IN SITU SEAL TESTS AT THE WASTE ISOLATION PILOT PLANT (WIPP)*

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ABSTRACT

The first in a series of in situ tests on candidate seal performance has been conducted at the Waste Isolation Pilot Plant (WIPP). These tests represent a phase of testing intermediate between laboratory and full-scale seal evaluations, and are significant because they will provide an in situ evaluation of the thermal, mechanical, and fluid flow performance of seal systems. The scale of the tests allowed the cost-efficient conduct of numerous tests under a wide range of conditions.

The first test series is evaluating an expansive, salt-water based concrete emplaced in boreholes drilled in the floor of the WIPP facility. Emplaced seals range in size from 3-ft(91-cm)-dia by 3-ft(91-cm)-length to 6-in(15-cm)-dia by 1-ft(30-cm)-length to examine size effects. In some emplacements, the seal material and the adjacent rock was instrumented to obtain data on the temperature, stress, strain, and displacement fields. Results after 180 days indicate substantial interface pressures from creep of the surrounding rock salt. After the seals had cured about 1 month, a series of gas and brine permeability measurements, including tracers, were made. These measurements reveal that the concrete seal system is an excellent barrier to both brine and gas. These measurements will be repeated in the future to discern time-dependent effects.

INTRODUCTION

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 2150 feet (650m) below ground surface in a bedded salt deposit. The WIPP facility is 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 tests directed toward developing acceptable sealing technology for the eventual decommissioning of the WIPP facility.[1]

Sealing design concepts have been presented for WIPP penetrations.[1,2] These concepts include the use of cementitious materials (grouts and concretes) and "natural" materials (salt and bentonite). Primary features of the conceptual seal designs include bulkhead-type seals in the shafts and at the entries to waste disposal panels, and backfills in waste-containing rooms as well as non-waste containing rooms. The bulkhead-type seals may be comprised of concrete and salt and/or bentonite block and mortar components. Backfills are envisioned to be crushed or mined salt, possibly with the addition of bentonite in some instances. Boreholes are planned to be sealed with cementitious grouts.

To validate seal design concepts,.in situ testing of seal components is required. Full size, or nearly so, tests of major seal components are planned. 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).

These intermediate scale tests are important because they will be conducted in the WIPP facility, and thus conditions encountered will be those which will ultimately be faced when the WIPP is sealed. Attempts at duplication of the in situ condition in the laboratory can be very difficult at best, and the imposed environment is never certain to represent the real case. Equally important is the fact that these tests will be the largest tests to date and information on seal performance as a function of size will be gathered. Significantly limiting the size of these test seals below "full size" makes them more manageable and less expensive. More tests can be conducted under a wider range of conditions and the analysis may be more straightforward than if they were full scale tests. These tests will ensure that when costly full scale tests are conducted they will be most relevant to the sealing of the WIPP and have the greatest chance of success.

TEST DESCRIPTION

The Small Scale Seal Performance Tests (SSSPT)[3] are a series of in situ experiments designed to evaluate the performance of various candidate seal materials emplaced in boreholes from 6-in- (15.2-cm) to 36-in- (91.4-cm) diameter in rock. Seal system (comprised of the seal, seal/rock interface, and the rock adjacent to the seal) performance will be evaluated using thermal/structural and fluid flow data generated by these tests under repository conditions. Figure 1 illustrates the general test configuration. An emplacement hole is drilled either in the rib (wall) or invert (floor) of the excavation. The seal material, in some cases containing instrumentation, is emplaced over a select *interval in this* hole. Small-diameter holes may also be drilled adjacent to the emplacement hole for rock instrumentation. An access or injection hole is drilled at an

