PERMEABILITY MEASUREMENTS AT THE WASTE ISOLATION PILOT PLANT (WIPP)

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ABSTRACT

A series of in situ permeability measurements were conducted at the Waste Isolation Pilot Plant (WIPP) facility horizon. These measurements were preceded by numerous laboratory permeability measurements, and measurements made from wellbores which extended from the surface through the facility horizon. The permeability of the facility horizon is a fundamental parameter, one which describes its inherent isolation capabilities and is therefore paramount in determining its suitability for the long-term disposal of radioactive waste. Further, the permeability of the formation is important to seal design and evaluation, as flow through the total seal system is in part dependent on the permeability of the host rock. Results of a limited number of flow tests conducted to date suggest that the competent salt is essentially impermeable. However, small flows did occur along some clay-anhydrite seams. Existence of these seams may possibly have performance assessment inplications and may affect internal repository room isolation properties as well as influence associated seal designs. Additional tests are required in order to fully-characterize the permeability of the WIPP facility horizon.

INTRODUCTION

The Waste Isolation Pilot Plant (WIPP) is being developed by the Department of Energy to demonstrate the safe geologic disposal in rock salt of radioactive waste resulting from the defense programs of the United States. A part of the WIPP Research and Development Program is the Plugging and Sealing Program (PSP). The activities of the PSP will result in acceptable technology for sealing penetrations (boreholes, shafts, drifts) associated with the WIPP facility.

The Plugging and Sealing Program is responsible for determining the permeability of the formation surrounding the WIPP facility. The WIPP facility horizon is located 650 meters below the ground surface in the Salado formation, which is a bedded salt deposit. The host rock permeability is a fundamental parameter required to access the suitability of the potential repository. Permeability and fluid transport measurements will indicate the formations's inherent isolation capabilities, and values for these parameters will be incorporated into various performance assessments which describe postulated fluid flow through the repository and radionuclide migration away from the underground facility. The permeability of the formation is an important input to development of the sealing strategy and designs, as flow through and/or around a seal system is partially-dependent on the permeability and fracture extent of the host rock. The magnitude of the pressure buildup and dissipation associated with natural and waste-generated gases within the repository also depends directly on the permeability of the surrounding formation.

The permeability of the WIPP horizon is not constant but rather will vary with the specific geology, time after excavation, distance from an excavation, and test technique. The geology in the vicinity of the WIPP facility is comprised mainly of halite, but also contains clay, anhydrite, polyhalite, and argillaceous halite. The excavation of the facility may alter the permeability of the formation by creating a disturbed zone surrounding the excavation. Because of the time-dependent deformation properties of salt (creep), this disturbed zone may change with time. Further, the test technique may influence the derived permeability value. For example, laboratory tests may give different values than obtained with in situ tests, and permeability values inferred from liquid tests may differ from those determined from gas tests.

This paper will discuss the laboratory and field permeability measurements made to date on WIPP rocks. This includes numerous laboratory permeability measurements, as well as measurements made from surface boreholes and from boreholes in the facility itself. Conclusions about the in situ permeability of the formation surrounding the WIPP facility are drawn, and implications for waste isolation are considered. Remaining testing requirements are given.

Four series of laboratory permeability measurements have been made on WIPP site rocks[1,2,3,4]. The vast majority of these measurements used gas as the working fluid, and were made on halite samples obtained from surface boreholes and boreholes from the WIPP underground workings. All four studies found the permeability of the as-received core to be very high and variable. When subjected to confining stresses for some low level--typically below the resolution of the tests (0.05 to 0.01 microdarcy). This process, referred to as healing, is illustrated in Fig. 1. The healing process was observed to be largely irreversible in these tests; that is, once healed, the sample permeability appeared to be independent after healing; however, any such dependence was beyond the resolution of the tests.

