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Fluid Flow Measurements of Test Series A and B for the Small Scale Seal Performance Tests

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Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of Energy
under Contract DE-AC04-76DP00789

Printed December 1987

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
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SAND--87-7041

DE88 004437

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FLUID FLOW MEASUREMENTS OF TEST SERIES A AND B FOR THE SMALL SCALE SEAL PERFORMANCE TESTS*

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Abstract

The degree of waste isolation achieved by a repository seal system is dependent upon the fluid flow characteristics (or permeability) of the seals. In order to obtain meaningful, site-specific data on the performance of various possible seal system components, a series of in situ experiments called the Small Scale Seal Performance Tests (SSSPT) are being conducted at the Waste Isolation Pilot Plant (WIPP). This report contains the results of gas flow, tracer penetration, and brine flow tests conducted on concrete seals in vertical (Test Series A) and horizontal (Test Series B) configurations. The test objectives were to evaluate the seal performance and to determine if there existed scaling effects which could influence future SSSPT designs.

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*The work described in this report was performed for Sandia National Laboratories under Contract No.'s 64-0242, 95-4004, and 01-6319.

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1. INTRODUCTION AND BACKGROUND

The U.S. Department of Energy (DOE) is developing the Waste Isolation Pilot Plant (WIPP) facility in southeast New Mexico. The WIPP disposal horizon is located approximately 656 m (2150 feet) below ground surface in a bedded salt deposit. The WIPP facility is being developed for the purpose of providing a research and development facility to demonstrate the safe disposal of radioactive waste resulting from defense programs of the United States (Public Law 96-164). A part of the WIPP Research and Development (R&D) Program conducted by Sandia National Laboratories (SNL) is the Plugging and Sealing Program (PSP). The Plugging and Sealing Program is an integrated program of modeling, laboratory materials testing, and *in situ* testing directed toward developing acceptable sealing technology for the eventual decommissioning of the WIPP facility.

To validate seal design concepts, *in situ* testing of seal components is required. Because of the extremely large size difference between laboratory tests and full-scale *in situ* emplacements, the conduct of a series of intermediate *in situ* experiments is required. Such testing will provide valuable experience with regard to *in situ* seal performance, and thus will be fundamental in evaluating present design concepts and planning for full-scale tests. These tests are called the Small Scale Seal Performance Tests (SSSPT).

The SSSPT involve the emplacement of candidate seal materials in various configurations. Each group of tests is referred to as a test series. From the time of seal emplacement until the termination of a specific test series, thermal and mechanical data will be obtained by instrumentation in boreholes in the rock adjacent to the seal and by instrumentation embedded in the seal itself. Flow characteristics of the seal system will be evaluated by fluid flow measurements. These measurements will use both brine and gas as the working fluid and will be conducted at various working pressures.

The following five test series are currently planned, or are in progress:

<u>Test Series</u>	<u>Seal Material</u>	<u>Direction</u>	<u>Scheduled Emplacement</u>
A	Salt-Based Concrete	Vertical	7/85
B	Salt-Based Concrete	Horizontal	2/86
C	Salt and Bentonite Block and Mortar	Horizontal	3/87
D	Salt and Bentonite Backfill	Vertical	9/87
E	Salt-Based Concrete	Vertical (thru Marker Bed 139)	3/88

Figure 1 illustrates the general test configuration. An emplacement hole is drilled either in the rib (wall) or invert (floor) of the excavation. Seal material, in some cases containing instrumentation, is emplaced over a selected interval in this hole. Small-diameter holes for rock instrumentation are also sometimes drilled adjacent to the emplacement hole. An access hole, to be used for gas or brine injection, is drilled at an angle which allows it to intersect the bottom of the emplacement hole. A dual-packer system is used to seal this access hole so that the interval beneath the plug can be pressurized as required for fluid flow measurements.

The SSSPT program is designed to obtain *in situ* seal design and performance data. These data are important to the selection of materials and configurations suitable for conceptual seal designs at the WIPP. In particular, objectives of the SSSPT are to:

- Determine *in situ* fluid flow performance for various seal systems;
- Determine *in situ* structural performance of the host-rock and seal materials;
- Assess seal emplacement techniques; and
- Support the development of numerical predictive capabilities.

Figure 1. Illustration showing test configuration for the Small-Scale Performance tests.

This report describes results of flow tests conducted on the Test Series A and Test Series B seals. Other pertinent information regarding Test Series A and B are contained in the following reports.

J. C. Stormont, Test Plan: Small-Scale Seal Performance Tests, Sandia National Laboratories, March 1985.

J. C. Stormont, Technical Editor, Development and Implementation: Test Series A of the Small-Scale Seal Performance Tests, SAND85-2602, Sandia National Laboratories, May 1986.

L. D. Wakeley and D. M. Walley, Development and Placement of an Expansive Salt-Saturated Concrete (ESC) for the Waste Isolation Pilot Plant (WIPP), SL-86-36, Waterways Experiment Station, September 1986.

L. L. Van Sambeek and J. C. Stormont, Thermal/Structural Modeling of Test Series A of the Small-Scale Seal Performance Tests, SAND87-0177, Sandia National Laboratories, 1987. (In preparation.)

G. Cones, *et al.*, Small-Scale Seal Performance Tests Laboratory Testing: Results of Test Series A and B, SL-----, Waterways Experiment Station, 1987. (In preparation.)

J. C. Stormont, Thermal/Structural Data Through 180 Days of Test Series A of the Small-Scale Seal Performance Tests, SAND 87 —, Sandia National Laboratories, 1987.

J. C. Stormont and C. L. Howard, Development and Implementation: Test Series B of the Small-Scale Seal Performance Tests, SAND 86-1329, Sandia National Laboratories, December 1986.

This report is arranged as follows. A test description is provided in Section 2. Data obtained during the Series A and B tests is described in Section 3. Analyses of these data and the associated uncertainties inherent in the data interpretation are presented in Section 4, with the discussion focusing on the MAE22 test results. Section 5 presents the Series A test results. The Series B test results are summarized in Section 6. Conclusions are provided in Section 7. There are also two Appendices: Appendix A contains plots of the field data, while Appendix B contains results of a sensitivity study.