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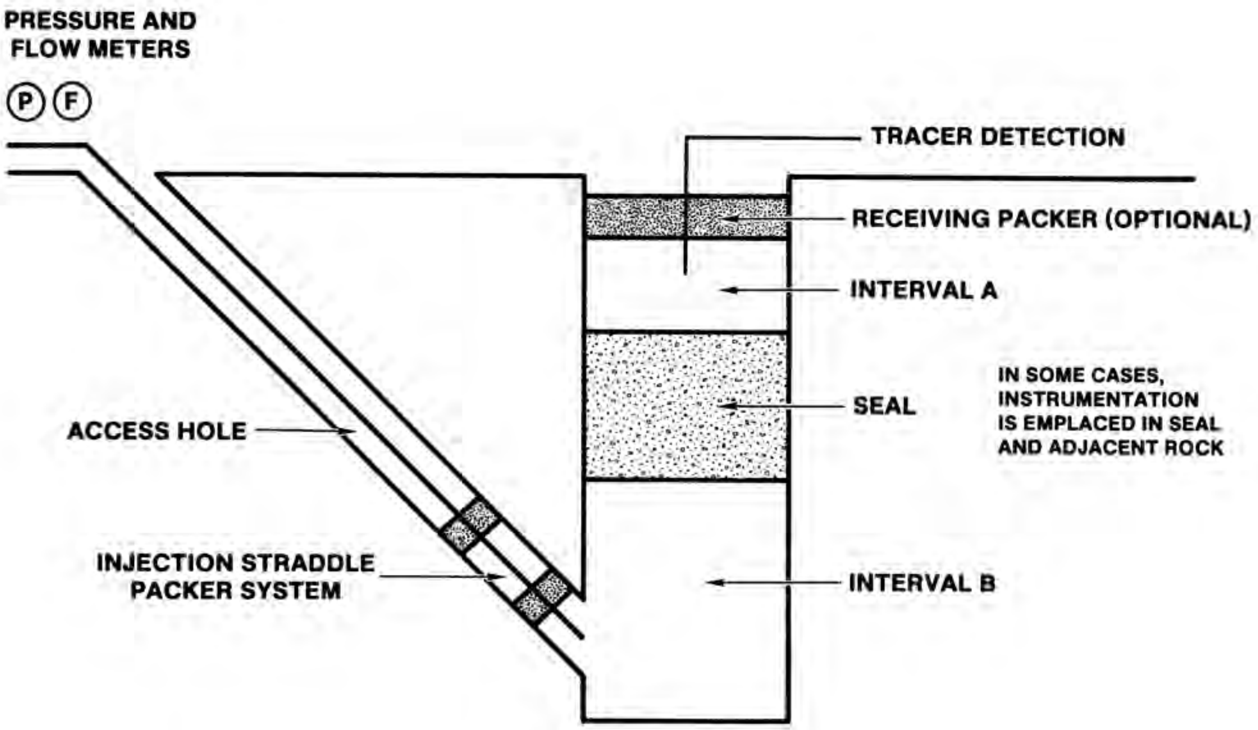

Fig. 1. General Test Configuration for Small Scale Seal Performance Tests.

angle so that it intersects the bottom of the emplacement hole. A packer system is placed in the access hole, and the interval beneath the plug can be pressurized with gas and brine for permeability measurements.

The SSSPT will provide a great deal of data applicable to in situ seal design and performance. This data will be important to the selection of materials and configurations for conceptual seal designs for the WIPP. In particular, objectives of the SSSPT are to:

1. determine in situ fluid flow performance for various seal systems;
2. determine in situ structural performance of the host-rock and seal materials for various seal systems;
3. assess seal emplacement techniques; and
4. support the development of numerical predictive capabilities.

There are five test series currently planned for the SSSPT:

Test Series	Seal Material	Direction	Scheduled Emplacement
A	Salt-based concrete	Vertical	Emplaced 7/85
B	Salt-based concrete	Horizontal	2/86
C	Salt and bentonite block and mortar	Horizontal	6/86
D	Salt and bentonite backfill	Vertical	1/87
E	Salt-based concrete	Vertical (thru anhydrite layer)	6/87

This paper will discuss preliminary results from Test Series A. More complete and detailed analyses are in progress.

Test Series A involves the placement and testing of salt-water-based concrete seals in vertical (down) boreholes. Three sizes were emplaced: 6-in (15-cm) dia., 1-ft (30-cm) length; 16-in (41-cm) dia., 2-ft (60-cm) length; 3-ft (91-cm) dia., 3-ft (91-cm) length. There are six total emplacements in Test Series A, two of each size. One set contains structural instrumentation in the seal and rock, the other set has no instrumentation. Permeability measurements were made on both sets of seals.

Figures 2, 3, and 4 provide details of emplacement MAE21; similar detail is available for the remaining emplacements in Stormont[4]. Figure 2 is an east-west cross-section, showing the actual dimensions of the holes, seal, *and backfill*. Figure 3 is a north-south cross-section of the same hole, and provides details pertaining to the location of the instrumentation. The three stations or levels of instrumentation are detailed in Fig. 4.

SEAL MATERIAL

The conduct of Test Series A required the development of a suitable candidate concrete seal material. Such a concrete must utilize salt-saturated mix water to preclude dissolution of the

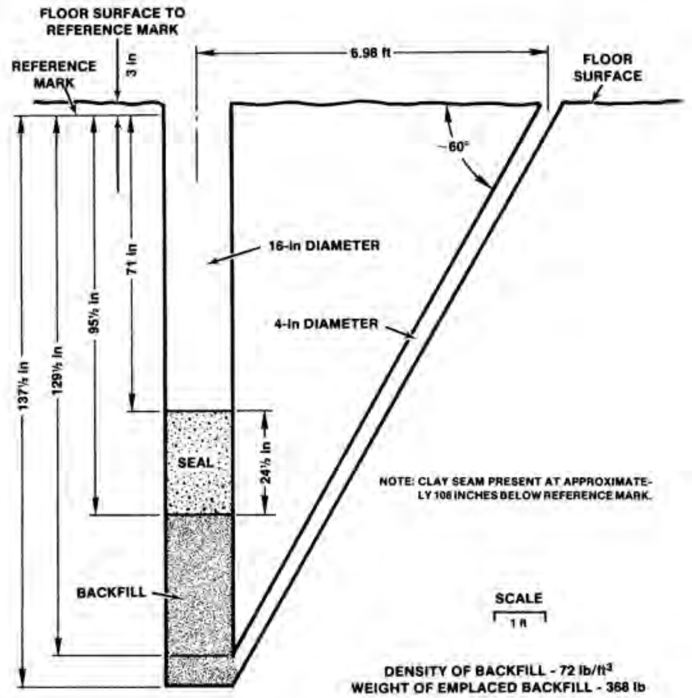

Fig. 2. As Built East-West Cross Section of a Typical SSSPT Emplacement.

