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FIELD AND LABORATORY TESTING OF SEAL MATERIALS PROPOSED FOR THE WASTE ISOLATION PILOT PLANT

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ABSTRACT

The Small Scale Seal Performance Tests (SSSPT) were a series of *in situ* tests designed to evaluate the feasibility of various materials for sealing purposes. Testing was initiated in 1985 and concluded in 1995. Materials selected for the SSSPT included salt-saturated concrete, a 50%/50% mixture of crushed salt and bentonite, bentonite, and crushed salt. This paper presents a summary of the SSSPT field program, results of the *in situ* testing, and a discussion of post-testing laboratory studies of salt-saturated concrete. Results of the SSSPT support the use of salt-saturated concrete, compacted bentonite clay, and compacted crushed salt as sealing materials for the WIPP.

BACKGROUND

The Waste Isolation Pilot Plant (WIPP), located in southeastern New Mexico, is being developed by the U. S. Department of Energy (DOE) as a potential disposal site for transuranic wastes. The disposal site is located approximately 650 meters below ground surface and consists of a repository mined in a bedded salt deposit. Disposal of wastes in salt is considered advantageous because over time the salt will creep, closing around the waste and thereby encapsulating and isolating hazardous constituents from the accessible environment. Prior to certification as a disposal site and initiation of disposal activities, the DOE must demonstrate that the WIPP will meet all regulatory requirements. As part of this demonstration, Sandia National Laboratories (SNL) is working with the DOE to develop a sealing system design for the four shafts that provide access to the repository.

This paper discusses the Small Scale Seal Performance Tests (SSSPTs), a series of *in situ* tests designed by SNL and conducted by SNL and Westinghouse Electric Corporation, Waste Isolation Division to evaluate the feasibility of various materials for sealing purposes. The discussion is focused on the results of the field program, with a brief summary of the post-test laboratory analysis of concrete seal materials. The positive results of the SSSPTs support the inclusion of salt-saturated concrete, compacted crushed salt, and compacted bentonite clay in the current WIPP shaft sealing system design.

The system design (DOE, 1995) is based on the use of effective seal materials and the reduction of uncertainty through functional redundancy. Seal components must maintain structural integrity and act as barriers to fluid flow throughout their design life. Redundancy is obtained through the use of multiple components and materials. Salt-saturated concrete, asphalt, and compacted bentonite clay components will serve as barriers to fluid flow for several hundred years following shaft seal construction, allowing time for the primary long-term crushed salt seal to become fully effective. Crushed salt and compacted bentonite clay materials comprise the long-term components for the shaft seal system. These components are expected to remain functional for thousands of years. A conceptualization of the proposed WIPP shaft sealing system design is depicted in Figure 1.

SMALL SCALE SEAL PERFORMANCE TESTS: PROGRAM GOALS AND DESCRIPTION

To assess the performance of candidate seal materials *in situ*, the SSSPTs were initiated several years before the current WIPP sealing system de-