2. TEST SERIES DESCRIPTIONS

2.1 TEST SERIES A CONFIGURATION.

Test Series A involves the placement and testing of salt-saturated, expansive concrete seals in vertical (down) boreholes. Six seals, two each of three sizes (e.g., 15.2 cm diameter by 30.4 cm length; 40.6 cm diameter by 60.8 cm length; and, 91.4 cm diameter by 91.4 cm length) were emplaced during July 1985. One seal of each size contained thermal/structural instrumentation both in the seal and adjacent rock; the other seal contained no instrumentation. Fluid flow measurements were made on both the instrumented and non-instrumented seals.

Test Series A was located in the area designated as the M-Room in the WIPP facility, as shown on Figure 2. A plan view of the holes associated with Test Series A layout is given in Figure 3. A complete description of the as-built test hole locations, dimensions, and configurations is given in the Development and Implementation Report (Stormont, 1986).

2.2 TEST SERIES B CONFIGURATION.

Test Series B involves the placement and testing of salt-saturated, expansive concrete seals in horizontal boreholes. The three Series B seals emplaced in February 1986 were 91.4 cm in diameter by 91.4 cm in length. Two seals contained thermal/structural instrumentation, the remaining seal had no instrumentation. Fluid flow measurements were made on all seals.

Test Series B was also located in M-Room of the WIPP facility (see Figure 2). An elevation view of the Test Series B boreholes is given in Figure 4. A complete description of the as-built test hole locations, dimensions, and configurations is given in the Development and Implementation Report (Stormont and Howard, 1986).

Figure 2. Plan view of WIPP facility test area.

Figure 3. Borehole locations for the Test Series A Small-Scale Seal Performance Tests.

Figure 4. Borehole locations for the Test Series B Small-Scale Seal Performance Tests.

2.3 SEAL MATERIAL.

The Test Series A and B seals were made from a salt-saturated expansive concrete designated ESC. Development of the ESC was detailed by Wakeley and Valley (1986). Its placement in Test Series A is described by Stormont (1986), and in Test Series B by Stormont and Howard (1986). Laboratory measurements of physical properties of the ESC were contained in Comes, *et al* (1987). The ESC properties at 90 days were reported to be:

Unconfined Compressive Strength	48.3 MPa
Modulus of Elasticity	24.1 GPa
Poisson's Ratio	0.19
Density	2422 kg/m ³
Permeability	0.8 x 10 ⁻⁶ darcy

2.4 TEST SYSTEM

A schematic of the test system used to perform the gas flow, tracer penetration, and brine flow tests is shown on Figure 5. This measurement system, and the associated data analysis technique, is described in Reference 1.

Figure 5. Schematic showing the Permeability Test System.

3. DATA ACQUISITION

The complete suite of data obtained during the Series A and B tests is included in Appendix A. A general description of these data will be provided using results obtained from the MAE22 Series A tests as examples. These MAE22 data are typical of the data obtained during Test Series A and B.

Tests were performed on the MAE22 (41 cm diameter seal) in the following sequence. First, the test region shown on Figure 1 was pressurized to approximately 2.0 MPa using ^{1.6}Nitrogen. Once a steady flow had been established, tracer was then injected into the test region, and the test was either continued until the tracer was detected above the seal or until some pre-established time period had elapsed. These data were then used to determine the seal and/or formation permeabilities and to estimate the maximum aperture of any fractures which may connect the test region with the open hole above the seal. Once the tracer-gas/flow tests were completed, gas was evacuated from the test region using a vacuum pump. This region was then filled with brine and a brine flow test was initiated. During these tests, measurements were made of the test region pressure and brine flowrate. In addition, the seal surface was periodically checked for evidence of brine flow through the seal. These brine flow data were then used to determine the seal and/or formation brine permeabilities and to estimate the maximum brine flow fracture apertures. A detailed description of the data follows.

The MAE22 gas flow test region pressure history is shown on Figure 6. The region below the seal was initially pressured to approximately 2.0 MPa for 15 hours to establish the gas flow and to determine the resulting flowrate. Nitrogen containing a 2×10^{-9} concentration of bromochlorodifluoromethane as a tracer was slowly injected into the test region through the injection module located at the base of the seal. This process increased the test region pressure to about 2.3 MPa. The borehole was then shut in, and the pressure decay was monitored as a function of time. Simultaneously, gas samples taken in the

Figure 6. Test region pressure history measured during the MAE22 gas flow test.

region above the borehole, were examined for evidence of tracer in order to verify whether flow did occur through or around the seal; and, if it did, to establish the travel time. The gas flow portion of the test was terminated after about 70 hours.

During the test, the pressure was monitored in the guard region of the dual-packer assembly shown on Figure 1. This measurement was made to ensure that the flowrate inferred by the pressure decay data shown on Figure 6 actually represented flow into or through the seal/formation system rather than leakage past the packer assembly. If, for example, significant flow occurred past this assembly, the dual-packer system would be moved within the borehole and re-set at a position where leakage past the packer was small compared to the measured test region flowrate. The guard region pressure history for the MAE22 gas flow test is shown on Figure 7. In this test, there was no flow out of the test region around the test region packer into the guard region.

Changes in gas temperature must be considered when calculating the volumetric flowrate from measured changes in pressure. As expected, the gas temperature increases during pressurization of the test region. However, within a few hours (as shown on Figure 8) the temperature decays to the ambient level where it remains for the duration of the test. In effect, these tests are conducted under isothermal conditions.

During the MAE22 brine flow test, flow to the test region was measured while maintaining an approximate 3.5 MPa downhole pressure for approximately 140 days. As shown on Figure 9, slight variations in pressure occurred during this time. These generally occurred when flow to the test region was stopped and the region isolated in order to measure the associated pressure decay rate or to refill the high-pressure brine supply system. Even with these small pressure excursions, the downhole pressure was maintained between 3.4 and 3.7 MPa for the duration of the test.

During the test, the top of the borehole seal was periodically checked for evidence of brine. A finding of brine above the seal would verify that flow

Figure 7. Guard region pressure history measured during the MAE22 gas flow test.

Figure 8. Test region temperature history measured during the MAE22 gas flow test.

