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MEASUREMENTS OF MATRIC AND WATER POTENTIALS IN UNSATURATED TUFF AT YUCCA MOUNTAIN, NEVADA

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Abstract

Two types of instruments were installed in a borehole in order to monitor matric and water potentials of various hydrogeologic units consisting of tuff. The borehole was drilled as part of a study to provide information to the U.S. Department of Energy for their use in evaluating Yucca Mountain, Nevada, for a repository for high-level radioactive waste. Heat-dissipation probes were used to monitor matric potentials and thermocouple psychrometers were used to monitor water potentials.

Two major concerns regarding the use of these instruments in deep boreholes are: (1) The effect of length of the lead wires, and (2) the inability to recalibrate the instruments after installation. The length of the lead wire contributes to the source resistance and lead capacitance, which affects the signal settling time. Both instruments tested proved to be insensitive to lead-wire length, except when connected to smaller input-impedance data loggers. Thermocouple wires were more sensitive than heat-dissipation probe wires because of their greater resistance and quality of voltmeters used.

Two thermocouple psychrometers were installed at every instrument station for backup and verification of data, because the instruments could not be recalibrated in situ. Multiple scanning rather than single-point scanning of the evaporation curve of a thermocouple psychrometer could give more reliable data, especially in differentiating between very wet and very dry environments. An isolated power supply needs to be used for each heat-dissipation probe rather than a single power supply for a group of probes to avoid losing data from all probes when one probe malfunctions. This type of system is particularly desirable if the site is unattended by an operator for as long as a month.

Introduction

The U.S. Geological Survey is conducting studies in the unsaturated zone at Yucca Mountain, Nevada, a potential high-level radioactive waste repository. These studies, part of the Nevada Nuclear Waste Storage Investigations (NNWSI) Project, are being conducted in cooperation with the U.S. Department of Energy, Nevada Operations Office, under Interagency Agreement DE-AI08-78ET44802.

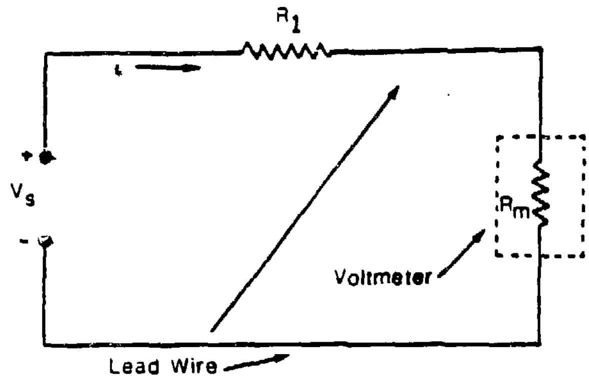
Borehole USW UZ-1 was drilled in unsaturated tuff to a depth of 1,269 ft (387 m) and is 17.5 in. (44.5 cm) in diameter. The borehole was drilled using the vacuum reverse-air circulation method, which created a borehole wall free from liquid drilling-fluid contamination. Specific purposes of this borehole are described in Montazer et al., 1985 (this proceedings), and Whitfield, 1985 (this proceedings).

Matric and water potentials of the various hydrogeologic units penetrated by this hole are being monitored with two types of instruments. Heat-dissipation probes are being used to monitor matric potential, and thermocouple psychrometers are being used to monitor water potential, which is the sum of matric and osmotic potentials. Long lead wires are used to transmit voltage signals from the instruments to the recording devices at the land surface. The error in the recorded voltage at the land surface largely depends on the lead-wire resistance and capacitance. As shown in figure 1, the measured voltage (V_m), approaches the source voltage (V_s) if the input resistance of the measuring device (R_m) is considerably greater than the lead-wire resistance (R_l). This factor is considered when the source voltage is given sufficient time to settle.

