Performance Assessment of Bentonite as a Borehole Seal When Tested In Situ in a Medium-Grained Granite

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ABSTRACT

Commercial bentonite was tested in situ as a borehole seal using two 15.25 cm-long plugs emplaced in a 16.50 cm-diameter borehole. The borehole was located in a medium-grained granite in the Santa Catalina Mountains, near Tucson, Arizona. The hydraulic conductivity of the host rock was determined with pressure slug and constant pressure injection tests using straddle-packer assemblies to isolate the test interval. The hydraulic conductivity of the bentonite seals and seal-rock interfaces was estimated from observed pressure decays and volumes of water injected into the sealed test interval. The seals were emplaced in a two-plug configuration that provided for the collection of injection mass balance.

INTRODUCTION

The United States Department of Energy (DOE), the agency responsible for developing licensed, high-level nuclear waste respositories, has stated that "penetrations into the host-rock system shall be sealed as necessary to exclude water, retard radionuclide migration and prevent communication between aquifers to the extent necessary for adequate isolation based upon performance assessments of the system."[1] Sealing all boreholes and shafts that penetrate a repository requires sealing materials and sealing technologies that meet regulatory requirements for seal performance. Research conducted by the University of Arizona's Department of Mining and Geological Engineering has as its objective, an experimental assessment of the sealing performance of existing rock mass sealing technology. This study is part of that effort.

Any assessment of seal materials should have as criteria the ability of the materials to prevent or retard fluid flow and limit radionuclide mobility.[2] The seal zone to be assessed has three components: the seal material; the interface between the seal and the host-rock; and any disturbed zone created by the excavation in the host rock.

Bentonite is one of several clay materials currently being considered as a sealing material. Some properties of bentonite viewed as favorable to seal performance include fine grain size, low internal permeability, workability, and swelling capacity.

Regional studies are currently underway to identify candidates for a crystalline repository. Crystalline rocks, such as granites, have received consideration as hosts for repositories because they are widespread geographically at depths appropriate for repository design. In addition, their mechanical strength, low porosity and permeability, resistance to stress, and relatively low moisture content recommend them as potential repositories.[3]

In Situ Testing

In situ testing at the Cargodera Canyon study area was divided into three basic stages. The first involved site characterization of the study area and the surrounding geologic environment. It had as its objective determining the suitability of the site for the types of seal testing proposed. The second stage had as its objective the geologic and hydrogeologic characterization of the geologic medium to be sealed. The third stage involved the actual emplacement of bentonite plugs and testing to determine seal performance.

Site Characterization

The Cargodera Canyon study area is located approximately 40 km from the University of Arizona in Tucson, Arizona (Fig.1). The site is at an elevation of approximately 1122 m and is within the Santa Catalina Ranger District of the Coronado National Forest. The study area is situated in the Rincon-Santa Catalina-Tortolita complex. The rocks of this complex have been affected by a number of superposed deformations and, as a result, are considered a metamorphic core complex.[4] The Cargodera Canyon study area lies on the northwest flank of the Santa Catalina Mountains. Three major plutonic intrusions outcrop in the vicinity of the study area. These include the Wilderness granite, the Catalina quartz monzonite, and the Tortolita quartz monzonite. The Tortolita quartz monzonite is younger than the other units and postdates the deformation events that metamorphically altered the surrounding rock.[5] The Tortolita quartz monzonite is the host rock for the boreholes used in this study.[6]

The Cargodera Canyon study area includes fifteen boreholes with an aggregate drilled depth of 97 m. These include eleven 6.35 cm-diameter holes and four 16.5 cm-diameter boreholes. Study of the core indicates that the host rock is primarily a fine to medium-grained biotitic granite with visible alignment of biotite flakes, feldspar lath and quartzplagioclase zones. A whole rock analysis on a sample of core confirms the quartz monzonite description of the host rock.

An evaluation of the core established the existence of a number of relatively unfractured zones in the larger diameter boreholes that appeared suitable for testing. This evaluation was confirmed by using a downhole photologging device designed and constructed to meet the requirements

Fig. 1. Location of the Cargodera Study Area in the Rincon-Santa Catalina-Tortolita Complex.[7]

of the site. The photo record suggested that an interval suitable for testing in one of the large diameter holes extended from 1.07 m to 1.98 m from the surface (Fig. 2).