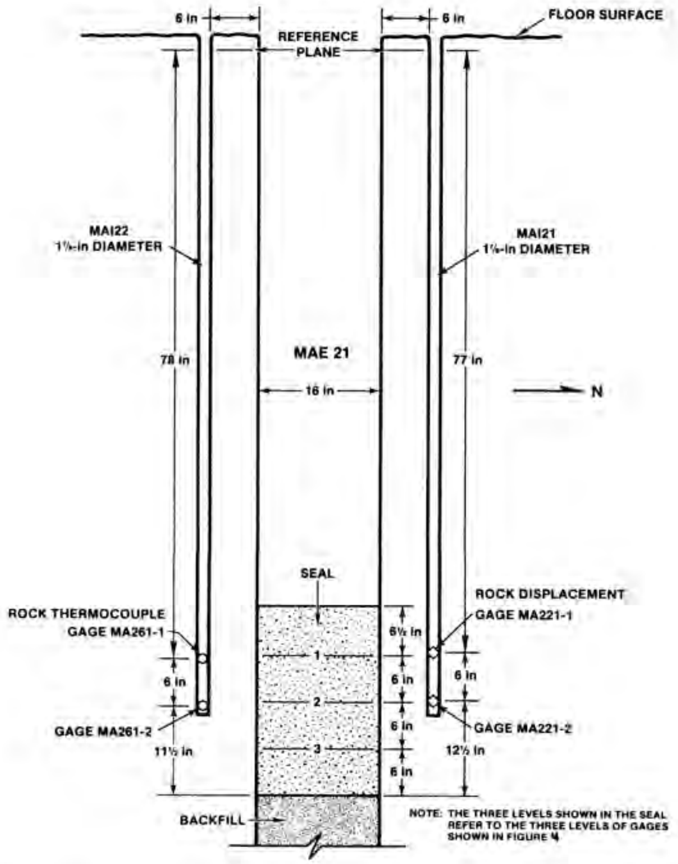

Fig. 3. As Built North-South Cross Section of a Typical SSSPT Emplacement. The Indicated Levels Correspond to Instrumentation Detailed in Fig. 4.

adjacent host salt during hydration. Further, the concrete was required to be expansive to produce a tight seal-rock interface. While it was recognized that the creep of the salt surrounding the seal would tend to force the seal rock together, and expansive concrete was desired because it is likely that the shrinkage of a typical concrete would exceed the inward closure of the borehole for some period of time. This condition had to be avoided to ensure that the seal could be self-supporting in the vertical borehole, and to allow representative permeability measurements to be conducted soon after concrete placement and not to have to wait for the rock to close in on the concrete. In addition, it is doubtful that an interface which has been "open" for some time can be expected to close in a manner which will restore it to a condition which is comparable to an interface which has always been relatively tight.

Previously developed salt-water based concretes[5] did not possess sufficient expansion believed to be required for the in situ test. Through a series of laboratory investigations conducted at the U.S. Army Corps of Engineers Waterways Experiment Station (WES) facility, an expansive, salt-water mix water concrete was developed. This concrete is referred to as the ESC--Expansive Saltwater Concrete. The ESC mix ingredients are given in Table I.

The ESC contains two cement types: a Class H cement which has been used in previously developed cementitious grouts for the WIPP, and a Type K cement which was added to increase the net expansion of the concrete system. Sodium citrate was added to reduce the required water content and to slow the hydration so that the mix would remain workable for a sufficient period of time. Both the aggregate and sand were local (Carlsbad, NM) products and the remaining ingredients are available nationally.

TABLE I

Expansive Salt-Water Concrete Mixture

Material	Wt. lb. to make 1 ft3
Class H cement	13.5
Chem. Comp. III (Type K) cement	9.0
Fly Ash	7.6
Plaster	2.7
Aggregate, 3/4" max.	51.7
Concrete Sand	51.0
Fine salt (NaCl)	3.7
Sodium Citrate	0.16
De-Air #1	0.32
Water	10.6

The concrete has the following properties at 60 days:

Unconfined compressive strength	4500 psi (31.0 MPa)
Modulus of Elasticity	2.8×10^6 psi (19.3 GPa)
Poisson's Ratio	0.15
Density	149.5 lb/ft^3 (2422 kg/m^3)
Restrained expansion	0.06 percent

SEAL EMPLACEMENT

The installation of Test Series A represented the first placement of a concrete seal material in the