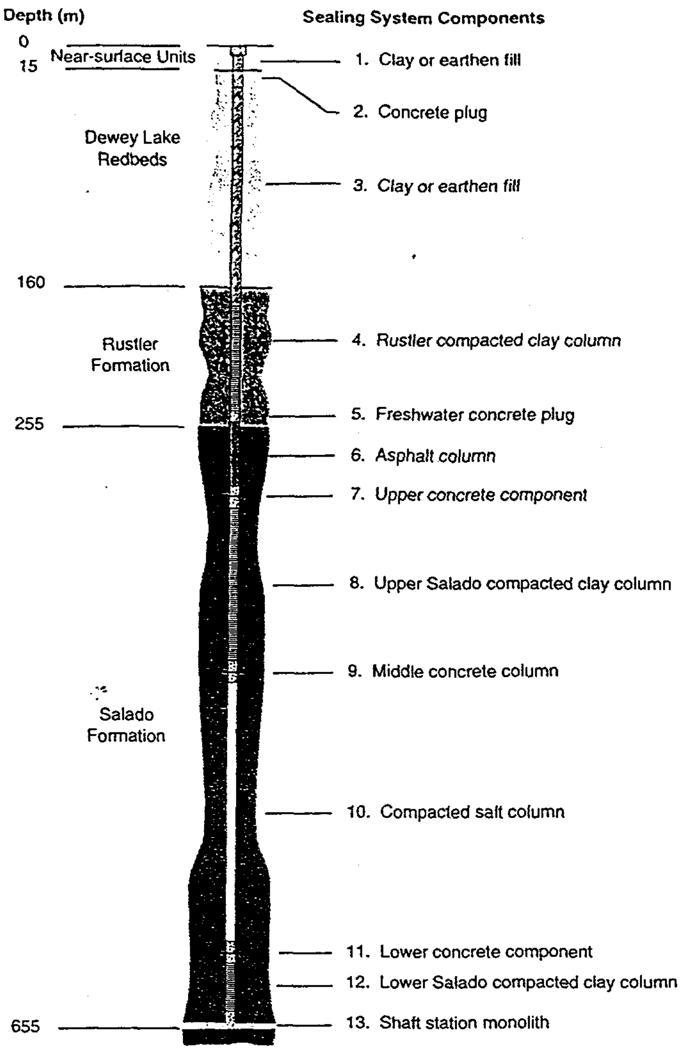
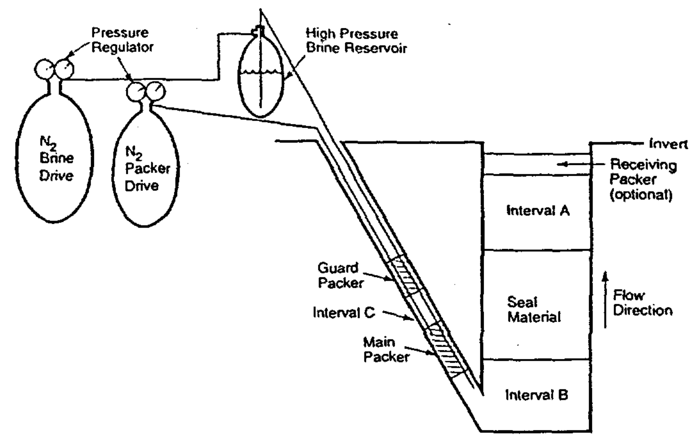


Figure 1. Proposed seal design for the WIPP Air Intake Shaft.



Fluid Flow Testing Procedure
1) Inflate packers
2) Pressurize interval B
3) Monitor pressure in interval C to assess any leakage
4a) Monitor interval A for tracer-gas presence for tracer-gas testing, OR
4b) Monitor fluid flow rate into interval C for constant pressure injection testing, OR
4c) Monitor pressure decay rate in interval C for constant volume testing

Figure 2. General test configuration and fluid flow test procedures for Small-Scale Seal Performance Tests (SSSPT).

sign. Five series of tests were conducted on seals up to 1m in diameter. Essential SSSPT goals were to (1) use seal emplacement technologies that are compatible with standard industrial practices, (2) demonstrate reduction in fluid flows, and (3) verify that seal components remain structurally sound. Test results were used to evaluate materials in terms of the sealing program goals. The small scale of the field tests (hence the name) allowed performance of numerous tests under a range of conditions and configurations.

A series of five SSSPT tests (A-D and F) was initiated in 1985 under the guidance of the original Test Plan. Series F consisted of a grating demonstration and is not discussed in this paper. (The fourth test was later expanded into two phases.) Details on the development, construction, and proposed testing sequence for each series were documented as addenda to the original Test Plan. Each test series evaluated a different seal material and/or seal configuration. Seal materials were emplaced in either horizontal or vertical boreholes at the repository horizon. Figure 2 presents a schematic of a typical SSSPT for the emplacement borehole, seal structure, and fluid flow test apparatus configuration. Many of the emplaced seals were equipped with internal stress and strain gages.