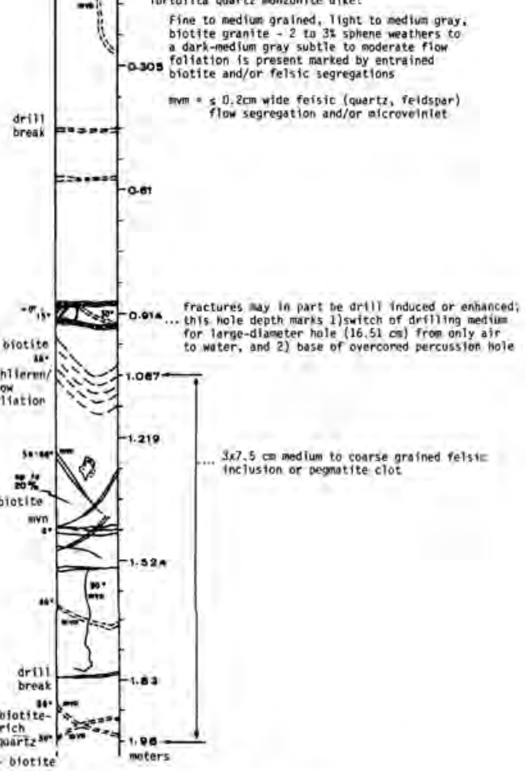

Fig. 2. Corelog of CCR/C-1.

Hydraulic Conductivity Testing

A comparative literature review was conducted of existing methods of in situ determination of the hydraulic conductivity of low permeability rock. Of these methods, the pressure slug test was selected because of the relative simplicity of its procedures, the short period of time available for testing, and the rigor of solutions available for the test. A review of available analytical procedures suggested the solutions developed by Cooper, Bredehoeft and Papadopulos[8, 9, 10] as most appropriate for the conditions and low hydraulic conductivities experienced at the Cargodera Canyon study area. Four pneumatic packers were used for pressure slug testing at the Cargodera Canyon study area. Two were capable of inflating to seal the 16.5 cm-diameter boreholes at the study site. Two inflated to seal the 6.35 cm.-diameter holes. The packers were used in two straddle-packer assemblies, one for each size of hole to be tested. Figure 3, illustrates the straddle-packer assembly as used in the field for pressure slug testing. The packers were connected by wire cable or rigid aluminum bracing. High pressure plastic tubing was used for injection. Separate injection lines allowed each packer to inflate individually. There is some axial shortening and creep during packer inflation. Inflating the lower packer first provided one definite test interval boundary. All four packers were tested in the laboratory using steel pipe with appropriate diameters. Decay of induced pressure in the test interval was monitored using externally mounted 345 KPa Dynisco transducers, a Dynisco AD converter, and a 3-pen, quartz controlled Servogor 430 strip chart recorder capable of measuring from 0 to 110 volts.

Packers were inflated to pressures from 690 KPa to 1380 KPa. Pressures were kept low to avoid the lifting some researchers associate with injection pressures in shallow boreholes.[11]

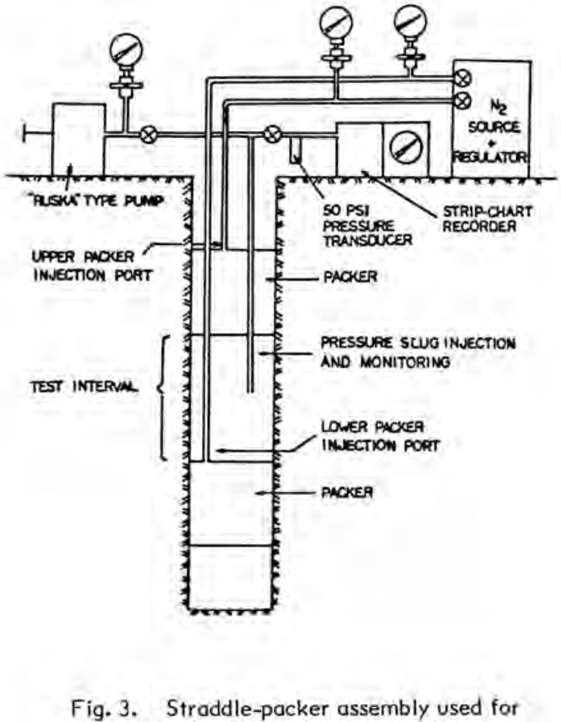

Fig. 3. Straddle-packer assembly used for hydraulic conductivity testing.