When a fast scanning rate of the same source is desired, then the lead-wire capacitance as well as resistance needs to be considered. As shown in figure 2, the signal settling time depends on the time constant. If the scanning rate is equivalent to 1 time constant, then the relative error is about 37%. Scanning every 5 time constants would reduce the relative error to 0.7%. Lead-wire resistance and capacitance usually are listed in manufacturers' specification sheets.

Two thermocouple psychrometers were used at every instrument station to increase the reliability of measurements. This duplication is important when it is not possible to retrieve instruments for recalibration. A continuity (or resistance) inspection across the leads of the measuring instruments provides a method for checking instrument operation and for detecting any electrical shorts along the lead wires and in the instruments.

Both types of instruments were calibrated in the laboratory, assembled into a bundle with other instruments, strapped onto a tubing pipe and lowered into the borehole, which later was stemmed with various materials up to the land surface. A data-acquisition station was installed at the borehole site and serviced once every 2 to 3 weeks. The instrumentation and stemming of the borehole are described in more detail by Montazer et al. (1985, this proceedings).



EXPLANATION

- V_s SOURCE (INPUT) VOLTAGE
- R_l LEAD-WIRE RESISTANCE, IN OHMS
- V_l VOLTAGE DROP THROUGH LEAD WIRES
- R_m INPUT RESISTANCE OF THE MEASURING INSTRUMENT, FOR EXAMPLE DIGITAL VOLTMETER, IN OHMS
- V_m VOLTAGE DROP ACROSS R_m
- i CURRENT, IN AMPERES

$$i = \frac{V_s}{R_l + R_m}$$

$$V_m = i \cdot R_m$$

$$V_l = i \cdot R_l \text{ , and}$$

$$V_s = V_m + V_l$$

if $R_m >> R_l$ then

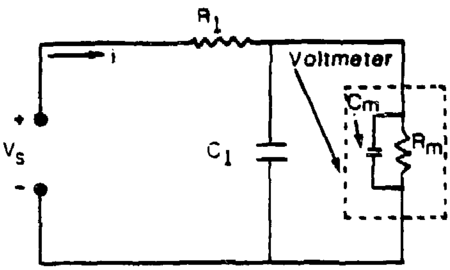
$$i = \frac{V_s}{R_m} \text{ , and } V_m = V_s$$

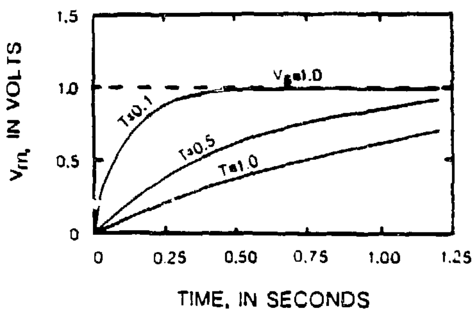
Figure 1. Effect of lead-wire resistance on the value of measured voltage.

Heat-Dissipation Probes

Principle of Operation

The rate of heat conduction in a partially saturated porous medium (in which the solid matrix has low heat conductivity) is dependent primarily on water content of the medium (Phene et al., 1971). Air is a poor conductor of heat compared to water, so that 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, then an empirical relationship between the matric potential and temperature difference could be obtained. A cross section of a heat-dissipation probe is shown in figure 3.





EXPLANATION

V_s	SOURCE (INPUT) VOLTAGE
R_l	LEAD-WIRE RESISTANCE, IN OHMS
C_l	LEAD-WIRE CAPACITANCE, IN FARADS
V_l	VOLTAGE DROP THROUGH LEAD WIRES
R_m	INPUT RESISTANCE OF THE MEASURING INSTRUMENT, FOR EXAMPLE DIGITAL VOLTMETER, IN OHMS
C_m	INPUT CAPACITANCE OF THE MEASURING INSTRUMENT, IN FARADS
V_m	VOLTAGE DROP ACROSS R_m
C_{tot}	TOTAL CIRCUIT CAPACITANCE, IN FARADS
t	TIME, IN SECONDS
T	TIME CONSTANT, IN SECONDS
i	CURRENT, IN AMPERES

$$C_{tot} = C_l + C_m$$

$$T = R_l \cdot C_{tot}$$

$$V_m = V_s\,(1 - \exp(-t/T))$$

$$\%\ error = \frac{V_s - V_m}{V_s} \cdot 100$$

time, in multiples of T	% error
0	100.0
1	36.8
2	13.5
3	5.0
5	0.7
8	0.03
10	0.005

Figure 2. Effect of lead-wire resistance and capacitance on voltage-signal settling time.