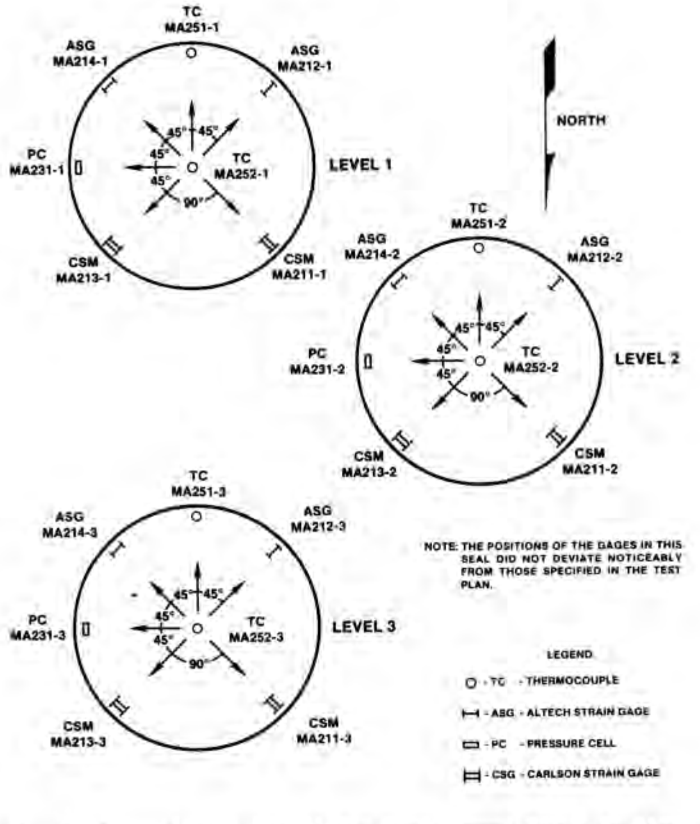

Fig. 4. Instrumentation Detail for Emplacement Shown in Figs. 2 and 3.

WIPP facility. Thus, the method of mixing, transport, and placement of the concrete had to be developed.

Prior to pouring the concrete seals, a salt backfill was placed in the bottom 3 feet (1 m) of the emplacement holes. This backfill serves as a support for the seal, and provides a test zone used for the introduction of gas and brine below the seal (see Fig. 1). The backfill also ensures that the brine, mixed to saturation at ambient pressure, will be saturated at test pressures to preclude preferential dissolution along the seal/rock interface. Test batches of the ESC placed on the backfill indicated no bleeding of the concrete through the backfill. The test interval also contains a gas/brine release and recirculation module, used for the permeability measurements.

It is important to have field acceptance tests which can confirm that any given batch of concrete mixed has properties similar to those intended by design, particularly for contractors who will be emplacing the seal materials on a commercial basis. If the mixture does not meet the field acceptance criterion, it can be discarded or corrected if possible. In the case of Test Series A, a slump (a measure of the concrete's workability) measurement of at least 10 inches (25-cm) was selected as a requirement before the concrete was accepted. Test Series A provided an opportunity to assess the practicability and usefulness of slump as a field acceptance test.

The concrete used for the test was mixed at the surface as opposed to underground at the site of seal emplacements. This was done as a practical matter (size of mixer required, handling large volumes of sand,aggregate and cement underground) as well as to make the emplacement as representative of large-scale sealing operations as possible. The emplacement was executed between 4 am and 9 am on July 30, 1985. The cooler air temperature in the early morning helped to maintain a longer working time as suggested by previous trial mix batches. Also, there was less interference with the daily activities of the WIPP facility. Iced water was used when mixing the concrete because this would help increase the working time of the mix. When the final mixing was complete the concrete had a slump of 10 1/4 (26-cm) inches. The entire mixing operation took 36 minutes. The concrete was transported to the emplacement site in one cubic yard buckets. The six seals, requiring a total of about 3 yards of concrete, were emplaced in 90 minutes from the time the first concrete was lowered into the WIPP. A total of 78 field samples were cast and taken to Waterways Experiment Station for further laboratory evaluation. The ESC maintained excellent workability throughout, with a slump in excess of 8 inches (20-cm) well beyond three hours.

PERMEABILITY MEASUREMENTS

A permeability measuring system was developed for use in these tests.[6] The system is capable of performing three simultaneous tests using gas, including injecting and detecting tracer gases, or brine up to 2000 psi. The system can perform automatic measurements unattended during long tests. Fig. 5 illustrates the permeability measuring system. A dual packer system emplaced in the access hole is used to isolate the test interval beneath the seal. The packer is connected to the data acquisition and flow control systems. The downhole test interval pressure and temperature, packer pressure, and guard zone pressure are monitored and controlled. Both constant pressure and pressure decay tests can be performed. Examples of interpretation of field permeability data are given in analyses associated with the Bell Canyon Test[7] and recent WIPP horizon permeability measurements[8]. The values reported here should be considered as order-of-magnitude values as the detailed analysis of the data is not yet complete.