Figure 9. Test region pressure history measured during the MAE22 brine flow test.

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occurred either through or around the seal. The associated brine arrival time would be used to estimate the maximum aperture of those fractures which may connect the test region to the open borehole above the seal.

An average brine flowrate was determined each time the high-pressure brine reservoir was filled from the low-pressure supply system. Flowrates were calculated from the measured low-pressure brine supply pressure drop rate. The MAE22 low-pressure brine supply pressure history is shown on Figure 10. Corresponding brine flowrates are given on Figure 11. Flow into the MAE22 test region remained approximately constant at a rate of 0.01 cc/min throughout the test.

Flow into the seal/formation system is taken as the measured total flow into the test region (shown on Figure 11) minus that going from the test region to the guard region enclosed by the dual-packer assembly. Flow past the lower packer (shown on Figure 5) was determined from the measured guard region pressure changes. Continuous excursions in guard region pressure were seen to occur, and are shown on Figure 12. The pressure drops result because the guard region was vented once the pressure approached 0.80 MPa. The large pressure spike, at about 19 days, was a result of system adjustments. However, the remaining excursions represent flow into the guard region.

One should note that if the 0.01 cc/min flow into the test region were instead to enter the guard region, the guard region pressure would increase to the test region value in about 2 hours. For these tests, the flow to the guard region represents less than 1% of that which is being injected into the test region. Reasons for the higher flow to the guard region at around 120 days remain unknown. Note that even at the higher flowrates, flow to the guard region represented less than 10% of that entering the test region.

Test region temperatures were also measured during the brine flow tests. The MAE22 results are shown on Figure 13. During the first 25 days, the test region temperature remained constant. After this time, the indicated temperature value gradually increased until the RTD used to measure temperature failed after

Figure 10. Brine supply pressure history measured during the MAE22 brine flow test.

Figure 11. MAE 22 brine flowrate calculated from the brine supply pressure history shown on Figure 10.

Figure 12. Guard region pressure history measured during the MAE22 brine flow test.

Figure 13. Test region temperature history measured during the MAE22 brine flow test.

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approximately 50 days. The small variations in temperature observed during the brine flow tests were insignificant in terms of evaluating brine flowrates.

In summary, data obtained during the MAE22 borehole seal tests are shown on Figures 6 through 13. These data are typical of data obtained during Series A and B tests.

4. DATA ANALYSIS AND EVALUATION

The data analysis methods are summarized in Section 4.1, again using the MAE22 test results as examples. Uncertainties inherent in these analyses and interpretations are addressed in the discussion presented in Section 4.2.

4.1 DATA ANALYSIS.

The majority of the Test Series A and B data were analyzed using the one-dimensional steady-state planar and radial flow formulae given in Reference 1. These formulae were used to estimate seal permeabilities, formation permeabilities, and fracture dimensions. Typically, seal permeabilities were determined assuming the surrounding formation was impermeable, while formation permeabilities were estimated assuming an impermeable seal. Clearly, flow in the seal/formation system could result from any combination of these two effects. Reported permeability numbers should, therefore, be interpreted as maximum possible values, rather than actual values.

An extensive quantity of gas flow and brine flow data were obtained during the MAE22 seal tests. These data were analyzed in detail using one- and two-dimensional numerical codes. These analyses will be described in the following paragraphs. The simple one-dimensional calculations used to analyze the majority of the experimental data provide estimates of formation and/or seal permeability values which agree within factors of two of those obtained from the detailed numerical analyses. This agreement is considered acceptable in light of the uncertainties in data interpretation discussed in Section 4.2.

Seal and formation 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 described in Reference 1. To determine a permeability for a gas flow test, the test region shut-in pressure decay was calculated as a function of time for selected permeability and porosity values. If the calculated decay rate corresponded to the measured value, the assumed properties were taken as correct. Recall that

during a gas flow test, the test region shown on Figure 1 was pressured to some desired level, then shut-in, and the subsequent pressure decay history monitored as a function of time.

To determine permeability for a brine flow test, the test region flowrate was calculated as a function of time using the measured test region pressure history together with selected permeability and porosity values. If the calculated flowrate corresponded to the measured value, the assumed properties were taken as correct. Recall that during a brine flow test the test region was maintained at a constant pressure and the corresponding flowrate was measured.

Permeability values were determined for the MAE22 seal and surrounding formation based on the gas flow and brine flow test results. Comparisons of the measured pressure and flow histories with those calculated using the selected seal and formation permeability and porosity values are discussed in the following paragraphs.

Additional comparisons between the calculated and measured responses are provided in Appendix B. For example, the ordinate on the pressure decay curves has been amplified in the 2.0 to 2.5 MPa region so that a more detailed comparison of the pressure decay histories can be made. In addition, results are also presented in Appendix B which show the sensitivity of the calculated responses to the selected permeability and porosity values.

The formation permeability has been determined for both the brine and gas flow tests based on an arbitrarily selected 0.001 porosity. As shown in Appendix B, at these low porosity values, the calculated results are quite insensitive to further reductions in porosity but moderately sensitive to increased porosity values. The calculated results are however quite sensitive to changes in the selected permeability values since the quasi-steady flow is approximately proportional to the permeability.

To determine the seal gas flow permeability, the seal porosity was arbitrarily selected as 0.01. For gas flow through the seal, the sensitivity of the

calculated results to changes in permeability and porosity are as described in the preceding paragraph.

The calculated brine flow through the seal is sensitive to both permeability and porosity since the quasi-steady flow, which is primarily sensitive to permeability, may not be established for a significant portion of the approximate 140-day test period. In contrast, quasi-steady gas flow through the seal is quickly established because the gas viscosity is much lower than that of brine.

A comparison of the calculated and measured MAE22 pressure decay histories obtained assuming gas flow through a seal surrounded by an impermeable formation is shown on Figure 14. The measured and calculated values compare favorably when the seal is assumed to have a 2×10^{-7} darcy permeability and 0.01 porosity. Figure 15 shows results of a calculation in which an impermeable seal was surrounded by a permeable formation. In this case, the measured and calculated pressure histories are compatible, assuming a 6×10^{-9} darcy formation permeability and 0.001 porosity.