Pressure Slug Test Results

A long term pressure slug test was conducted in the large diameter borehole (CCR/C-1) in an interval with a length of 88.9 cm. Figure 4 is the decay curve for that test. It shows dimensionless pressure decay plotted against the log of time in minutes. Two similar tests were performed in a small diameter borehole (CCR/D-4) in an interval with a length of 86.4 cm.

The results of these tests, in the form of pressure decay curves, were analyzed using the solutions developed by Cooper, Bredehoeft, and Papadopulos[8, 9, 10] with type curve plots for alpha values of 10 to 10^{-10}. In addition, the significance of packer compliance was determined using the solution described by Hsieh[12] for non-rigid packers in a borehole. Hydraulic conductivity values calculated from these solutions are presented in Table I. For the two tests in the small diameter borehole two analyses were performed for each test with different alpha values to indicate the sensitivity of the solution procedure to differences in curve matching.

TABLE I

Summary of Pressure Slug Test Analyses

Borehole	Test	Alpha	Hydraulic Conductivity (cm/sec)
CCR/C-1	1	10^{-6}	1.19×10^{-8}
CCR/D-4	1	10^{-4}-10^{-5}	8.78×10^{-10}
CCR/D-4	1	10^{-4}	9.69×10^{-10}
CCR/D-4	1	10^{-5}	7.67×10^{-10}
CCR/D-4	2	.1	1.56×10^{-11}
CCR/D-4	2	1	5.98×10^{-10}

The hydraulic conductivity calculated for the large diameter hole (CCR/C-1) is significantly higher than the values reported for the small diameter hole (CCR/D-4). A review of the respective core logs suggested that the permeability of the interval in CCR/C-1 may be influenced by microfracturing near the top of the interval as well as some of the seams and infillings found throughout its length. The larger volumes of the packers used in testing CCR/C-1 may have contributed to the difference in K values as any error or approximation involved in determining their compliance is magnified by their size with respect to the volume of the interval tested.

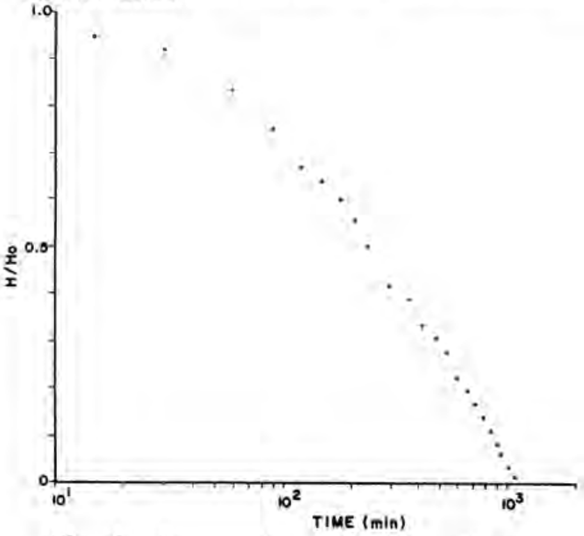

Fig. 4. Pressure Decay Curve For CCR/C-1.

Constant Pressure Injection Testing

A long-term constant pressure injection test in a suitable and proximate small diameter borehole was conducted to provide a continuous record of hydraulic conductivity changes. It also provided a comparison of hydraulic conductivity values as derived from two different types of testing.

The constant pressure injection test method used at Cargodera Canyon employed straddlepackers to isolate a borehole test interval. Fluid was then injected into the interval at a constant pressure. This is essentially the procedure for this type of test as described by Bennett and Anderson[13]; Zeigler[11]; and Hsieh[12]. A small nitrogen over water pump and reservoir was used to apply pressure and monitor flow. Packer pressures were set at 1240 KPa. Test interval pressure was maintained at approximately 34.5 KPa to avoid deformation of the interval associated with high interval pressures in shallow boreholes.