Table I lists the seal material, configurations, and construction dates of SSSPT Series A-D. A brief description of the seal materials is presented in Table II.

The SSSPT field program verified that the candidate materials could be emplaced using standard industrial equipment and practices. The *in situ* fluid flow and structural behavior of the seal materials were also assessed. In addition to the field test program, samples from a salt-saturated concrete seal (emplaced in 1985) and the surrounding host rock were extracted from the field configuration for labo-

Table I. Small Scale Seal Performance Tests: Series A–D

Series	Number of Seals	Seal Material	Seal Orientation	Borehole Diameter (cm)	Seal Length (cm)	Construction Date
A	6	Salt-Saturated Concrete	Vertical	15–91	95	July 1985
B	3	Salt-Saturated Concrete	Horizontal	91	91	February 1986
C	6	Crushed Salt Blocks, Bentonite Blocks, and 50%/50% Salt/ Bentonite Blocks	Horizontal	91	91	September 1986 through December 1990
D Phase 1	3	Salt Blocks	Vertical	97	300	January 1988
D Phase 2	2	Bentonite Block Core	Vertical	97	91	September 1989

Table II. Seal Material Descriptions

Seal Material	Material Description
Salt-Saturated Concrete	Salt saturated concrete, slightly expansive.
Crushed Salt	Salt block density relative to intact salt was 82%.
50%/50% Salt/Bentonite Blocks	Salt/ Bentonite Blocks were a mixture of 50% salt and 50% bentonite by weight. Density relative to intact materials was approximately 78%.
Bentonite Block Core	Core of one seal was 1.8 g/cc dry density. Core of second seal was 2.0 g/cc dry density.

ratory analysis in 1994. The analysis included visual observation of the seal/rock interface, quantitative evaluation of the gas permeability of the seal material, and petrographic analysis of the seal material and the surrounding host rock.

EMPLACEMENT TECHNIQUES

A primary goal of the SSSPT program was to use or adapt existing technology to the construction of repository seals. Methods used to construct seals for SSSPT Series A–D were all direct applications of widely used construction practices. Emplacement configurations for each series are summarized.

Test Series A consisted of concrete seals emplaced in vertical-down boreholes. Salt-saturated concrete was emplaced in selected seal intervals using gravity flow. No forms were used. In some cases, vibration was used to promote even concrete distribution around structural performance gages (Stormont, 1986).

Series B seals were also comprised of concrete, but were emplaced to plug horizontal boreholes. Construction of these seals employed a small pump to fill pre-formed intervals with concrete. Vibration was not applied (Stormont and Howard, 1986).

Series C seals consisted of precompacted salt and salt/bentonite block structures that were constructed to plug horizontal boreholes. One-meter intervals of the round boreholes were enlarged to create square chambers into which the blocks were emplaced. The blocks were manufactured using a modified pressed-earth adobe block machine and emplaced to form a seal structure with minimal void spaces. No mortar was used between blocks (Stormont and Howard, 1987).

Series D seals were also constructed of precompacted salt, salt/bentonite, and pure bentonite blocks, but the seal structures were built to plug vertical-down boreholes. Phase 1 seals consisted of salt blocks. Phase 2 seals consisted of a 100% bentonite core with layers of 50%/50% crushed salt/bentonite and/or 100% crushed salt above and below the core. Emplacement techniques were essentially the same as for Series C except that blocks were trimmed to conform to the cylindrical geometry. Portions of blocks were excavated as necessary to accommodate gages placed for monitoring structural performance (Torres et al., 1992). In some cases, crushed salt was compacted directly into the seal interval using a hand-operated tamper to achieve densities approximating those achieved using precompacted blocks.