Prior to the conduct of the seal system permeability tests, gas and brine tests were performed in a hole with the seal replaced by an inflatable packer to obtain baseline formation permeability values. These values were similar to previous WIPP horizon rock permeability measurements, and indicated a permeability of the rock of less than a microdarcy.

Gas permeability tests were then performed on all six seal systems after the concrete had cured at least 28 days. These were pressure decay tests which included a tracer gas injection and detection and were typically performed at about 300 psi (2 MPa) pressure. With the exception of the instrumented 36-inch(91-cm)-diameter seal (MAE31), seal system permeabilities well below a microdarcy were inferred and there were no breakthroughs of any tracers through the seals. These tests were typically in excess of 48 hours in duration.

The gas tests in MAE31 revealed that there was some flow through the seal. The presence of bubbles in a small layer of water on the top of the seal identified cabling routes and the interface (which has instrumentation attached to it) as being the primary flow paths. A tracer test produced the only measured arrival through any seal 1.5 hours after injection under a pressure of 300 psi (2 MPa) at the bottom of the seal. The maximum effective permeability of MAE31, however, is still quite small--on the order of 2 microdarcies. During the testing of MAE31, it was discovered that the majority of the flow was actually into the formation. A horizontal clay parting approximately 9 feet (3 m) below the invert was suspected of being responsible in part for the flow.

Three long-term brine tests were initiated in late September of 1985. In the case of two tests, the test interval pressure could not be maintained in excess of 250 psi (1.7 MPa) without relatively large flows into the formation. The third test was maintained at 500 psi (3.5 MPa) without similar effects. Small quantities of brine were observed to be accumulating in adjacent holes. A likely path for the flow may be the same previously mentioned clay parting, which may be forced open somewhat by the fluid pressure in the test interval. After 100 days of testing, there was no breakthrough of brine through any of the seals. The inferred seal system permeabilities are considerably less than a microdarcy.

STRUCTURAL MEASUREMENTS

Instrumentation used in Test Series A included stress cells, strain gages, and thermocouples in the concrete and displacement gages and thermocouples in the adjacent rock. The majority of the gages in the concrete were assembled on a support tree and positioned in the holes prior to pouring the concrete. In the instrumented 36-inch(91-cm)-diameter hole, some gages were fixed to the borehole wall. A complete description of the instrumentation and how it was installed is given elsewhere.[4]

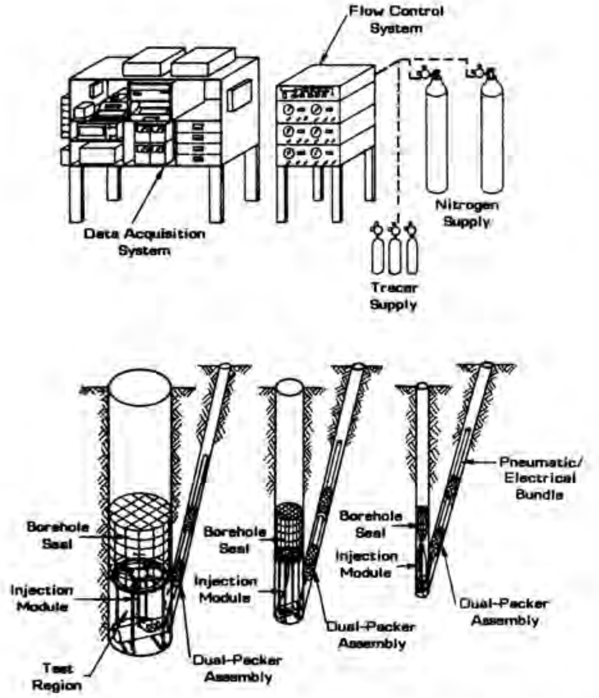

Fig. 5. Schematic of Permeability Measuring System Developed by S-Cubed.

Temperature Measurements

A typical temperature history is given in Fig.6 The most striking feature of the temperature data is the presence of a "double hump." The time delay and approximately equal magnitude of the peak temperatures illustrate the atypical hydration of this complex mixture. The double hump may be beneficial by reducing the peak temperature experienced, and thereby reducing detrimental thermal effects on cooling. In Test Series A, the entire thermal transient takes about 250 hours after which time essentially all of the heat produced by the concrete hydration has been dissipated and the seal-rock system is in thermal equilibrium.

Strain Measurements

Strain measurements were made in the concrete near the seal/rock interface in both the radial and tangential direction and at three depths in the seal (one-quarter, mid, and three-quarter depth). Neglecting measured strains in the first 8 hours after concrete placement, the strains indicate the concrete is experiencing net compressive strains. Typical data is given in Fig. 7. The rate for the first 4 days is about 40 microstrains per day. The strain rates slow to about 3 microstrains per day after 4 days, and slowly decrease so that by 180 days the strain rate is 1 to 2 microstrains per day. While there is some scatter in the data, there are no discernable trends in the strain rates with regard to seal size, or orientation (radial or tangential.)