Permeability of salt can be attributed to flow along grain boundaries. Tests on a single crystal of salt, performed by Shelby (as reported by Sutherland[1]) and by Reynolds and Gloyna[5], indicated a less than 10E-12 darcy permeability and no permeability, respectively. Laboratory samples may have enhanced permeabilities compared to their in situ values since the interconnected porosity along grain boundaries may be increased as a result of the coring and handling processes. The healing process occurs when the application of confining stresses decreases this porosity, primarily by plastic flow at the grain boundaries. This process should not be reversible, for the most part; as a result, the porosity and associated permeability should not substantially increase even if the stresses are decreased. The hydrostatically-healed condition is most representative of the undisturbed in situ permeability of salt because of the hydrostatic stresses that the salt has been subjected to for geologic time. Thus, the laboratory measurements suggest that the permeability of the virgin undisturbed WIPP salt is less than 0.05 microdarcy.

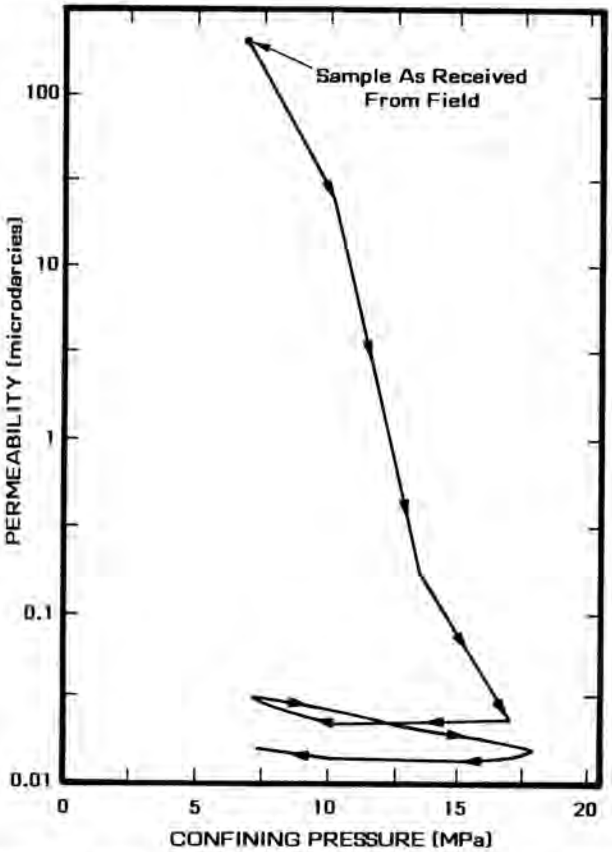

Fig. 1. Typical laboratory permeability vs. confining pressure.

The salt surrounding the excavations has experienced a change in stress from the initial virgin conditions. The permeability of this salt after excavation may therefore correspond to laboratory measurements made on samples which have first been healed and then have undergone stress changes. As previously stated, no stress-permeability relationship can be discerned from the laboratory tests on WIPP salt. If such a relationship did exist, the permeability field around WIPP excavations could be predicted based on the assumed stress distribution around the excavation.

A compilation of laboratory permeability data for both bedded and domal salt by Isherwood[6] does suggest a definable stress-permeability relationship. However, the derived relationship is questionable in two regards. First, careful examination of the data attributed to Sutherland and Cave[1] and Reynolds and Gloyna[5] reveal that these were non-healed samples. The measurements were made without any prior application of a confining pressure. The observed permeability decrease with increasing confining stresses is likely to be a result of sample healing rather than representing an explicit stress-permeability relationship which is applicable to in situ conditions. Second, it may not be appropriate to compare bedded and domal salt permeability values. Measurements by Reynolds and Gloyna[5] indicate a much lower permeability value for bedded salt, possibly due to the different content of inpurities which restrict flow or to the lower porosity of the bedded salts[7]. Thus, for the WIPP site, insufficient information exists to predict from laboratory measurements the permeability field surrounding an excavation.

The measurements made by Sullivan[4] included rock types not predominantly halite which are found at the WIPP facility horizon. These rocks, referred to as interbed materials, contained significant amounts of polyhalite[5] and had a high argillaceous content. The permeability values of these rocks were comparable to the halite rocks tested. Sullivan also measured the permeability of cores taken from horizontal and vertical boreholes in the WIPP facility. No discernible difference in permeability was measured as a result of the core orientation.

The 1978 Terra Tek[2] study included permeability measurements made with silicone and brine as the working fluids. The permeability values obtained using these liquids were lower than obtained for comparable gas tests. There was no difference observed between the silicone fluid and the brine. This contrasts with measurements made on domal salt, which indicates that permeabilities measured using gas and nonreactive fluids are similar, and substantially greater than permeabilities measured using brine solutions[5,8].

