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WIPP AIR-INTAKE SHAFT DISTURBED-ROCK ZONE STUDY

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ABSTRACT

The disturbed-rock zone surrounding the air-intake shaft at the Waste Isolation Pilot Plant (WIPP) site was investigated to determine the extent and the permeability of the disturbed-rock zone as a function of radial distance from the 6.1 m diameter shaft, a different elevations within the Salado. Gas- and brine-permeability tests were performed in the bedded halite of the Salado formation at two levels within the air-intake shaft. The gas- and brine-permeability test results demonstrated that the radial distance to an undisturbed formation permeability of 1×10^{-21} m^2 was less than 3.0 m.

INTRODUCTION

As continuum creep deformation of the salt immediately adjacent to an underground opening occurs, conditions for the formation of microfractures become favorable. The salt experiences a progressive increase in microfracturing and as the fractures become interconnected, a zone of increased permeability in the formation surrounding an excavated opening develops. This region is known as the disturbed-rock zone (DRZ). A DRZ is known to exist around the shafts in the Waste Isolation Pilot Plant (WIPP) and may be a controlling feature of fluid flow through the shaft seal system. The field test program described in this paper was designed to gather pertinent information about the DRZ to aid in the evaluation of the shaft sealing system design. The WIPP is a US Department of Energy (DOE) research and development facility located near Carlsbad, New Mexico, which is designed to demonstrate the safe disposal of transuranic (TRU) radioactive wastes generated by US defense programs.

Testing of the Salado formation surrounding the air-intake shaft (AIS) was conducted between July and November of 1995. The AIS is a 6.1 m diameter vertical shaft upreamed in 1988 from the WIPP horizon at 665 m below ground surface (bgs)

(Figure 1). The AIS penetrates the upper 393 m of the 610 m thick Salado formation. The Salado formation consists predominantly of halite with interbed layers of anhydrite and polyhalite (Holt and Powers, 1990).

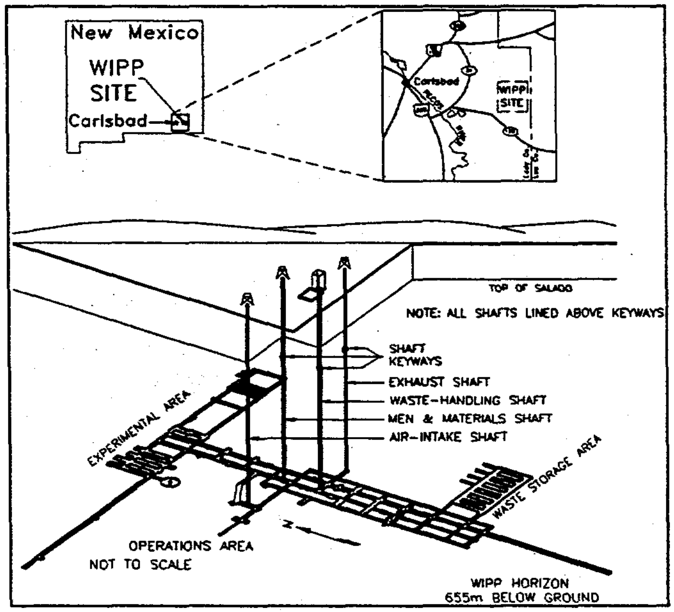

Figure 1 - WIPP and Air-Intake Shaft Site Location Diagram

The permeability of the Salado formation surrounding the AIS was estimated from the results of both gas-permeability and brine-permeability tests conducted from within the AIS. Previous investigations at the WIPP site have used these testing methodologies to obtain estimates of the formation permeability. Gas-permeability testing has been performed in areas surrounding excavations in the WIPP underground facility to determine the extent and permeability of a brine-desaturated DRZ (Ahrens et al., 1996).

Brine-permeability testing has been extensively conducted at the WIPP horizon to obtain estimates of the formation permeability of the Salado halite and associated interbeds (Beauheim et al., 1991 and 1993; and Domski et al., 1996). Saulnier and Avis (1988) conducted a series of brine-permeability tests in the Salado formation halite from within the waste-handling shaft at WIPP.

The initial testing conducted in the AIS was designed to determine the permeability and extent of the brine desaturated region in close proximity to the shaft wall using gas-permeability testing. Beyond the radial distance at which the formation was determined to be fully brine saturated, brine-permeability testing was conducted to characterize how the formation permeability changes as a function of distance away from the shaft wall.