FLUID FLOW PERFORMANCE

Seal system permeabilities for the SSSPTs, derived from a series of *in situ* fluid flow measurements, are presented in Table III. The concrete seals have been subjected to the most extensive fluid testing program. All seals were either gas- or brine-flow tested immediately following seal construction in 1985 to 1987, and a selected subset was retested from 1993 to mid-1995. Fluid injection pressures of up to 2.3 MPa were used in the field testing program. Tracer-gas testing, constant-pressure gas- and brine-flow testing, and constant-volume brine-flow testing were conducted on the concrete seal systems. The seal system consists of the seal material, the seal/host rock interface, the zone of rock immediately surrounding the seal, and the far-field host rock. These tests do not provide information regarding the flow paths of the test fluid. Therefore, the calculated system permeability represents a composite fluid barrier presented by the seal system. From an engineering perspective, these tests provide an excellent means for evaluating the entire seal system.

Seal system permeabilities for the concrete SSSPT were derived through numerical computer simulations of brine- and gas-flow behavior. Fluid injection was simulated for a conceptualized model of the seal system. Estimated ranges for the formation and seal permeabilities, formation storativity, and seal porosity were used to generate pressure-decay and mass-flow-rate curves. The generated curves were then compared to the field data. Hundreds of computer simulations were used in the analysis, and a best fit to the field data was obtained using an optimization routine. This technique produced a best estimate of the permeability for each seal system. Details of the analysis tool and conceptual model may be found in Pickens et al. (1987) and Beauheim et al. (1993).

To improve confidence in the data interpretation, additional testing was conducted to characterize the actual flow paths. Several boreholes were drilled in the formation surrounding a Series A seal. Gas flow testing was conducted in these boreholes to assess the extent and permeability of the disturbed rock zone in the test area. The permeability of the disturbed zone was found to be approximately 10^{-20} m^2,

Table III. Summary of SSSPT Seal System Permeabilities

Test Fluid	Concrete Permeability (m^2)	Concrete Permeability (m^2)	50%/50% Salt/bentonite Permeability (m^2)	100% Bentonite Permeability (m^2)
Test Period	**(1985-1987)**	**(1993-1995)**	**(1986-1990)**	**(1988-1995)**
Gas	$10^{-17} - 10^{-20}$	$10^{-19} - 10^{-23}$	–	see Figure 3
Brine	$\sim 10^{-19}$	$10^{-19} - 10^{-22}$	$\sim 10^{-16}$	$\sim 10^{-19}$

which was consistent with the permeability of the complete seal system.

Brine flow testing was conducted on 50%/50% crushed salt/bentonite seals. A high rate of brine injection led to failure of the first seal, so the brine injection rate was reduced for the second and third test sequences. An average pressure differential of less than 0.013 MPa was maintained throughout the testing period. The steady-state flow rate of brine into the test interval was monitored for approximately 800 days. Brine that seeped through the front of the seal was recirculated during this period (Finley and Jones, 1994). Assuming that all flow occurred through the seal and that one-dimensional Darcy flow approximations are valid, the permeability of the 50%/50% salt/bentonite seal material was derived from Darcy's Law. Attempts to conduct gas flow testing were unsuccessful because of a small separation at the seal/host rock interface. The brine permeability of the 50%/50% salt/bentonite seal material was two orders of magnitude higher than laboratory values of similar materials.

The crushed salt seals constructed for Series D, Phase 1 were not expected to present a barrier to flow until the salt had reconsolidated to at least 90% of the density of intact halite. At the time of test termination in mid-1995, the seal material was determined to have a porosity of at least 12% (i.e., a fractional density of 88% of the density of intact halite compared to 82% at the start of the test). Attempts to develop gas pressure in the seal test interval confirmed that the permeability of the crushed salt was too high to constitute an effective fluid barrier. This finding was consistent with the expected behavior of reconsolidating crushed salt.

Brine injection testing was conducted on the two vertically emplaced bentonite core seals. Testing was initiated in 1990 for one seal and in 1994 for the second seal. Throughout the testing period, the pressure differentials across the seals were maintained at approximately 0.72 and 0.32 MPa, respectively. During the test period, no brine was observed at the top of either seal. A conservative estimate for the seal system permeability was made by assuming that (1) the seal material was saturated; (2) test conditions were at steady state; (3) all flow was into the seal material; and (4) formation brine contributions were negligible. The permeability was then derived from Darcy's Law in a manner similar to that used for the 50%/50% crushed salt/bentonite seals, and is listed in Table III.

