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Abstract

As part of a series of prototype tests conducted in preparation for site characterization of the potential nuclear-waste repository site at Yucca Mountain, Nevada, air-injection tests were conducted in the welded tuffs in G-Tunnel at the Nevada Test Site. The objectives were to characterize the permeability of the highly fractured tuff around a horizontal heater emplacement borehole, and to determine the effect of a heating and cooling cycle on the rock-mass permeability. Air was injected into packed-off intervals along the heater borehole. The bulk permeability of the rock adjacent to the test interval and the aperture of fractures intersecting the interval were computed from the air-flow rate, temperature, and pressure at steady state. The bulk permeability of intervals along the borehole varied from a minimum of 0.08 D to a maximum of over 144 D and the equivalent parallel-plate apertures of fractures intersecting the borehole varied from 70 to 589 μm . Higher permeabilities seemed to correlate spatially with the mapped fractures. The rock was then heated for a period of 6.5 months with an electrical-resistive heater installed in the borehole. After heating, the rock was allowed to cool down to the ambient temperature. The highest borehole wall temperature measured was 242°C. Air injection tests were repeated following the heating and cooling cycle, and the results showed significant increases in bulk permeability ranging from 10 to 1830% along the borehole.

Introduction

The Department of Energy's (DOE) Yucca Mountain Site Characterization Project Office (YMPO) is investigating the suitability of a site at Yucca Mountain, Nevada, for permanent disposal of high-level radioactive waste and spent fuel. The YMPO has assigned Lawrence Livermore National Laboratory (LLNL) the task of designing the waste packages, and of assessing the expected performance of the engineered barrier system in the repository environment. LLNL plans to conduct Engineered Barrier System Field Tests (EBSFT) in an Exploratory Study Facility (ESF) that will be constructed at Yucca Mountain as part of an extensive site characterization effort. The tests will include the use of electrical heaters to simulate the thermal loading expected from emplacement of high-level radioactive waste. Results from the EBSFT will be used, together with laboratory studies and numerical simulations, to assess the behavior of the repository environment with which the waste packages will interact.

Prior to the EBSFT at Yucca Mountain, we conducted the Prototype Engineered Barrier System Field Tests (PEBSFT) in G-Tunnel at the Nevada Test Site (NTS). The objectives of the PEBSFT were to (1) investigate the thermohydrologic, thermomechanical, and geochemical processes in fractured, porous, densely welded tuff; (2) evaluate the effectiveness of various measurement techniques and instrumentation for monitoring the hydrologic and thermomechanical rock responses under realistic conditions; and (3) develop procedures for the investigation to be performed in the EBSFT at Yucca Mountain (Ramirez and Wilder, 1990).

G-Tunnel is located in the Grouse Canyon tuff formation. The PEBSFT were performed within highly fractured, welded tuff with properties believed to be similar to the tuffs of the potential repository horizon in Yucca Mountain (Zimmerman and Finley, 1986). The tests were carried out in a section of the tunnel referred to as the G-Tunnel Underground Facility (GTUF). Figure 1 shows a plan view of the borehole layout. The test area is bounded by the Small Diameter Heater Alcove and the Rock Mechanics Incline. A 30.5-cm (12-in.) horizontal heater emplacement borehole was drilled to a depth of 10.7 m. A 3-m long heater element was placed inside the borehole with its midpoint positioned at 8.5 m from the collar. A heating power level of about 3.2 kW was maintained for 128 days. The power was then ramped down to zero over a 67-day period. The highest borehole wall temperature measured was 242°C. Twelve instrumentation boreholes of 60.3 and 76 mm in diameter were also drilled to monitor the rock temperature, moisture content, and other hydrothermal parameters. All instrumentation boreholes were grouted after drilling. The PEBSFT are described in more detail by Ramirez and Wilder (1990).

As part of the PEBSFT in G-Tunnel, we conducted single-borehole air injection tests to characterize the in-situ permeability of the fractured tuff around the heater emplacement borehole, and to determine the effect of a heating and cooling cycle on the rock mass permeability. We made a number of measurements to determine the bulk permeability along packed-off sections of the borehole prior to heating the rock mass. We repeated these measurements following a heating and cooling cycle, permitting a direct comparison of the preheating and postheating borehole permeability profiles. Air-injection data were correlated with fracture-mapping data to estimate the equivalent parallel-plate apertures of fractures intersecting the borehole.