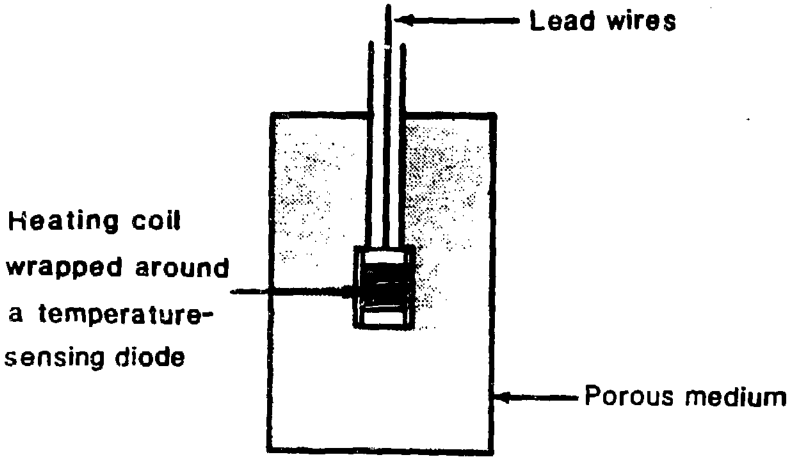


Figure 3. Heat-dissipation probe sensor (modified from Phene et al., Soil Science Society of America Proceedings, Vol. 35, 1971, pg. 30, by permission of the Soil Science Society of America)

General Description and Specifications

The heat-dissipation probes were made by Moisture Control Systems[1], model MCS 6000. The output voltage of this probe is nearly linearly proportional to the matric potential between 0 and -0.6 bar (-0.06 MPa). Below -0.6 bar, the sensitivity decreases slowly, but it begins to decrease rapidly at values less than -5 bars (-0.5 MPa) (fig. 4 and table 1).

Method of Calibration

The sensors were saturated with 0.01 M calcium selenate ($CaSeO_4$) solution, to prevent bacterial growth, then placed in a pressure extractor with saturated silica flour between the sensing tip and a ceramic plate, to insure hydraulic continuity. Different matric potentials were achieved by applying air pressure to drive out pore water (fig. 5). The ceramic plate needs to be rated at or above the highest calibration pressure at any stage. Calibration results of output voltage versus applied pressure (matric potential) are collected for each sensor as shown in table 1 and plotted as shown in figure 4.

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[1]Use of firm and brand names in this report is for identification only and does not constitute endorsement by the U.S. Geological Survey.

