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AN INVESTIGATION OF THE INTEGRITY OF CEMENTED CASING
SEALS WITH APPLICATION TO SALT CAVERN SEALING AND
ABANDONMENT

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An Investigation of the Integrity of Cemented Casing Seals with Application to
Salt Cavern Sealing and Abandonment

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EXECUTIVE SUMMARY

BACKGROUND

Underground caverns developed in salt are a popular and economical method for the storage of oil and gas, the disposal of oil field and hazardous solid wastes, and the production of brine. Entry into these caverns requires the completion (cementing) of cased wells that extend from the surface through the nonsalt overburden and terminate at the casing shoe set in the salt above the cavern. Eventually, some caverns will be taken out of service and abandoned. A common method for abandonment is simply to pull or cut the hanging string and then to fill the inner casing or tubing with alternating intervals of concrete and cement grout.

The space left behind in an abandoned cavern generally contains fluid (e.g., brine). Over time, the fluid becomes pressurized because (1) the confined fluid tries to expand as its temperature rises to equilibrate with the temperature of the surrounding salt and (2) the volume of the cavern decreases through creep deformations of the salt, thereby compressing the confined fluid. An important question relating to cavern abandonment and operating caverns as well is how to establish a maximum cavern pressure while maintaining the structural integrity of the cavern sealing system; i.e., the salt surrounding the cavern, the cement seals and plugs, and the casing and tubing providing access to the cavern. Typically, the maximum casing shoe pressure allowed during the operational phase of a cavern is established by regulation using a stress gradient based on depth (i.e., 0.80 to 0.90 psi/foot). However, the fluid pressure in an abandoned cavern is likely to increase indefinitely because of creep closure of the cavern and may eventually approach or even exceed the lithostatic stress in the vicinity of the cavern. To date, there has been limited research to study the effect of high fluid pressures on the hydraulic and mechanical behavior of salt and virtually no definitive tests or analyses to investigate the effect of high fluid pressures on the integrity of plugged well casings.

In 1996, the Solution Mining Research Institute (SMRI) approved a long-term research program that focused on the uncertainties associated with Cavern Sealing and Abandonment (CS&A) issues. The initial efforts of the SMRI CS&A Research Program were the development of a comprehensive bibliography and a critique of the state-of-the-art in the understanding and practice of CS&A. As the research program developed, cooperative funding was obtained from the United States Department of Energy, and SMRI solicited proposals to pursue research in three key areas including:

1. Salt permeability testing under complex stress states
2. Hydraulic and mechanical integrity investigations of the well casing shoe through bench-scale testing
3. Geomechanical modeling of the fluid/salt hydraulic and mechanical interaction of a sealed cavern.

The bench-scale testing performed to investigate the integrity of the well casing shoe is the focus of this technical report.

TECHNICAL APPROACH AND SCOPE

In developing its solicitation to investigate the integrity of cemented well casings, the SMRI was particularly interested in the conditions of the casing/cement and cement/salt interfaces both initially after the casing was cemented into the salt and later after the interfaces were subjected to pressures approaching and even exceeding lithostatic conditions. In addition, the investigation was to provide information on the maximum pressures that could be applied to the interfaces; the location of any leakage paths that may develop; and the stress and deformation history in the salt, cement, and steel casing under conditions that simulate cavern sealing and abandonment scenarios. In response to these requirements, a technical approach was developed using bench-scale testing with a focus on

- Development and validation of an appropriate test configuration to simulate both the physical characteristics of a casing shoe set in the salt above an abandoned cavern and the state of stress in the vicinity of the casing shoe
- Testing to investigate the hydraulic and mechanical integrity of the casing seal at fluid pressures approaching and exceeding lithostatic stress
- Development of diagnostic techniques to assess the condition of the casing-cement-salt interfaces and the leakage rates through these interfaces
- Numerical analyses of the tests to predict deformations and stress states in the vicinity of the casing shoe.

Test Method and Configuration

A mock-up of the typical bench-scale test configuration is shown in Figure 1. The testing made use of large salt cores recovered from the Avery Island Dome, Louisiana, USA. These cores were machined to produce thick-walled, hollow cylinder test specimens with nominal lengths of 16 inches and nominal external and internal diameters of 12 inches and 6.5 inches, respectively. A steel casing (4.5 inches in diameter with a wall thickness of 0.25 inch) was cemented into the internal bore of each salt specimen, and the specimen was placed inside the pressure vessel of a large special-purpose test system capable of simultaneously applying load to all external surfaces of the test specimen and pressurizing the internal salt bore. The external stress and internal pressure simulated the in situ lithostatic stress and cavern pressure, respectively. The external stress was 2,000 psi in all tests, which corresponded to a cavern depth of approximately 2,000 feet. The internal pressure was increased in a step-wise manner, while a leak detection system monitored brine flow rates through the casing seal. The tests were terminated when the observed leakage rates were so high they could no longer be measured accurately.

Figure 1. Mock-Up of a Bench-Scale Specimen.

Cement Testing

Cement cylinders were cast from each batch mix used in the installation of the casings and also from a trial batch prepared at the beginning of the study. The cylinders were subsequently used to determine the mechanical properties of the cement as it cured. The mechanical properties measured in the tests included: (1) unconfined and triaxial compressive strengths, (2) Young's modulus of elasticity, and (3) Poisson's ratio. Typically, unconfined compressive strength tests were conducted on cylinders from each batch following curing times of 1, 3, 7, 14, and 28 days. Limited triaxial compression testing was performed at a confining pressure of 2,000 psi to investigate the effect of pressure on cement strength. A total of 24 tests was completed, including 22 unconfined compressive strength tests and 2 triaxial compressive strength tests. The data from the tests were used directly in the numerical analyses and also in establishing the curing time required before the internal bore of the bench-scale specimens could be safely pressurized.

Bench-Scale Testing

Initially, three bench-scale tests were performed to develop and validate an appropriate test procedure and test configuration. In these tests, the casings were cemented into the internal bore of the salt and the cement was allowed to cure for 28 days at normal room temperature (68°F) and ambient pressure conditions. Following the 28-day curing time, the test specimens were placed in the test system and proportionally loaded with an external stress and internal brine pressure. During the proportional loading, the external stress was applied at a rate twice that of the brine pressure. Loading continued until high brine flow rates were observed. High flow rates were measured at low internal brine pressures (i.e., 1,000 psi or lower) for all three tests which was attributed to deficiencies in the test procedure and test configuration rather than the casing integrity. These deficiencies were remedied before any production testing was performed.

Four production bench-scale tests were conducted according to a revised test procedure and test configuration. The most significant revision to the original test procedure was the method used to cure the cement after the steel casing was installed in the inner bore of the salt specimen. Instead of curing the cement under ambient pressure conditions, the cement was cured while the stress was applied to the external surfaces of the salt specimen. This change required the installation of the casing with the specimen mounted in the test system and the immediate loading of the specimen following assembly.

The internal brine pressure and the external stress were not applied simultaneously in the revised procedure because the "green" cement would likely be displaced by the brine during pressurization. Instead, the brine was pressurized only after the cement achieved an unconfined compressive strength of 3,500 psi (based on cement cylinder test results). Once the cement strength had been achieved (typically requiring 7 days), the internal brine pressure was increased in a load-hold manner. The hold time was typically several days, during which time, the brine flow rate was monitored.

One of the four production tests was aborted prematurely because of a test system malfunction; however, the other three tests were considered successful. In two of the successful tests, the internal brine pressure reached 2,100 psi and 2,200 psi, or 105 percent and 110 percent of the applied external stress, respectively. In the other successful test, the maximum brine pressure was only 1,600 psi (or 80 percent of the external stress). This low pressure was attributed to a "worm-hole" in the cement rather than a breakdown of the casing-cement-salt interfaces.

Diagnostic Techniques

Several diagnostic techniques were developed during the study to assess the integrity of the cemented casing, including the casing-cement-salt interfaces. In some cases, the techniques were used in combination with one another to improve the results. Visual inspection was used

whenever possible to look for voids in the cement and macroscopic fractures and separations along the interfaces. The brine used to pressurize the internal bore was doped with a fluorescent dye that could be viewed using a black light to facilitate the visual inspection. In addition, the test specimens were sawn into 1-inch-thick disks so the casing-cement-salt interfaces could be examined along the full length of the cemented portion of the test specimen. Other diagnostic techniques included the use of compressed air and liquid soap and a vacuum pump/manometer system used to measure vacuum loss through the thickness of the individual 1-inch-thick disks.

Numerical Analyses

Numerical analyses of the three successful tests were performed using the finite-difference program **FLAC**. The analyses predicted (1) the displacement profiles of the internal and external diameters of the salt at the end of both the Phase 1 and Phase 2 loading and (2) the radial stress histories at relevant locations within the finite difference model; e.g., at the casing-cement-salt interfaces located near the casing midheight and the casing bottom. A separate constitutive model or material law was used for each of the materials comprising the bench-scale test specimens. The steel components (i.e., casing and platens) and the cement in the annulus between the casing and salt were treated as homogeneous and isotropic materials and were simulated using linear elastic models. The elastic properties of the cement were made time-dependent to account for the stiffening of the cement as it aged. The Waste Isolation Pilot Plant (WIPP) reference creep model was used for the salt and was capable of simulating both transient and steady-state creep deformation.