Field Testing Program

Apparatus

Figure 2 shows the arrangement of the G-Tunnel air permeability testing equipment. The straddle packer assembly, composed of three inflatable packers, was fitted to a 51-mm aluminum pipe. Each packer had a seal length of 43 cm and an uninflated diameter of 27.9 cm. The length of the borehole test zone straddled between two packers was 36 cm. A single 6.35-mm line was used to inflate all three

packers to about 689 kPa with nitrogen supplied from a cylinder. When the packers were inflated, the assembly isolated three zones in the 30.5-cm borehole. Air was injected through separate 25-mm lines leading to the isolated zones. The temperature in each zone was measured with a Type E thermocouple. The air pressure was transmitted through a plastic tube and measured with a pressure gage located outside the borehole. The thermocouple and the plastic tube were fitted to two ports provided at the back end of each packer. The thermocouple extension wires and the plastic tubes were fed through the aluminum pipe.

The compressed air from the G-Tunnel line flowed through an air filter and a pressure regulator before it entered a four-branch manifold. Each branch contained a flow meter capable of measuring a different range of flow rate. The manifold covered flow rates ranging from 0.5 to 6300 slm. The pressure regulator maintained a constant test-zone pressure as the flow rate was adjusted to the steady-state condition. To determine the mass flow rate of a highly compressible fluid such as air, the thermodynamic character of the fluid expansion must be considered. Therefore, the temperature and pressure of air leaving the manifold were measured by an in-line thermocouple and a pressure gage before being transmitted to the isolated zones.

Pressures were read by pressure transmitters with an accuracy of 0.5% of full scale. These transmitters provided mechanical readings as well as electrical signals for automatic recording. Variable area flow meters measured flow rates with an accuracy and repeatability of 2 and 0.5% of full scale, respectively. Calibrations of the pressure gages, flow meters, and thermocouples were performed before and after field testing. Temperatures and pressures measured in the manifold and isolated test zones were recorded by the data acquisition system (DAS).

Testing Procedures

The packer assembly was first placed in the deepest location—about 30 cm from the bottom of the borehole. To secure the packer assembly, the aluminum pipe was attached to rock bolts adjacent to the borehole collar. We then inflated the packers to isolate three zones in the borehole: Zone 1, between the central packer and the packer nearest the borehole collar; Zone 2, between the central packer and the deepest packer; and Zone 3, behind the deepest packer. Zones 1 and 2 each had a fixed length of 36 cm, while the length of Zone 3 varied with the location of the packer assembly.

Compressed air was injected into Zone 2 at three to five different steady-state pressures ranging from about 14 to 207 kPa, followed by similar injections into Zone 3. Zone 1 functioned only as an observation zone. To approximate steady-state conditions, air injection was continued until the observed flow rate and test zone pressure remained constant for at least 10 min. The injection pressure was limited to a maximum value of about 207 kPa to minimize the effects of fracture deformation and turbulence, which could introduce significant errors in the measurements. For borehole intervals that included very large fractures, it was not possible to establish steady-state pressures of more than a few kPa and, therefore, only one or two steady-state pressures were used.

During air injection, the flow rates and test zone pressures were recorded manually. In addition, the DAS recorded temperatures and pressures in the manifold and borehole zones automatically at 1-min intervals. When a test zone was pressurized, the remaining two zones served as observation zones. Pressures and temperatures were monitored in observation zones to warn of any air leakage around or through the packers.

When one packer assembly location was completely tested, the assembly was moved outward about 25 cm and tests on Zones 2 and 3 were repeated. This sequence was repeated until a length of about 4.5 m, measured from the bottom of the borehole, was completely tested.

Data Analysis

The use of fluid injection for bulk permeability tests in fractured rock assumes that the scale of the fractures is small relative to the scale of measurement, so that an equivalent continuum analysis is justified. For gas flow through porous media, under both laminar and turbulent conditions, the appropriate flow equation is Forchheimer's quadratic equation, which in radial coordinates is (Katz et al., 1959)

$$-\frac{dP}{dr} = \frac{\mu q}{k} + \beta \rho q^2 \quad (1)$$

where

P = gas pressure
 r = radial flow distance
 μ = viscosity
 q = darcy velocity
 k = bulk permeability
 β = turbulence factor
 ρ = density.