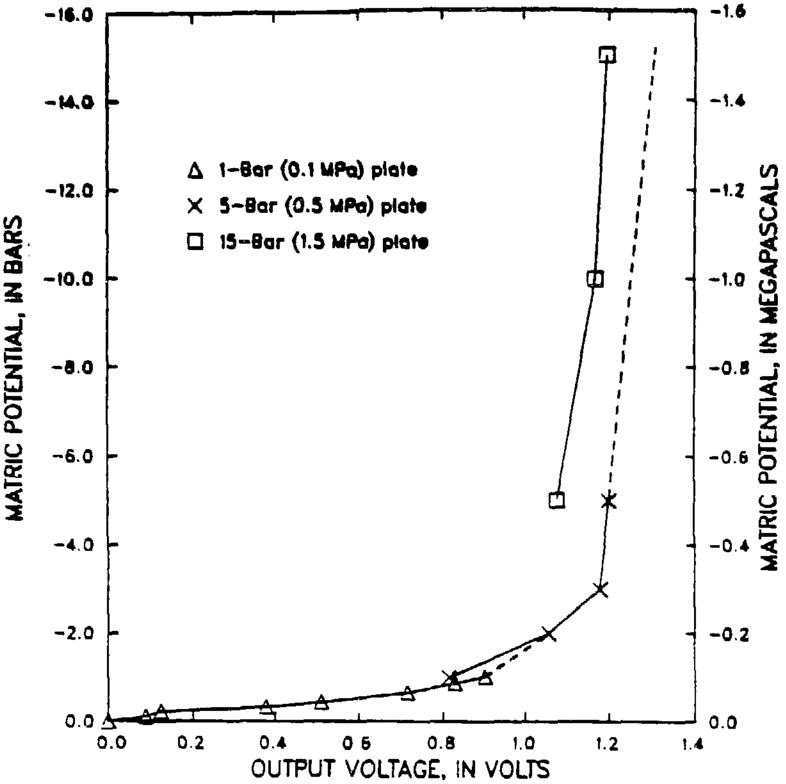

Figure 4. Calibration data of a heat-dissipation probe.

Table 1. Calibration data of a heat-dissipation probe

Matric potential, in bars (MPa)	Output voltage, in volts	Ceramic-plate pressure rating, in bars (MPa)
-0.11 (-0.011)	0.088	1.0 (0.1)
- .22 (- .022)	.123	1.0 (.1)
- .33 (- .033)	.378	1.0 (.1)
- .44 (- .044)	.510	1.0 (.1)
- .66 (- .066)	.713	1.0 (.1)
- .87 (- .087)	.827	1.0 (.1)
-1.02 (- .102)	.901	1.0 (.1)
-1.0 (- .100)	.814	5.0 (.5)
-2.0 (- .200)	1.057	5.0 (.5)
-3.0 (- .300)	1.179	5.0 (.5)
-5.0 (- .500)	1.078	15.0 (1.5)
-10.0 (-1.000)	1.169	15.0 (1.5)
-15.0 (-1.500)	1.194	15.0 (1.5)

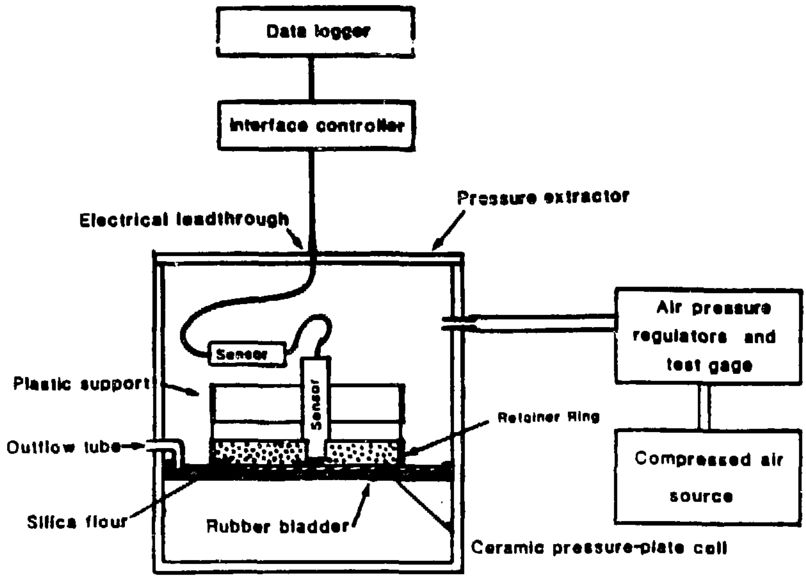

Figure 5. Calibration of heat-dissipation probes.