The displacement profiles of the internal and external diameters were predicted reasonably well both at the end of Phase 1 and at the end of Phase 2. The good agreement was a result of the trial-and-error numerical modeling process used to establish the frictional properties of the interfaces between the test specimen and the loading platens.

In response to the application of the external stress and the subsequent curing of the cement and inward creeping of the salt, high compressive radial stresses (in excess of the applied external stress) were predicted for the casing-cement-salt interfaces at the bottom of the casing. The application of the internal brine pressure had significant consequences for the radial stresses, and these consequences depended on the cemented casing length. In the simulation conducted with the longer cemented casing (i.e., 15.5 inches), the radial stresses increased only moderately as the brine pressure was incremented. However, in the simulations conducted for the shorter cemented casings (i.e., 10 inches), the radial stresses dropped instantaneously to the value of the external stress when the brine pressure was initially applied and then continued to decrease by small amounts as each new brine pressure increment was applied.

The radial stresses predicted at the casing midheight interfaces were similar in all numerical simulations in that the stresses increased immediately following the installation of

the casing and also after the internal bore pressure was applied and subsequently incremented. The cemented casing length again affected the radial stress predictions, primarily in terms of the stress magnitude. In the simulation of the longer cemented casing, the radial stress increased and ultimately reached the value of the applied external stress. Then as the internal salt bore was pressurized, the radial stresses continued to rise until they exceeded the external stress by as much as 20 percent. In the simulations of the shorter cemented casings, the radial stresses initially rise to only about 30 percent of the applied external stress and ultimately reach values that are only about 50 percent of the external stress, even after the internal bore pressure approaches and exceeds the external stress.

The effect of cemented casing length on the predicted radial stresses at the casing midheight and casing bottom is attributed to the differences in the flexural bending of the salt wall caused by the external stress, the internal brine pressure, and the position of the casing bottom relative to the loading platens. These differences arise from differences in the position of the flexure points in the salt as well as the frictional constraints at the ends of the test specimen.

Although the effect of including a Phase 1 loading on the radial stresses predicted during Phase 2 is small, the radial stresses in the casing-cement-salt interfaces build more quickly and reach higher values in the simulation that omits the Phase 1 loading when compared to the simulations that retain the Phase 1 loading. This difference is attributed to the higher transient deformation rates that occur in the salt when the Phase 1 loading is omitted from the Phase 2 simulation.

CONCLUSIONS

During the course of the bench-scale testing and subsequent numerical analyses, several observations and conclusions were made relative to the test method/configuration and the application of the results in practice. The observations and conclusions are summarized below.

Observations

- As expected, the unconfined compressive strength and Young's modulus (stiffness) of the salt-saturated cement increase with curing time. The maximum unconfined strength is achieved in approximately 30 days, while the maximum value of Young's modulus is achieved after only 14 days. The time-dependent properties of the cement (particularly Young's modulus) need to be accounted for in the numerical analyses in order to predict accurately the specimen deformations.
- The unconfined compressive strength of a 5.2 gallons/sack cement mix is only about 60 percent of the strength of a 4.3 gallons/sack cement mix at comparable curing times (~28 days). The effect of water-to-cement ratio on Young's modulus is negligible for the two ratios investigated in the study.

- Based on limited testing, Young's modulus of cement is not affected by confining pressure provided the curing time is a constant. Therefore, the values of Young's modulus determined from the unconfined compression tests can be used in modeling cement subjected to compressive stress states.
- The curing of the cemented casings under ambient pressure conditions produces reasonably good bonds between the casing and cement and cement and salt in the bench-scale tests, but does not simulate either the creeping of the salt into a wellbore or the pressure induced in the cement by the weight of the cement column placed in the field. The inward creeping of the salt can be simulated in the bench-scale tests by applying external stress to the test specimen while the cement is curing.
- When the cement is allowed to cure under ambient pressures, the subsequent external loading of the test specimen results in the cracking of the cement and debonding of interfaces because of mismatches in material stiffness. In practice, this condition seldom occurs in the field.
- The length of the casing and the frictional end effects of the loading platens influence the deformation profiles of the bench-scale specimens. In general, the applied external stress induces the inward displacement of both the external and internal surfaces of the hollow cylinder. This inward movement is restrained at the ends of the specimen by the friction between the specimen and the loading platens. The deformation profile is discontinuous near the bottom of the casing with larger deformations occurring below the casing bottom and smaller deformations occurring above the casing bottom.
- Brine flow or leakage was observed in all the bench-scale tests even at low internal brine pressures. The flow rates increased instantaneously with each increment of the internal brine pressure, but then decayed to constant values. The flow rates were not correlated to the magnitude of the internal brine pressure except at brine pressures approaching the applied external stress.
- The total brine flow was less than 150 milliliters in two tests and nearly 3,500 milliliters in a third test. The higher flow could be a result of brine seeping around the seals used to isolate the internal bore rather than flow through the cement or interfaces.
- Based on simplistic assumptions regarding the deformed geometry of the test specimens, the salt may have dilated a small amount during testing.
- Diagnostic techniques can be developed and used to assess casing-cement-salt interface damage and to identify leakage paths. In addition to visual inspection, the diagnostic techniques included (1) doping of the brine with fluorescent dye, (2) injecting air into the internal bore followed by the application of liquid soap to the cement and interfaces, (3) sectioning of the specimen into thin disks, and (4) inspecting the thin disks using a vacuum/manometer system. The fluorescent dye was ineffective in identifying flow paths relative to the other methods developed.

- The deformation profiles of both the internal bore and the external diameter of the bench-scale specimens can be predicted from numerical analyses provided the interface friction at the ends of specimen is well defined.
- The radial stresses predicted at the casing bottom and casing midheight indicate flexural bending of the salt wall and, therefore, are strongly influenced by the casing length and frictional effects of the platens at the ends of the specimen.
- Based on the predictions from the analyses, the radial stresses will develop more quickly and reach higher values when the casing is cemented into the salt bore immediately following the application of the external stress rather than waiting several days before the casing is installed.

Conclusions

- The bench-scale test can adequately simulate the loading conditions and cross-sectional geometry along a horizontal plane of a cemented casing shoe set in salt. Lithostatic stresses and internal brine pressures as high as 2,000 psi can be simulated in the test. In addition, the diameter of the casing and the thickness of the cemented annulus used in the tests approximate what is used in the field. Limitations of the bench-scale test include: (1) inability to simulate the pressure in the cement induced by the weight of a tall column of cement and (2) significant frictional effects in the platen-specimen interfaces which induce deformations and stress states that may not simulate the deformations and stresses in the vicinity of an actual casing shoe.
- Leakage of brine through the cemented seal system will occur even at low brine pressures; however, the leakage rates do not appear to be proportional to the applied brine pressure so Darcy flow is probably not a valid assumption for explaining the leakage. The flow could be a result of the “squeezing” of brine out of the pore spaces of the cement, interfaces, and salt immediately following the application of the brine pressure increment.
- Internal brine pressure can exceed the applied external stress by as much as 10 percent (i.e., a brine pressure-to-external stress ratio of 1.1) without a breakdown of the casing-cement-salt interfaces. However, these high pressures may cause a breakdown of other casing seal components (e.g., the salt below the casing may fracture).
- Based on the numerical analyses, the radial stresses in the casing-cement-salt interfaces develop more quickly and reach higher values when the casing is cemented into the salt bore immediately following the application of the external stress rather than waiting several days before the casing is installed. This result implies that the maximum radial stress in the vicinity of an actual casing shoe could be reduced if the hole is left open for a period of time before the casing is installed to complete the well.

1.0 INTRODUCTION

1.1 BACKGROUND

Underground caverns developed in salt are a popular and economical method for the storage of oil and gas, the disposal of oil field and hazardous solid wastes, and the production of brine for industrial applications. Entry into these caverns requires the completion of cased wells that extend from the surface through the nonsalt overburden and terminate at the casing shoe set in the salt above the cavern. In a typical entry well completion, the annulus between the outermost casing and the rock, as well as the annuli between smaller diameter inner casings and larger outer casings, are filled with cement. The cements used in the completions are those commonly available in the oil and gas industry. The technology for both the emplacement of the cement and the testing to assure correct emplacement is well developed.

Eventually, caverns will be taken out of service and abandoned. A common method for abandonment is simply to pull or cut the hanging string and then to fill the inner casing or tubing with alternating intervals of concrete and cement grout. In general, the cavern space left behind contains fluid (e.g., brine), which is at a lower temperature than that of the surrounding salt. Over time, the fluid becomes pressurized because (1) the confined fluid tries to expand as its temperature rises to equilibrate with the temperature of the surrounding salt and (2) the volume of the abandoned cavern decreases through creep deformation of the salt, thereby compressing the confined fluid. Theoretically, the fluid pressure will continue to rise even after the fluid and formation temperatures equilibrate because creep closure is expected to continue indefinitely (e.g., Ratigan [2000]).