The relevant continuity and constitutive equations are:

$$Q_m = 2\pi r \rho q L \quad (2)$$

and

$$\rho = \frac{MP}{ZRT} \quad (3)$$

where

Q_m = mass flow rate
 L = length of borehole interval
 M = molecular weight of gas
 Z = gas compressibility factor (approximately 1.0 for the low pressures used here)
 R = universal gas constant
 T = absolute temperature.

For steady-state radial and isothermal flow of a gas injected into a packed-off borehole interval, Eqs. (1), (2), and (3) can be used to derive the following equation from which the bulk permeability is obtained:

$$\frac{\pi LM(P_b^2 - P_e^2)}{\mu RT Q_m \ln(r_e/r_b)} = \frac{\beta Q_m (1/r_b - 1/r_e)}{2\mu \pi L \ln(r_e/r_b)} + \frac{1}{k} \quad (4)$$

where P_b is the borehole injection pressure, r_b the borehole radius, and r_e the effective radius, or radius at which the pressure returns to the ambient value P_e .

Equation (4) may be rewritten in the form of a linear equation:

$$Y = \beta X + \frac{1}{k} \quad (5)$$

This linear relationship can be plotted to obtain the bulk permeability k from the inverse of the intercept and the turbulence factor β from the slope. Therefore, k and β can be determined for a borehole test interval by conducting steady-state injection tests at two or more injection pressures.

One practical difficulty in applying Eq. (4) to single-borehole fluid injection measurements is the need to measure two boundary pressures in the rock. The first boundary pressure is the injection pressure, which is easily measured in the packed-off borehole interval. The second boundary pressure is usually taken as the ambient fluid pressure, which for this test is barometric pressure. Therefore, an effective radius r_e , or radius of influence, must be estimated. Because the test area is bounded on one side by a wall of the Small Diameter Heater Alcove at a distance of 5 m from the heater-borehole axis (Fig. 2), we use 5 m as an estimate for r_e .

To make rough estimates of the apertures of fractures intersecting the heater borehole, we assume that the fractures behave like smooth, parallel plates oriented normal to the borehole axis. For n fractures of equal aperture intersecting a borehole interval of length L , the aperture is

$$e = \left(\frac{12Lk}{n} \right)^{1/3} \quad (6)$$

Results and Discussions

The test data are tabulated in Appendix A: Table A1 lists the preheating data, and Table A2 lists the postheating data.

Preheating Permeability Results

Figure 3 shows bulk permeability values that were calculated from measurements along the length of the heater borehole, from 6.25 m to a total depth (TD) of 10.72 m. Mapped fracture locations are also shown. The bar location and width represent the actual position and width of the test interval. The permeability varies from a minimum of 0.08 D at a depth of 9.23 m to a maximum in excess of 144 D. We were unable to quantify the largest permeabilities, which occurred within intervals centered at depths of 6.73, 7.48, and 7.73 m in highly fractured zones. At these locations, flow rates in excess of 2800 slm were generated by injection pressures of only a few kPa. Therefore, we were unable to make at least two sufficiently distinct pressure measurements to allow application of Eq. (4) for bulk permeability determination. In general, we found that higher permeabilities correlated with mapped fractures.

Figure 4 shows estimates of the equivalent parallel-plate apertures of fractures along the borehole. Aperture estimates varied from a minimum of 70 μm at a depth of 9.23 m to a maximum of about 589 μm at a depth of 6.98 m. As with the bulk permeability results, measurements made in the highly fractured zones could not be used to estimate apertures. Figure 4 shows fracture aperture estimates at some test intervals along the borehole where no fractures are mapped. Since the matrix permeability of the rock is on the order of microdarcys (Lin and Daily, 1984), it appears that the resolution of the television-camera mapping of fractures (Ramirez and Wilder, 1989) accounted only for relatively major features; the mapping omitted smaller fractures that allowed substantial flows in some intervals. For these intervals with no mapped fractures, an equivalent single fracture aperture was computed. One such borehole interval, centered at 9.23 m, yielded the minimum aperture of the profile.

Effect of Heating and Cooling Cycle

The heating and cooling cycle resulted in some significant increases in bulk permeability along the borehole. In Table 1 and Fig. 5, the borehole permeability profile prior to heating is compared with the profile following the heating and cooling cycle. Because the measurement system could not adequately measure the high permeabilities of the test intervals centered at 6.73, 7.48, and 7.73 m, we were unable to make any meaningful comparisons at these three intervals. The computed permeability increases varied from 10% to more than one order of magnitude. Figure 6 shows the percentage increase as a function of depth along the borehole. The maximum increase is 1830% at a depth of 8.98 m. Higher percent increases in permeability seem to occur closer to the midpoint of the heater axis, implying that sections of the rock mass that are heated to higher temperatures show larger percent permeability increases. However, the higher relative increases also occur in the intervals of lower initial permeability, most of which were also located closer to the midpoint of the heater axis.