Gas flow testing was conducted on one of the bentonite core seals to evaluate the gas threshold pressure of the seal material. The test interval was pressurized in 0.67-MPa intervals. After each increase in pressure, the interval was shut in to allow the system to come to equilibrium. As shown in Figure 3, the seal exhibited negligible gas flow until the test interval pressure exceeded 4 MPa. This test was conducted to provide qualitative information on the behavior of bentonite seals subjected to high gas pressure.

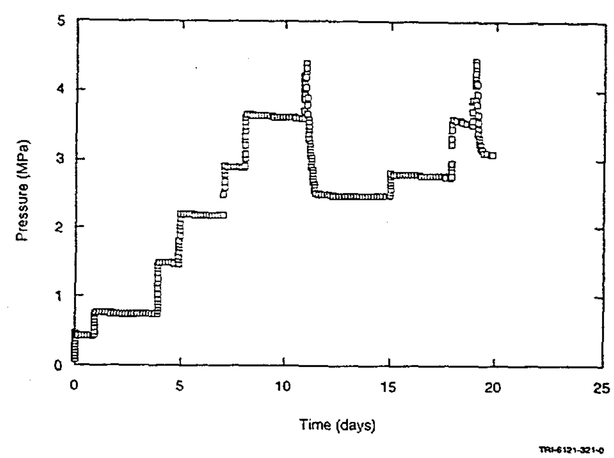


Figure 3. Results of gas flow testing of a 100% bentonite core seal.

STRUCTURAL PERFORMANCE

Many of the SSSPTs were equipped with internal stress and strain gages. Measurements taken from these gages were used to monitor the seal structural performance. Structural failure of a seal material would be detected through seal stress- and strain-state monitoring, fluid flow measurements, and visual observation. The creep behavior of the host rock would also influence the structural response of a seal material. Quantification of the salt creep was derived from borehole closure measurements, which were made in both open and closed boreholes. Gage type, orientation, and location are specified in the applicable test plan addendum. A representative sampling of the SSSPT gage data is presented here.

The structural response of the concrete seals can be evaluated from inspection of radial and circum-

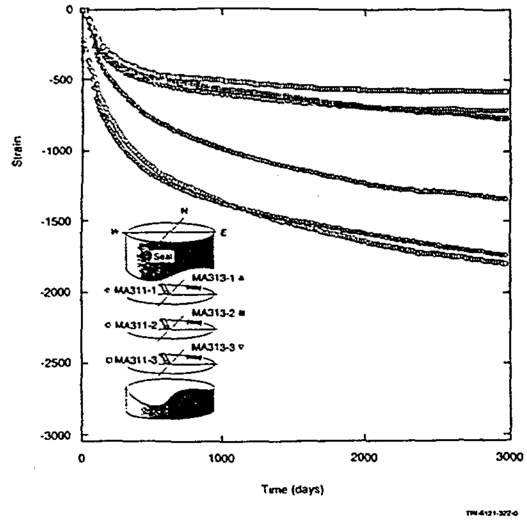


Figure 4. Radial and circumferential strain gage data from vertically-emplaced concrete seals.

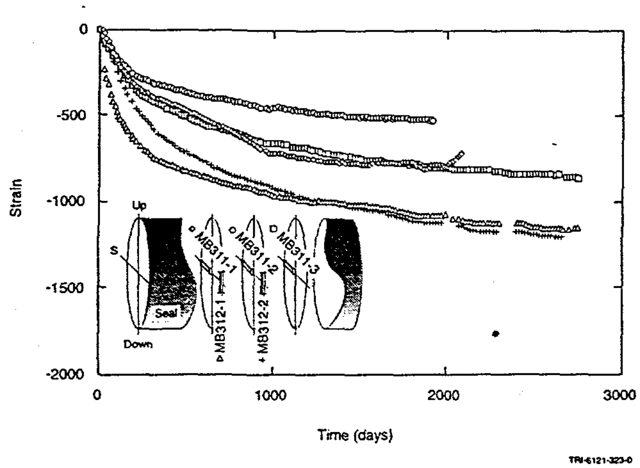


Figure 5. Radial and circumferential strain gage data from horizontally-emplaced concrete seals.