TESTING AND ANALYSIS METHODOLOGIES

Field testing was conducted to estimate the permeability and radial extent of the DRZ in the halite of the Salado formation surrounding the AIS at two dephts within the Salado. The two horizons investigated were at an elevation of 345.9 m bgs (Level A) and 629.4 m bgs (Level C). Permeability tests were performed at each level in three 10.2-cm diameter boreholes. The boreholes were drilled at an angle of 6° below horizontal to a total depth of 6.1 m. Each borehole was located 120° from the others. The boreholes at Level A were designated VA1, VA2, and VA3 and were oriented N, ESE, and WSW, respectively. The boreholes at Level C were designated VC1, VC2, and VC3 and were also oriented N, ESE, and WSW, respectively.

A suite of gas-permeability tests were conducted within each borehole to determine the radial extent at which the formation permeability to gas decreased to zero. At this point, the formation was assumed to be fully saturated with respect to brine. Brine-permeability testing was then conducted starting at the radial distance at which the formation was determined to be brine saturated, as concluded from the gas-permeability testing. The brine-permeability testing was performed at two intervals within the boreholes to determine how the formation permeability to brine changed with radial distance. The maximum permeability of intact (undisturbed) halite is considered to be approximately 1×10^{-21} m^2. Therefore, the DRZ is considered to be any region where the permeability is greater than this value.

The permeability testing methodologies included constant-pressure-injection tests and pressure pulse-injection tests. A typical borehole fluid pressure response from a constant-pressure-injection and a pressure pulse-injection test is presented in Figure 2. Constant-pressure-injection tests were performed by increasing the pressure within the testing interval to a specified magnitude by injecting pressurized gas or brine into the testing interval, and maintaining the test pressure for a specified length of time. During the injection period, the rate of fluid injection into the testing interval over time was determined. After the injection period was terminated and the testing interval isolated, the decrease in the test-interval pressure was monitored. Pulse-injection tests were performed by rapidly increasing the pressure in the testing interval to a specified magnitude by injecting pressurized gas or brine. Once the test pressure was obtained, the fluid injection was terminated and the subsequent pressure decrease in the testing interval was monitored.

The permeability tests were conducted using multi-packer test tools. For gas-permeability testing, the test tool consisted of four inflatable packer elements, resulting in four potential testing intervals (Figure 3). The packer elements were 0.33 m in length with testing interval lengths between the packer elements of 0.38 m. The brine-permeability testing tool consisted of two inflatable packer elements and two testing intervals (Figure 4). The brine test tools were configured so that the testing interval closest to the shaft wall (interval B) was 1.0 m in length. The length of the second test interval (interval A) was dependent on the placement location of the tool within the borehole.

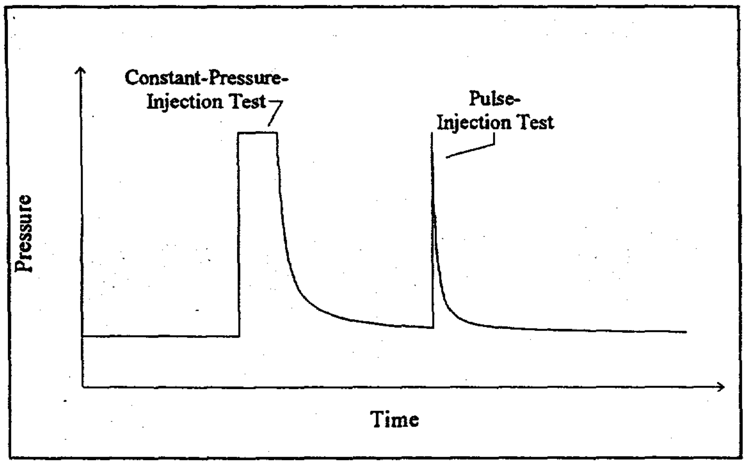

Figure 2 - Typical Pressure Response During Permeability Testing.

Gas-Permeability Testing

The gas-permeability testing consisted of a single constant-pressure-injection test per test interval. Using compressed nitrogen gas as the testing fluid, the test-interval pressure was raised from atmospheric to approximately 140 kPa. The pressure was maintained at this magnitude until either a quasi-steady-state flow rate was achieved or until the gas-supply reservoir decreased below a predetermined pressure. When one of these two conditions occurred, the injection portion of the test was terminated and the subsequent pressure change in the test interval was monitored. The monitoring was terminated when either the test-interval pressure had decreased to ambient pressure conditions (atmospheric) or the rate of pressure decay was determined to be insufficient to reach ambient pressure conditions within 7200 seconds (120 minutes).

