HIGH LEVEL RADIOACTIVE WASTE MANAGEMENT

Proceedings of the Fifth Annual International Conference
Las Vegas, Nevada, May 22-26, 1994

VOLUME 4
1994

Sponsored by the
American Society of Civil Engineers
American Nuclear Society

in cooperation with:

American Association of Engineering Societies
American Chemical Society
American Institute of Chemical Engineers
American Medical Association
American Society for Testing and Materials
American Society for Quality Control
American Society of Mechanical Engineers
Center for Nuclear Waste Regulatory Analysis
Edison Electric Institute
Geological Society of America
Health Physics Society
Institute of Nuclear Materials Management
National Conference of State Legislatures
Society of Mining Engineers
U.S. Department of Energy
U.S. Geological Survey
U.S. Nuclear Regulatory Commission
University of Nevada Medical School
American Institute of Mining, Metallurgical and Petroleum Engineers
American Underground-Space Association
Atomic Energy Council Radwaste Administration
Atomic Energy of Canada Ltd.
British Nuclear Fuels Ltd.
Chinese Institute of Civil and Hydraulic Engineering
Commission of the European Communities
Conseil National des Ingenieurs et des Scientifiques de France
Electric Power Research Institute
Her Majesty's Inspectorate of Pollution
Hungarian Nuclear Society
Institution of Civil Engineers
Institution of Engineers-Australia
Institution of Engineers of Ireland
Japan Society of Civil Engineers
Korea Advanced Energy Research Institute
Korean Society of Civil Engineers
Ministerio de Industria y Energia-Uruguay
National Association of Corrosion Engineers
National Association of Regulatory Utility Commissioners
Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle (NAGRA)
National Society of Professional Engineers
Organization for Economic Cooperation and Development (OECD)- Nuclear Energy Agency
Power Reactor and Nuclear Fuel Development Corp.
Romanian Nuclear Energy Association
Swedish Nuclear Fuel and Waste Management Company
Swedish Nuclear Power Inspectorate
Swiss Society of Engineers and Architects
U.S. Council for Energy Awareness
Verein Deutscher Ingenieure

Hosted by
University of Nevada, Las Vegas
Howard R. Hughes College of Engineering

Published by the

American Nuclear Society, Inc.
La Grange Park, Illinois 60525, USA

American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398, USA

RESULTS OF AIR-PERMEABILITY TESTING IN A VERTICAL BOREHOLE AT YUCCA MOUNTAIN, NEVADA

G. D. LeCain
U. S. Geological Survey
P.O. Box 25046, MS 421
Denver, CO 80225
(303) 236-5020

J. N. Walker
U. S. Geological Survey
P. O. Box 327, MS 721
Mercury, NV 89023
(702) 295-5345

ABSTRACT

Air-injection testing to determine air permeabilities was conducted in borehole UE-25 UZ#16 as part of the Yucca Mountain Surface-Based Borehole Investigations Project. Air permeabilities of the rocks tested are: 1) Tiva Canyon Member; 2.0 E-13 m^2 to 88.0 E-13 m^2, 2) Topopah Spring Member; 1.1 E-13 m^2 to 12.0 E-13 m^2, and 3) tuffaceous beds of Calico Hills; 0.8 E-13 m^2 to 1.1 E-13 m^2. Based on the moisture observed on the downhole equipment, the borehole wall is dry down to 268.3 meters below surface level and wet below this depth. Testing above 268.3 meters showed no wellbore storage or skin effects. Tests conducted below 268.3 meters showed both wellbore storage and skin effects. Tests that forced water out of the rock exhibited a characteristic pressure drop in the arithmetic pressure plots. The stabilization pressure of the steady-state testing following this pressure drop provides an estimate of the test interval *in-situ* capillary pressure. Permeabilities calculated from the steady-state period following the pressure drop were less than those calculated from the transient tests, because the steady-state analysis did not account for skin effects.