Difficulties Encountered During Calibration

Theoretically, the output voltage of a heat-dissipation probe during calibration should not depend on the ceramic-plate pressure rating provided that the pressure used is less than or equal to the rated value of the plate. As shown in figure 4, a difference exists between the 1-bar (0.1-MPa) reading collected using a 1-bar plate and a 5-bar (0.5-MPa) plate. The discrepancy is seen in the 5-bar reading. This difference could be caused by the way the pressures were applied. The 1-bar pressure was reached after several pressure increases using the 1-bar plate and in one stage with the 5-bar plate. Applying a greater pressure in one stage could cause the sensor tip to desaturate faster, causing uneven water and air movement in the porous tip. This movement would isolate some moisture inside the tip that could be surrounded by air and would not be driven out of the sensing tip. This effect could cause a lower reading (wetter sensor) for the same applied pressure.

Limited time and equipment were available for the calibrations described in this study. Plates with lesser pressure ratings were used at the lesser pressures to minimize calibration time. The shorter equilibrium times when ceramic plates rated for lower pressures were used are summarized in table 2. Equilibrium time is the time required to reach steady voltage readings at an applied pressure. Because of the problems mentioned above, effort will be made in the future calibrations to use a 15-bar ceramic plate for the entire calibration curve. Alternatively, if more than one plate is used, more pressure steps will be included before attaining the pressure of interest.

Table 2. Equilibrium time of heat-dissipation probes during calibration with different ceramic plates

Pressure rating of plate, in bars (MPa)	Equilibrium time, in hours
1.0 (0.1)	3 to 5
5.0 (0.5)	10 to 40
15.0 (1.5)	30 to 80

Lead-wire length did not affect the output voltage, especially when using data loggers having large input impedance and lead wires with little resistance.

Borehole Installation

Plastic cups with O-rings were placed on the tips of the heat-dissipation probes while they were being transported and connected to the lead wires at the borehole site. This placement was done to preserve the saturation and integrity of the tips. The cups were removed and replaced with cloth bags containing saturated silica flour to prevent the tips from desaturating while the probes were bound to a central, stabilizing tubing pipe and lowered into the borehole. Zones around the heat-dissipation probes were stemmed with silica flour.

Data Acquisition

The probes were connected in groups of 10 or less to a common controller. Each controller has one common power supply for all probes connected to it. The output voltages of all probes are recorded by one data logger installed at the borehole site.

Difficulties Encountered During Field Measurements

A common power supply to a group of probes could cause the loss of data from all the probes in the event of an electrical short caused by a malfunctioning probe. This condition has proved to be a problem, especially since the site is unattended for a long period of time. Isolating the power supply, rather than using a common power supply or connecting each probe to a current limiter, would solve this problem.

Data Reduction

Laboratory calibration data for each probe was used to convert the output-voltage readings of the heat-dissipation probes into matric potentials. Linear interpolation between measured calibration points was used between 0 and -5 bars (-0.5 MPa). Data from the 1-bar (0.1-MPa) plates were used for the -1-bar readings; the -1-bar readings taken with 5-bar plates were discarded. To convert output voltages that correspond to matric potentials less than -5 bars, linear extrapolation using the last linear spline is used because of the discontinuity in the calibration data at -5

Table 2.--Results of air-permeability calculations from barometric fluctuations

Depth		Hydraulic conductivity (equivalent)		Air-filled matrix porosity (assumed)	Air-filled fracture porosity
ft	m	ft/d	m/d		
Test borehole USW UZ-1					
0-42	0-12.8	20	6	0.2	0
42-93	12.8-28.3	7	2	.1	.10
93-131	28.3-39.9	20	6	.22	.03
131-201	39.9-61.3	8	3	.23	.02
201-266	61.3-81.1	.6	.2	.25	0
266-340	81.1-103.6	2	.7	.13	.02
Test borehole UE-25a#4					
0-124	0-37.8	50	15	0.15	Not considered
124-150	37.8-45.7	.06	.02	.04	Do.
150-313	45.7-95.4	.1	.04	.29	Do.
313-351	95.4-10.0	30	10	.02	Do.
251-399	107.0-121.6	2	.6	.04	Do.