The gas testing was conducted primarily in interval B (Figure 3) with interval C monitored for potential leakage of gas between the packer elements and borehole wall. After an individual test was completed, the test tool was moved 0.05 to 0.10 m deeper into the borehole and another test performed. This process was completed until it was observed that the formation permeability to gas was insufficient to transmit gas through the formation.

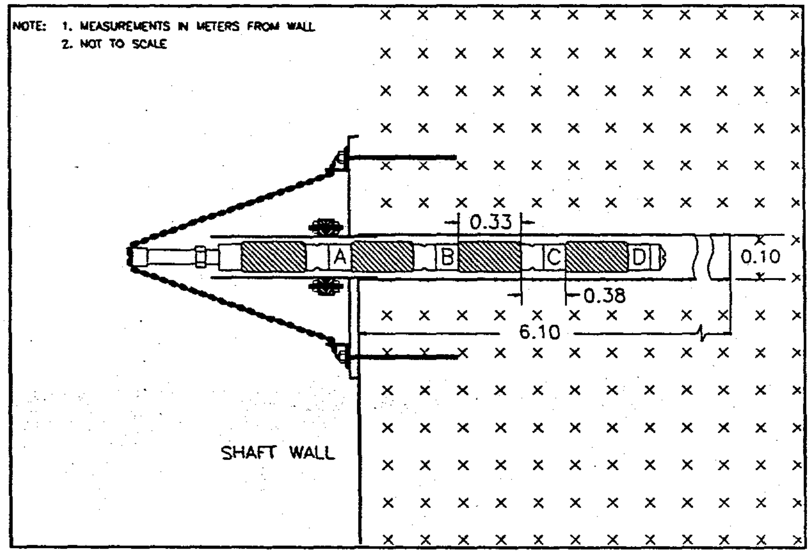

Figure 3 - Typical Gas-Permeability Multi-Packer Test Tool Installation Showing Standard Packer and Interval Dimensions

Brine-Permeability Testing

The brine-permeability testing was conducted using both constant-pressure-injection and pressure pulse-injection tests. The dual-packer test tools were inserted into the brine filled boreholes to a depth such that interval B (Figure 4) was located beyond the distance at which the formation was determined to be fully brine saturated, based on the gas testing results. The packer elements were inflated and all entrapped air was removed from test intervals A and B. The test intervals were then isolated for approximately 3 to 4 days before testing was initiated.

The testing pressure used in the constant-pressure-injection and pressure pulse-injection tests was determined by increasing the interval pressure by 1 to 2 MPa. The testing duration for brine-permeability testing is significantly longer than for the gas-permeability testing. Therefore, the test tool was not moved and only two intervals were tested per borehole. However, multiple tests were conducted in each test interval with testing lasting for approximately 30 days per borehole.

Analysis

The analysis of the permeability testing data was conducted using the numerical well-test interpretation code Graph Theoretic Field Model (GTFM), presented in Pickens et al., 1987. The analysis of borehole pressure data using GTFM can be performed using either a manual fit or a parameter optimization/goodness-of-fit routine, given a range of input parameters. For the analyses presented below, both fit routines were used to obtain a range of permeability estimates for the gas- and brine-permeability testing conducted in the AIS.

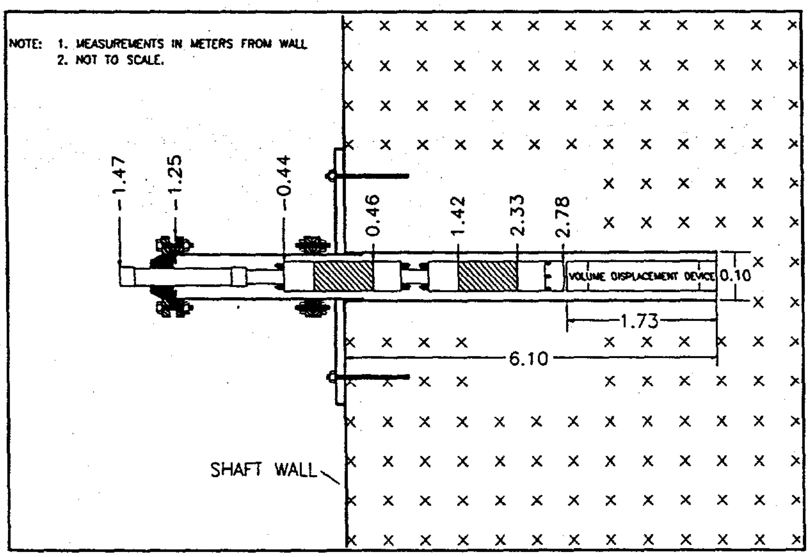

Figure 4 - Brine-Permeability Multi-Packer Test Tool Installation Diagram for Testing Conducted in Borehole VA3