I. INTRODUCTION

The purpose of conducting pneumatic tests (air injection) in the surface-based vertical boreholes at or near Yucca Mountain is to quantify the *in-situ* air permeability of the unsaturated fractured and unfractured volcanic rocks (tuff). It is the permeabilities of these tuffs, combined with the pneumatic and hydraulic gradients, that control the movement of all fluids in Yucca Mountain. This includes the potential transmission of water from the surface downward to the repository horizon, and the movement of gas, including water vapor, from the repository horizon to the surface. Variations in the tuff permeability can result in perched water zones, fast-pathways, and capillary barriers. These variations occur between stratigraphic units and within individual stratigraphic units. An understanding of the spatial and directional variability of permeability is necessary for the formulation of conceptual models and is required input to flow and transport models that attempt to represent the flow system at Yucca Mountain.

Because the air permeability of a rock changes with water content, it is important to recognize that a given permeability also has an associated capillary pressure. Capillary pressure is the pressure difference across the interface between the gas and liquid phases. Capillary pressure increases when this interface is confined to smaller pores or fractures, and decreases as this interface moves to larger pores or fractures. The larger pores and fractures are potentially the most conductive features and are dry at all but the wettest conditions (lowest capillary pressures). Using the capillary equation:[1]

$$P = \frac{2\gamma}{r} \tag{1}$$

where:

P = *pressure* $\left(\frac{N}{m^2}\right)$,

γ = *surface tension of water* $\left(\frac{N}{m}\right)$, *and*

r = *radius of tube* (m),

it is possible to approximate the size of the pores and fractures that will be dry at a given capillary pressure. At a capillary pressure of 101.3 kiloPascals (kPa) pores and fractures with a diameter or aperture larger than 3.0 microns will be dry. The air-permeability testing program is primarily interested in testing on pores and fractures with diameters and apertures larger than 3.0 microns; therefore, successful air-permeability testing can be conducted when the capillary pressure is greater than 101.3 kPa because the fractures and pores of major interest will be air filled. In the cases where the capillary pressure is between 0 and 101.3 kPa, and therefore the larger fractures and pores of interest are water filled, the air-permeability testing equipment is designed to allow downhole testing at gas-injection gage pressures up to and greater than 101.3 kPa. Testing at gas-injection gage pressures greater than 101.3 kPa will force water out of the larger pores and fractures, and provide an estimate of air permeability at a capillary pressure of at least 101.3 kPa. In addition, multiple tests, at incremental increasing flow rates, conducted on the same interval, will provide the relation of permeability to capillary pressure for capillary pressures from 0 to 101.3 kPa.

II. FIELD TESTING METHODS

The surface-based air permeability testing activity at Yucca Mountain consists of pneumatic testing (air injection) in the unsaturated zone in 0.31 meter diameter boreholes up to 823 meters in depth. The equipment consists of state-of-the-art hydraulic, pneumatic and electrical systems that allow the installation of pneumatic packers to isolate selected test intervals in the boreholes. Pneumatic testing is then performed on the isolated test interval (Figure 1). The packer system consists of four pneumatic packers each approximately 2.5 meters in length, weighing 90 kilograms, and capable of inflating in boreholes ranging from 0.2 meters to 0.36 meters in diameter. The four packers are assembled end to end, and connected by aluminum pipe, forming a packer assembly with three intervals between the four packers. Each interval contains: 1) one pressure transducer for measuring absolute pressure, 2) one thermistor for measuring temperature, and 3) one thermocouple psychrometer for measuring relative humidity. The two end-intervals are called guard intervals and are a fixed distance of 1.0 meters between packers. The middle interval is the test interval; the length of the test interval can be extended from 2.0 meters up to 28.0 meters by inserting additional aluminum pipe sections between the packers. The packer system is connected to the surface with a tubing bundle that contains: 1) electrical cable for powering and monitoring the instruments, 2) nylon tubing for inflation of the packers and injection of the test gas, and 3) a steel cable to support the weight of the packers and tubing bundle. The packer assembly is lowered and raised in the borehole with a surface-mounted hydraulic winch. The instruments are powered, monitored, and