ferential strain (Figures 4 and 5), radial stress (Figure 6), and borehole closure measurements (Figure 7). The general strain gage trend depicts a compressive strain rate that was relatively rapid after seal emplacement but that monotonically decayed with time and continued to increase, but at ever slower rates. This behavior reflects the concrete strains under the compressive loading applied by the surrounding salt. The stress gage data showed that seal compressive stresses rose rapidly immediately following seal construction, attaining steady-state after 100 to 200 days. Creep closure of the borehole was inhibited by the presence of the concrete seal, as illustrated in Figure 7.

Visual observations of the concrete seals revealed no spalling or other external evidence of structural degradation. The relatively smooth trend

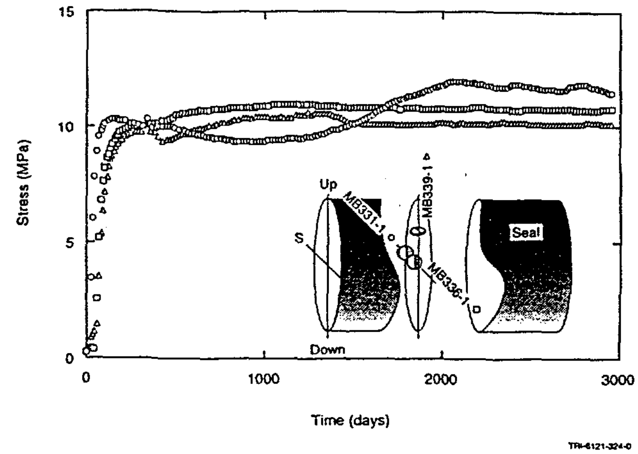


Figure 6. Radial stress data from horizontally-emplaced concrete seals.

of stress and strain gage data, coupled with the results of fluid flow testing, visual observations, and laboratory analysis (presented in the next section) corroborate the conclusion that the salt-saturated concrete maintained structural integrity throughout the testing period. The unconfined compressive strength of the salt-saturated concrete exceeds predicted formation *in situ* stresses by more than a factor of three (Wakeley et al., 1995).

The constitutive model for reconsolidation of crushed salt (Callahan et al., 1995) predicts very little resistance to porosity reduction for porosities greater than 10%. Borehole closure measurements from the 100% crushed salt seals (Figure 8) support this prediction. These seals were emplaced with an initial porosity of approximately 18%. Seven years

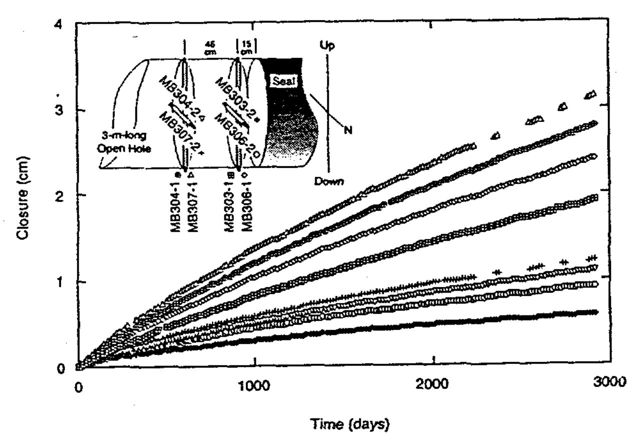


Figure 7. Borehole closure data from horizontally-emplaced concrete seals.