DISCUSSION OF RESULTS

A total of 44 gas-permeability tests were conducted in the six boreholes. Figure 5 presents a plot of test-interval pressure versus elapsed time for a test conducted in borehole VC3 between 0.15 and 0.53 m, as measured from the shaft wall. The plot demonstrates the typical pressure behavior for a zone of rock that has significant permeability to gas. Figure 6 presents the test-interval pressure versus elapsed time plot for a test conducted in borehole VC3 between 0.56 and 0.91 m. This figure demonstrates the typical pressure response (no pressure decay after termination of injection) observed for a zone of rock that has effectively no permeability to gas.

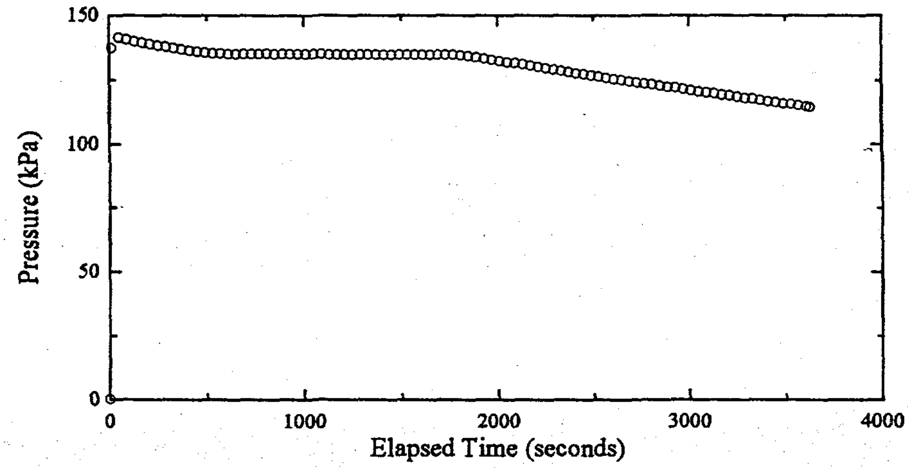

Figure 5 - Pressure Plot for the Gas-Permeability Testing Conducted in the 0.15 to 0.53 m Depth Within Borehole VC3.

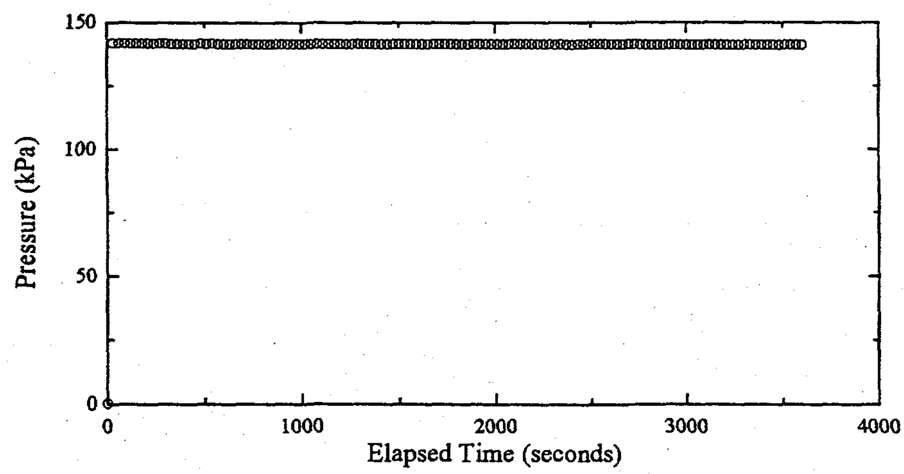

Figure 6 - Pressure Plot for the Gas-Permeability Testing Conducted in the 0.56 to 0.94 m Depth Within Borehole VC3.