A comparison of the calculated and measured MAE22 brine flowrates obtained assuming flow through an initially unsaturated seal surrounded by an impermeable formation is shown on Figure 16. The calculated and measured values are seen to be reasonably compatible, assuming a 2×10^{-7} darcy permeability and 0.03 porosity. Results shown on Figure 16 were obtained using a one-dimensional analytical solution. Initially, the seal fills with brine and, as a result, the flow continues to decrease until it reaches a steady-state level after about 85 days. At this time, brine should begin flowing through the top surface of the seal. An absence of brine at the top surface suggests that at least some of the brine does not flow through the seal.

Results shown on Figure 17 were obtained assuming brine flow into a permeable saturated formation surrounding an impermeable seal. The calculated and measured results are in rough agreement for a 1.2×10^{-8} darcy permeability and 0.001 porosity. For calculational purposes, a transmissive outer boundary was located at a distance 5 m from the cylindrical borehole.

Figure 14. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal.

Figure 15. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation.

Figure 16. Comparison of calculated and measured MAE22 brine flowrates assuming flow through and initially unsaturated seal.

Figure 17. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Transmissive outer boundary at $r = 5$ meters.)

The influence of the outer boundary condition used in the numerical calculation may be evaluated by comparing results shown on Figure 17 with those on Figure 18. Replacement of the transmissive boundary located at the 5 m radius with a zero flow boundary is seen to change the calculated flowrate by less than 10%.

It can be seen on Figures 16 through 18 that the measured flowrate continually decreased with time. This decrease may be simulated to an extent by assuming the flow is through an initially unsaturated seal. However, even after the time at which the calculations suggest the flowrate should become constant, it continues to decrease. The reasons why the measured flowrate decreases with time cannot be determined from the simple Test Series A pressure and flow measurements.

4.2 DATA EVALUATION.

Many *in situ* flow reports emphasize that permeability values inferred from the data are accurate to within an order-of-magnitude. Reasons for these uncertainties, as they apply to seal testing, will be discussed briefly in this subsection.

First, it is important to realize that for Test Series A and B, the order-of-magnitude uncertainty in the inferred permeability values is not associated with the accuracy of the measurement system. This measurement system can determine pressures and temperatures to within a few percent (as reported in Reference 1). Flowrates can easily be inferred from these data to within a factor of two, even for the very low rates shown on Figure 11. In fact, flowrates which are at least one order-of-magnitude lower could also be determined to within factors of two by simply testing over longer time intervals.

The major uncertainties are introduced by the assumptions which must be made when calculating formation characteristics, such as permeability, from measured data. Some of these uncertainties will be described in a qualitative manner in the following paragraphs.

Figure 18. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Zero flow outer boundary at $r = 5$ meters.).

In Test Series A and B, the parameter of primary interest is the seal permeability. Maximum values for seal permeability have been determined by assuming all flow goes through the seal. However, as discussed in this report, one cannot determine whether the flow is going through the seal, into the surrounding formation, or some combination thereof. Furthermore, the test itself may perturb the formation--thereby affecting apparent flowrates. Such perturbations may not always be as readily identifiable as those which occurred during the MAE12 and MAE32 brine tests described in Section 5.2. Consequently, the reported seal and formation permeabilities represent maximum values. In fact, actual permeabilities may be orders-of-magnitude lower than this maximum reported value.

Since the flow paths cannot be identified, reporting a seal permeability may itself be misleading since the flow could possibly occur through the seal/formation interface. In that case, it may be more enlightening to describe the performance of the various diameter seals in terms of flow-per-unit interface length.

The measured flow into the test region may not represent flow through the seal or into the formation at all. For instance, if the brine mix (which is saturated at ambient pressure) is undersaturated at the 3.5 MPa downhole pressure, the back-fill and borehole walls may slowly dissolve. In fact, if one assumes a 10% undersaturated brine initially, then approximately 15% of the measured MAE22 brine flow into the test region could be due solely to dissolution of the halite formation. The relative salt/water volume change associated with dissolution of the halite represents approximately 12% of the actual value of the halite which is dissolved. Another possible volume change involves borehole closure due to salt creep. The maximum estimated hole closure rate at 3.4 MPa is consistent with a change in the measured flowrate of less than $1 \text{ cm}^3/\text{day}$ or about 7% of the total measured flow. If this occurs, then the flow through the formation/seal system would be larger than that indicated by the brine flow measurements.

The fact the MAE22 seal brine flowrate decreased slowly with time (as illustrated on Figure 18) can be extremely important when modeling the very long-term response. Possible mechanisms causing this decrease can include precipitation, healing, or creep closure of the open pore spaces, particularly if the flow is into the formation. However, a decay similar to this may also result if there exists a non-uniform stress-field surrounding the hole with stresses increasing and the pore volume decreasing with increasing distance from the hole.

In these low permeability formations, threshold pressure effects may also be important. If so, a higher test region pressure could substantially increase the flowrate compared to that which would be anticipated from pressure changes alone. Furthermore, gas flow permeabilities may be in error by factors of two to three as a result of the Klinkenberg effect. Estimates of gas and brine permeabilities also depend strongly on the degree of pore saturation, and this is unknown for the WIPP Site formation.

With the exception of brine flow through the seal, for the tests described here, the transient effects associated with filling the pore space or developing a steady-state pressure profile are generally negligible due to the extended test time. These effects occur on time scales which are short compared to those associated with creep closure precipitation, dissolution, etc.

Temperature changes can be very important when testing with gas, and possibly with brine. Fortunately, the temperatures of the formation surrounding the WIPP facility are essentially constant; hence, the flow can be considered isothermal.

Tracers are primarily used to identify flow paths and to provide conclusive evidence that the flow does or does not go through the seal. However, tracer flow arrival times can also be measured and can then be used to estimate maximum fracture aperture dimensions.

A number of factors significantly limit the accuracy to which fracture aperture dimensions can be determined. First, operational realities are such that

rapid arrival times under the 0.1 to 0.2-hour period are not accurately measured, and are therefore often overestimated. Second, if the total fracture dimension is very small, the quantity of tracer which comes through may be small and hence may not be detectable for some period of time following its initial arrival. Finally, the fracture path length (which, for analysis purposes, is taken as the seal length) may actually be quite tortuous and be much longer than assumed. All of these factors tend to lead to estimates of the fracture aperture which are, in effect, too small.

