturated Flow and Transport Through Fractured Rock Related to High-Level Waste Repositories. Prepared for U.S. Nuclear Regulatory Commission, Washington, DC, NUREG/CR-4655.

Reynolds, W.D. and Elrick, D.E., 1985, Measurement of Field-Saturated Hydraulic Conductivity, Sorptivity and the Conductivity-Pressure Head Relationship using the "Guelph Permeameter". Proceedings NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, OH, p. 9-33.

Richards, L.A., Ed., 1954, Diagnosis and Improvement of Saline and Alkali Soils. USDA Handbook No. 60.

Richards, L.A. and Gardner, W., 1936, Tensiometer for Measuring the Capillary Tension of Soil Water. Am. Soc. Agronomy J., 28:353-358.

Richards, L.A. and Ogata, G., 1958, Thermocouple for Vapor Pressure Measurement in Biological and Soil Systems at High Humidity. Science, 128:1089-1090.

Richards, L.A., 1981, Capillary Conduction of Liquids Through Porous Mediums. Physics 1.

Richards, S.J., 1965, Soil Suction Measurement with Tensiometers. in C.A. Black (ed.), Method of Soil Analysis. Amer. Soc. of Agronomy, Madison, WI, 153-163.

Rijtema, P.E., 1959, Calculation of Capillary Conductivity from Pressure Plate Outflow Data with Non-Negligible Membrane Impedance. Neth. J. Agr. Sci. 7:209-215.

Rubin, L.A., Griffin, J.N., and Still, W.L., 1976, Subsurface Site Investigation By Electromagnetic Radar. Final Report, NSF (RANN) Grant No. APR75-13414.

Shen, L.C., 1985, A Laboratory Technique for Measuring Dielectric Properties of Core Samples at Ultra-High Frequencies. Society of Petroleum Engineers Journal, vol. 25, no. 4.

Spanner, D.C., 1951, The Peltier Effect and Its Use in the Measurement of Suction Pressure. J. Exp. Botany, 2:145-168.

Thamir, F., and McBride, C.M., 1985, Measurements of Matric and Water Potentials in Unsaturated Tuff at Yucca Mountain, Nevada. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, OH, p. 470-487.

Timur, A., 1982, Advances in Well Logging. Journal of Petroleum Technology, vol. 34, no. 6.

Tyler, S., 1985, Moisture Monitoring in Large Diameter Boreholes. Proceedings of the NWWA Conference on Characterization and Monitoring of the Vadose Zone, National Water Well Association, Dublin, OH, p. 97-106.

Van Genuchten, M.Th., 1978, Calculating the Unsaturated Hydraulic Conductivity with a New Closed-Form Analytical Model. Water Resource Program, Dept. of Civil Engineering, Princeton University, NJ, Research Report 78-WR-08.

Van Genuchten, M.Th. and Nielsen, D.R., 1985, On Describing and Predicting the Hydraulic Properties of Unsaturated Soil. Annales Geophysicae 3(5), in press.

Van Genuchten, M.Th., 1980, A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Sci. Am. J., (44):892-898.

Wagner, G.H., 1962, Use of Porous Ceramic Cups to Sample Soil Water Within the Profile. Soil Science, vol. 94, p. 379-386.

Wengel, R.W., and Griffen, G.F., 1971, Remote Soil-Water Sampling Technique. Soil Science Society of America Proceedings, 35(4), p. 661-664.

Wood, W.W., 1973, A Technique Using Porous Cups for Water Sampling at Any Depth in the Unsaturated Zone. Water Resources Research, 9(2), p. 486-488.

Glossary of Terms

Atmosphere: One atmosphere is a conventional unit of pressure equal to 14.7 lbs per square inch, 76 centimeters of mercury, or 1033 centimeters of water.

Bar: A bar is an international unit of pressure equal to 10^6 dynes/cm^2. 1 bar = 0.987 atmospheres.

Gravitational Potential (ϕg): Gravitational potential is equal to the elevation (z) of the measurement point relative to some arbitrary reference level multiplied by the acceleration due to gravity (g) [$\phi g = gz$].

Matric Potential (ϕp): (not to be confused with matrix) Matric Potential is a negative potential which results from the capillary and adsorptive forces due to the soil matrix. These forces attract and bind water in the soil and lower its potential energy below that of bulk water. The term "matric potential" denotes the total effect resulting from the affinity of water to the whole matrix of the soil, including its pores and particle surfaces together (Hillel, 1971). When water in the unsaturated zone is at a pressure lower than atmospheric, the matric potential is considered to be negative and the water is considered to be held under tension or suction.

Matrix: (not to be confused with matric) Matrix refers to a mass of soil or porous rock that contains solid material and embedded pores. The term refers to the relative size and disposition of the particles, and no particular particle size is implied (American Geological Institute, 1974).

Matrix Porosity: Matrix porosity refers to the void space within the matrix of a sample of soil or porous rock. Openings due to fractures and certain other secondary features usually are not included in the measurement of matrix porosity.

Osmotic Potential: Osmotic potential refers to the effect of the presence of solutes in soil water. The presence of solutes affects the thermodynamic properties of the soil water and lowers its potential energy. Solutes lower the vapor pressure of soil water.

Soil-Water Diffusivity: Soil-water diffusivity is defined as the ratio of the hydraulic conductivity of a sample of soil or porous rock to the specific water capacity of the sample. This relationship is used to relate the flux to the water content (wetness) gradient rather than to the matric potential gradient (Hillel, 1971).

Specific Water Capacity: Specific water capacity is the slope of the soil-moisture characteristic curve. This slope is the change of matric potential (Hillel, 1971).

Tension or Suction: Tension and suction are synonymous terms that are used in lieu of "negative (or) subatmospheric pressure." These terms are semantic devices to avoid use of the negative sign which generally characterizes the pressure of soil water (Hillel, 1971).

Total Water Potential (ϕ_t): Total water potential usually is equal to the sum of gravitational (or elevational) potential (ϕ_g), the matric (or pressure) potential (ϕ_p), and the osmotic potential (ϕ_o) [$\phi_t = \phi_g + \phi_p + \phi_o + \ldots$]. Additional terms theoretically can be added to the aforementioned terms under specific conditions (Hillel, 1971).

Water Content: Water content is the volume of water in a sample of soil or porous rock divided by the bulk volume of the sample.