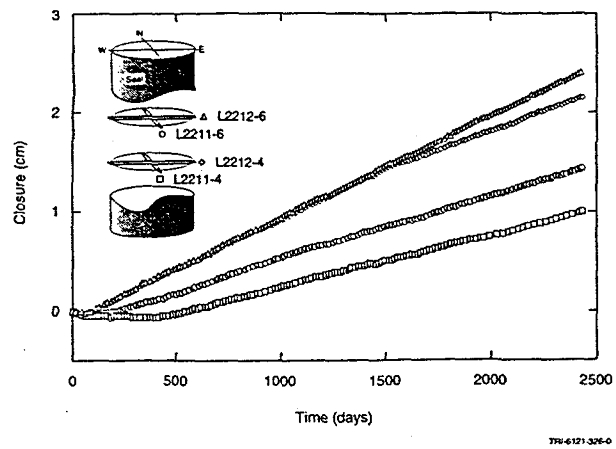


Figure 8. *Borehole closure measurements for 100% crushed salt seals. Gages are located internally at approximately 1.5m and 2.1m below the top of the seal.*

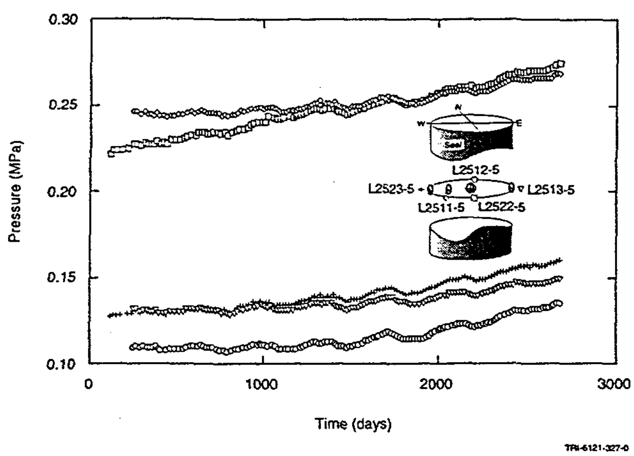


Figure 9. *Internal pressure data for 100% crushed salt seals.*

later, closure measurements indicate that the porosity may have been reduced to approximately 12%. These internal closure measurements differ only slightly from closure in an empty borehole. Measures of stresses internal to these seals are nominally between 0.1 and 0.2 MPa, as shown in Figure 9. This finding is also consistent with model predictions that the crushed salt will offer little resistance to closure when the material porosity is greater than 10%.

Nominal internal stresses for the 100% bentonite core seals are shown in Figures 10 and 11. The increasing trend shown in Figure 10 could be the result of compression resulting from borehole closure, bentonite swell pressure, or a combination of the two processes. The reduction in stress at approximately 1400 days, shown in Figure 11, may be related to