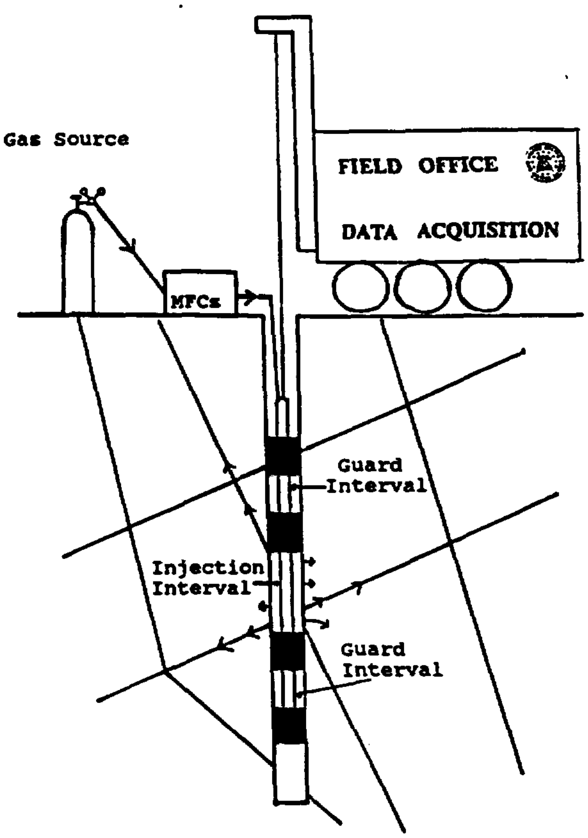

Figure 1. Schematic of pneumatic (air-injection) testing.

data recorded by data loggers at the surface. When a test interval is located, the packer assembly is lowered to the selected interval and all four packers are inflated. At a constant flow rate of 1.0 to 1500.0 standard liters per minute (slpm) air is injected downhole into the middle test interval causing a pressure, temperature and relative humidity response. The data from the pressure transducer, thermistor, and thermocouple psychrometer are then converted into engineering units of pressure, temperature, and relative humidity. The pressure response is used to calculate the permeability of the test interval while the temperature and relative humidity data are required to evaluate assumptions of isothermal conditions and a constant water potential. The purpose of the guard intervals is to monitor for leakage around the packers isolating the test interval. If there is no leakage the data output from the instruments in the guard intervals will remain constant.

III. TEST ANALYSIS METHODS

The methods and models used to analyze pneumatic tests are similar to those used in aquifer, petroleum, and natural gas well analysis. The difference is that most methods were designed for use with incompressible fluids while the pneumatic tests must account for the compressibility of the gas. Modification of these methods to work with compressible fluids is possible by use of the pressure squared differences.[2] In addition to the standard assumptions for analyzing tests using incompressible fluids the following assumptions must be included: 1) the ideal gas law applies, 2) the system is isothermal, and 3) gravitational effects can be excluded.

Semilog and type-curve analysis were used to evaluate the transient tests from the Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff. The semilog method uses a modified version of the Cooper and Jacob [3] straight-line radial-flow solution for homogeneous isotropic systems. The solution states that when the radius is small or time is large, or both, the permeability can be calculated from,

$$k=\frac{.366P_{stp}Tq_{stp}\mu}{mT_{stp}l} \tag{2}$$

where: m is the pressure-squared difference for one log *cycle of the pressure transient, straight-line flow-period and,*

k = *permeability* (m^2),
P_{stp} = *standard pressure* (1.013 *E5 Pa*)
T = *temperature* (°*K*)
q_{stp} = *flow at standard pressure and temperature* (*slpm*)
μ = *gas viscosity* (*Pa*(*s*)),
T_{stp} = *standard temperature* (273.17 °*K*), *and*
l = *length of test interval* (*m*)

The transient test data from the Tiva Canyon and Topopah Spring Members best fit a type curve for a well with partial penetration and vertical leakage. Hantush [4,5] developed a solution for radial flow that included components for leakage, and partial penetration. Using the Hantush type curve, with a leakage component of 5.0, the permeability is calculated from,

$$k=\frac{\Delta P_D Tq_{stp}P_{stp}\mu}{(P_2^2-P_1^2)lT_{stp}\pi} \tag{3}$$

where:

ΔP_D = *dimensionless pressure, and*
$\left(P_2^2 - P_1^2\right)$ = *pressure squared difference* (Pa^2).