The results of the constant pressure injection test cover a period of approximately 20 days. During this time, however, testing was stopped several times to make equipment adjustments. Injection pressures fluctuated from 31.4 KPa to 48.3 KPa. Table 2 presents these results as change in volume injected over time as well as calculated hydraulic conductivity. Late time values agree within an order of magnitude with pressure slug testing for the same borehole and interval as reported in this study.

TABLE II

Results of Constant Injection Pressure Test in CCR/D-4

Date	Time	Pressure (psi)	Volume Water Injected (ml)	Hydraulic Conductivity (cm/s)
7/31	1000	5	-	-
8/31	1010	5	5.47	1.09×10^{-9}
8/3	1100	5	0.9653	9.51×10^{-11}
8/4	1300	5	1.93	3.57×10^{-10}
8/4	1426	5	-	-
8/6	1021	5	-	-
8/7	1130	7	1.29	1.78×10^{-10}
8/8	1030	7	1.93	2.65×10^{-10}
8/8	1315	5	-	-
8/9	1030	5	0.6435	1.46×10^{-10}
8/12	1035	5	1.29	8.61×10^{-14}
8/15	1140	5	-	-
8/16	0800	5	-	-
8/20	0745	4.7	1.29	6.89×10^{-11}

In Situ Performance Testing of Bentonite Seals

This phase of in situ testing at the Cargodera Canyon study area had as its ojectives the secure emplacement of bentonite plugs and the testing involved in assessing their performance. This assessment required long-term testing over a range of pressure and saturation conditions. The equipment and instrumentation involved in this testing had to be secured from human or animal interference and protected from the elements. To this end, two bunkers were constructed at the site with the permission of National

Forest Service authorities. Once the boreholes were secure, bentonite plugs were emplaced using methods and equipment developed in laboratory prototype studies. Transient pulse testing was used to determine if the plug injection and collection structures were competent and ready for performance testing. Finally, long-term performance testing was initiated on the emplaced bentonite plugs.

The boreholes tested at the Cargodera Canyon study area are single-access holes in an unsaturated rock. Meaningful performance assessment required long-term injection testing to determine the hydraulic conductivity of the seal and the seal interface. This type of testing estimates conductivity values on the basis of measured flow through the plug being tested. Plug design for the boreholes at Cargodera Canyon is based on the need to determine the mass balance for the plug-rock-seal system under injection pressure.

Figure 5 shows the double-plug and collection/tracer system in place. The system uses two plugs to enclose an injection zone. Below the lower plug and above the upper plug, collection of the mass balance between inflow and outflow occurs. The lower collection system is sealed at the bottom with a 16.5 cm. diameter PVC cap, itself glued to a fixed wooden disk. The upper collection interval is sealed with a cement plug. The collector and injector systems are connected to the surface with .64 cm O.D. stainless steel tubing. Tubing for the lower collection interval passes through both lower and upper seals. Tubing for the injection interval passes through the upper seal. Inside the .64 cm. stainless steel tubing is a .32 cm O.D. stainless steel tube. This double tube arrangement allows for simultaneous flow up and down the test interval into each collection or injection area. This arrangement is illustrated in Fig. 6. Actual collection or injection occurs through the two lines shown running parallel to the base of the plug. These are actually spirals of .64 O.D. copper tubing perforated on both sides to optimize fluid circulation. The collector system operates as a conduit for fluid in the collection interval displaced by flow through the seal or seal-rock interface. The double-tube system can also circulate tracer in any of the three isolated zones until a desired concentration is reached.

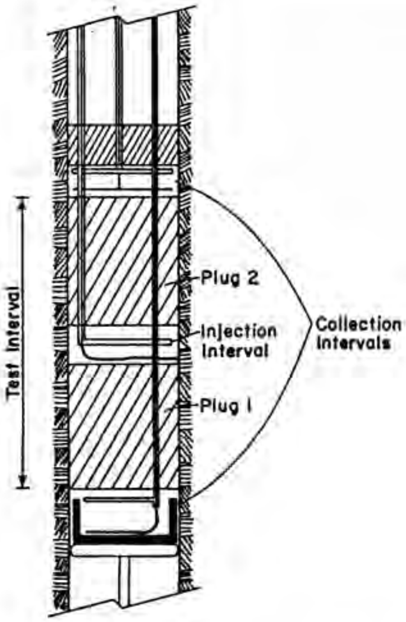

Fig. 5. Double plug system in place.