TESTS FROM SURFACE BOREHOLES OF WIPP ROCK PERMEABILITY

Mercer[9] compiled results of drill-stem tests conducted from surface boreholes in the vicinity of the WIPP facility to characterize the geohydrology of the Salado formation. Results of thirteen conventional drill-stem tests are reported. A typical drill-stem test consists of isolating an interval of the open holes, relieving the mud (drilling fluid) pressure, and allowing the formation to produce into the drill pipe. Results are in the form of pressure-time data, and can be used to estimate formation permeability, reservoir pressure, productivity index, and extent of formation damage. An obvious advantage of this type of testing is the relatively large interval of rock tested, as test intervals are typically in excess of 10 meters.

For half of these tests, permeability values could not be derived because the extremely low permeability exceeded the sensitivity of the test equipment. (Conventional drill-stem tests are usually performed over regions likely to be capable of producing oil or gas, and thus are configured to measure millidarcy to darcy values rather than the microdarcy and lower values of interest here.) In the ERDA-9 drillhole, which is located very near a WIPP shaft, permeabilities in the Salado salt ranged from 0.07 to 25 microdarcies [10]. In the Cabin Baby drillhole, Beauheim, Hassinger, and Klaiber[11] reported permeability values in the Salado salt of about 0.01 to 0.08 microdarcy. They stressed that these results should be considered order-of-magnitude approximations.

In an effort to obtain more accurate, less ambiguous, in situ data, measurements were made by Peterson et al.[12] using the Guarded Straddle Packer (GSP) system developed and patented by S-CUBED. This system, shown schematically on Fig. 2 was used to test the formation surrounding the 20-centimeter diameter AEC-7 borehole.

The GSP system is similar to a conventional drill-stem tool in that it incorporates two packers, one located on each end of the test zone. However, it differs significantly from the standard tool in that it uses two additional packers to form guard zones located on each side of the test zone.

Inclusion of the guard zones provides the GSP system with a number of critical advantages over conventional tools. These include the capability to: 1) measure both horizontal and vertical permeability components, 2) distinguish between isotropic porous flow and anisotropic fracture flow, 3) distinguish packer bypass and wellbore damage flow from flow into the surrounding formation, and 4) obtain data in which the measured flow and pressure values can be explained and defended without resorting to assumptions pertaining to tool performance.

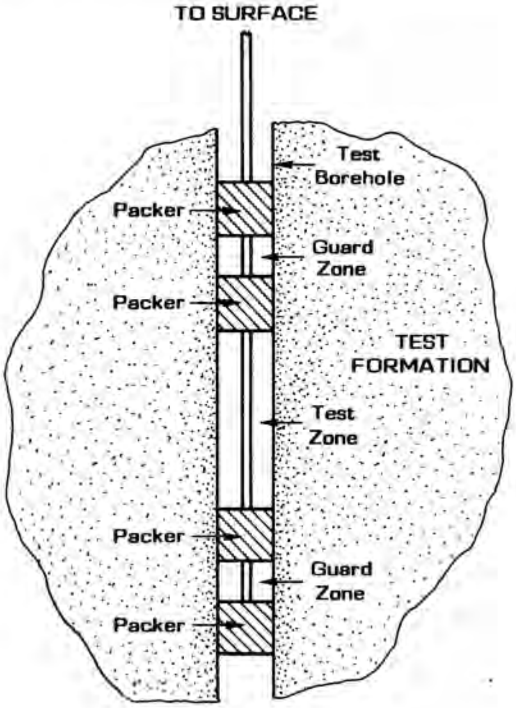

Fig. 2. Schematic Showing the S-CUBED Patented Guarded Straddle Packer (GSP) System in a Typical Permeability Test Configuration.

Four gas flow tests were performed using a 30-meter long test zone centered at the 690 meter, and 180-meter depths. Throughout each test, measurements were made of the test zone pressure, temperature, flow, and guard zone pressures.

Permeability values were determined from the measured data in an iterative manner, using one or two-dimensional, axisymmetric, numerical solutions to the appropriate diffusion equations[12,13]. This diffusion model can be used to describe gas flow through a low-permeability formation, or even along thin fractures as long as the flow is dominated by viscous effects[14,15].