Steady-state analysis was used to evaluate the data from the long-term (overnight) injection tests conducted in the tuffaceous beds of Calico Hills. The analysis uses a modified version of the Hvorslev [6] solution for steady-state elliptical flow. Testing assumes that the pressure in the injection interval is at steady state. The permeability can then be calculated from,

$$k=\frac{P_{stp}Q_{stp}\mu\ln\left(\frac{l}{2r}\right)T}{\pi l(P_2^2-P_1^2)T_{stp}}. \tag{4}$$

The transient tests conducted in the tuffaceous beds of Calico Hills best matched a type curve that assumes radial flow and accounts for wellbore storage and skin effects. [7] For analysis of the transient tests in the tuffaceous beds of Calico Hills, the wellbore storage was set at 100.0 and the skin effect at 5.0; the permeability was calculated using equation 3.

IV. RESULTS

At the present time, testing and permeability analysis has been completed on: 1) four intervals of the Tiva Canyon Member, 2) three intervals of the Topopah Spring Member, and 3) one interval of the tuffaceous beds of Calico Hills. Examination of the moisture on the downhole tubing bundle showed that the borehole wall changes from dry to wet at 268.3 meters below surface level. Based on the rock dust coating the packer assembly and tubing bundle, it appears that the borehole wall is coated with fine drill cuttings.

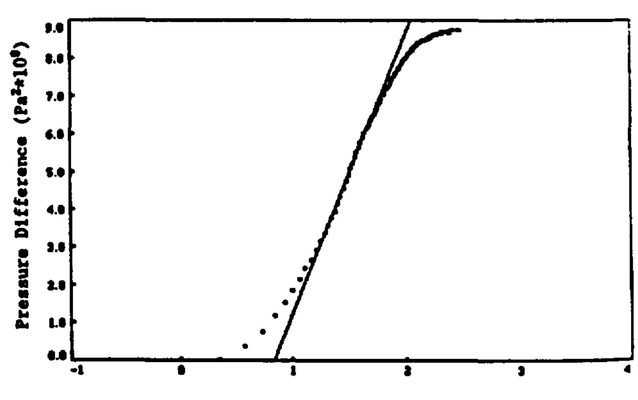

Figure 2. Semilog plot of the pressure-squared differences during a pneumatic test in the Topopah Spring Member, depth interval 78.0-82.0 meters.

The Tiva Canyon Member and Topopah Spring Member test-interval permeabilities are presented in Table 1. Figures 2 and 3 show representative examples

Table 1. Permeabilities for the Tiva Canyon and Topopah Spring Members (all units of permeability are 10E-13 meters squared).

Member	Depth (meters)	Unit	Injection Rate (slpm)	Semilog Analysis (10E-13 m²)	Type-Curve Analysis (10E-13 m²)
Tiva Canyon					
	18.3-22.3	lithophysal-hackly transition	250	21.0	18.0
			500	13.6	9.5
			750	11.0	7.4
	21.3-25.3	lithophysal-hackly transition	250	5.8	4.8
			500	3.7	2.6
			750	2.8	2.0
	25.9-37.2	hackly	500	77.0	62.3
			750	66.0	50.7
			1000	57.0	35.0
	36.3-40.2	hackly	250	88.0	64.0
			500	49.0	36.0
			750	42.4	26.0
Topopah Spring					
	78.0-82.0	upper nonlithophysal	500	12.0	8.3
			250	11.7	9.4
			500	6.6	4.4
	82.6-86.6	upper nonlithophysal	250	2.4	2.2
			500	2.0	1.5
			750	1.7	1.1
	88.1-92.1	upper nonlithophysal	250	1.9	1.2
			500	1.8	1.4