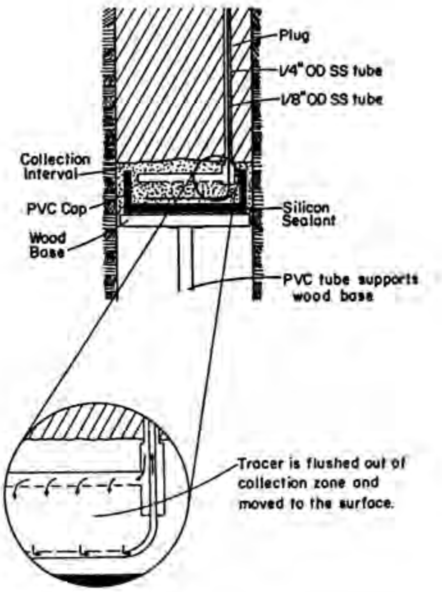

Fig. 6. Collection system for in situ testing.

Injection equipment for plug testing at Cargodera Canyon was designed to provide a range of controlled pressures as injection to the borehole seals and to measure the mass balance of inflow and outflow through the seals and seal rock interfaces. Figure 7 is a schematic of the injection apparatus connected to the downhole apparatus.

Two sources of injection pressure were available to the system. The first was a stainless steel pump 30.5 cm. long with an inside diameter of 6.35 cm. A piston inside the pump is pushed by nitrogen pressure. The piston displaces water into the injection system. The second system utilized nitrogen over water and contained a large water reservoir to prevent evacuation of all the water which would allow the nitrogen to interact with the plug.

The system was designed so that pressure could be maintained on the injection interval while the pressure pump system was refilled. Transducers could be mounted to all three of the interval lines without losing system pressure.

Collection was accomplished using 10 ml capacity pipettes mounted in series with 2.54 cm diameter overflow tubes.

Plug Installation

Borehole CCR/C-1 was sealed using two plugs made with American Colloid 1.27 cm diameter Volclay bentonite tablets. The interval selected for testing was 88.9 cm long and began 106.7 cm from the surface. Plug emplacement was initiated with the installation of the PVC base. The silicone seal between the base and the borehole wall was allowed to cure for 24 hours. The lower collection interval of saturated sand was poured in two steps to allow emplacement of the lower collection apparatus. The lower plug was formed by dropping tablets of bentonite through water at a ratio of 1 tablet to 4 ml of water. Initially, 200 tablets were dropped. Approximately 48 hours later, 600 more tables were dropped. Finally, after 48 hours, the last

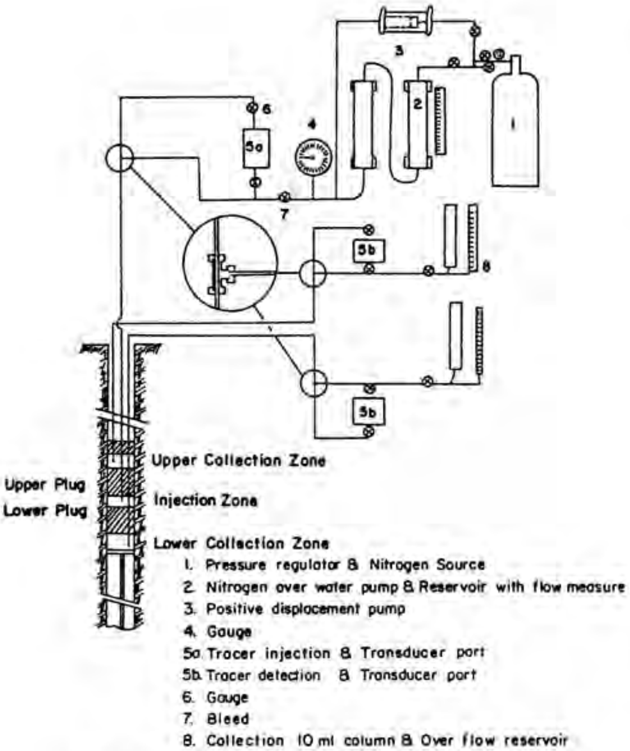

Fig. 7. Schematic of double plug injection assembly.