It is important to note that in the low-porosity, WIPP facility rock the bulk of the fluid is contained within the wellbore rather than in the surrounding formation. Data interpretation is therefore based on the entire flow history and considers the associated wellbore storage effects.

Table I provedes a summary of the AEC-7 gas flow test results. Analysis of data obtained during the first test at the 690-meter depth, gave permeability values of 18 and 12 microdarcies for the flow and shut-in portions of the test, respectively. A second test performed at this depth gave 21 and 12 microdarcy values. Flow measurements at the 570-meter depth were consistent with a 3 microdarcy permeability value; however, the associated shut-in test indicated a zero permeability. This later result is not understood. Results of the test performed at the 180-meter depth, where the GSP system was set in the well casing in order to determine the system sensitivity, gave permeability values of 0.05 and 0.02 microdarcy for the flow and shut-in tests, respectively.

TABLE I

Summary of Salt Horizon Permeability Tests
(Guarded Straddle Packer System)

TEST DEPTH (meters)	PERMEABILITY * (microdarcies)		REMARKS
	FLOW	SHUT-IN	
690	21	12	
690	18	12	System run out of hole and leak checks performed before doing second test at 690-meter depth.
570	3	-0-	Results of shut-in test not understood.
180	.05	.02	System set in casing: check sensitivity.

* Permeability values shown assume a formation porosity of 0.001.

The permeability values shown in Table I were obtained assuming gas flow through a uniform unsaturated homogenous isotropic formation. If the connected pore volume was partially or fully-saturated with brine so that the gas movement was limited by the brine motion, the associated permeability values could be as much as a factor of 40 higher than shown. In addition, if the connected pore space was saturated, threshold pressure effects could be important[16] and disproportionately larger flows could possibly occur at higher driving pressures or if a brine solution were used.

At the relatively low pressures used for these tests, the gas molecule mean free path may be on the order of the flow channel width. Under such conditions, the apparent permeability constant (as determined with gases) is dependent upon the nature of the gas and would differ from that determined using a liquid. Klinkenberg[17] has shown that these gas permeability values, which are characteristically high, can be related to a true permeability constant which is characteristic of the porous medium only. The Klinkenberg correction could be applied to data presented here to lower reported permeability values by at most a factor of three. However, because parameters such as porosity, saturation, and fracture extent remain unknown, such adjustments could be presumptuous.

Guard zone pressure measurements obtained during the AEC-7 tests indicate that flow in the vertical direction, and therefore the vertical permeability, is small compared to that in the radial direction. This absence of flow in the vertical direction suggests that the measured flow from the test interval may occur along small formation discontinuities or fractures which do not intersect the guard intervals.

Data from the test conducted at the 690-meter depth were also evaluated assuming the flow occurred through thin fractures, rather than through a uniform isotropic porous formation. As shown in Fig. 3, the measured data can be equally well fit using either a fracture flow or porous flow model. The important point is that it is impossible to determine from standard straddle packer tool test results which Fig. 3 solution is correct. In contrast, results from the GSP system guard zones clearly show that the uniform isotropic porous formation assumption is inappropriate.