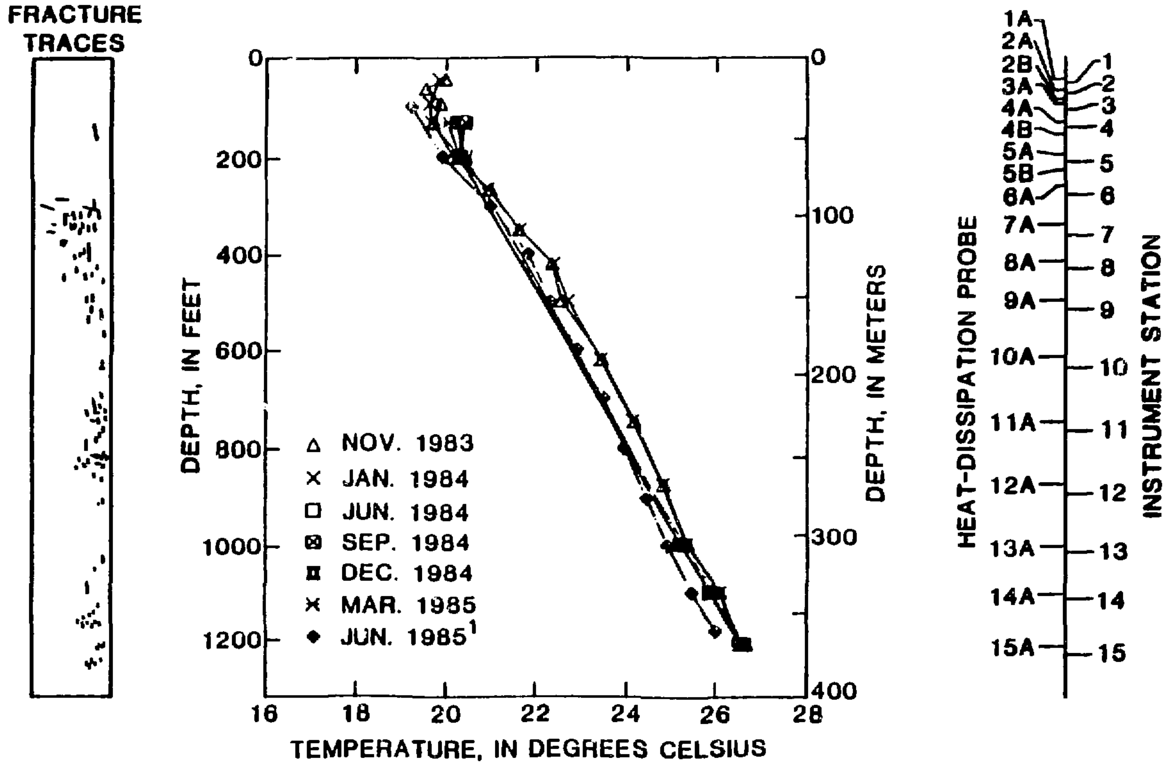

Figure 12.--Temperature profiles and distribution of fracture traces at test borehole USW UZ-1. Data for June 1985 from John Sass (U.S. Geological Survey, written commun., 1985).