200 tablets were dropped. One week later the plug was measured as approximately 15.25 cm long. At that time, the injection interval was emplaced with saturated sand sufficient to form a column 15.25 cm. high. The upper plug was formed by dropping 1000 bentonite tables through 4000 ml water. One week later plug height was measured at 12.7 cm. Another 200 tables of bentonite were dropped through water to bring the plug to the desired 15.25 cm. length. The upper collection interval was formed by pouring a volume of sand sufficient to create a column 15.25 cm. high. Finally, 5.1 cm of sand was added to create a buffer between the collection interval and the cement cap poured above it.

Transient Pulse Testing of Bentonite Seals

The objective of transient testing of bentonite seals was to assess the effectiveness of the seals before long-term testing was initiated. The hydraulic conductivity of bentonite is a function of the degree of saturation.[14] This is important in the seal environment where achieving complete saturation may require an extended period of injection time. In addition, actual flow through the plugs may not be measured for an extended period of injection time. The collection system on the outflow side of each plug also functions as a drainage path allowing the bentonite plugs to consolidate to some degree under injection pressure. This suggests that at least some part of any initial outflow may be the result of consolidation and not flow through the plugs. These factors make analysis of long-term flow through the seals and seal-rock interfaces difficult. Transient testing provided a means of approximating the competence of the plugs and entire tested interval in a short period of time.

The injection system designed and installed for long-term testing of bentonite seals in CCR/C-1 was equally suited for short-term transient pulse testing. A pressure pulse was generated by the pressure system and isolated between valves while it was bled to an appropriate level. By connecting the injection line to the line leading to the collection interval, the pressure pulse could be delivered to collection intervals as well as the injection interval. Decay of the pressure pulse was monitored by a 25 psi Dynisco transducer mounted on the appropriate interval line. A continuous record was maintained by the three-channel strip chart recorder used previously in pressure slug testing. Intervals were tested individually to avoid interference from pressure leaking out of the other intervals.

Four pressure decay tests were performed on the three sealed intervals in borehole CCR/C-1. Table III summarizes the results of these tests.

TABLE III

Results of Pressure Slug Testing of Bentonite Seals

Test	Interval	K (cm/sec X 10^{-7})
1	Injection	.342
2	Injection	.0341
3	Upper Collection	3.40
4	Lower Collection	4.35

The hydraulic conductivities listed in this table apply to the bentonite seals and the seal-rock interfaces. Analysis of the results of these tests is complicated by the flow assumptions that underlie existing methods of treating pressure slug data. The Cooper, Bredehoeft and Papadopulos method[8, 9, 10] discussed previously treats all flow in the borehole as acting perpendicular to the axis of the test interval. The pressure slug tests of in situ bentonite plugs at Cargodera Canyon take place in intervals where flow acts in two directions. An approximation method was used in this study that treated the plugs as compliant seals at the ends of the test interval. In this way, flow through the plugs and seal-rock interfaces could be estimated separately from radial flow through the walls of the borehole. This approximation method utilizes the compliance term as described by Hsieh[12] for the compressibility of non-rigid packers and allows the back calculation of hydraulic conductivity for the seals and seal-rock interface using values of hydraulic conductivity for the borehole wall arrived at in earlier pre-seal testing. The values in this table for the injection interval tests are close to the values determined for the host rock. Hydraulic conductivities for the collection intervals suggest that the seals were allowing for pressure release by consolidating, leaking or drawing water into unsaturated areas. Figure 8 is a plot of the dimensionless pressure decay against time in minutes for the first injection interval test.