Table 1. Comparison of preheating and postheating bulk permeability values.

Zone no.	Interval (m)	Interval center (m)	Preheating permeability (D)	Postheating permeability (D)	Permeability increase (%)
2	9.69–10.05	9.87	1.29	1.78	38
2	9.30–9.66	9.48	4.77	6.46	35
2	9.05–9.41	9.23	0.08	0.77	856
2	8.80–9.16	8.98	0.10	1.93	1830
2	8.55–8.91	8.73	1.89	5.57	195
2	8.30–8.66	8.48	0.62	4.82	677
2	8.05–8.41	8.23	0.51	3.75	635
2	7.80–8.16	7.98	1.22	10.10	728
2	7.05–7.41	7.23	2.87	5.68	98
2	6.80–7.16	6.98	144.00	179.00	24
2	6.25–6.61	6.43	110.00	237.00	115
3	10.49–10.73	10.61	1.05	1.24	18
3	10.09–10.73	10.41	1.55	1.71	10

To determine any possible effects of the repeatability of the measurements on comparisons between preheating and postheating results, air-injection measurements were repeated at six borehole locations and deviations in bulk permeability were computed. Deviations ranged from 0.5 to 8.7%. The maximum deviation is quite small relative to the large permeability changes observed following the heating and cooling cycle.

Discussion

The reasons for the observed increases in permeability along the heater borehole are unclear; however, we can suggest a few possible mechanisms. Thermal expansion might have caused some relative movement or shearing across the fracture surfaces. For a fracture of significant roughness, such movement would result in some dilation as surfaces ride up asperities causing an increase in the average fracture aperture. Contraction associated with cooling might have lessened the aperture increase but probably not enough to attain the original fit and return the aperture to its preheating value.

Thermally induced microfracturing is another possible cause for the permeability increase; significant microcracking has been observed in granites heated above 200°C (Wang et al., 1989). Thermally

induced microfracturing could have created new fractures and propagated existing fractures. However, since the bulk permeability of this welded tuff is dominated by larger fractures, it is doubtful that microfracturing could have been the major mechanism responsible for the observed large increases in permeability.

Dehydration of clay minerals might have also contributed to the permeability increase. Although no attempt was made to analyze the filling material from fractures that were logged from the heater and instrument boreholes, we know that smectites are present in small to moderate amounts (1–10%) in virtually all stratigraphic units in Yucca Mountain (Bish, 1985). If a significant amount of clay was present in the fractures tested in G-Tunnel, then clay dehydration could have resulted in an increase in average fracture void volume and, therefore, an increase in bulk permeability of the rock.

Finally, a higher water saturation in the fractures prior to heating, compared with the water saturation following the heat cycle, has the potential to cause an apparent permeability increase. However, when the matrix is partially saturated, the fractures are essentially dry because of the higher capillary suction forces in the matrix pores adjacent to the fractures (Klaveter and Peters, 1986). Therefore, it would seem that essentially all the drilling fluid pumped into the rock (drilling ended about two months before the beginning of permeability measurements) was either drained away through the predominantly vertical fractures or imbibed into the rock matrix.

Conclusions and Recommendations

The bulk permeability measured in intervals along the heater emplacement borehole showed a high degree of heterogeneity, varying from a minimum of 0.08 D to a maximum of more than 144 D. Equivalent parallel-plate hydraulic apertures of fractures intersecting the borehole varied from a minimum of 70 μm to a maximum of about 589 μm . A comparison of borehole permeability profiles showed significant permeability increases ranging from 10 to 1830% as a result of the heating and cooling cycle.

In future tests, an attempt should be made to eliminate uncertainties concerning the possible effects of preheating and postheating fracture saturation differences. This can be accomplished by a third measurement of the borehole permeability profile, after a sufficiently long period is allowed for the rock to return close to the moisture conditions that existed during the preheating measurements. The rewetting process could be accelerated by flooding the borehole and then measuring the rock moisture content with either neutron gage or high frequency electromagnetic (HFEM) methods to determine when the preheating moisture conditions are reattained.