A total of 10 brine-permeability tests were conducted in five boreholes. Due to limitations on the amount of time available for testing, no brine-permeability tests were conducted in borehole VC1. Figure 7 presents a data plot of interval pressure versus elapsed time for the testing conducted in intervals A and B in borehole VA3. Interval B extended from 0.46 to 1.4 m and interval A extended from 2.3 to 6.1 m, as measured from the shaft wall. This plot demonstrates the differences in the typical pressure response observed in intervals A and B.

The interpretation of each gas- and brine-permeability test produced an upper and lower bound on the estimated formation permeability to gas/brine. For presentation of the interpretation results, an average permeability value for each gas- and brine-permeability test was calculated and this value was assigned at a radial distance located at the end of the testing interval closest to the shaft wall. Average permeability values for the testing conducted at a horizon depth of 345.9 m bgs (Level A) and 629.4 m bgs (Level C) are presented in Figures 8 and 9, respectively.

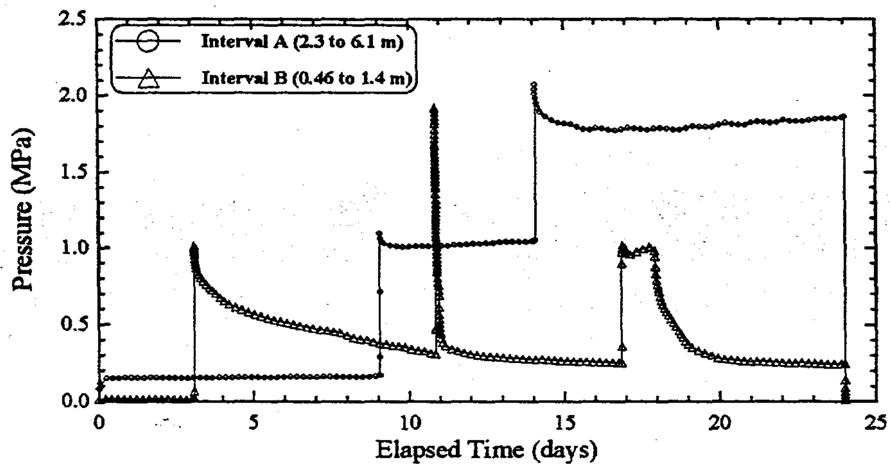

Figure 7 - Plot of Interval A and B Pressures for the Brine-Permeability Testing Conducted in Borehole VA3.

The gas permeability as a function of distance for boreholes VA1 and VA3 show similar trends (Figure 8). The gas permeability for these two boreholes decreased to 1 x 10^{-23} m^2 at a radial distance of approximately 0.3 m. The minimum permeability which could be obtained using the gas-testing equipment was 1 x 10^{-23} m^2. This value was based on the resolution and sensitivity of the testing equipment. The formation permeability to gas was taken to be effectively zero at a permeability of 1 x 10^{-23} m^2. The results from borehole VA2 showed a gas permeability of effectively zero at a distance of approximately 1.0 m. The gas permeability as a function of radial distance at Level C (Figure 9) demonstrate consistent behavior between all three test boreholes. The radial distance at which the gas permeability decreased effectively to zero was between 0.6 to 0.9 m.

Analysis of the gas-permeability testing determined the magnitude of the effective formation permeability to gas. This value may not necessarily represent the intrinsic permeability of the formation. The determination of the intrinsic permeability of a formation requires assessment of the saturation state. If all pathways available for flow within the formation (effective porosity) are fully saturated with respect to gas, then the measured permeability corresponds to the intrinsic permeability. If portions of the flow paths are partially saturated with respect to another fluid, such as brine, the gas-permeability value will be less than the intrinsic permeability. This lower value is a result of the resistance between the two fluids within the formation (Slider, 1983).