Long-Term In Situ Performance Testing of Bentonite Plugs

Long-term in situ testing of bentonite plugs involved the injection under constant pressure of water into the injection interval between the two bentonite plugs and collection on the downstream side of each plug. Injection pressure was kept low (69 KPa) to avoid deformation in the test interval associated with higher injection pressures. The injection interval continued to take water under pressure at a rate that declined over time for the duration of the testing. Both of the collection intervals have continued to take water over time under the small head induced by the difference in height between the intervals and the collection reservoirs at the surface. Table IV presents the flow as ml/day into each interval as it has decreased over time. The table shows that the collection intervals approached a state of equilibrium with no flow into or out of the intervals. Similarly, the injection interval seemed to reach stable flow into the plugs over time.

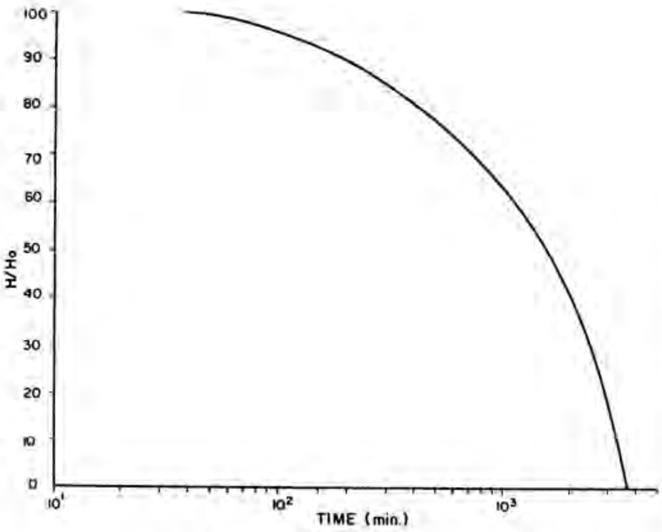

Fig. 8. Decay curve for injection interval Test 1.

CONCLUSIONS

Two boreholes were tested using the pressure slug method. Hydraulic conductivities determined from the testing ranged from 10^{-8} to 10^{-10} cm/sec, depending on the density of the microfracturing present in the test interval. Once the equipment was assembled at the site, the testing was limited to boreholes of shallow depths. The dependence of the testing on the effectiveness of packers and transducers suggestes that this equipment should be tested extensively before it is used in the field.

Plug construction utilized a method of dropping bentonite tablets through water. Though this method seems to provide an adequate seal, it does not allow any control of the composition of the plug in terms of density and homogeneity. Plug volumes can only be estimated before actual seal emplacement and final volume is a function of how long the plugs are allowed to swell. If the plugs are constrained at either end by sand columns of any saturated medium, they will continue to draw water in quantities significant enough to make testing difficult. The tablets used in this study retain their air-filled void spaces even when hydrated and are, therefore, not saturated. These void spaces may provide a flow path that reduces the seal effectiveness. The test method used at Cargodera Canyon allows the plugs to drain as they are pressurized by injection water. This suggests that they may consolidate under pressure even as they swell from the presence of availabile water. This makes volume control of the plugs difficult.

TABLE IV

Summary of flow rates into sealed borehole intervals.

	Flow (ml/day)		
Time Elapsed (Days)	Lower Collection Interval	Upper Collection Interval	Injection Interval
5	1.10	.20	67
10	1.20	.12	65
15	1.30	.50	60
20	1.80	1.50	75
25	.15	1.40	69
30	.16	1.20	64
35	.26	1.00	34
40	.24	1.30	58
45	.14	1.00	67
50	.12	.90	53
55	.10	.90	56
60	.09	1.00	61

The sealed intervals were tested using the pressure slug method. The pressure decay results are analyzed in terms of two-dimensional flow in the test interval. The method of analysis is empirical and approximate. The values it suggests for the hydraulic conductivity of the seals and seal-rock interfaces range from 10^{-7} cm/sec to 10^{-9} cm/sec. These values are considered to be conservative and represent an upper bound of actual seal performance. The results of this test indicate that the seals are performing at a hydraulic conductivity close to the conductivity of the host rock. The testing is relatively simple to perform once the test apparatus is assembled in the sealed intervals.

The seals were also tested using constant pressure injection. The evidence of this study suggests that this type of test requires an extended test time, possibly more than a year, before any meaningful hydraulic conductivity values can be determined. Large quanitities of water have been injected or allowed to flow into the test intervals and a small decrease in the flow rate for all the intervals has been observed.

ACKNOWLEDGEMENTS

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