References

- Bish, D. L., and D. P. Vanniman (1985), *Mineralogic Summary of Yucca Mountain, Nevada*, Los Alamos National Laboratory, Los Alamos, NM, LA-10543-MS. NNA.870407.0330
- Katz, D. L., D. Cornell, R. Kobayashi, F. H. Poettmann, J. A. Vary, J. R. Elenbaas, and C. F. Weinaug (1959), *Handbook of Natural Gas Engineering*, (McGraw-Hill, New York). NNA.900626.0212
- Klavetter, E. A., and R. R. Peters (1986), *Estimation of Hydrologic Properties of an Unsaturated, Fractured Rock Mass*, Sandia National Laboratories, Albuquerque, NM, Report No. SAND84-2642. NNA.870317.0738
- Lin, W., and W. Daily (1984), *Transport Properties of Topopah Spring Tuff*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-53602. NNA.891026.0025
- Ramirez, A., and D. Wilder (Eds.) (1989), *Prototype Engineered Barrier System Field Tests (PEBSFT), Progress Report Through November 1, 1988*, Lawrence Livermore National Laboratory, Livermore, CA, UCID-21640. NNA.910207.0024
- Ramirez, A., and D. Wilder (Eds.) (1991), *Prototype Engineered Barrier System Field Tests (PEBSFT), Final Report*, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-ID-106159. (Readily available)
- Wang, H. F., B. P. Bonner, S. R. Carlson, B. J. Kowallis, and H. G. Heard (1989), "Thermal Stress Cracking in Granite," *J. Geophys. Res.* **94**(B2), 1745–1758. NNA.910131.0265
- Zimmerman, R. M., and R. E. Finley (1986), *Summary of Geomechanical Measurements Taken in and Around the G-Tunnel Underground Facility, NTS*, Sandia National Laboratories, Albuquerque, NM, Report No. SAND86-1015. HQS.880517.2366

Figure 1. Plan view of the borehole layout. The location of the Rock Mechanics Incline and the Small Diameter Heater Alcove in G-Tunnel are shown for reference (Ramirez and Wilder, Eds., 1990).

Figure 2. Schematic of gas permeability measurement apparatus.

Figure 3. Preheating bulk permeability and mapped fracture locations between depths of 6.25 and 10.72 m along heater borehole. Bar width equals length of test interval.

Figure 4. Preheating fracture apertures and mapped fracture locations between depths of 6.25 and 10.72 m along heater borehole. Bar width equals length of test interval.

Figure 5. Comparison of preheating and postheating bulk permeability values along heater borehole. Locations of heater and mapped fractures are indicated. Bar width equals length of test interval.

Figure 6. Percent bulk permeability increases following heat cycle. Locations of heater and mapped fractures are indicated.

Table A1. Preheating permeability data.

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
A11	2	9.70–10.06	2	23.2	17.6	0.101×10^{-2}		
A11	2	9.70–10.06	2	93.7	17.6	0.366×10^{-2}		
A11	2	9.70–10.06	2	169.3	17.6	0.661×10^{-2}	140.1	0.129×10
A11	3	10.49–10.73	1	25.0	17.2	0.928×10^{-3}		
A11	3	10.49–10.73	1	95.4	17.1	0.342×10^{-2}		
A11	3	10.49–10.73	1	168.6	17.0	0.621×10^{-2}	164.7	0.105×10
A12	2	9.30–9.66	2	27.9	17.5	0.346×10^{-2}		
A12	2	9.30–9.66	2	99.4	17.4	0.966×10^{-2}		
A12	2	9.30–9.66	2	171.9	17.1	0.158×10^{-1}	216.7	0.477×10
A12	3	10.09–10.73	1	30.0	17.0	0.165×10^{-2}		
A12	3	10.09–10.73	1	100.2	16.8	0.511×10^{-2}		
A12	3	10.09–10.73	1	166.9	16.7	0.887×10^{-2}	187.6	0.155×10
A13	2	9.05–9.41	1	29.4	17.3	0.914×10^{-4}		
A13	2	9.05–9.41	1	92.8	17.3	0.283×10^{-3}		
A13	2	9.05–9.41	1	169.1	17.4	0.569×10^{-3}	70.1	0.809×10^{-1}
A13	3	9.84–10.73	3	32.8	16.7	0.238×10^{-2}		
A13	3	9.84–10.73	3	98.3	16.9	0.684×10^{-2}		
A13	3	9.84–10.73	3	165.5	16.8	0.116×10^{-1}	144.2	0.211×10
A14	2	8.80–9.16	1	36.2	17.5	0.144×10^{-3}		
A14	2	8.80–9.16	1	106.6	17.6	0.449×10^{-3}		
A14	2	8.80–9.16	1	172.1	17.6	0.772×10^{-3}	76.2	0.104
A14	3	9.59–10.73	5	24.3	16.9	0.237×10^{-2}		
A14	3	9.59–10.73	5	104.7	16.7	0.882×10^{-2}		
A14	3	9.59–10.73	5	164.9	16.5	0.142×10^{-1}	135.2	0.290×10