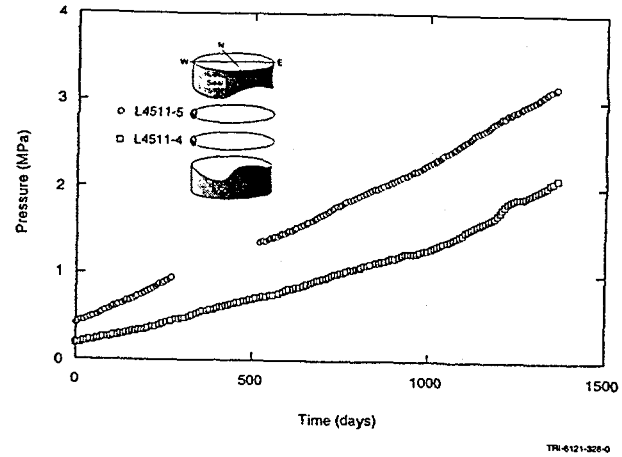


Figure 10. *Internal pressure data for 100% bentonite core seal.*

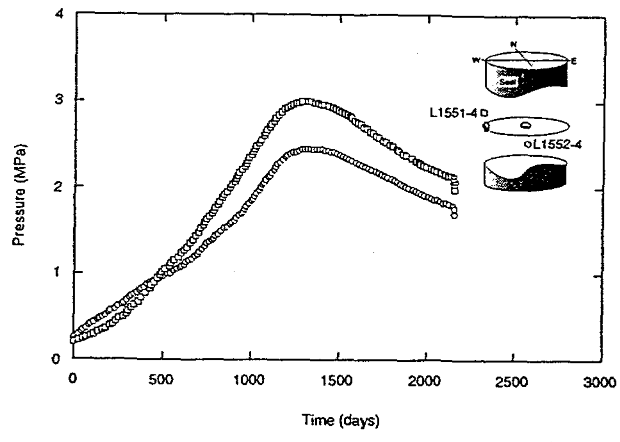


Figure 11. *Internal pressure data for 100% bentonite core seal.*

ion-exchange with permeant brines in the bentonite fabric. These issues are currently being addressed by a separate laboratory program.

Structural performance data (as derived from stress, strain, and borehole closure data) were consistent with current understanding and expectations of the respective seal materials. To the extent necessary for demonstrating sealing design adequacy, these data will be incorporated into the material models used to evaluate the shaft sealing design.

LABORATORY TESTING OF SSSPT CONCRETE

In late 1994, approximately nine years following construction of the vertically-emplaced concrete seals, a "post-mortem" analysis of the sealing system was conducted. Cores of intact host rock and samples of the concrete seal material and seal/host rock interface were extracted from the test region. Petrographic studies of the phase assemblages of the concrete seal material and the microstructure of the intact rock were conducted. Gas permeability testing was conducted on concrete core samples.

Preliminary results of the laboratory tests indicate that, although the concrete seal was exposed to native brines during the testing period, the material experienced no deterioration in performance capabilities. Phase assemblage analysis of the concrete showed minimal degradation of the seal material. This result is consistent with a more extensive analysis of concrete specimens extracted from the WIPP underground in 1991 (Wakeley et al., 1993). The gas permeability of the concrete core samples was found to be approximately 10^{-20} m^2, which is consistent with the field measurements.

The seal/host rock interface was visually inspected for signs of brine migration and deterioration along the interface zone. No signs of degradation or separation were found. In addition to visual inspection of the interface, field observations of the retrieval were recorded. During extraction of the seal/host rock interface material, breakage occurred preferentially through the seal material rather than along the interface. This observation was consistent with direct shear testing of concrete specimens extracted from the WIPP underground in 1991 (Wakeley et al., 1993).

Microstructural analysis of the intact rock showed dilation along the salt grain boundaries for specimens taken from the immediate vicinity of an open borehole. Specimens taken in the immediate vicinity of the concrete seal, as well as those from a far-field location, showed no dilation. The calculated gas permeability for these regions also showed that, in the immediate vicinity of the concrete seal, a disturbed zone did not exist. The absence of a disturbed zone in this vicinity indicates that either the seal prevented the formation of a disturbed zone or that, through the process of creep closure, any disturbed rock zone that had formed around the seal was subsequently eliminated. The post-mortem testing sequence provided additional confidence in the ability of salt-saturated concrete to retain fluid flow and structural performance capabilities in WIPP salt.

SUMMARY AND CONCLUSIONS

The goals of the SSSPT series to use standard industrial practices for seal emplacement and to evaluate seal materials for their ability to retard fluid migration and remain structurally sound were met. No new technologies were developed for the emplacement of the SSSPTs. Fluid flow testing of the sealing systems provided strong evidence that both salt-saturated concrete and bentonite would function effectively as barriers to fluid flow. The testing also supported model predictions of the behavior of a crushed salt seal and resulted in elimination of 50%/50% crushed salt/bentonite as a viable seal material. Stress, strain, and borehole closure data, when coupled to visual observations and fluid flow test results, demonstrated that all seal materials maintained structural integrity throughout the testing period. A post-mortem analysis of the concrete sealing system provided additional confidence in the ability of this material to function effectively at the WIPP horizon.

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