5. TEST SERIES A RESULTS

Results of the gas and brine flow tests performed on the Test Series A seals are described in Sections 5.1 and 5.2 respectively. The seal performances with the different flow media are then compared in Section 5.3.

5.1 GAS FLOW TESTS.

A summary of the Test Series A tracer-gas/flow tests is provided in Table 1. The listed seal test characteristics will be described separately in the following paragraphs.

The permeability values shown were calculated assuming either a permeable seal placed in an impermeable formation, or an impermeable seal placed in a permeable formation. Clearly, some combination of these models is more realistic. All permeability values shown were determined from the data using simple one-dimensional steady-state flow models.

The Test Series A seals, with the exception of MAE31 (which had an obvious leak), had calculated permeabilities of approximately 5×10^{-7} darcy for an assumed 0.01 porosity. In contrast, calculated formation permeability values steadily increased with increasing borehole diameter. This result suggests that the flow may actually occur through the seal, or through some formation discontinuity that exhibits flow dimensions which change as the ratio of seal area divided by seal length. If flow occurred only at the seal/formation interface, then the permeabilities calculated based on the seal cross-section areas should decrease with increasing seal diameter.

It should be noted that the formation permeability values shown on Table 1 are consistent with those determined during the formation permeability tests described in Reference 2. Furthermore, the variation in permeability values shown in Table 1 are within the data scatter obtained during the Reference 2 tests.

Table 1
Summary of Series A Tracer Gas Flow Tests

SEAL	PERMEABILITY ¹ {darcy}		TRACER ARRIVAL (hours)	ESTIMATED ² MAXIMUM FRACTURE APERTURE (cm)	COMMENTS
	SEAL	FORMATION			
MAE11	3×10^{-7}	5×10^{-8}	No Arrival	$(< 10^{-6})$	--
MAE12	8×10^{-7}	4×10^{-8}	No Arrival	$(< 10^{-6})$	--
MAE21	4×10^{-7}	1×10^{-8}	No Arrival	$(< 10^{-6})$	--
MAE22	3×10^{-7}	1×10^{-8}	No Arrival	$(< 10^{-6})$	--
MAE31	2×10^{-5}	2×10^{-6}	1.5	1.3×10^{-5}	Obvious Leak Through Seal
MAE32	5×10^{-7}	3×10^{-8}	No Arrival	$(< 2 \times 10^{-6})$	--

¹ Calculated assuming all flow is either through the seal or through the formation.

$(\phi_{\text{formation}} = 0.001, \phi_{\text{seal}} = 0.01)$

² Numbers in parentheses suggest test sensitivity in that tracer arrival should have occurred by the end of the test if the fracture aperture were greater than the value shown.

Tracer flow tests were performed on each of the Test Series A seals. For these tests, a different tracer was injected below each seal. With the exception of MAE31, no tracer was detected above a seal. Failure to detect tracer above a given seal implies that, if fractures exist, their maximum apertures are less than the dimension shown. It should be noted for reference purposes, that under uniform porous flow conditions, a tracer would travel through the 3×10^{-7} darcy MAE22 seal in about 36 hours.

The MAE31 seal clearly leaked. Gas could be seen bubbling through a thin layer of brine covering the seal surface. Furthermore, as shown in Table 1, its calculated permeability was approximately two orders-of-magnitude greater than the values determined for the other Test Series A seals.

Tracer was first injected below the MAE31 seal, following the same procedure used to test the other Test Series A seals. Even though the seal was known to leak, there was no tracer found above the seal within 48 hours following injection. A second tracer, having a higher concentration (which increased its detectability by a factor of 10^5), was therefore introduced. Its arrival was measured at the time shown in Table 1.

Since all the Test Series A seals were tested using the lower concentration tracer gas mix, it is possible that minute fractures exist in the other seals that were not detected. However, this possibility is considered slight in light of the fact that the relative seal/formation permeabilities of these other systems were almost two orders-of-magnitude below that of MAE31.

5.2 BRINE FLOW TESTS.

Brine flow tests were conducted on the MAE12, MAE22, and MAE32 seals. During these tests, the test region pressure and flowrate were measured. In addition, the top surface of the seal was continuously monitored for evidence of brine penetration. Results of these tests are summarized in Table 2.

Table 2
Summary of Series A Brine Flow Tests

SEAL	PERMEABILITY/POROSITY (darcy)		ESTIMATED ⁴ MAXIMUM FRACTURE APERTURE (cm)	COMMENTS
	SEAL	FORMATION		
MAE12	-- ¹	--	$< 7 \times 10^{-7}$	No Visible Flow Through Seal During 140-day Test With 250 psig Brine Pressure
MAE22	$2.0 \times 10^{-7} / 0.03$ ²	$1.2 \times 10^{-8} / 0.01 \pm 0.001$ ³	$< 1 \times 10^{-6}$	No Visible Flow Through Seal During 140-day Test With 500 psig Brine Pressure
MAE32	-- ¹	--	$< 2 \times 10^{-6}$	No Visible Flow Through Seal During 140-day Test With 250 psig Brine Pressure

¹ Plug and formation permeabilities could not be determined, as brine flowed to adjacent boreholes -- possibly along horizontal fractures. The test pressures were reduced from the 3.5 MPa design level (at which the flowrates continued to increase as a function of time) to 1.8 MPa (where the rates remained constant).

² Assumes seal is initially unsaturated.

³ Assumes formation is saturated.

⁴ Suggests test sensitivity in that tracer arrival should have occurred by the end of the test if the fracture aperture were greater than the value shown.

Permeability values could only be determined for the MAE22 seal/formation system during the Test Series A brine flow tests. Horizontal fractures apparently opened in the floor when the MAE12 and MAE32 test regions were pressured to 3.5 MPa, resulting in rapidly increasing flowrates as shown in the Appendix A data. Subsequently, the test region pressure was lowered to the 1.8 MPa level in order to maintain a constant flowrate. Even at this lower test region pressure, flow was still observed to be traveling from the test regions to nearby access holes. As a result, the MAE12 and MAE32 tests can only be used to determine whether flow occurs through the seal, given a 1.8 MPa test region pressure.