Table A1. (cont'd)

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
A15	2	8.55–8.91	1	30.8	17.4	0.177×10^{-2}		
A15	2	8.55–8.91	1	100.7	17.4	0.491×10^{-2}		
A15	2	8.55–8.91	1	168.2	17.4	0.809×10^{-2}	200.5	0.189×10
A15	3	9.34–10.73	5	28.4	16.5	0.601×10^{-2}		
A15	3	9.34–10.73	5	96.5	16.3	0.168×10^{-1}		
A15	3	9.34–10.73	5	166.8	16.2	0.294×10^{-1}	178.2	0.663×10
A16	2	8.30–8.66	1	35.2	17.3	0.871×10^{-3}		
A16	2	8.30–8.66	1	100.6	17.4	0.254×10^{-2}		
A16	2	8.30–8.66	1	173.0	17.4	0.493×10^{-2}	138.3	0.621
A16	3	9.09–10.73	5	21.3	16.5	0.492×10^{-2}		
A16	3	9.09–10.73	5	88.0	16.3	0.154×10^{-1}		
A16	3	9.09–10.73	5	156.1	16.2	0.277×10^{-1}	183.1	0.720×10
A17	2	8.05–8.41	1	29.4	17.3	0.438×10^{-3}		
A17	2	8.05–8.41	1	105.8	17.3	0.133×10^{-2}		
A17	2	8.05–8.41	1	180.0	17.4	0.217×10^{-2}	129.6	0.510
A17	3	8.84–10.73	6	27.6	16.4	0.583×10^{-2}		
A17	3	8.84–10.73	6	95.4	16.3	0.170×10^{-1}		
A17	3	8.84–10.73	6	156.7	16.2	0.278×10^{-1}	168.5	0.674×10
A18	2	7.80–8.16	1	25.0	17.5	0.908×10^{-3}		
A18	2	7.80–8.16	1	98.9	17.5	0.288×10^{-2}		
A18	2	7.80–8.16	1	167.3	17.5	0.477×10^{-2}	173.2	0.122×10
A18	3	8.59–10.73	6	23.6	16.9	0.645×10^{-2}		
A18	3	8.59–10.73	6	72.8	16.6	0.165×10^{-1}		
A18	3	8.59–10.73	6	150.2	16.5	0.337×10^{-1}	181.2	0.837×10

Table A1. (cont'd)

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
A19	3	8.34-10.73	6	25.0	16.6	0.675×10^{-2}		
A19	3	8.34-10.73	6	106.8	16.4	0.249×10^{-1}		
A19	3	8.34-10.73	6	182.5	16.4	0.416×10^{-1}	182.2	0.851×10
A20	3	8.09-10.73	6	190.6	16.5	0.435×10^{-1}		
A20	3	8.09-10.73	6	32.0	16.2	0.914×10^{-2}		
A20	3	8.09-10.73	6	68.2	16.0	0.171×10^{-1}	191.0	0.981×10
A21	2	7.05-7.41	3	32.3	17.1	0.272×10^{-2}		
A21	2	7.05-7.41	3	99.0	17.1	0.725×10^{-2}		
A21	2	7.05-7.41	3	166.1	17.1	0.117×10^{-1}	159.8	0.287×10
A21	3	7.84-10.73	7	27.0	16.2	0.849×10^{-2}		
A21	3	7.84-10.73	7	97.2	16.1	0.262×10^{-1}		
A21	3	7.84-10.73	7	170.6	16.1	0.420×10^{-1}	191.8	0.116×10^2
A22	2	6.80-7.16	3	23.5	16.7	0.347×10^{-1}		
A22	2	6.80-7.16	3	68.1	16.0	0.706×10^{-1}	589.4	0.144×10^3
A24	2	6.25-6.61	3	14.9	16.4	0.272×10^{-1}		
A24	2	6.25-6.61	3	36.1	16.1	0.491×10^{-1}		
A24	2	6.25-6.61	3	62.9	15.6	0.744×10^{-1}		
A24	2	6.25-6.61	3	98.4	15.2	0.102	538.6	0.110×10^3

Table A2. Postheating permeability data.