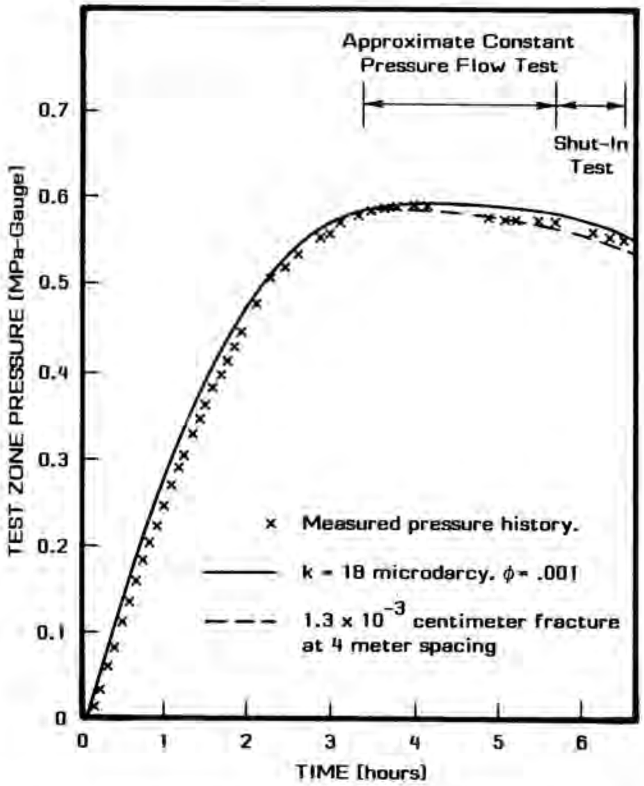

Fig. 3. Comparison of the Measured 690-meter Depth Test Interval Pressure History With Those Calculated for Porous and Fracture Flows.

The difference in the fracture versus porous flow results are striking in terms of repository performance assessment. For example, during the test period, the pressure front penetrates to a distance of approximately 210 meters for the fracture flow geometry described on Fig. 3, as compared to 8.5 meters for flow through the homogenous isotropic formation. This difference in penetration distance is of significant importance if radionuclide migration, which depends on flow velocity and flow channel width, is to be modeled. Values for flow velocity and flow channel width can only be obtained by performing tracer measurements together with flow measurements such as those described in this paper.

IN SITU TESTS FROM THE MINED REPOSITORY

A total of 18 gas permeability tests were conducted in two Phases at the WIPP facilities horizon located at the 650-meter depth. The objectives of the twelve Phase I tests were to determine: 1) the permeability and porosity of the competent salts, 2) the permeability variation with distance from the mine surface, and 3) the influence of the interspersed clay/anhydrite seams on the measured permeability values. Six short-duration, order-of-magnitude permeability tests were performed as Phase II of this project. These tests were used to provide confirmation of the Phase I test results.

The test system, test techniques, and data analysis methods were similar to those used for the AEC-7 borehole tests. The downhole measurement system shown on Fig. 4 consisted of a dual-packer assembly which isolated a test zone located at the bottom of the 13-centimeter diameter borehole, and, an adjacent guard zone. During a test, continuous measurements were made of the test zone pressure, temperature, flow, and of the guard zone pressure. Even though the total flow out of the test zone was low, a significant fraction of this total did not go into the formation but entered the guard zone as a result of packer bypass. Thus, if guard zone pressures were not measured, erroneous formation flowrates would have been used in subsequent permeability calculations.

Permeability and porosity values were inferred from the measured data using one-dimensional and two-dimensional axisymmetric numerical solutions to equations describing gas diffusion through an unsaturated isotropic homogenous porous medium. In those cases where the analytical/numerical solutions failed to describe the measured response, additonal tracer/flow testing is required to evaluate the formation flow characteristics.

The competent salt, which includes all rock types which are predominantly halite (from argillaceous to polyhalitic to clear halite), was found to have less

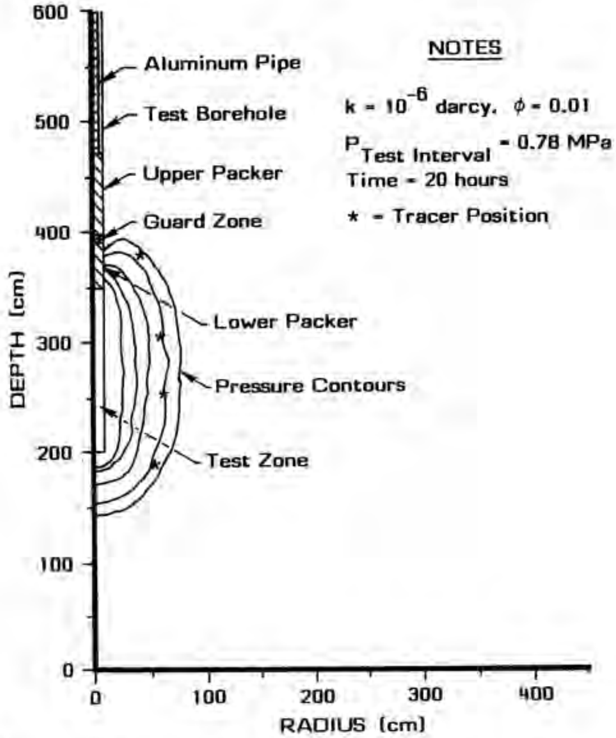

Fig. 4. Schematic Showing the Downhole Measurement System and Results of the Calculations Showing Pressure Contours Illustrating Flow into the Formation and Around the Bottom Packer into the Guard Zone.