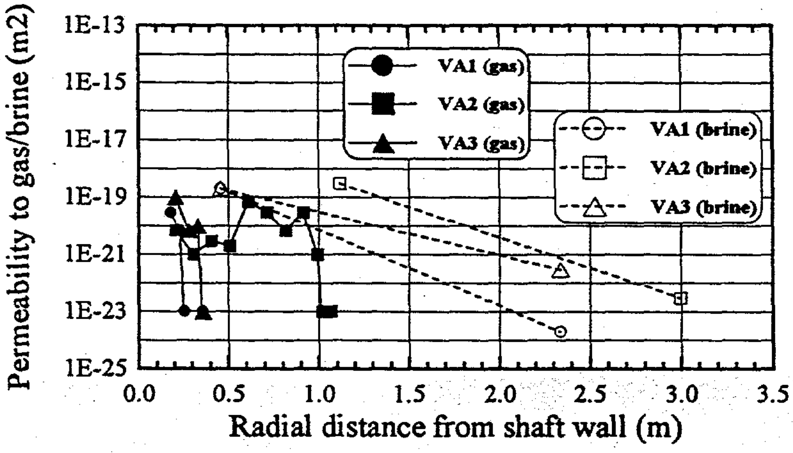

Figure 8 - Gas- and Brine-Permeability Results from Testing Conducted at the 345.9 m bgs Horizon (Level A).

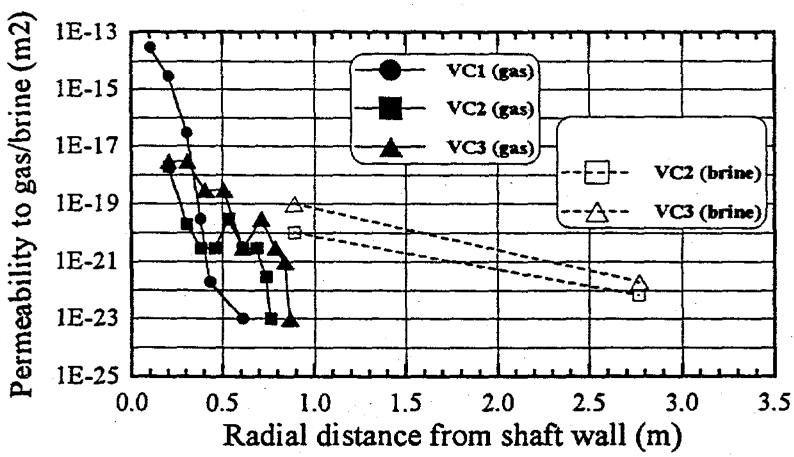

Figure 9 - Gas- and Brine-Permeability Results from Testing Conducted at the 629.4 m bgs Horizon (Level C).

The principal flow paths present in the formation in close proximity to the AIS were assumed to be dilation induced fractures due to the development of the DRZ. The GTFM analysis was conducted on the assumption that all of the flow pathways were saturated with respect to gas and no brine was present. The analysis of the test results indicates that decreasing permeability with radial distance from the shaft wall may be attributed to two mechanisms. The first mechanism is the decrease in the number and/or aperture width of the dilation induced fractures present in the formation. If the only pathways available for gas flow are the dilation induced fractures, then a decrease in the flow path area would result in a decrease in the gas permeability. The second mechanism is the presence of brine in the gas-flow pathways. With the introduction of brine into the gas-flow pathways, the area available for gas flow would decrease, thereby decreasing the effective gas permeability of the formation.

The analysis approach of the brine-permeability testing data assumed that the formation was fully saturated with respect to brine. The interpretation results demonstrated that the formation permeability to brine decreased as a function of radial distance from the AIS (Figures 8 and 9). The brine-testing intervals located closest to the shaft wall (interval B) had an effective brine permeability of 2 to 3 orders of magnitude higher than the testing interval located further from the shaft wall (interval A). The permeability values for interval B at both the upper and lower levels range from approximately 1×10^{-20} to 1×10^{-19} m^2. The permeability values for interval A are all less than 1×10^{-21} m^2. Because the brine-permeability testing intervals were located within the region of the Salado formation that is fully brine saturated, the permeability estimates are equivalent to the intrinsic formation permeability.

CONCLUSIONS

This field testing program gathered pertinent information about the extent and permeability of the DRZ surrounding the AIS at the WIPP. The gas-permeability testing results demonstrate that the formation permeability to gas decreased as a function of radial distance from the shaft wall. In addition, the gas-permeability results from the lower horizon at 629.4 m bgs (Level C) show that the formation permeability to gas is higher and extends further into the formation than at the upper horizon at 345.9 m bgs (Level A). Therefore, the extent of the brine-desaturated DRZ is greater at the lower horizon than at the upper horizon. The brine-permeability results demonstrate that at a maximum distance from the shaft wall of approximately 2.3 m at 345.9 m bgs and 2.8 m at 629.4 m bgs, the formation surrounding the AIS is undisturbed. Therefore, the maximum extent of the DRZ surrounding the AIS at WIPP is less than 3.0 meters.

ACKNOWLEDGMENT

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