The MAE22 test data are consistent with a brine flow through a seal having a 2×10^{-7} darcy permeability and 0.03 porosity, or through a saturated formation having a 1.2×10^{-8} darcy permeability and 0.01 to 0.0001 porosity. Note that these permeability values were determined using the numerical techniques described in Section 4.1.

During the brine flow tests there was no visible evidence of flow through any seal during the approximate 140-day test period. Absence of flow through the seals suggests that if fractures do exist connecting the test region to the open volume above the seal, their maximum aperture should be less than the listed values.

Brine flow tests had previously been performed on a 1.8 m long by 20 cm diameter cement grout seal installed in anhydrite at the 1370 m depth in the AEC-7 borehole. This 20 cm diameter seal was found to have a brine flow permeability of about 5×10^{-5} darcy. Tracer flow studies performed during that test (described in Reference 3) suggested a maximum fracture aperture of approximately 2×10^{-5} cm, which is similar to that found during the gas flow tests conducted in the MAE31 borehole.

5.3 COMPARISON OF GAS AND BRINE TESTS.

A comparison of the MAE22 seal gas and brine flow test results is shown in Table 3. Values shown for the plug and formation permeabilities were determined using the multi-dimensional numerical analyses described in Section 4.1. The gas flow results, therefore, differ slightly from the Table 1 values obtained using simple one-dimensional steady-flow models.

If all flow is assumed to go through the seal, then the MAE22 seal gas and brine flow permeability values are seen to be identical. This would be expected if the connected pore space were unsaturated over the duration of the gas flow tests, and saturated during the brine flow tests.

If all flow is assumed to enter the formation, then the formation permeability to gas (calculated assuming an unsaturated formation) differs only by a factor of two from the brine permeability value calculated assuming a saturated formation. The similarity in these permeability values, calculated under very different assumptions, is striking. It suggests that if the flow were into the formation, those flow channels responsible for these measurements were indeed unsaturated. If the flow channels were saturated and the gas flow data had been analyzed assuming an unsaturated formation, the resulting gas permeability value would be about a factor of 30 less than the indicated brine permeability value.

Both tracer gas and brine flow tests were conducted on the MAE22 seal in order to determine flow arrival times. Steady-state gas flow through a uniform seal having a 2×10^{-7} darcy permeability and 0.01 porosity would yield a flow arrival of about 54 hours, given a 2.3 MPa test region pressure. Similarly, brine flow through an initially unsaturated seal having a 2×10^{-7} darcy permeability and 0.03 porosity would yield an arrival in 85 days, for a 3.5 MPa test region pressure. No arrivals were seen in 50 hours for gas or 137 days for brine. The inability of the tracer gas or brine to penetrate the seal in these times suggests that its permeability may be less than the 2×10^{-7} darcy value.

Table 3
Summary of Analysis of MAE22 Gas and Brine Flow Tests

TEST	PERMEABILITY/POROSITY (darcy)		COMMENTS
	SEAL	FORMATION	
Gas Flow	$2.0 \times 10^{-7} / 0.01$ ¹	$6.0 \times 10^{-9} / 0.001$ ²	No Measured Tracer Gas Penetration Through Seal
Brine Flow	$2.0 \times 10^{-7} / 0.03$ ³	$1.2 \times 10^{-8} / 0.01 \leftrightarrow 0.001$ ⁴	No Visible Brine Flow Through Seal

¹ Assumes seal is unsaturated.

² Assumes formation is unsaturated.

³ Assumes seal is initially unsaturated.

⁴ Assumes formation is saturated

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6. TEST SERIES B RESULTS

A summary of the Test Series B tracer gas flow test results is provided in Table 4. There were no brine flow tests performed on the horizontally-emplaced Series B seals.

The shut-in pressure decay rates measured during the April 1986 MBE31, MBE32, and MBE33 tests implied formation and seal permeability values which were within a factor of two of those determined during tests on the vertically-emplaced MAE32 seal. Only the MBE31 seal/formation system had a permeability value larger than obtained in the MAE32 test. Recall that in the MAE32 test there was no observable leakage through or around the seal.

All the Test Series B seals leaked during the April 1986 tests. However, the leak rates were small. Measured tracer arrival times ranged between 0.1 and 0.3 hours--although the actual arrivals were thought to be much sooner. Actual maximum fracture aperture dimensions are, therefore, thought to be greater than or equal to the dimensions listed in Table 4. The tracer concentrations used for the Series B tests were essentially the same as those used on the second MAE31 test.

A dominant leak path was identified in each of the Test Series B seals. In the uninstrumented MBE31 seal/formation system, the leak (at least in the region of the seal face) was through a small formation fracture located below the seal center-line. In the instrumented MBE32 and MBE33 seals, the leak occurred along the instrumentation bundle. There was no detectable leakage at the seal/formation interface on any of these seals. However, due to the high concentration of tracer being emitted from the small observed leaks, the seal/formation interface leakage measurement was not extremely sensitive.

The tracer gas/flow tests were repeated in May 1987. Results of those tests are included in Table 4.

Table 4
Comparison of the April 1986 and May 1987 Series B Tracer Gas Flow Tests

SEAL	PERMEABILITY* (darcy)		TRACER ARRIVAL (hours)	ESTIMATED MAXIMUM FRACTURE APERTURE (cm)	COMMENTS
	SEAL	FORMATION			
MBE31 April 1986	1×10^{-8}	8×10^{-8}	< 0.3	$> 2 \times 10^{-5}$	Leak Through Fracture In Formation Below Seal
MBE31 May 1987	2×10^{-7}	1×10^{-8}	No Arrival (264 hours)	$< 8 \times 10^{-7}$	-
MBE32 April 1986	4×10^{-7}	3×10^{-8}	< 0.2	$> 3 \times 10^{-5}$	Leak Along Instrumentation Bundle
MBE32 May 1987	2×10^{-7}	1×10^{-8}	No Arrival (26 hours)	$< 3 \times 10^{-6}$	-
MBE33 April 1986	2×10^{-7}	1×10^{-8}	< 0.1	$> 4 \times 10^{-5}$	Leak Along Instrumentation Bundle
MBE33 May 1987	7×10^{-7}	5×10^{-8}	No Arrival (24 hours)	$< 3 \times 10^{-6}$	-
MAE 32	5×10^{-7}	3×10^{-8}	No Arrival	$< 2 \times 10^{-6}$	-

- * Calculated assuming all flow is either through the seal or through the formation.
 $[\phi_{\text{formation}} = 0.001, \phi_{\text{seal}} = 0.01]$

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During the second series of tests, no measurable quantity of tracer penetrated the seals. Clearly a significant reduction in flow path size had occurred during the interim period. For example, during the April 1986 tests, tracer penetration occurred through all seals in less than .3 hours. In contrast, no measurable tracer arrivals occurred during the May 1987 test periods (shown in parenthesis on Table 4).