Pressure Measurements

Pressure or stress measurements were made in the concrete near the seal/rock interface in the radial direction and at three depths. The data is more variable than with the temperature and strain data. Nonetheless, basic trends can be observed. A relatively rapid increase on the order of 70 psi/day (.48 MPa/day) for the first 4 days after concrete placement is observed, after which time the rate slows so by 10 days the rate is about 10 psi/day (.07 MPa/day). The rate continues to slowly decrease and, after 180 days, the rate is on the order of 5 psi/day (.03 MPa/day).

DISCUSSION

Neglecting early-time thermal effects, the measured strains and pressures in the concrete are a result of external loading by the surrounding salt, expansion or shrinkage of the concrete, and creep of the concrete. Expansion of the concrete would induce tensile strains and compressive interface stresses; concrete shrinkage would induce compressive strains and tensile or no interface pressure; and loading of the concrete by creep of the surrounding salt would induce compressive strains and compressive interface pressure. The compressive nature of the measured strains and pressure near the seal/rock interface infer that the creep of the adjacent salt toward the concrete seal is the predominant mechanism for the development of strains and pressures in the concrete.

The increasing pressure at the salt-concrete interface reduces the deviatoric stresses which drive the salt creep and, eventually, the pressure will equilibrate at some value. If this value does not approach the strength of the concrete, then the substantial interface pressure is considered to be favorable as it is conducive to a low-permeability interface.

The concrete responds to this pressure by developing elastic and creep strains. The elastic strains can be estimated by considering an elastic cylinder subjected to an external pressure under plane strain

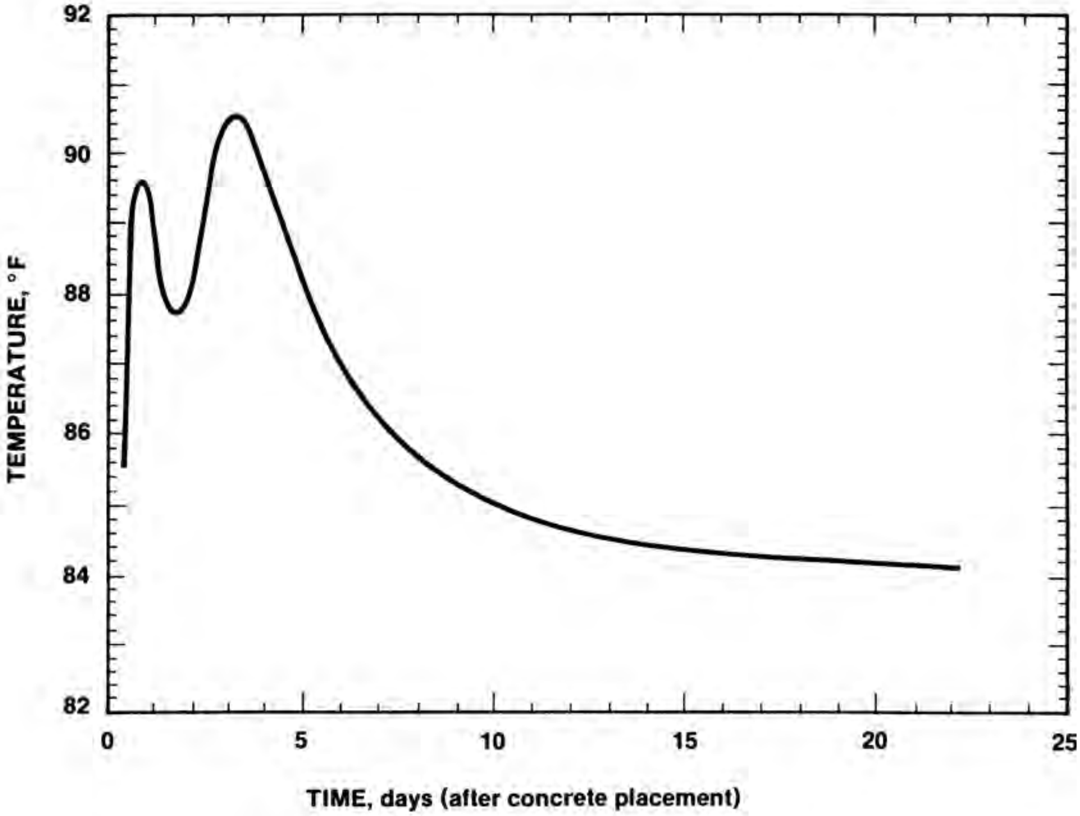

Fig. 6. Temperature History Plot for 36-Inch-Diameter by 3-Feet-Long Concrete Plug in Test Series A.