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
B4	2	9.70–10.06	2	22.3	26.7	0.128×10^{-2}		
B4	2	9.70–10.06	2	94.8	25.0	0.501×10^{-2}		
B4	2	9.70–10.06	2	170.0	24.4	0.899×10^{-2}	156.1	0.178×10
B4	3	10.49–10.73	1	29.6	25.3	0.125×10^{-2}		
B4	3	10.49–10.73	1	100.7	25.0	0.420×10^{-2}		
B4	3	10.49–10.73	1	168.5	24.5	0.729×10^{-2}	174.1	0.124×10
B5	2	9.30–9.66	2	27.3	25.4	0.423×10^{-2}		
B5	2	9.30–9.66	2	99.5	24.1	0.121×10^{-1}		
B5	2	9.30–9.66	2	169.2	23.0	0.193×10^{-1}	239.7	0.646×10
B5	3	10.09–10.73	1	29.4	24.8	0.170×10^{-2}		
B5	3	10.09–10.73	1	94.7	24.5	0.522×10^{-2}		
B5	3	10.09–10.73	1	164.4	24.1	0.933×10^{-2}	194.1	0.171×10
B6	2	9.05–9.41	1	29.6	26.5	0.754×10^{-3}		
B6	2	9.05–9.41	1	93.8	26.3	0.213×10^{-2}		
B6	2	9.05–9.41	1	171.1	25.7	0.406×10^{-2}	148.3	0.765×10
B6	3	9.84–10.73	3	33.4	25.4	0.260×10^{-2}		
B6	3	9.84–10.73	3	104.2	24.7	0.816×10^{-2}		
B6	3	9.84–10.73	3	167.7	24.2	0.134×10^{-1}	148.0	0.228×10
B7	2	8.80–9.16	1	32.7	23.2	0.200×10^{-2}		
B7	2	8.80–9.16	1	105.6	23.0	0.628×10^{-2}		
B7	2	8.80–9.16	1	169.8	22.6	0.984×10^{-2}	202.0	0.193×10
B7	3	9.59–10.73	5	24.3	24.1	0.244×10^{-2}		
B7	3	9.59–10.73	5	106.3	23.6	0.105×10^{-1}		
B7	3	9.59–10.73	5	170.9	23.1	0.170×10^{-1}	136.9	0.301×10

Table A2. (cont'd)

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
B8	2	8.55–8.91	1	29.2	25.5	0.457×10^{-2}		
B8	2	8.55–8.91	1	95.1	24.2	0.131×10^{-1}		
B8	2	8.55–8.91	1	161.8	22.7	0.212×10^{-1}	287.5	0.557×10
B8	3	9.34–10.73	5	30.3	24.6	0.652×10^{-2}		
B8	3	9.34–10.73	5	94.1	23.5	0.170×10^{-1}		
B8	3	9.34–10.73	5	170.9	22.6	0.330×10^{-1}	175.3	0.632×10
B9	2	8.30–8.66	1	32.1	24.7	0.433×10^{-2}		
B9	2	8.30–8.66	1	97.4	23.8	0.114×10^{-1}		
B9	2	8.30–8.66	1	173.7	22.8	0.195×10^{-1}	274.0	0.482×10
B9	3	9.09–10.73	5	23.7	24.5	0.557×10^{-2}		
B9	3	9.09–10.73	5	95.4	23.6	0.207×10^{-1}		
B9	3	9.09–10.73	5	161.8	22.6	0.345×10^{-1}	185.1	0.744×10
B10	2	8.05–8.41	1	25.3	24.1	0.286×10^{-2}		
B10	2	8.05–8.41	1	101.5	23.3	0.100×10^{-1}		
B10	2	8.05–8.41	1	179.1	22.8	0.172×10^{-1}	252.0	0.375×10
B10	3	8.84–10.73	6	25.1	24.2	0.657×10^{-2}		
B10	3	8.84–10.73	6	101.9	23.8	0.248×10^{-1}		
B10	3	8.84–10.73	6	162.2	22.8	0.380×10^{-1}	182.6	0.856×10
B12	2	7.80–8.16	1	26.1	24.3	0.593×10^{-2}		
B12	2	7.80–8.16	1	97.6	23.1	0.160×10^{-1}		
B12	2	7.80–8.16	1	168.4	22.2	0.262×10^{-1}	350.7	0.101×10^2
B12	3	8.59–10.73	6	27.4	24.0	0.104×10^{-1}		
B12	3	8.59–10.73	6	74.5	23.2	0.240×10^{-1}		
B12	3	8.59–10.73	6	154.9	22.1	0.461×10^{-1}	216.8	0.143×10^2