than a 0.01 microdarcy permeability and an approximate 0.001 porosity. Furthermore, the test results suggest that the salt is isotropic and has no preferred flow direction since similar permeability values were obtained in holes drilled in the vertically-up, vertically-down, and horizontal directions.

There is some indication that the permeability decreases with increasing distance from the mined surface. This is illustrated on Fig. 5, which shows all the permeability test results for the competent salt. It should be noted that a guard zone was not used in Test No. 1 and Test No. 9; therefore, those results represent an upper limit on the permeability. If subsequent testing confirms that permeability values increase as the face is approached, the maximum value is still less than 1.0 microdarcy for depths greater than 0.5 meters.

Generally, those clay and anhydrite regions tested had permeabilities similar to that of the competent salt. There were three exceptions. A clay/anhydrite seam located about 4 meters above the back of Room L-2 produced a small flow of gas, even when pressured to 0.65 MPa. The clay/anhydrite seam located about 2.1 meters above the back in the middle of Room L-2 (about 15 meters from the heading) accepted gas at a rate of 9,000 SCCM when presured to 0.33 MPa. This same seam, together with the adjacent salt, exhibit a 0.04 microdarcy permeability when tested in a borehole located near the heading--thereby suggesting the enhanced permeability in the borehole drilled near the center of the room may result from roof sag. A test done in Marker Bed 139, a 1 meter-thick predominately anhydrite layer, about 2 meters below the invert accepted gas at a rate of 8,300 SCCM when pressurized to 0.42 MPa in a borehole located approximately 15.2 meters from the heading and midway between the ribs.

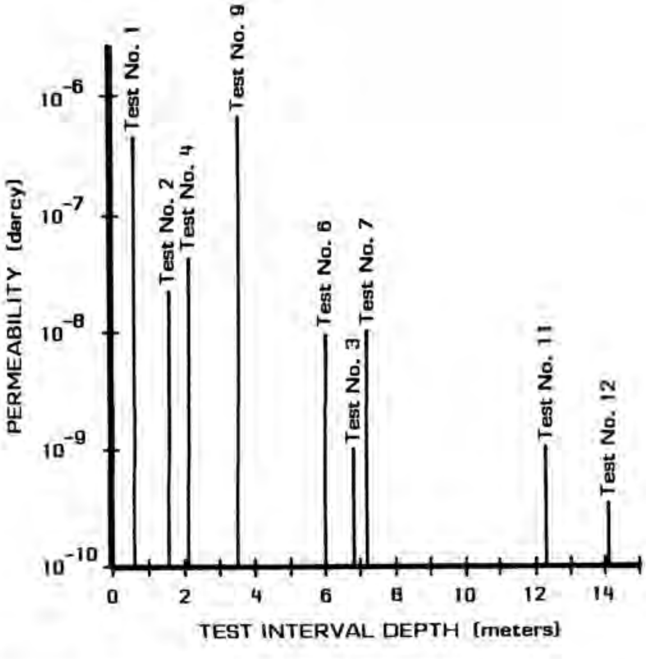

Fig. 5. Illustration Showing the Variation in Measured Permeability With Increasing Test Interval Depth.

During the Phase II confirmation tests, Marker Bed 139 and the clay/anhydrite seam located about 2.1 meters above the back accepted gas at rates of 1.7 x 10E5 SCCM and 1.1 x 10E5 SCCM when pressured to 0.11 MPa and 0.66 MPa, respectively, from boreholes drilled in the center of Room 4. In contrast, Marker Bed 139 and this same clay seam exhibited permeability values below the 10 microdarcy level of sensitivity of the order-of-magnitude permeability tests when examined from a vertical borehole position near the rib, or from an inclined borehole which intersected Marker Bed 139 in the undisturbed free field. Results of the confirmation tests again suggest that the large permeabilities measured in Marker Bed 139 and this clay seam occur as a result of floor heave or roof sag.