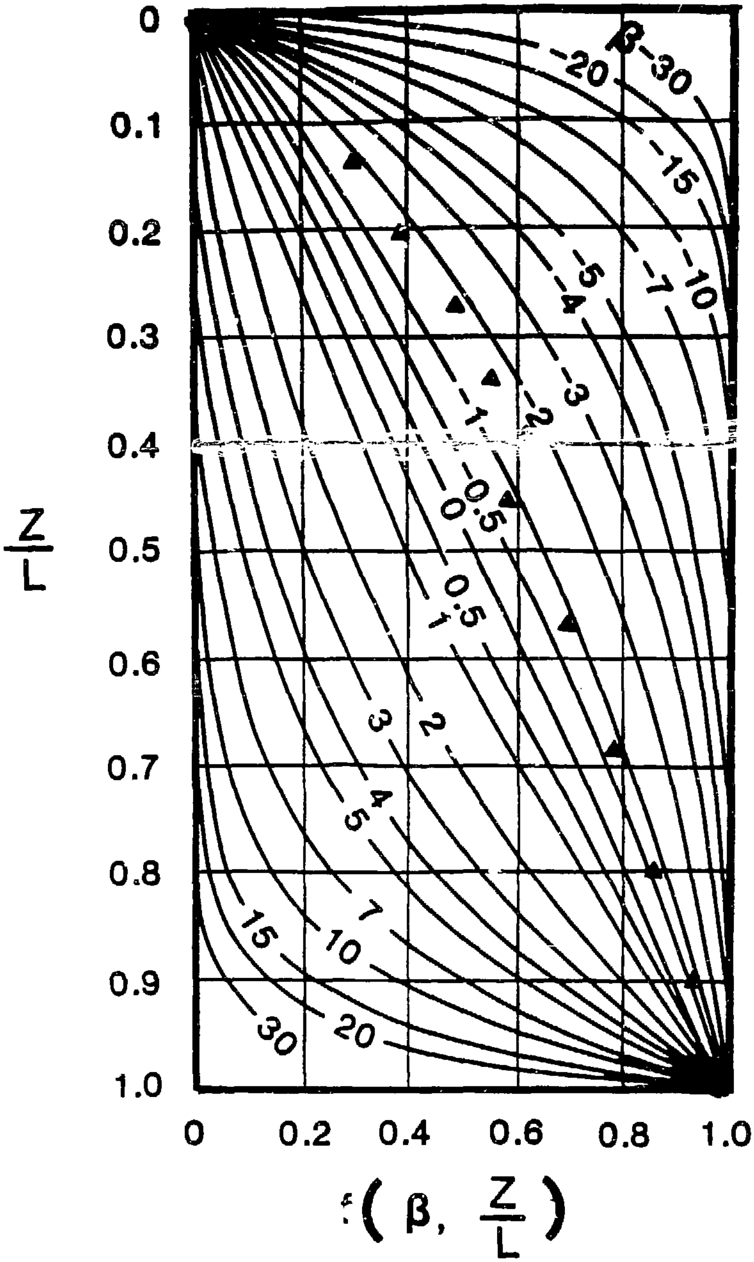

Figure 13.--Type curves of function f(β.z/L) (after Bredehoeft and Papadopulos, 1965) and data from test borehole USW UZ-1 (solid triangles): z is depth; L is thickness of the section considered (1,076 ft, or 328 m, in this case); $\beta = C_o \rho_o v_z L/k$; C_c = specific heat of fluid (0.83 cal/g K for vapor-saturated air); ρ_o is vapor-saturated air density; v_z is air flux; and k is thermal conductivity of the medium (0.0011 cal/cm-s).

of the air, where small temperature and pressure gradients exist. Sorey (1971), using data from Kunii and Smith (1961), demonstrated that this equation can approximate convection of helium. The solution to the equation is provided by Bredehoeft and Papadopulos (1965) in the form of type curves. The type curve closely matching the data from the present study is shown in figure 13, with the parameters used for calculation of the vapor-saturated air flux. The air flux calculated ranges from 49 to 98 in./yr (1,250 to 2,500 mm/yr) upward, depending on the type curve used; β is between 1 and 2. The quantity of water in the form of vapor can be calculated by multiplying these fluxes by the moisture content of the air at saturation, which is approximately 1.24×10^{-3} lb/ft^3 (2×10^{-5} g/cm^3) of dry air at 72°F (22°C). Therefore, the quantity of water that can move upward in the unsaturated zone by these air fluxes is from 1×10^{-3} to 2×10^{-3} in./yr (0.025 to 0.05 mm/yr).