Table A2. (cont'd)

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
B14	3	8.34–10.73	6	26.3	23.9	0.946×10^{-2}		
B14	3	8.34–10.73	6	110.9	22.4	0.376×10^{-1}		
B14	3	8.34–10.73	6	178.8	21.0	0.558×10^{-1}	206.9	0.125×10^2
B15	3	8.09–10.73	6	62.9	22.3	0.222×10^{-1}		
B15	3	8.09–10.73	6	192.3	20.7	0.638×10^{-1}		
B15	3	8.09–10.73	6	31.9	22.1	0.127×10^{-1}	209.9	0.130×10^2
B16	2	7.05–7.41	3	28.6	22.5	0.452×10^{-2}		
B16	2	7.05–7.41	3	101.6	22.0	0.130×10^{-1}		
B16	2	7.05–7.41	3	166.9	20.8	0.209×10^{-1}	200.6	0.568×10
B16	3	7.84–10.73	7	26.9	22.9	0.111×10^{-1}		
B16	3	7.84–10.73	7	100.3	21.7	0.368×10^{-1}		
B16	3	7.84–10.73	7	174.8	20.9	0.598×10^{-1}	207.8	0.147×10^2
B17	2	6.80–7.16	3	21.7	19.9	0.431×10^{-1}		
B17	2	6.80–7.16	3	59.5	18.1	0.847×10^{-1}	634.1	0.179×10^3
B19	2	6.25–6.61	3	32.6	20.9	0.433×10^{-1}		
B19	2	6.25–6.61	3	60.5	19.3	0.645×10^{-1}		
B19	2	6.25–6.61	3	81.0	18.4	0.792×10^{-1}		
B19	2	6.25–6.61	3	12.7	19.7	0.244×10^{-1}	695.6	0.237×10^3
B20	2	9.70–10.06	2	22.1	21.9	0.127×10^{-2}		
B20	2	9.70–10.06	2	96.4	22.0	0.493×10^{-2}		
B20	2	9.70–10.06	2	170.2	21.8	0.878×10^{-2}	154.7	0.174×10
B20	3	10.49–10.73	1	30.0	23.1	0.143×10^{-2}		
B20	3	10.49–10.73	1	101.0	23.1	0.466×10^{-2}		
B20	3	10.49–10.73	1	165.2	23.0	0.786×10^{-2}	180.9	0.139×10

Table A2. (cont'd)

Test no.	Test zone no.	Test interval (m)	No. of fractures	Zone pressure (kPa)	Zone temperature (°C)	Mass flow rate (kg/s)	Fracture aperture (μm)	Bulk permeability (D)
B21	2	8.30-8.66	1	31.9	23.0	0.447×10^{-2}		
B21	2	8.30-8.66	1	96.1	22.2	0.118×10^{-1}		
B21	2	8.30-8.66	1	172.7	21.5	0.206×10^{-1}	272.6	0.475×10
B21	3	9.09-10.73	5	23.7	23.2	0.635×10^{-2}		
B21	3	9.09-10.73	5	92.5	22.5	0.196×10^{-1}		
B21	3	9.09-10.73	5	160.6	21.7	0.336×10^{-1}	198.4	0.916×10
B22	2	8.80-9.16	1	34.5	22.7	0.223×10^{-2}		
B22	2	8.80-9.16	1	101.2	22.4	0.619×10^{-2}		
B22	2	8.80-9.16	1	171.2	22.1	0.103×10^{-1}	205.7	0.204×10
B22	3	9.59-10.73	5	27.2	23.5	0.260×10^{-2}		
B22	3	9.59-10.73	5	110.2	23.0	0.106×10^{-1}		
B22	3	9.59-10.73	5	172.6	22.5	0.171×10^{-1}	133.3	0.278×10

Appendix A

This report does not use any information from the Reference Information Base nor contain any candidate information for the Reference Information Base or the Site and Engineering Properties Data Base (SEPDB).

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