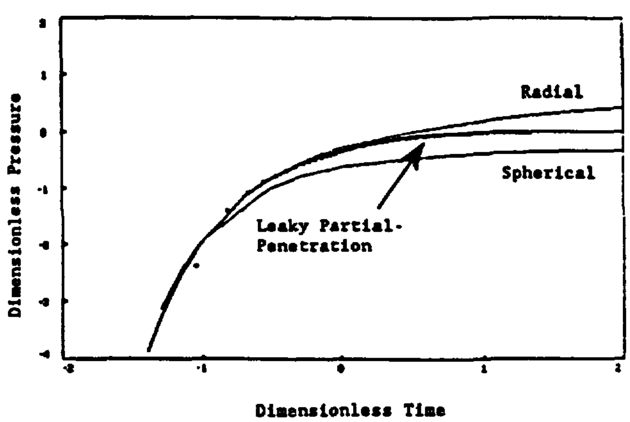

Figure 3. Log-log plot of the pressure-squared differences during a pneumatic test in the Topopah Spring Member, depth interval 78.0-87.0 meters.

of the semilog and log-log plots of the pressure-squared ifferences versus time. Figure 3 shows the data from an injection test in the Topopah Spring Member matched with a Hantush [4] type curve for leaky partial-penetration. Also shown in Figure 3 are the idealized line-source radial-flow type curve [6] and the idealized point-source spherical-flow type curve. [2] Because the test interval is long compared to the borehole radius, the early test-period flow is radial. Because the test interval is short compared to the formation thickness, the latter flow takes on a vertical component, drops below the radial-flow type curve, and begins to resemble a spherical-flow model. Figure 2 shows the semilog plot of the pressure-squared differences versus time of the same injection test in the Topopah Spring Member. Since the early time data follows the radial-flow model, it is possible to use this early transient data to estimate permeability by the semilog straight line method. The straight-line section of Figure 2 corresponds to the data that plots on the radial-flow type curve in Figure 3.

The Tiva Canyon Member test intervals at 18.3-22.3 meters and 21.3-25.3 meters are located in the transition zone from the lower lithophysal unit to the hackly unit.[9] The unit is densely welded and fractured. Permeabilities agree very well between the type curve and semilog analysis but decrease with increasing flow rate. The maximum pressure during testing of these two intervals was 31.6 kPa. It is not likely that the testing forced water out of the rock; all evidence (core samples and television logs) suggests that the water potential of these intervals are drier (greater) than 31.6 kPa. Another possible explanation is turbulent flow. In a fractured rock, such as the Tiva Canyon Member, the air flow is restricted to the limited surface area where the fractures intersect the borehole wall. This restriction of flow paths means the potential for turbulent flow is greatly increased compared to a matrix flow system of the same permeability. The Tiva Canyon Member test intervals, 25.9 to 37.2 meters and 36.3 to 40.3 meters, are located in the hackly unit. This unit is also densely welded and fractured. Permeabilities agree well between the two test intervals, but again show decreasing permeability with increasing flow rates. The maximum pressure during testing of the hackly unit was 2.5 kPa. Again, it is very unlikely that the injection testing forced water from the rock.

The three test intervals in the Topopah Spring Member are located in the upper nonlithophysal unit. The unit is partially to moderately welded and fractured. The shallowest interval (78.0 to 82.0 meters) has slightly greater permeabilities but the range for all three test intervals and all injection rates is less than one order of magnitude. As was found in the Tiva Canyon Member, there is a decrease in permeability with increasing flow rates.

Table 2. Permeabilities in the tuffaceous beds of Calico Hills, test interval 1297-1310 feet below surface; tests are listed in order of occurrence (all units of permeability are in 10E-13 meters squared).

Test Type	Injection rate (slpm)	Permeability (10E-13 m^2)
Steady-State	20	0.17
Transient	10	1.1
Transient	20	0.8
Steady-State	30	0.19

The permeabilities determined from tests in the tuffaceous beds of Calico Hills are shown in Table 2. All four tests were conducted at one test interval from 395.4 to 399.4 meters. The test interval is a nonwelded, zeolitized tuff with an estimated porosity of 30%. Matrix permeabilities of zeolitized tuffaceous beds of Calico Hills core samples from borehole USW G-1 ranged from 0.1 to 4.7 E-16 meters squared[10]. The test interval is located below the 268.3 meter depth where the borehole wall becomes wet.