An important question relating to cavern abandonment and operating caverns as well is how to establish a maximum cavern pressure while maintaining the structural integrity of the cavern system; i.e., the salt surrounding the cavern, the cement seals and plugs, and the casing and tubing providing access to the cavern. Typically, the maximum casing shoe pressure allowed during the operational phase of a cavern is established by regulation using a stress gradient based on depth (i.e., 0.80 to 0.90 psi/foot). However, as described above, the fluid pressure in an abandoned and sealed cavern is likely to increase indefinitely and may eventually approach or even exceed the lithostatic stress in the vicinity of the cavern. To date, there has been limited research to study the effect of high fluid pressures on the hydraulic and mechanical behavior of salt (e.g., Fokker et al. [1993]) and virtually no definitive tests or analyses to investigate the effect of high fluid pressures on the integrity of plugged well casings.

In 1996, the Solution Mining Research Institute (SMRI) approved a long-term research program that focused on the uncertainties associated with Cavern Sealing and Abandonment (CS&A) issues. The initial efforts of the SMRI CS&A Research Program were the development

of a comprehensive bibliography and a critique of the state-of-the-art in the understanding and practice of CS&A. As the research program developed, cooperative funding was obtained from the United States Department of Energy (US DOE), and SMRI solicited proposals to pursue research in three key areas, including:

1. Salt permeability testing under complex stress states
2. Hydraulic and mechanical integrity investigations of the well casing shoe through bench-scale testing
3. Geomechanical modeling of the fluid/salt hydraulic and mechanical interaction of a sealed cavern.

Contracts for the proposed work were issued to three separate research organizations in 1998. The bench-scale testing performed to investigate the integrity of the well casing shoe is now complete and is the focus of this technical report.

1.2 TECHNICAL APPROACH AND SCOPE

In its request for proposals, the SMRI suggested that the integrity of well casings should be investigated either through bench-scale laboratory testing or through larger-scale field testing. The SMRI was particularly interested in the conditions of the casing/cement and cement/salt interfaces both initially after the casing was cemented into the salt and later after the interfaces were subjected to pressures approaching and even exceeding lithostatic conditions. In addition, the study was to provide information on the maximum pressures that could be applied to the interfaces; the location of any leakage paths that may develop; and the stress and deformation history in the salt, cement, and steel under conditions that simulate cavern sealing and abandonment scenarios.

In response to the SMRI requirements, a technical approach was developed using bench-scale tests. Bench-scale testing was selected over small-scale laboratory testing and larger-scale field testing because in the bench-scale testing, (1) the sizes of both the casing and the cement-grouted annulus between the casing and salt can be more realistically simulated than at the smaller laboratory scale and (2) the stress states and deformations can be measured and/or controlled more accurately than in a larger-scale field test. The focus of the bench-scale testing was in four technical areas, including:

- Development and validation of an appropriate test configuration to *simulate* both the physical characteristics of a casing shoe set in the salt above an abandoned cavern and the state of stress in the vicinity of the casing shoe
- Testing to investigate the hydraulic and mechanical integrity of the casing seal at fluid pressures approaching and exceeding lithostatic stress

- Development of diagnostic techniques to assess the condition of the casing-cement-salt interfaces and the leakage rates through these interfaces
- Numerical analyses of the tests to predict deformations and stress states in the vicinity of the casing shoe.

All bench-scale and diagnostic testing was performed in RESPEC's Materials Testing Laboratory, Rapid City, South Dakota, USA. The numerical analyses efforts were shared jointly by RESPEC and Terralog Technologies USA Inc., Arcadia, California, USA.

1.2.1 Test Configuration

A mock-up of a typical bench-scale test is shown in Figure 1-1 with prominent features labeled for reference. The features of primary importance are the following:

- Salt Specimen. Each salt specimen was a thick-walled cylinder having an outside diameter of 12 inches and an overall height of 16 inches. The inside diameter of the specimen was 6.5 inches over the cemented length of the casing, and depending on the test, was either 6.5 inches or 4 inches below the casing (i.e., smooth versus stepped bore). All salt specimens were prepared from dome salt recovered from Avery Island, Louisiana, USA.
- Casing. The casing was a standard steel pipe. The outside diameter and wall thickness of the pipe were 4.5 inches and 0.25 inch, respectively. The length of the casing varied, depending on the test.
- Cement. The cement placed in the 1-inch annulus between the casing and salt specimen was a standard salt-saturated oil field cement having a water-to-cement ratio of either 4.3 gallons/sack or 5.2 gallons/sack.
- Casing Plug. The casing plug placed in the interior bore of the steel pipe was fabricated from steel and its length could be adjusted to either prevent or allow brine to contact the inside of the casing.
- Pressure Vessel. The pressure vessel consisted of a steel shell that confined the hydraulic fluid (silicone oil) placed in the annulus between the salt specimen and the pressure vessel shell or wall.
- Loading Platens and Spacers. The loading platens and spacers were fabricated using high-strength steel and transmitted the axial force from the test system to the salt specimen.
- Seals. Flexible seals were fabricated from Viton to prevent the pressurized brine injected into the void space below the cemented casing from escaping either along the casing plug/casing interfaces or the salt specimen/lower spacer interface.
- Viton Jacket. The Viton jacket used in the study was a flexible tube placed over the outside of the salt specimen to prevent the hydraulic fluid from contaminating the salt.

Figure 1-1. Mock-Up of a Typical Bench-Scale Specimen.

During testing, hydraulic fluid and brine were injected, respectively, into the annulus between the salt specimen and the pressure vessel wall and the void below the cemented casing using the external and internal pressure ports shown in Figure 1-1. These ports were connected to hydraulic systems that could be pressurized independently to control the pressures applied to the outside of the specimen as well as the inner bore of the specimen. The external pressure and the stress applied to the ends of the specimen simulated the lithostatic stress conditions found in the field. The internal or brine pressure applied to the inner salt bore simulated the build up of pressure inside a sealed and abandoned cavern.

1.2.2 Bench-Scale Testing

A total of seven bench-scale tests was performed during the study. The first three tests were performed primarily to develop and validate an appropriate test method and test configuration. The other four tests were production tests used to assess the effect of brine pressure on casing seal integrity. Even though the objectives of the two groups of tests were different, the procedural steps followed in each test were generally the same; i.e.,

- Prepare a thick-walled cylinder of salt.
- Install and cement the steel casing into the internal bore of the salt specimen.
- Cure the cement.
- Apply a stress of 2,000 psi to the external surfaces of the salt specimen either before or while the cement was curing.
- Increase the brine pressure in the internal bore of the salt specimen until a breakdown of the casing/cement or cement/salt interface was observed.
- Use diagnostic tests to identify the location of the breakdown (flow path).

After the first three tests had been completed, the original test method and test configuration were evaluated and subsequently revised to eliminate or modify procedural steps that were ineffective and to adjust test control variables to better simulate field conditions. The most significant procedural difference between the first three tests and the four production tests was the method used to cure the cement placed in the annulus between the casing and the salt. In the first three tests, the cement was cured under ambient laboratory conditions (i.e., atmospheric pressure and room temperature (68°F)), while in the four production tests, the cement was cured at room temperature under a stress of 2,000 psi applied to all external surfaces of the salt specimen.

Although a general method was followed for all testing, variations to the method and test configuration were adopted in individual tests to improve the method during the study as well as to assess the integrity of the casing seals. Table 1-1 gives a summary of the test

methods/configurations used in each of the seven tests based on the following six control variables:

- Inner bore configuration
- Water-to-cement ratio
- Cement curing method
- Casing length
- Internal pressurization of the casing
- External pressurization rate.

Table 1-1. Summary of Bench-Scale Test Configurations

Test No.	Bore Configuration	Water-to-Cement Ratio (gals/sack)	Cement Curing Condition ^(a)	Internally Pressurized Casing	Casing Length ^(b) (in)	External Loading Rate ^(c)
1	Stepped	5.2	Ambient	No	10	Rapid
2	Stepped	5.2	Ambient	No	10	Rapid
3	Stepped	5.2	Ambient	Yes	10	Slow
4	Smooth	4.3	Pressurized	Yes	15.5	Rapid
5	Smooth	4.3	Pressurized	Yes	10	Rapid
6	Smooth	4.3	Pressurized	Yes	10	Rapid
7	Smooth	4.3	Pressurized	Yes	10	Rapid

(a) Under ambient conditions, the cement cured under normal laboratory conditions. Under pressurized conditions, the test specimen was placed inside the pressure vessel shown in Figure 1-1 and the cement cured under a stress of 2,000 psi applied to all external surfaces of the test specimen.

(b) Measured from the top of the test specimen.

(c) Rapid loading implies the external stress was applied in less than 1 hour. Slow loading implies the stress was applied over a 2-week period.

Two different bore configurations were investigated during the testing. In the first three tests, the stepped bore configuration shown previously in Figure 1-1 was employed. In this configuration, the inner diameter of the salt specimen stepped from 6.5 inches through the upper cemented interval down to 4 inches through the interval located below the cemented casing. The smooth bore configuration was used in each of the four production tests. The inner diameter of each smooth bore specimen was uniform (6.5 inches) throughout its length.