During the May 1987 tests, the seal permeabilities were found to be less than 7×10^{-7} darcy, under the assumption that all flow went through the seal. If the seals were assumed impermeable, with all flow going into the formation, the resulting formation permeabilities would be less than 5×10^{-8} darcy. These values are similar to those obtained for the 91 cm diameter MAE32 vertical seal.

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7. CONCLUSIONS

A series of tests has been performed to evaluate the flow characteristics of salt-based concrete plugs placed in both vertically-down boreholes and horizontal boreholes. Both gas-with-tracer tests and brine flow tests were conducted on the seals placed in the vertically-down boreholes. Only the gas-with-tracer tests were performed on the seals placed in the horizontal boreholes.

The permeabilities of the 15 cm, 41 cm, and 91 cm seals placed in the vertical boreholes were (with one exception) found to be less than 5×10^{-7} darcy, under the assumption that all flow went through the seal. If the seals were assumed to be impermeable, with all flow going into the formation, the resulting formation permeabilities would be less than 3×10^{-8} darcy. These formation permeabilities are consistent with results determined during previous formation tests.

There was little indication that the performance of the vertically-emplaced seals depended on the seal diameter. However, the influence, if any, of such scaling effects could not be determined with certainty, since the relative fraction of the flow which went through the seal or into the formation during these tests could not be determined.

For five of the six seals emplaced in the vertical boreholes, there was no measurable tracer gas or brine penetration through the seal or along the seal/formation interface. This result is consistent with the measured permeability values. The 91 cm diameter instrumented seal leaked; however, the leak path could not be identified.

Tracer-gas/flow tests conducted in April 1986 showed that all three horizontally-emplaced, 91 cm diameter seals had small leaks. The uninstrumented seal leaked through a small formation fracture located directly below the seal. The two instrumented horizontal seals leaked along the instrumentation bundles. There was no evidence during tests on the

horizontally-emplaced seals that leakage occurred around the seal/formation interface.

The tracer-gas/flow tests were repeated on the horizontal seals in May 1987. During these tests, no detectable quantity of tracer penetrated the seals. Clearly a significant reduction in flow path size had occurred during the interim period between tests. The permeabilities of the horizontal seals, during the May 1987 tests, were found to be less than 7×10^{-7} darcy under the assumption that all flow went through the seal. If the seals were assumed impermeable, the resulting formation permeabilities would be less than 5×10^{-8} darcy. These values are essentially identical to those obtained for the 91 cm diameter vertical seal.

Brine flow test results obtained on the 41 cm diameter seal placed in the MAE22 vertical borehole were consistent with a 2×10^{-7} darcy seal permeability and 10^{-8} darcy formation permeability. These values agreed with those determined from the gas flow tests, suggesting that those flow paths responsible for the measured flow results were initially unsaturated.

Additional tests remain to be performed. The most important of these is to determine whether the measured flow characteristics of both the horizontally and vertically-emplaced seals continue to change with time. These tests, or similar tests, will therefore be repeated on the already-tested boreholes at some later date. Those data will subsequently be compared to the data presented in this report.

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APPENDIX A

SSSPT FLUID FLOW MEASUREMENT DATA

This Appendix contains plots of the field data used to determine the results presented in the body of this report. These data were originally recorded on a Hewlett Packard Model 3056 Data Logger. A general description of these data is provided in Section 2.

The pressure acquisition system was calibrated in psi units. Note that 14.7 psi is equivalent to 0.1 MPa, and 1 psi equals 6.8×10^{-3} MPa.

Figure A-1. Test region pressure history measured during the MAE11 gas flow test.

Figure A-2. Guard region pressure history measured during the MAE11 gas flow test.

Figure A-3. Test region temperature history measured during the MAE11 gas flow test.

Figure A-4. Test region pressure history measured during the MAE12 gas flow test.

Figure A-5. Guard region pressure history measured during the MAE12 gas flow test.

Figure A-6. Test region temperature history measured during the MAE12 gas flow test.

Figure A-7. Test region pressure history measured during the MAE21 gas flow test.

Figure A-8. Guard region pressure history measured during the MAE21 gas flow test.

Figure A-9. Test region temperature history measured during the MAE21 gas flow test.

Figure A-10. Test region pressure history measured during the MAE22 gas flow test.

Figure A-11. Guard region pressure history measured during the MAE22 gas flow test.

Figure A-12. Test region temperature history measured during the MAE22 gas flow test.

Figure A-13. Test region pressure history measured during the MAE31 gas flow test.

Figure A-14. Guard region pressure history measured during the MAE31 gas flow test.

Figure A-15. Test region temperature history measured during the MAE31 gas flow test.

Figure A-16. Test region pressure history measured during the MAE32 gas flow test.

Figure A-17. Guard region pressure history measured during the MAE32 gas flow test.

Figure A-18. Test region temperature history measured during the MAE32 gas flow test.

Figure A-19. Test region pressure history measured during the MAE12 brine flow test.

Figure A-20. Brine supply pressure history measured during the MAE12 brine flow test.

Figure A-21. MAE12 brine flowrate calculated from the brine supply pressure history shown on Figure A-20.

Figure A-22. Guard region pressure history measured during the MAE12 brine flow test.

Figure A-23. Test region pressure history measured during the MAE12 brine flow test.