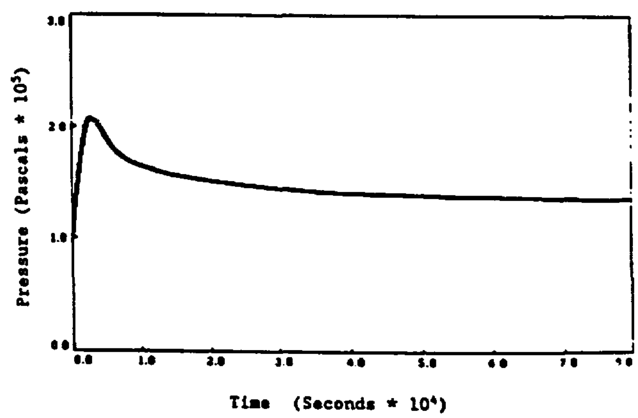

Figure 4. Arithmetic plot of the pressure during a pneumatic test in the tuffaceous beds of Calico Hills, depth interval 395.4-399.4 meters.

Figure 4 shows a plot of the pressure response during the steady-state 20 slpm air-injection test. Plots of the pressures and pressure-squared differences do not resemble tests of the Tiva Canyon and Topopah Spring Members. The peak at 207.0 kPa and subsequent pressure decline reflects the transient drainage of water-filled pores and/or fractures. Initially the pores cannot drain fast enough to conduct the air-flow; however, with time, water is forced from enough pores and/or fractures that the pressure stabilizes at a lower value than the peak of 207.0 kPa. The associated steady-state pressure of 136.0 kPa means that the pre-test capillary pressure of the test interval was less than 136.0 kPa minus the atmospheric pressure (92.7 kPa) or 43.3 kPa. This is very interesting because the test interval for the tuffaceous beds of Calico Hills is located approximately 91.5 meters above the water table. In a system at static equilibrium the capillary pressure at this elevation should be approximately 870.0 kPa, not the 43.3 kPa inferred from the pneumatic testing. This means that there must be a source of moisture somewhere other than the water table.

Following the first steady-state test, two transient tests were conducted at 10 and 20 slpm. The transient tests rates were kept at or below the 20 slpm steady-state test rate in order to keep from forcing any additional water from the rock. The transient tests best match a type curve that accounts for wellbore storage and skin effects (Figure 5). The transient tests show

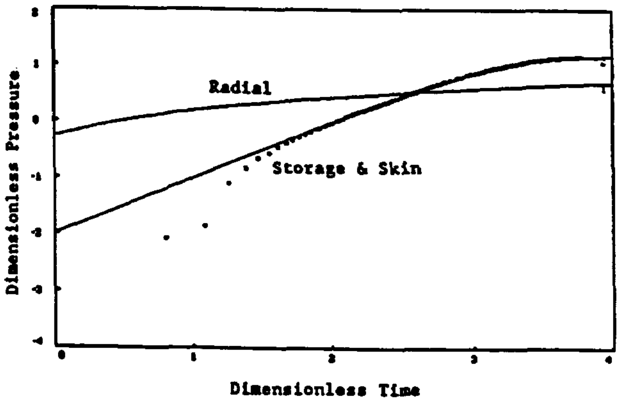

Figure 5. Log-log plot of the pressure-squared differences during a pneumatic test in the tuffaceous beds of Calico Hills, depth interval 395.4-399.4 meters.

higher permeabilities than the steady-state tests. This is probably due to the borehole skin effect. The transient test analysis accounts for the skin effect in the match point values used in equation 3; however, the steady-state analysis does not, and therefore the smaller steady-state permeabilities are due to the influence of a lower permeability skin.

Following the transient tests from the tuffaceous beds of Calico Hills, a second steady-state test was conducted at 30 slpm. The second steady-state test had a similar pressure response as seen in the first steady-state test except that the peak pressure was lower, 181.0 kPa, and the steady-state pressure was higher, 146.0 kPa. The lower peak pressure occurs because the first test had already forced water from most of the pore space that would be utilized by the second, higher flow-rate test. The higher steady-state pressure of the second test is due to the increased flow rate. Theoretically the second steady-state test should show a higher permeability because the increased pressure will force water out of additional pore space. Using an atmospheric pressure of 92.7 kPa, the differential pressures for the 20 and 30 slpm steady-state tests are 43.3 and 53.3 kPa. These capillary pressures correspond to pores and fractures with radii and apertures of approximately 6.6 and 5.4 microns. This means that during the first steady-state test all pores and fractures, with radii and apertures larger than 6.6 microns, were air-filled during testing and that during the second steady-state test, all larger than 5.4 microns were air-filled. The small increase in the permeability between the 20 and 30 slpm steady-state tests is due to this increased air-filled pore space.