Water-to-cement ratios of 4.3 gallons/sack and 5.2 gallons/sack were investigated in the study with the higher ratio used in the first three tests and the lower ratio used in the production tests. In both cases, the water was saturated with salt before it was added to the dry cement. Two different cement curing methods were also used for the two groups of tests. The different methods, ambient cure and pressurized cure, were described previously.

The inner surfaces of the steel casing, as well as the void below the casing, were pressurized with brine in five of the tests, including all four of the production tests. In the other two tests, the length of the casing plug was adjusted to confine the brine (and therefore, the pressure) to the void below the casing. With one exception, the casing length in all tests was 10 inches. In Test No. 4, the casing length was 15.5 inches extending down to within 0.5 inch of the bottom of the salt specimen.

External stresses were applied in each test by pressurizing the hydraulic fluid in the annulus between the shell of the pressure vessel and the salt specimen while simultaneously applying axial force to the top and bottom of the salt specimen. In all but one test, the loading rate was rapid; i.e., the 2,000 psi external stress was applied in less than 1 hour. In Test No. 3, the loading rate was much slower. In this test, the 2,000 psi external stress was applied in uniform steps over a 2-week period.

1.2.3 Diagnostic Techniques

In addition to visual inspection, several diagnostic techniques were developed and used during the study to assess casing-cement-salt interface integrity. The techniques included:

1. Injection of compressed air into the inner bore of the salt specimen and the application of liquid soap films to the outer exposed casing-cement-salt interfaces
2. Addition of water-soluble fluorescent dye to the brine
3. Vacuum loss measurements.

The first technique was performed on both the untested and tested specimens, while the other techniques were used only during the test or at the conclusion of the test. Using the second technique, brine flow patterns were observed using a black light to illuminate the residue of the dye transported along with the brine. The third technique involved sectioning the specimen into sixteen 1-inch-thick disks. Each disk was inspected visually (both with and without the black light) and then examined using an air manometer system to measure vacuum loss through the thickness of the individual disks.

1.2.4 Numerical Analyses

Numerical analyses were performed to predict the deformations and stresses in Test Nos. 4, 5, and 7. The modeling made use of the commercially available finite difference code, **FLAC**

[Itasca Consulting Group, Inc., 1996]. Separate material models were used for the salt, cement, and steel casing. The salt was characterized using the Waste Isolation Pilot Plant (WIPP) baseline creep model [Senseny, 1983]. The cement and steel casing were treated as linear elastic materials; however, the elastic properties of the cement were incremented through time to simulate the stiffening of the cement that occurred during curing. The elastic properties of the cement were determined from compression tests conducted on cylinders cast at the same time the steel casings were cemented into the salt bore and tested at 1, 3, 7, 14, and 28 days.

1.3 REPORT ORGANIZATION

In addition to this introduction, this report contains six chapters and one appendix. Chapters 2.0 and 3.0 describe, respectively, the materials used to prepare each of the test specimens and the test equipment and procedures used in the bench-scale testing. The results of the seven bench-scale tests, as well as the compression tests performed on the cement cylinders, are presented in Chapter 4.0. Chapter 5.0 describes the finite difference model and material laws used in the numerical analyses of the tests and summarizes the results of the analyses. The report concludes with a summary of the research project in Chapter 6.0 and a list of cited references in Chapter 7.0. Appendix A contains stress-strain plots for each of the cement compression tests.

2.0 MATERIALS

Each bench-scale specimen consisted of several different materials, including salt, cement, and a steel casing. In addition, brine was used in the cement mixture and in the internal bore of each test specimen. These materials are briefly described below under separate headings.

2.1 SALT

The thick-walled salt cylinders used in the study were machined from 13-inch-diameter salt cores stored in the RESPEC core facility. These cores were originally recovered from the 500-foot level of the International Salt Company Mine (now owned by Cargill Salt) located in the dome at Avery Island, Louisiana, USA. Avery Island salt was used in the study because (1) large cores were already available, thereby eliminating the cost of both a large core barrel and the labor required to recover new salt cores; (2) the salt is clean, relatively fine-grained, and essentially free of fractures, so it can be easily machined and has low intrinsic permeability; and (3) the mechanical properties of the salt have been extensively investigated [Hansen and Mellegard, 1980a, 1980b; Hansen et al., 1981; Hansen and Carter, 1981; Mellegard and Senseny, 1983; Mellegard et al., 1983], thereby providing a large database of constitutive properties for the numerical analyses.

Carter and Hansen [1980] characterized the fabric and mineralogy of the Avery Island salt using optical microscopy. The salt is composed of dominantly strain-free halite grains ranging in size from 2.5 to 15 millimeters with an average of 7.5 millimeters. The salt is unusually clean (99 percent pure halite or NaCl) with little anhydrite or clayey material along grain boundaries. The grains themselves do, however, contain some anhydrite and a few negative crystals.

2.2 CEMENT

The dry cement used in the cement/brine mixture was an American Petroleum Institute (API) Class G cement. Class G cement is a basic oil-well cement used for sealing oil wells from the surface to a depth of 8,000 feet [Halliburton, 1994]. It is chemically similar to API Class B cement but is manufactured to more rigorous chemical and physical specifications, resulting in a more uniform product. As manufactured, it contains no accelerators, retarders, or viscosity control agents other than gypsum, which is normally ground with the portland cement clinker.

The Class G cement was manufactured and provided by the Dacotah Cement Company, Rapid City, South Dakota, USA. The certificate of compliance data for two chemical and

physical analyses of the cement are summarized in Table 2-1 along with the relevant API cement specifications. In general, the data meet or exceed the API specifications.

Table 2-1. Summary of the Chemical and Physical Analyses Conducted for the Class G Cement Used in the Study

Analysis	API Specification	Trial 1	Trial 2
<i>Chemical</i>			
Magnesium Oxide, MgO (max. %)	6.00	1.09	1.14
Sulfur Trioxide, SO ₃ (max. %)	3.00	2.05	2.20
Loss on Ignition (max. %)	3.00	0.87	0.90
Insoluble Residue (max. %)	0.75	0.13	0.21
Tricalcium Silicate, C ₃ S (max. %) (min. %)	58.00 48.00	62.32	61.55
Tricalcium Alumina, C ₃ A (max. %)	8.00	4.48	4.44
Alkalies (max. % as Na equivalent)	0.75	0.31	0.30
<i>Physical</i>			
Blaine Fineness (m ² /Kg)		301	332
325 Mesh (% passing)		79.82	88.24
Free Water (max., ml)	3.5	2.0	1.0
Compressive Strength, 8-Hour Curing Time, Atmospheric pressure (psi) 100°F min. 140°F min.	300 1,500	269 1,105	481 2,062
Pressure-Temperature Thickening Time (max., min.)	120	125	121

2.3 CASING

The casing was prepared using a standard 4.5-inch-diameter pipe having a nominal wall thickness of 0.25 inch. The pipe was fabricated from mild steel, had a welded seam that extended down its full length, and was purchased from Ace Steel and Recycling, Rapid City, South Dakota, USA. Before use, the internal bore of the pipe was polished, and the outer surface was cleaned with a wire brush to remove any loose scale or oil. The polishing of the

internal bore was necessary to ensure a good seal between the bore and the adjustable casing plug used during testing.

2.4 BRINE

The saturated brine used in the cement/brine mixture and the internal bore of the salt specimen was prepared using distilled water and pulverized salt. The pulverized salt was recovered from the cuttings produced during the milling of the large Avery Island salt specimens. The saturation of the brine was verified by measuring the density of the mixture and comparing the measured density to the theoretical density of a fully saturated NaCl brine solution. In addition, the brine used as the pressurizing fluid in the internal bore of the salt specimens was doped with a water-soluble fluorescent dye powder manufactured and sold by the Magnaflux Company, Glenview, Illinois, USA, under the tradename Zyglo ZL-5. The powder is an organic material designed specifically as an additive to water for detection of leaks in pressure vessels, storage tanks, radiators, and other liquid system containers. The ZL-5 dye produces fluorescence under black light at 365 nanometers. The powder was added to the brine in the proportions of 1 pound of powder per 25 gallons of brine.

3.0 TEST EQUIPMENT AND PROCEDURES

3.1 TEST EQUIPMENT

Two mechanical test systems were used to complete the bench-scale testing. Both systems were manufactured by MTS Systems Corporation (MTS), Eden Prairie, Minnesota, USA. The primary test system used in the study was the Hollow Cylinder System (HCS), which is a large, special-purpose testing machine capable of applying the pressures and forces needed in the large bench-scale tests. The other test system used was the Universal Test System (UTS), which is a standard testing machine within the MTS product line. The UTS was used exclusively for unconfined and triaxial compression testing of the cement cylinders cast during the cementing of the steel casings into the internal bore of each bench-scale test specimen. Both systems, including instrumentation, are described below followed by a brief discussion of the approach used to calibrate the instrumentation.

3.1.1 Hollow Cylinder System

Using custom specifications prepared by RESPEC, MTS manufactured the HCS for the specialized purpose of testing large (12-inch-diameter), thin-walled, hollow cylinder specimens of salt under conditions of multiaxial stress. The HCS is a computer-controlled servohydraulic test system comprising (1) an MTS 315 load frame and customized pressure vessel, (2) a microprocessor, and (3) a control console. In addition, the test system makes use of electronic transducers to measure force, pressure, displacement, and temperature during testing. For this study, the HCS required several modifications, and these modifications are described following a brief description of the test system itself.