Figure A-24. Test region pressure history measured during the MAE22 brine flow test.

Figure A-25. Brine supply pressure history measured during the MAE22 brine flow test.

Figure A-26. MAE22 brine flowrate calculated from the brine supply pressure history shown on Figure A-25.

Figure A-27. Guard region pressure history measured during the MAE22 brine flow test.

Figure A-28. Test region temperature history measured during the MAE22 brine flow test.

Figure A-29. Test region pressure history measured during the MAE32 brine flow test.

Figure A-30. Brine supply pressure history measured during the MAE32 brine flow test.

Figure A-31. MAE32 brine flowrate calculated from the brine supply pressure history shown on Figure A-30.

Figure A-32. Guard region pressure history measured during the MAE32 brine flow test.

Figure A-33. Test region temperature history measured during the MAE32 brine flow test.

Figure A-34. Test region pressure history measured during the April 1986 MBE31 gas flow test.

Figure A-35. Guard region pressure history measured during the April 1986 MBE31 gas flow test.

Figure A-36. Test region temperature history measured during the April 1986 MBE31 gas flow test.

Figure A-37. Test region pressure history measured during the April 1986 MBE32 gas flow test.

Figure A-38. Guard region pressure history measured during the April 1986 MBE32 gas flow test.

Figure A-39. Test region temperature history measured during the April 1986 MBE32 gas flow test.

Figure A-40. Test region pressure history measured during the April 1986 MBE33 gas flow test.

Figure A-41. Guard region pressure history measured during the April 1986 MBE33 gas flow test.

Figure A-42. Test region temperature history measured during the April 1986 MBE33 gas flow test.

Figure A-43. Test region pressure history measured during the May 1987 MBE 31 gas flow test.

Figure A-44. Guard region pressure history measured during the May 1987 MBE 31 gas flow test.

Figure A-45. Test region temperature history measured during the May 1987 MBE 31 gas flow test.

Figure A-46. Test region pressure history measured during the May 1987 MBE 32 gas flow test.

Figure A-47. Guard region pressure history measured during the May 1987 MBE 32 gas flow test.

Figure A-48. Test region temperature history measured during the May 1987 MBE 32 gas flow test.

Figure A-49. Test region pressure history measured during the May 1987 MBE 33 gas flow test.

Figure A-50. Guard region pressure history measured during the May 1987 MBE 33 gas flow test.

Figure A-51. Test region temperature history measured during the May 1987 MEE 33 gas flow test.

APPENDIX B

PARAMETER SENSITIVITY

This Appendix contains plots which compare calculated pressure and flow histories with measured data. The sensitivity of the data interpretation to the selected seal and formation permeability and porosity values can be determined by comparing the results shown on these Figures.

Notes

- The "Time" shown on Figures B-1 through B-10 is measured beginning from the time the calculated and measured pressures are compared on Figures 14 and 15.
- The calculations for Figures B-16 through B-20 assume a transmissive outer boundary at $r = 5$ meters.

Figure B-1. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal (see Figure 14).

Figure B-2. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal. (Compare with Figure B-1 to determine the effect of changing the seal porosity from 0.01 to 0.001.)

Figure B-3. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal. (Compare with Figure B-1 to determine the effect of changing the seal porosity from 0.01 to 0.1.)

Figure B-4. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal. (Compare with Figure B-1 to determine the effect of changing the seal permeability from 2×10^{-7} darcy to 2×10^{-6} darcy.)

Figure B-5. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow through the seal. (Compare with Figure B-1 to determine the effect of changing the seal permeability from 2×10^{-7} darcy to 2×10^{-8} darcy.)

Figure B-6. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation (see Figure 15).

Figure B-7. Comparison of calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation. (Compare with Figure B-6 to determine the effect of changing the formation porosity from 0.001 to 0.0001.)

Figure B-8. Compare the calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation. (Compare with Figure B-6 to determine the effect of changing the formation porosity from 0.001 to 0.01.)

Figure B-9. Compare the calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation. [Compare with Figure B-6 to determine the effect of changing the formation permeability from 6×10^{-9} darcy to 6×10^{-8} darcy.]

Figure B-10. Compare the calculated and measured MAE22 pressure decay histories assuming gas flow into an unsaturated formation. (Compare with Figure B-6 to determine the effect of changing the formation permeability from 6×10^{-9} darcy to 6×10^{-10} darcy.)

Figure B-11. Comparison of calculated and measured MAE22 brine flowrates assuming flow through an initially unsaturated seal (see Figure 16).

Figure B-12. Comparison of calculated and measured MAE22 brine flowrates assuming flow through an initially unsaturated seal. (Compare with Figure B-11 to determine the effect of changing the seal porosity from 0.03 to 0.015.)

Figure B-13. Comparison of calculated and measured MAE22 brine flowrates assuming flow through an initially unsaturated seal. (Compare with Figure B-11 to determine the effect of changing the seal porosity from 0.03 to 0.15.)

Figure B-14. Comparison of calculated and measured MAE22 brine flowrates assuming flow through an initially unsaturated seal. (Compare to Figure B-11 to determine the effect of changing the seal permeability from 2×10^{-7} darcy to 2×10^{-6} darcy.)

Figure B-15. Comparison of calculated and measured MAE22 brine flowrates assuming flow through an initially unsaturated seal. (Compare with Figure B-11 to determine the effect of changing the seal permeability from 2×10^{-7} darcy to 2×10^{-8} darcy.)

Figure B-16. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation (see Figure 17).

Figure B-17. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Compare to Figure B-16 to determine the effect of changing the formation porosity from 0.001 to 0.01.)

Figure B-18. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Compare to Figure B-16 to determine the effect of changing the formation porosity from 0.001 to 0.0001.)

Figure B-19. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Compare with Figure B-16 to determine the effect of changing the formation permeability from 1.2×10^{-8} darcy to 1.2×10^{-7} darcy.)

Figure B-20. Comparison of calculated and measured MAE22 brine flowrates assuming flow into a saturated formation. (Compare to Figure B-16 to determine the effect of changing the formation permeability from 1.2×10^{-8} darcy to 1.2×10^{-9} darcy.)

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