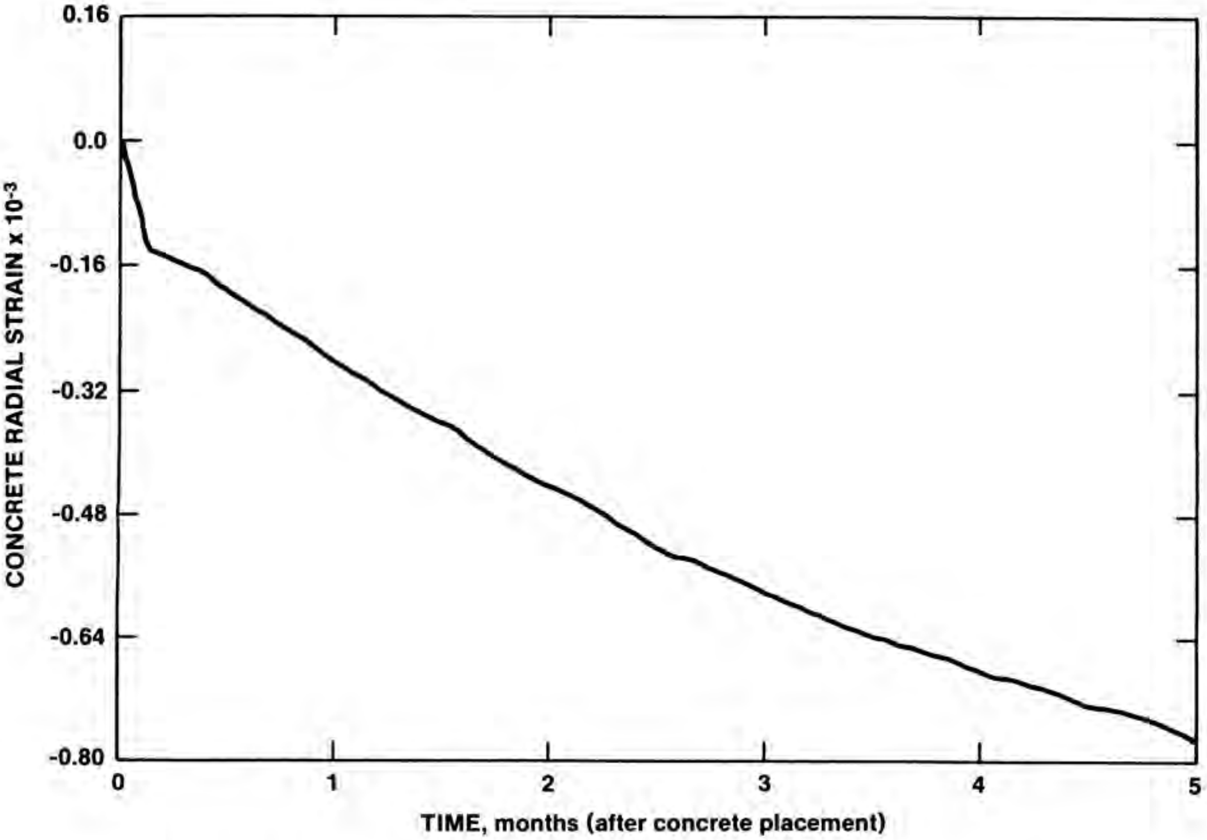

Fig. 7. Typical Strain History Plot for Concrete Plugs in Test Series A.

conditions. The change in elastic strain due to an incremental loading is given by:[9]

$$\Delta\epsilon_r = \Delta\epsilon_\theta = \Delta P \frac{(1+\nu)\ (1-2\nu)}{E} \qquad (1)$$

where

$\Delta\epsilon_r$ = incremental radial strain in the concrete
$\Delta\epsilon_\theta$ = incremental tangential strain in the concrete
ΔP = incremental applied pressure on the concrete
ν = Poisson's ratio of the concrete
E = Young's modulus of the concrete

The difference between the changes in measured strains and those calculated from Eq. (1) will be from creep of the concrete assuming no expansion or shrinkage changes. The scatter in the pressure data makes such an analysis somewhat difficult; however, average values indicate that at 180 days the creep strain may contribute on the order of 30 to 50 percent of the total incremented strain.

The structural response of the Test Series A configuration was modeled using the two-dimensional structural finite element code SANCHO[10]. A model, symmetric about the axis of the concrete cylinder, was developed which incorporated the elastic and creep characteristics of the salt and the assumed constant elastic properties of the concrete.[11] The salt properties and applied boundary conditions were consistent with WIPP modeling practices. The structural response of the seal system was calculated at points which correspond to those at which measurements were made in the 36-inch(91-cm)-diameter seal.

The calculated response is compared with the measured values in Figs. 8 and 9. These results indicate that the trends and values of the pressure measured to date (180 days) can be predicted reasonably well with this model. The measured strains are larger and decreasing at a slower rate than the predicted strains, suggesting that concrete creep may be appreciable. The predicted trends beyond 180 days indicate continued reduction in the stress and strain rate, approaching constant values after about one year.