The original configuration of the HCS load frame and pressure vessel is shown in Figure 3-1. A hydraulic actuator located in the base of the load frame is capable of applying an axial force of 700,000 pounds. The pressure vessel, having an inner bore of 15 inches and height of 26 inches, contains the hydraulic fluid (silicone oil) used to pressurize the external surface of hollow cylinder specimens. Two pressure intensifiers mounted on the load frame are connected to the external and internal pressure ports of the pressure vessel using high-pressure stainless steel tubing and are capable of producing hydraulic pressures up to 4,500 psi. In this configuration, hydraulic pressure can be applied independently both to the external and internal surfaces of a hollow cylinder specimen.

A Digital Equipment Corporation (DEC) LSI-11/23 microprocessor provides for programmable control of the test system as well as data acquisition. The microprocessor interfaces with the load frame through a control console that houses all signal conditioners for the electronic transducers and feedback and valve driver modules for the hydraulics.

Figure 3-1. Hollow Cylinder Test System.

The only data collected during the bench-scale testing were axial force, external and internal hydraulic pressures, and the volume of brine that flowed through the cement annulus and interfaces. Axial force was inferred from the output of a pressure transducer connected to the hydraulic actuator used to apply axial force. The output of this transducer was calibrated against load standards to provide a relationship between pressure transducer output and axial force. External and internal hydraulic pressures (i.e., the external oil pressure and internal brine pressure) were measured by pressure transducers located in the high-pressure tubing leading to the external and internal ports of the pressure vessel, respectively. Brine flowing through the cement annulus and/or the casing-cement-salt interfaces was measured by a buret connected to a vent port leading to the top of the bench-scale specimen.

The original HCS configuration was modified before any testing was performed to accommodate the dimensions of the thick-walled, hollow cylinder test specimens. In the original configuration, the pressure vessel, axial loading platens, and Viton jacket were designed for a 24-inch-long test specimen. The bench-scale specimens were only 16 inches long, so solid steel spacers were inserted above and below the bench-scale specimen, as shown previously in Figure 1-1. This simple modification permitted the use of the original pressure vessel, loading platens, and jacket. After the first production test (Test No. 4) was completed, a decision was made to run the remaining tests for longer durations so the brine flow rate could be established more accurately. This decision prompted the need for a second modification to the HCS. In the second modification, the dynamic servohydraulic systems that controlled the axial force and the external and internal specimen pressures were replaced with static control systems using nitrogen-charged accumulators that could be adjusted manually. The dynamic control systems were replaced because the dynamic systems would shut down if an electrical utility power outage was to occur during testing, which seemed likely, especially for long duration tests (i.e., 60 to 90 days). If the dynamic control systems had shut down, the test specimen would have been immediately unloaded in an uncontrolled manner and may have been damaged such that posttest diagnostics could not be performed.

3.1.2 Universal Test System

Similar to the HCS, the UTS is a computer-controlled, servohydraulic test system comprising a pressure vessel and load frame, a microprocessor, and a control console. The UTS was used to conduct both unconfined and triaxial compression tests on the cement cylinders. No modifications to the UTS were required for this study.

Figure 3-2 shows the distinctive two-column design of the MTS 312.41 load frame and the custom-built pressure vessel. The hydraulic actuator located in the base of this test system is capable of applying an axial force of 110,000 pounds. The pressure vessel is mounted to the crosshead of the load frame which can be raised to provide access to the inside of the vessel during specimen assembly. The pressure vessel has an inner bore diameter of 8 inches and an overall height of 24 inches and accommodates test specimens that have a nominal diameter of

Figure 3-2. Universal Test System.

4 inches and a nominal length of 8 inches. The vessel is hydraulically connected to a pressure intensifier using high-pressure tubing. The pressure intensifier is capable of producing a pressure of 10,000 psi.

A DEC LSI-11/73 microprocessor provides programmable control and data acquisition for the UTS. A control console again provides the interface between the microprocessor and the load frame and houses signal conditioning for the electronic transducers and feedback and valve driver modules for the hydraulics

The UTS is equipped with electronic transducers for measuring force, pressure, and displacement. Axial force is measured by a load cell bolted to the moveable crosshead of the test frame. When triaxial compression tests are performed, a pressure transducer located in the hydraulic line between the pressure vessel and the pressure intensifier measures the confining pressure applied during the test. Axial and radial displacements are measured by an axial extensometer and a lateral disk gage, respectively. As shown in Figure 3-2, the displacement transducers are mounted directly on the specimen at its midheight.

3.1.3 Calibration

Each force, pressure, and displacement transducer was calibrated in its normal operating position on the test system, and its output was observed at normal data collection points. By using this approach, the signal conditioners, filters, and analog-to-digital converters were all included within the "end-to-end" calibration. Calibrations for force, pressure, and displacement were performed by determining the best straight-line fit to indicated readings versus standard input, after applying the standard input in 20 equal steps. The calibration constants were then verified by applying the standard input in ten equal steps over the calibrated range. The transducer response at each step was predicted using the calibration constants. The process of calibration/verification was repeated until the predicted values fell within acceptable levels of error; i.e., 1.0 percent of reading for load and pressure calibrations and 2.0 percent of reading for displacement calibrations.

3.2 TEST PROCEDURES

3.2.1 Salt Specimen Preparation

The thick-walled salt specimens were prepared from solid cores of Avery Island Dome salt using a two-step process. In the first step, the cores were sawn, turned in a lathe, and ground to produce solid cylinders with finished specimen dimensions of 12-inch diameters and 16-inch lengths. In the second step, the internal hole of the specimen was machined to produce either a stepped bore or a smooth bore. The stepped bore specimens were used in Test Nos. 1 through 3, while the smooth bore specimens were used in Test Nos. 4 through 7.

The stepped bore was machined in a lathe by coring a 2.125-inch-diameter hole along the central axis of the 12-inch-diameter solid salt cylinders using an NX core barrel. This central hole was terminated at a nominal depth of 11 inches and then was enlarged to a diameter of 6.5 inches using a boring bar and carbide tooling. The steel casing was then cemented into the internal bore and the cement was allowed to cure for 28 days. At the end of the 28-day cure time, a 4-inch-diameter core barrel was lowered into the internal bore of the casing and the internal hole of the salt specimen was extended from the bottom of the casing to the bottom of the salt specimen, thereby creating the stepped bore shown previously in Figure 1-1.

The smooth bore was machined by again coring a 2.125-inch-diameter hole along the central axes of the 12-inch-diameter solid salt cylinders. However, instead of terminating the hole at a depth of 11 inches, the hole was extended through the entire length of the salt specimen. A boring bar and carbide tooling were then used to enlarge the diameter of the central hole from 2.125 inches to 6.5 inches, creating a continuous smooth bore.

After each thick-walled salt specimen had been machined, the internal diameter, external diameter, and length were accurately determined. The diameters were measured at orthogonal points every 1 inch along the length of a specimen. The length was measured at 30-degree intervals (i.e., 12 positions) around the specimen perimeter. The measurement points were labeled on each specimen using a permanent marker and were used as landmarks for subsequent measurements made following the completion of the various stages of the bench-scale tests.

3.2.2 Salt-Saturated Cement Mixture Preparation

The salt-saturated cement mixture used to cement the steel casings into the internal bores of the salt specimens was prepared using Class G cement (see Section 2.2) and a fully saturated NaCl brine (see Section 2.4). Class G cement was added to the brine in small amounts and then stirred by hand to avoid clumping. After the correct mass of cement had been added to the brine to produce a 4.3-gallons/sack or 5.2-gallons/sack mixture, the mixture was blended for several minutes using an electric drill equipped with a fluted metal paddle. The mixture was allowed to stand for 10 minutes and then was blended for several more minutes using the drill and paddle. The mixture was then allowed to stand for 1 hour before it was used in the installation of the steel casing.

3.2.3 Casing Installation

The steel casing was cemented into the internal bore of the salt specimen using two different techniques. One technique was used for the stepped bore configuration while the other technique was used for the smooth bore configuration. In both techniques, cement cylinders were cast at the same time the casings were cemented into the bores. These cylinders were

used in subsequent compressive strength testing. The two casing installation techniques are summarized below.

3.2.3.1 Stepped Bore

A centering fixture was used to position the steel casing in the stepped bore. This fixture ensured that the central axis of the casing was coincident with the central axis of the bore of the test specimen and also held the bottom of the casing 1 inch above the bottom of the internal bore. The liquid cement (aged for 1 hour) was carefully poured into the 1-inch annulus created by the steel casing and the salt specimen. A solid plug, set at the bottom of the steel casing, prevented the liquid cement from rising up through the internal bore of the casing as the cement was being poured into the annulus.

When the annulus was full, the cement was allowed to cure for 28 days under ambient laboratory conditions (i.e., a temperature of 68°F and atmospheric pressure). At the end of 28 days, the plug at the bottom of the casing was removed and the internal bore of the specimen was extended down to the bottom of the salt specimen using a 4-inch-diameter core barrel, as described in Section 3.2.1.