All Phase I flow tests were sensitive enough to measure accurately permeabilities down to the 0.01 microdarcy value in a 0.001 porosity formation. However, for lower permeabilities, these short-duration tests do not examine a representative formation volume. Since the fluid penetration depth is a direct function of test time, longer duration tests are therefore needed to accurately measure permeability values less than 0.01 microdarcy.

Permeability and porosity values were determined from the data assuming an unsaturated connection pore volume. If this volume were partially or fully-saturated so that fluid migration and/or threshold pressure effects were important, the intrinsic formation permeability would be larger than reported. The influence of pore fluid effects on these in situ tests can only be determined for these low permeability formations through high-pressure, cross-hole flow and tracer tests. Some indication of these effects can possibly be determined through laboratory tests of properly confined core samples.

Those three regions which either produced gas or accepted large flows could not be adequately characterized by these tests as they did not respond as classical unsaturated homogenous formations. Cross-hole flow and tracer tests are therefore required to characterize Marker Bed 139 and the clay/anhydrite layers examined in two of the other tests. Since the measurement system is very sensitive to the measured four to five order-of-magnitude change in flow found between the competent formation and Marker Bed 139, this type of test could be used to examine the effect of floor heave or roof sag.

CONCLUSIONS

Laboratory and field permeability tests have been made on WIPP rocks. Gas flow tests performed in the laboratory using core samples placed under the appropriate confining stress and in boreholes drilled from the facility itself shown that the competent salt exhibits a permeability of less than 0.05 microdarcy. Tests conducted in surface boreholes using 10 to 30-meter long test intervals indicate the permeability of the bulk rock may approach the 25 microdarcy value.

Both the surface borehole tests performed using the GSP system and the tests conducted in boreholes drilled from the mined facility suggest the larger permeability values result from flow through formation discontinuities rather than through the competent salt. Additional tracer/flow tests are required to evaluate the flow characteristics of these discontinuities in order to determine the fluid transport distances and times necessary to evaluate repository performance.

Tests performed in boreholes drilled from the mined facility indicate that in the disturbed stress field surrounding the mine, the permeability of the competent salt may increase as the face is approached. However, additional longer-duration tests are required importantly, tests suggest that as a result of stress re-distribution, separation has occurred along clay/anhydrite seams located above the roof and below the floor. Flow along these seams was many orders-of-magnitude larger than could occur through the competent salt. Tracer/flow tests are currently being performed to characterize the flow capacity and extent of these seams. Because the tracer/flow tests are extremely sensitive (i.e., at least to the square of the fracture aperture dimension) they may be used to evaluate time-dependent stress re-distribution effects such as floor heave or roof sag or to evaluate heat loading induced permeability changes.

It is important to consider that the WIPP excavations are about three years old, and effective isolation may be required for thousands of years. It is likely that the continued creep of the rock salt surrounding the excavations will alter the permeability field. Periodic testing is planned to address this issue.

Gas permeability tests have been performed in boreholes drilled from the mined facility and the data interpreted assuming an unsaturated uniform isotropic porous medium. Gas tests alone are not conclusive measurements of the formation flow characteristics and must be complemented by brine flow tests which may give different results if saturation, threshold pressure, dissolution, Klinkenberg, etc., effects are important. Preliminary brine permeability tests are being performed as part of the Small Scale Seal Performance Test Program.

Tests performed to date have demonstrated that the GSP system can be used to measure in situ gas or brine permeabilities of the low-permeability WIPP rocks. These tests have also demonstrated that the guard zone data obtained with such a system is critical in determining the formation permeability, identifying fracture type flows, and evaluating packer sealing integrity.

In summary, permeability tests performed to date have a number of waste isolation related implications. First, gas permeability of the competent salt is so low that the salt could be considered to provide complete isolation. However, the enhanced permeabilities measured over 10 to 30-meter intervals suggest there may exist some flow along small discontinuities whose transport characteristics may be of interest to performance assessment. Finally, measured flows suggest that some separation has occurred along clay/anhydrite seams located above the WIPP facility roof and below the floor. Opening of these seams may affect internal repository room isolation properties and influence associated seal designs.

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