CONCLUSIONS

The results obtained to date have given confidence in the use of the ESC as an effective seal component for the WIPP facility. Preliminary conclusions from Test Series A of the Small Scale Seal Performance Tests are as follows:

1. The developed concrete--the ESC (Expansive Salt Concrete)--has properties desired of a repository seal material such as strength, low permeability and porosity, expansivity, adequate elastic properties, density, and workability. The field placement, including using slump as the field acceptance criterion, of the concrete was successful.
2. The majority of the measured flow was observed along discontinuities in the bedded salt, perpendicular to the axis of the concrete seal. There was no appreciable flow (gas or brine) through the concrete itself, the concrete/seal interface, or the rock immediately adjacent to the concrete with the exception of the seal where considerable instrumentation was present along the interface. The ESC seals are effective barriers to fluid flow, corresponding to a medium with a permeability less than a microdarcy.
3. A double-hump in the temperature history during concrete hydration is observed, reducing the peak temperature the concrete and its surrounding experience.
4. The predominant mechanism for stress and strain changes in the concrete seal system is the creep of the adjacent rock salt. This loading results in a considered normal stress at the seal/rock interface which is conducive to a tight interface. Preliminary analyses indicate that the concrete may be creeping in response to the sustained external load.

Both the structural and permeability measurements will continue in Test Series A. In particular, it will be seen whether or not the predicted trend toward structural equilibrium between the concrete and adjacent rock occurs. These analyses will be expanded to include concrete creep. Laboratory testing, such as creep tests, will support the ongoing evaluation of the field data.

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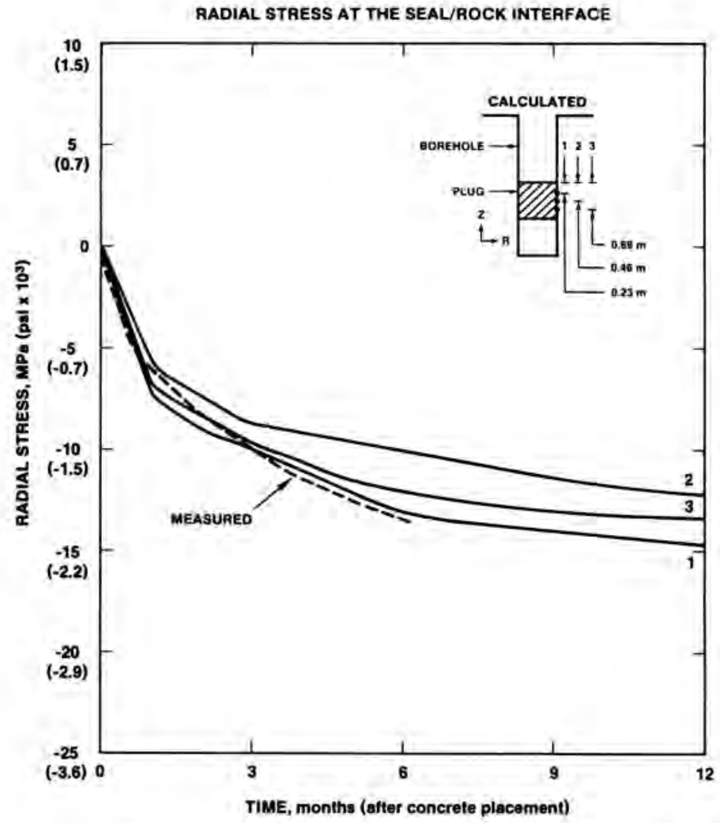

Fig. 8. Calculated vs Measured Interface Pressure for 36-inch-Diameter Plug in Test Series A.

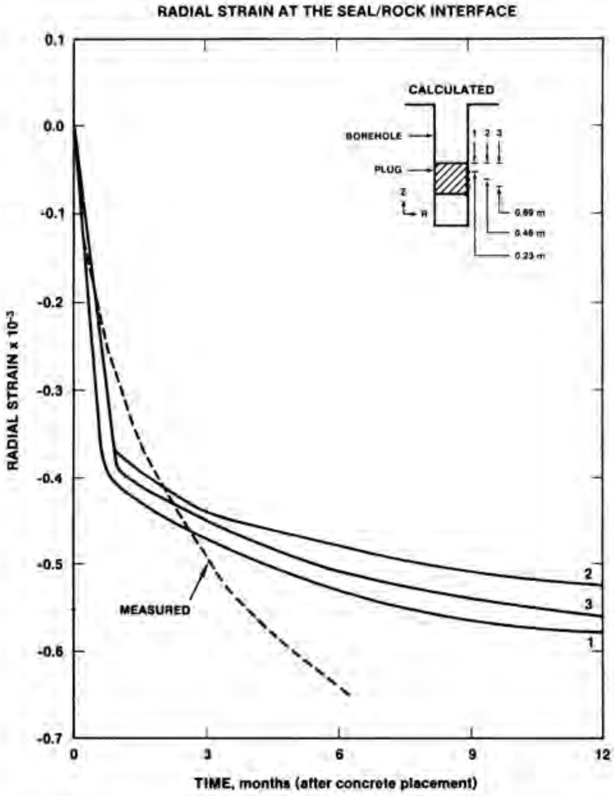

Fig. 9. Calculated vs Measured Concrete Strain for 36-Inch-Diameter Plug in Test Series A.

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