3.2.3.2 Smooth Bore

The cementing of the casing in the smooth bore specimens was performed while the test specimen was in the HCS test system used to conduct the bench-scale tests. The salt specimen was centered on the steel spacer located above the base plate of the test system. A Styrofoam spacer was placed at the bottom of the internal bore of the specimen. The thickness of the Styrofoam spacer was adjusted to accommodate the variable lengths of the casing. Rings of filter paper and porous felt metal were slid onto the end of the casing, and the casing was gently lowered into the internal bore of the salt specimen until it came to rest on the Styrofoam spacer. The liquid cement (aged for 1 hour) was carefully poured into the annulus between the casing and the internal bore of the salt. The Styrofoam, filter paper, and felt metal prevented the liquid cement from rising up in the internal bore of the casing and filling the void in the internal bore of the salt below the casing. The felt metal also served to center the casing in the bore during specimen assembly and provided for good hydraulic communication between the cemented annulus and the brine injected into the internal bore of the salt specimen during testing.

After the annulus was full, porous felt metal and filter paper were placed on the top of the salt specimen, including the cement annulus, and final assembly of the test system and pressure vessel was completed. Immediately following the cementing of the casing and the assembly of the test system, a stress of 2,000 psi was applied to the external surfaces of the salt specimen with no internal pressure. As the cement cured, the externally applied stress caused

the salt to creep in on the cemented casing, thus assuring good contact at the salt-cement-casing interfaces.

The final assembly of the test system required about 1 hour to complete, so the total elapsed time from the mixing of the cement through final assembly of the test system was about 2 hours. The cement was allowed to cure under pressure until it reached an unconfined compressive strength of 3,500 psi. The curing time was approximately 1 week, as determined by compression testing of the cement cylinders.

3.2.4 Cement Testing

As described above in Section 3.2.3, cement cylinders were cast at the same time the steel casings were cemented into the bores of the salt. These cylinders were 4 inches in diameter and 8 inches long and were cured under ambient temperature (68°F) and pressure (atmospheric) conditions. The cylinders were cast for use in unconfined and triaxial compression testing. The data from the tests were used to estimate (1) the unconfined and confined strength of the cement; (2) two elastic properties, Young's modulus and Poisson's ratio; and (3) the effect of curing time on both the strength and the elastic properties.

At typical intervals of 1, 3, 7, 14, and 28 days, a cylinder from a particular batch of cement was removed from its plastic mold, and its ends were machined in a surface grinder to produce a standard compression test specimen. The finished specimen was placed in the UTS and instrumented with electronic displacement transducers. Axial extensometers were used in all tests to measure axial displacement over a 3.937-inch (100-millimeter) gage length. Lateral disk gages were used in several tests to measure radial displacement across the diameter of the specimen (the gage length of the lateral disk gage was equivalent to the specimen diameter). In the unconfined compression tests, the displacement transducers were mounted directly on the surface of the specimen at its midheight. In the triaxial compression tests, the transducers were mounted on a specially fabricated ported jacket that was slipped over the test specimen. The ported jacket was fabricated by removing portions of the flexible jacket from the areas where the transducers contacted the jacket and replacing these portions with thin metal shims glued to the jacket.

In the case of the unconfined compression tests, the test was initiated after the test specimen assembly had been completed. For the triaxial compression tests, silicone oil was first injected into the annulus between the specimen and pressure vessel wall and then was pressurized using a pressure intensifier to apply the confining pressure specified for the test. A computerized test control program was used to perform both types of tests. The program prompted the operator for input information, such as specimen identification number and dimensions, loading rate, type of test, etc., and then automatically performed the test using the inputted information. In this study, the tests were conducted in axial strain control at an axial

strain rate of 1×10^{-5} /sec. The confining pressure was constant throughout the test¹. During each test, data were acquired from all electronic transducers, including the load cell, the axial extensometer, the lateral disk gage, and the pressure transducer monitoring the confining pressure. The loading was terminated by the program when a peak or ultimate axial stress had been recorded.

Following test termination, the data from each test were transferred from the micro-processor over a local area network to a personal computer and processed. The axial stress was calculated as the ratio of the axial force to the original area of the specimen. Axial and radial strains were calculated using the true or logarithmic definition of strain; i.e.,

$$\epsilon_a = -\ln\left(\frac{G_a - \Delta L}{G_a}\right) \quad (3-1)$$

$$\epsilon_r = -\ln\left(\frac{D + \Delta D}{D}\right) \quad (3-2)$$

where ϵ_a and ϵ_r are the axial and radial true strains, respectively; G_a is the gage length of the axial extensometer; D is the original diameter of the test specimen; and ΔL and ΔD are the measured change in length and diameter, respectively. In Equations 3-1 and 3-2, ΔL and ΔD are positive quantities and the sign convention has been established to yield positive strains in compression.

3.2.5 Bench-Scale Testing

As shown previously in Table 1-1, seven bench-scale tests were performed using variations in both the test methods and the test configurations. Significant variations in methods/configurations existed between the first three tests conducted primarily to assess the test method and the last four tests conducted primarily to assess the effect of brine pressure on the integrity of the casing seals. These two methods have been termed the original procedure and revised procedure, respectively, and are described below under separate headings.

3.2.5.1 Original Test Procedure (Test Nos. 1, 2, and 3)

Under the original test procedure, the steel casing was cemented into the stepped bore of a thick-walled, hollow cylinder of salt and the cement was allowed to cure at room temperature with no pressure applied to either the external surface of the salt specimen or its internal bore. After the cement had cured for 28 days, the specimen was placed inside the pressure vessel, as shown in Figure 3-3. Then the exterior surfaces of the specimen were loaded to simulate

¹ An unconfined compression test is a special case of a triaxial compression test in which the confining pressure is zero.

Figure 3-3. Mock-Up of a Typical Bench-Scale Test Based on the Original Test Procedure.

lithostatic stresses and the internal bore was simultaneously pressurized with brine. The exterior surfaces were loaded by (1) pressurizing the silicone oil filling the annulus between the specimen and the outer shell of the pressure vessel and (2) increasing the axial force on the ends of the specimen in a manner that induced an average axial stress in the salt equivalent to the applied oil pressure. The ratio of internal bore pressurization rate and the external pressurization rate was 0.5. A buret was connected to the leak detection port located at the top of the test specimen and provided a measure of the brine volume leaking through the cement casing seal. Each test was terminated when the observed leakage rate was excessive.

3.2.5.2 Revised Test Procedure (Test Nos. 4, 5, 6, and 7)

In the revised test procedure, the test system assembly and machine components remained essentially unchanged; however, the specimen geometry, the casing seal cementing procedure, and the loading procedure were changed appreciably. Details of the changes are summarized below.

The revised procedure called for two loading phases termed Phase 1 and Phase 2. These terms referred to the portions of a specimen history where a particular loading was applied. After a specimen had been machined, a short-term Phase 1 loading was applied and removed before a complete Phase 2 loading was begun. The exception was Test No. 5 that skipped Phase 1 and proceeded directly to Phase 2 loading.

Phase 1 Testing

In Phase 1, the thick-walled, hollow cylinder specimen (with a smooth, uniform internal bore) was mounted between the steel loading platens of the mechanical test system, covered with a Viton jacket, and placed in the pressure vessel without a cemented casing set in the internal bore. A stress of 1,000 psi was applied to all external surfaces of the specimen and the internal bore pressure was maintained at zero. This loading condition was held constant for about 2.8 days, and during that time, the specimen deformed, causing the diameters to decrease a small amount. At the end of 2.8 days, the specimen was unloaded, removed from the test system, and the specimen dimensions were measured to quantify the inelastic deformations that occurred during Phase 1.

The Phase 1 loading served two purposes. First, it was considered to be a reasonable simulation of field conditions; that is, there is a short time period when the borehole is left uncased (i.e., an open hole), allowing the salt around the hole to creep into the hole. Second, the comparison of specimen dimensions taken before and after the Phase 1 testing provided a measure of salt deformation under a well-defined state of stress that could be used later in the numerical analyses to verify the constitutive parameters used to model the salt-platen interfaces.

Phase 2 Testing

Phase 2 was initiated by cementing the casing into the internal bore of the salt specimen and completing the test assembly, as described above in Section 3.2.3. Figure 3-4 shows a mock-up of the bench-scale test used during Phase 2. Immediately following the assembly of the test system, a stress of 2,000 psi was applied to the external surfaces of the specimen with no internal pressure. Following the week of cement curing, the internal pressure was increased incrementally using saturated brine as the pressurization fluid. Each time the internal pressure was increased, the axial force was also increased to counteract the additional vertical force of the brine pressure acting over the cross-sectional area of the bore, thereby maintaining the appropriate axial stress on the specimen. The external stress was held constant at 2,000 psi throughout the internal pressurization process. A holding stage followed each brine pressure increment. During the holding stage, brine exiting the top of the specimen was collected in a buret that was read manually to acquire a flow-versus-time record.

The test was terminated when the brine flow rate measured at the top of the specimen became very large. Following termination of the test, the posttest specimen dimensions were determined and the specimen was examined to find evidence of both the position and orientation of the brine flow path. In all cases, this step resulted in the destruction of the specimen because the specimen was sawn into disks about 1 inch thick. The sawing of the specimen into disks allowed measurement of how far the salt displaced into the cement during the initial cement curing stage and also allowed examination of potential flow paths through the interfaces.