V. SUMMARY AND CONCLUSIONS

A. Pneumatic Testing to Define Air Permeabilities

Using downhole packers pneumatic testing was conducted in borehole UE-25 UZ#16 to define air permeabilities. Testing was conducted in the shallow, high capillary pressure, Tiva Canyon and Topopah Spring Members of the Paintbrush Tuff, and in the deeper, tuffaceous beds of Calico Hills, where the capillary pressure was less than 43.3 kPa. Because of fractures, the *in-situ* permeabilities of the tuffaceous beds of Calico Hills are several orders of magnitude larger than the permeabilities of the core samples from this unit in borehole USW G-1. Pneumatic testing showed a decrease in the calculated permeabilities with increasing flow rates. This may be because of turbulent flow. The lower flow rate tests provide good upper estimates of the combined fracture and matrix air permeability.

B. Testing on Near-saturated Rock

Testing conducted on near-saturated rock (small capillary pressure) showed that when water is forced out of the rock a characteristic response can be identified on the pressure plot. An arithmetic plot of pressure versus time will show an initial rapid increase, peak, and decrease to a steady-state flow pressure. The steady-state air-injection pressure minus the atmospheric pressure is the capillary pressure associated with the calculated permeability.

C. Use of Type Curves

Calculation of permeabilities from type curves, originally developed for incompressible fluids, and data plots of the injection tests pressure-squared differences, worked well. Testing on the deeper, wetter, tuffaceous beds of Calico Hills showed wellbore storage and skin effects. Testing on the shallower, drier, Tiva Canyon and Topopah Spring Members did not.

ACKNOWLEDGMENTS

This work was supported by the U. S. Department of Energy, Yucca Mountain Site Characterization Project Office, under contract DE-AI08-92NV10874.

REFERENCES

1. T. J.Marshall and J. W. Holmes, *Soil Physics*, 345 p., Cambridge University Press, New York, New York (1979).

2. Energy Resources Conservation Board, *Theory and Practice of the Testing of Gas Wells*, 3d ed., 1 v., Calgary, Alberta, Canada (1975).

3. H. H. Cooper, Jr. and C. E. Jacob, "A generalized graphical method for evaluating formation constants and summarizing well-field history," *American Geophysical Union Transcripts*, v. 27, No. 4, pp. 526-534 (1946).

4. M. S. Hantush, "Aquifer tests on partially penetrating wells," *American Society of Civil Engineers Transactions*, vol. 127, pp. 284-308 (1962).

5. M. S. Hantush, "Hydraulics of wells," *Adv. Hydrosci.*, 1, pp. 281-432 (1964).

6. M. J. Hvorslev, "Time lag and soil permeability in ground-water observations," *U. S. Army Corps of Engineers*, Waterways Experiment Station, Bulletin No. 36, 47 p., Vicksburg, Mississippi (1951).

7. Ram G. Agarwal, Rafi Al-Hussainy, and H. J. Ramey, "An investigation of wellbore storage and skin effect in unsteady liquid flow," *1. Analytical Treatment*, Society of Petroleum Engineers J. Trans., September, pp. 279-290 (1970).

8. H. J. Ramey, Jr., "Application of the line source solution to flow in porous media-- A Review," *Producers Monthly*, May 1967, pp. 25-27 (1967).

9. R. B. Scott and Jerry Bonk, "Preliminary geologic map of Yucca Mountain, Nye County, Nevada," *United States Geological Survey*, Open-File Report 84-494, 3 sheet, Denver, Colorado (1984).

10. A.L. Flint and L.E. Flint, "Preliminary permeability and water-retention data for nonwelded and bedded tuff samples, Yucca Mountain Area, Nye County, Nevada," *United State Geological Survey*, Open-File Report 90-569, 57 p., Denver, Colorado (1990).