Summary and Conclusions

Fifteen depth intervals were selected in a 17.5-in.- (44.5-cm-) diameter test borehole (borehole USW UZ-1), which was drilled in tuff with a reverse-air vacuum-drilling technique, for emplacement of TP, pressure transducers, and piezometers. An additional 18 depth intervals were selected for emplacement of HDP in silica-flour columns. The TP and pressure transducers were housed in well screens and were embedded in coarse sand. After more than 2 years of monitoring, a majority of the instruments were still functioning and producing reasonable results. Heat-dissipation probes that were placed adjacent to nonwelded tuff and alluvium attained equilibrium faster than those that were placed adjacent to welded tuff. Thermocouple psychrometers produced more reliable data for welded tuff than for nonwelded tuff and alluvium. The results indicated that matric potentials ranged from -0.5 to -25 bars (-0.05 to -2.5 megapascals) in nonwelded tuff and alluvium, and ranged from -2 to -10 bars (-0.2 to -1.0 megapascals) in welded tuff. No apparent correlation existed between matric-potential distribution and frequency of fracture traces observed in the borehole in the welded tuff. Therefore, water flow probably occurred mainly in the matrix of the welded tuff. With this assumption, the water flux through the welded tuff was estimated to be between 4×10^{-3} to 2×10^{-2} in./yr (0.1 to 0.5 mm/yr).

Values of air permeability were estimated from measurements of barometric fluctuations in the test borehole that were detectable to a depth of about 300 ft (91 m). Values of equivalent hydraulic conductivity, calculated from these values of air permeability, ranged from 0.6 to 20 ft/d (0.2 to 6.1 m/d) for nonwelded tuff and alluvium. A single value of 2 ft/d (0.6 m/d) was calculated for the air permeability of the welded tuff. The large air permeability of the nonwelded tuff could be attributed to existence of fractures or other depositional pathways in this unit. However, comparison with data from a nearby test borehole shows that this condition was not pervasive within this unit.

Long-term temperature measurements within this borehole indicated that the geothermal gradient was slightly convex upward within the welded unit. Deviation from the straight line correlated with frequency of fracture traces observed in the borehole. Assuming a uniform thermal conductivity, calculated air fluxes range from -49 to -98 in./yr (-1,250 to -2,500 mm/yr). The quantity of water that could be transported upward by this flux in vapor form was estimated to be from -1×10^{-3} to 2×10^{-3} in./yr (-0.025 to -0.05 mm/yr). This air flux probably occurred through the fractures of the welded tuff.

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Biographical Sketch

Parviz Montazer received his Bachelor of Science from Pahlavi University, Shiraz, Iran, in 1972, and his Master of Science and Doctor of Philosophy degree from Colorado School of Mines, Golden, Colorado, in geological engineering in 1978 and 1982, respectively. He has been employed by the Water Resources Division of the U.S. Geological Survey in Denver, Colorado since 1983. His research interests include flow through fractured rocks and hydrology of deep unsaturated zones. He is currently the Project Chief for Unsaturated-Zone Hydrologic Studies of Yucca Mountain, Nevada Test Site. His address is: U.S. Geological Survey, Box 25046, MS 416, Denver Federal Center, Denver, Colorado 80225.

Edwin Weeks received his Bachelor of Science in geological engineering from Colorado School of Mines, Golden, Colorado in 1958. He has worked in various aspects of ground-water research at the Water Resources Division of the U.S. Geological Survey from 1958 to present. Since 1958, he has served as the chief of various projects involving studies of the impacts of irrigation on ground-water systems, development of air-permeability techniques to characterize unsaturated zones, investigation of artificial

recharge methods, studies of anisothermal vapor transport and gaseous diffusion in the unsaturated zone, and measurement of evapotranspiration. He has also taught courses at the U.S. Geological Survey Training Center in various ground-water related subjects. He is currently Chief of the Unsaturated Zone Field Studies in Denver, Colorado. His address is: U.S. Geological Survey, Box 25046, MS 413, Denver Federal Center, Denver, Colorado 80225.

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(Biographical information for P.B. Hofrichter was unavailable at press time.)