3.2.6 Interface Integrity Diagnostic Techniques

Several diagnostic techniques were used during the study to assess the integrity of the cemented casing, including the casing-cement-salt interfaces. In some cases, the techniques were used in combination with one another to improve the results. The techniques are summarized below.

Visual inspection was used whenever possible to look for voids in the cement and macroscopic fractures and separation along interfaces. To facilitate the inspection, the brine used to pressurize the internal bore of the salt specimen was doped with fluorescent dye. The cement and interfaces could then be viewed under a black light to check for fluorescence. The only cement surfaces and casing-cement-salt interfaces visible during the inspection were those located at the top and bottom ends of the test specimen. This limitation was addressed by sawing the test specimen into sixteen 1-inch-thick disks. The cement and interfaces on either side of the disk could then be inspected visually and under the black light. Obviously, this technique could be applied only at the end of the test because the sawing destroyed the test specimen.

Figure 3-4. Mock-Up of a Typical Bench-Scale Test Based on the Revised Procedure.

Compressed air was another technique used to check for leakage paths. In this technique, compressed air was injected at a pressure of about 40 psi into the internal bore of the test specimen. A thin film of soap was spread over the top of the specimen, including the cement and the casing-cement-salt interfaces. Air bubbles forming in the soap film were used to identify flow paths as well as their locations. This technique was used only on the intact specimens.

In addition to the visual inspection conducted on the 1-inch-thick disks described above, a vacuum pump and manometer system was also used to assess the integrity of the cement and the interfaces. A single disk was pressed against an inflated rubber inner tube to form a seal around the perimeter of the disk. A seal plug equipped with a venting port was inserted into the casing at the center of the disk and connected to a vacuum pump. The vacuum created below the disk produced a small air pressure differential between the upper and lower faces of the disk. The locations of air leaking between the faces could then be determined by manually traversing the exposed face of the disk with one end of a manometer tube. Displacement of the fluid (water) in the manometer tube was an indication that a leakage path had been located.

4.0 TEST RESULTS

The casing sealing integrity study included (1) laboratory-scale testing designed to determine the strength and deformational properties of salt-saturated cement and (2) bench-scale testing designed to simulate the physical characteristics and stress conditions associated with the casing shoe region of a sealed and abandoned cavern in salt. The results of the laboratory and bench-scale testing are described below.

4.1 CEMENT TESTS

A total of eight salt-saturated cement batches was mixed for the study, including seven production batches used to cement the casings into the bores of the bench-scale specimens and one trial batch prepared at the beginning of the study to gain familiarity with the mixing procedure and equipment. The batches were mixed according to API specifications using water-to-cement ratios of either 4.3 gallons/sack or 5.2 gallons/sack.

Cement cylinders were cast from each batch, including the trial batch, and were subsequently used in compressive strength tests to determine the mechanical properties of the cement during curing. Typically, unconfined compressive strength tests were conducted on cylinders from each batch following curing times of 1, 3, 7, 14, and 28 days. The tests provided estimates for unconfined compressive strength and Young's modulus of elasticity, E . In several tests, Poisson's ratio, ν , was also determined. Limited triaxial compression testing was performed to study the effect of confining pressure on both compressive strength and elastic properties (E and ν). The confining pressure in the triaxial tests was 2,000 psi. The data from the unconfined tests were used directly in the numerical analyses (see Chapter 5.0) and also in establishing the curing time required before the internal bore of the bench-scale specimens could be safely pressurized.

Twenty-two unconfined compression tests and two triaxial compression tests were performed on cement cylinders prepared from the trial batch and five of the seven production batches. Stress difference² versus strain plots were prepared for each test and these plots are given in Appendix A. A typical stress-strain plot is shown in Figure 4-1 for a cylinder cured for 7 days. The stress difference versus axial strain and stress difference versus radial strain curves are essentially linear up to about 50 percent of the peak or ultimate stress difference, but then depart from linearity as the peak stress is approached. The compressive strength was defined as the peak stress difference observed during the test, while the elastic parameters, E and ν , were determined from the following equations:

² Stress difference is defined as the difference between the axial stress and the confining pressure (or radial stress).

Figure 4-1. Typical Stress Difference Versus Axial and Radial Strain Curves for an Unconfined Compression Test of Salt-Saturated Cement.

$$E = \frac{\Delta \sigma}{\Delta \epsilon_a} \quad (4-1)$$

$$\nu = - \frac{E}{\Delta \sigma / \Delta \epsilon_r} \quad (4-2)$$

where $\Delta \sigma$ is the change in stress difference and $\Delta \epsilon_a$ and $\Delta \epsilon_r$ are the corresponding changes in axial and radial strains, respectively. The right-hand side of Equation 4-1 and the denominator of Equation 4-2 represent the slopes of the stress difference versus axial strain curve and the stress difference versus radial strain curve, respectively. These slopes were determined by fitting straight lines to the stress-strain data between 0 percent and 50 percent of the peak or ultimate stress difference.

Table 4-1 gives a summary of the 24 strength tests performed on the cement. As shown, both strength and Young's modulus increase with curing time, as expected. The effect of curing time on Poisson's ratio could not be determined in the study because Poisson's ratio was measured in only a few tests. The 28-day strength of the 5.2-gallons/sack mix is only about 60 percent of the average 28-day strength of the 4.3-gallons/sack mix. The ultimate strength in the confined tests could not be estimated because the capacity of the load cell and test frame used in the triaxial compression tests was reached before peak stress was observed. Young's modulus and Poisson's ratio determined from the confined tests were comparable to the values determined from the unconfined tests, given identical curing times. Figures 4-2 and 4-3 plot unconfined compressive strength versus curing time and Young's modulus versus curing time, respectively. Most of the increase in unconfined strength and Young's modulus was observed within the first 14 days of curing.

4.2 BENCH-SCALE TESTS

Seven bench-scale tests were performed to investigate the effect of brine pressure on casing seal integrity. The first three tests were used primarily to develop and validate an appropriate test procedure. Following the completion of these tests, the test procedure and test configuration were revised and four additional production tests were conducted. The results from both series of tests are provided below.

4.2.1 Original Procedure (Test Nos. 1, 2, and 3)

Three tests were attempted using the original test procedure. Under this procedure, the cement was cured under ambient conditions of temperature and pressure before the bench-scale testing was initiated. Following a curing time of 28 days, the bench-scale specimens were placed in the pressure vessel of the test system and loaded in a proportional manner by increasing the external stress at a rate twice that of the internal brine pressure. The

Table 4-1. Summary of Cement Compressive Strength Tests

Test	Water-to-Cement Ratio (gals/sack)	Curing Time (days)	Confining Pressure (psi)	Strength (psi)	Young's Modulus, E (psi)	Poisson's Ratio, ν
<i>Trial Batch</i>						
G1	5.2	5	0	1,462	1,000,000	(b)
G2	5.2	28	0	3,043	1,500,000	0.40
G3	5.2	42	2,000	5,062 ^(a)	1,200,000	0.18
G4	5.2	45	2,000	5,358 ^(a)	1,200,000	0.16
G5	5.2	47	0	3,040	1,200,000	0.23
<i>Batch 1 (Bench-Scale Test No. 1)</i>						
G7	5.2	43	0	3,593	1,900,000	0.49
<i>Batch 4 (Bench-Scale Test No. 4)</i>						
G22	4.3	1	0	365	230,000	0.28
G23	4.3	3	0	2,056	870,000	0.37
G25	4.3	7	0	3,381	1,300,000	0.29
G26	4.3	14	0	4,555	1,600,000	(b)
G27	4.3	28	0	4,749	1,600,000	(b)
<i>Batch 5 (Bench-Scale Test No. 5)</i>						
G28	4.3	1	0	718	400,000	(b)
G29	4.3	3	0	2,680	1,000,000	(b)
G30	4.3	7	0	3,593	1,400,000	(b)
G31	4.3	14	0	4,438	1,500,000	(b)
G32	4.3	28	0	5,367	1,700,000	(b)
<i>Batch 6 (Bench-Scale Test No. 6)</i>						
G33	4.3	1	0	225	120,000	(b)
G35	4.3	3	0	1,970	1,110,000	(b)
G36	4.3	7	0	3,129	1,290,000	(b)
<i>Batch 7 (Bench-Scale Test No. 7)</i>						
G40	4.3	1	0	454	330,000	(b)
G41	4.3	3	0	2,314	1,160,000	(b)
G42	4.3	7	0	4,075	1,550,000	(b)
G43	4.3	14	0	3,977	1,780,000	(b)
G44	4.3	28	0	5,594	1,770,000	(b)

(a) Ultimate stress was not estimated because load cell and test frame capacities were reached.

(b) Value of Poisson's ratio is not available because radial strain was not measured.

Figure 4-2. Unconfined Compressive Strength Versus Curing Time for Salt-Saturated Cement.

Figure 4-3. Young's Modulus of Elasticity Versus Curing Time for Salt-Saturated Cement.

proportional loading was to continue until the external stress and brine pressure reached 2,000 psi and 1,000 psi, respectively, at which time, the external stress was to be held constant and the internal brine pressure increased until casing seal breakdown was observed. However, before the targeted external stress and brine pressure were reached, high brine leakage rates through the cement annulus were often observed. Although the internal brine pressure reached 1,000 psi in Test No. 1, it only reached 500 psi and 100 psi in Test Nos. 2 and 3, respectively. The low values of brine pressure measured in the first three tests were attributed to deficiencies in the test procedure.

Findings from the first three tests included:

- Shrinkage of the cement at the top of the annulus was pronounced during the 28-day curing period; however, diagnostic testing indicated the casing-cement-salt interfaces of the virgin specimens (i.e., specimens that had not experienced any external loading) were well bonded.
- The test system was able to apply and accurately control both the external stress and the internal brine pressure.
- The internal seals (including those used for the casing plug) worked well in preventing hydraulic fluid and brine from leaking out of their respective confined spaces.
- The leak detection system was successful in intercepting brine exiting the top of the specimen after it had flowed through the cemented annulus and casing-cement-salt interfaces.
- Diagnostic testing performed after the test specimen had experienced some external loading indicated leakage through the casing-cement-salt interfaces; however, the location of the leaks was not consistent from test to test (i.e., in some tests, the leak occurred at the casing-cement interface, while in other tests, the leak occurred at the cement-salt interface).
- Leakage through the interfaces occurred both with and without pressurization of the internal bore of the casing.
- In the stepped bore configuration, most of the external stress applied to the ends of the test specimen was carried by the stiff steel casing rather than the cement or salt. This type of loading caused significant stress concentrations in the stepped region of the salt bore and triaxial extensile stress states in other regions of the salt.
- Attempts at reducing the stress concentrations and extensile stress states by applying the external stress more slowly failed because the creep rates in the salt were not high enough to redistribute the stress either in the region below the casing or in the salt in general.

Based on the diagnostic tests and some limited numerical analyses, it was concluded that the application of the external stress, regardless of rate, was the likely cause of the cracking and debonding of the casing-cement-salt interfaces in the first three tests. During loading, the mismatches in stiffness of the materials on either side of the interfaces produced differential strains in the materials and these differential strains presumably led to the cracking and debonding of the interfaces. Using the experience gained from Test Nos. 1, 2, and 3, the original test procedure and test configuration were abandoned and a revised test procedure/configuration was developed for use in the four production tests.

4.2.2 Revised Test Procedure (Test Nos. 4, 5, 6, and 7)

Among other changes, the revised procedure included changes to the specimen geometry, cement curing methods, and loading sequence. Specifically, the changes incorporated in the revised procedure included:

- The water-to-cement ratio was reduced from 5.2 gallons/sack to 4.3 gallons/sack.
- The internal bore of the salt specimen was machined smooth to produce a uniform diameter extending through the entire length of the specimen.
- The casing plug was removed, allowing brine to enter the internal bore of the steel casing.
- The loading sequence was divided into two phases. In the first phase, an external stress of 1,000 psi was applied to an uncased, uncemented salt specimen and held for approximately 2.8 days. In the second phase of loading, the casing was cemented into the internal bore of the salt specimen, and a stress of 2,000 psi was immediately applied to all external surfaces of the specimen. After the cement had cured sufficiently (~7 days), the inner bore was incrementally pressurized with brine until a breakdown in the casing seal was observed.

Each of the changes was made to address a particular deficiency of the original test procedure.

The change in the water-to-cement ratio was made to reduce cement shrinkage during curing, while the elimination of the stepped bore in favor of a smooth bore was an attempt to reduce the stress concentrations directly below the steel casing. Removal of the casing plug resulted in the incremental pressurization of the internal bore of the casing which induced an incremental compressive stress across the casing-cement-salt interfaces as the brine pressure increased, thereby reducing the leak potential along the interfaces at low to moderate brine pressures.

The most significant changes were in the methods used (1) to cement the casing into the internal bore of the salt and (2) to apply the external stress and internal brine pressure. The Phase 1 loading of the uncased, uncemented salt specimen was meant to simulate an open

uncased borehole in the field and the transient creep response of the salt near the borehole. Recognizing that an uncased borehole contains some level of drilling fluid that would reduce the differential stresses on the surrounding salt, the external loading during Phase 1 was reduced to 1,000 psi. The Phase 2 loading was meant to simulate the interaction between "green" cement and creeping salt. By allowing the salt to creep into the internal bore of the specimen while the cement was curing, the bond between the cement and salt was strengthened and the differential straining that plagued the original test configuration was greatly reduced.

All the changes to the original test procedure were followed in Test Nos. 4, 6, and 7. However, in Test No. 5, the Phase 1 loading was intentionally omitted, so the bench-scale specimen was subjected only to the Phase 2 loading.

Typical results obtained from each test conducted under the revised test procedure included:

- External stress and brine pressure histories
- Brine leakage
- Maximum brine pressures
- Specimen deformations at the end of each loading phase.

These results are discussed below under separate headings.

4.2.2.1 External Stress and Brine Pressure Histories

The external stresses (i.e., external pressure and axial stress) and internal brine pressure were measured continuously during each test. These histories are provided in Figures 4-4 through 4-7 for Test Nos. 4, 5, 6, and 7, respectively. As shown, Test Nos. 4 and 7 comprised a Phase 1 loading as well as a Phase 2 loading. However, in Test No. 6, only the Phase 1 loading was performed because a test system malfunction caused the test to be aborted prematurely. In Test No. 5, the Phase 1 loading was intentionally omitted and the test was initiated using the Phase 2 loading instead.

As described previously, the objective of the Phase 1 loading was to simulate the lithostatic stress field around an open borehole before a casing is cemented in place. This simulation was accomplished in the bench-scale tests by simultaneously applying both an external pressure and an axial stress to the thick-walled cylinder of salt *before* the casing was cemented into the internal bore of the salt specimen. Once the external stress reached 1,000 psi, loading was suspended and the external pressure and axial stress were maintained at 1,000 psi for approximately 2.8 days. At the end of Phase 1, the stress was dropped to 0 psi and the specimen was removed from the test system so its dimensions could be measured. These dimensional measurements, together with those made on the virgin salt specimen, were used to estimate the inelastic deformations induced by the Phase 1 loading.

Figure 4-4. External Stress and Brine Pressure Histories for Bench-Scale Test No. 4.

Figure 4-5. External Stress and Brine Pressure Histories for Bench-Scale Test No. 5.

Figure 4-6. External Stress and Brine Pressure Histories for Bench-Scale Test No. 6.

Figure 4-7. External Stress and Brine Pressure Histories for Bench-Scale Test No. 7.

The Phase 2 loading followed Phase 1 by about 2 or 3 days to allow time for making the dimensional measurements of the test specimen. Phase 2 was initiated by (1) returning the test specimen to the test system, (2) cementing the steel casing into the internal bore of the salt specimen, and (3) immediately applying a stress of 2,000 psi to the external surfaces of the specimen. As the cement cured, the external stresses caused the salt to creep inward against the cement, ensuring good bonding between the salt and cement and cement and casing. The curing time for the cement was established as the time required for the cement to attain an unconfined compressive strength of 3,500 psi based on the results of the strength tests performed on the cement cylinders cast at the same time the casing was installed. As shown in Figures 4-4 through 4-7, the required curing time was typically about 7 days, as indicated by the elapsed time between when the casing was installed and when the internal pressure was first applied.

After the cement had cured sufficiently, brine was injected into the internal bores of both the salt specimen and casing and then pressurized in steps ranging from about 100 psi to 500 psi. The larger pressure increments were usually applied early in the test when the brine pressure was well below the applied external stress. The smaller pressure increments were applied when the internal brine pressure was nearly equal to the external stress. After each increment was applied, the brine pressure was held constant for several days so the brine flow rate could be determined. In general, the brine pressure was increased throughout Phase 2 until a pressure was reached that produced high brine flow rates. However, during Test No. 5, several brine pressure decrements (at about 30 days and 60 days, as shown in Figure 4-5) were substituted for the pressure increments to investigate the effect of pressure drops on the brine flow rate. Ultimately, Phase 2 was terminated whenever the brine flow rates were so high that manual readings of the buret could no longer be made accurately. The duration of Phase 2 ranged from about 23 days to 92 days. Following Phase 2, the specimen dimensions were measured once again and the diagnostic techniques were used to identify brine flow paths.

At the end of Test Nos. 4, 5, and 7, the massive leaks that occurred completely drained the brine-filled accumulator used for internal pressurization. When the internal pressure suddenly dropped to zero, the extra force that had been applied to counteract the internal pressure was suddenly transferred to the salt. Thus, the axial stress on the salt increased from 2,000 psi to between 2,500 psi and 2,750 psi.

4.2.2.2 Brine Leakage

Brine leaking through the cement annulus and casing-cement-salt interfaces was intercepted at the top of the specimen by a layer of porous felt metal. The porous felt metal directed the brine to the ports in the upper platen and ultimately to the buret used to measure the brine leaking through the casing seal.

Figures 4-8 through 4-10 give the total brine flow and brine pressure histories for Test Nos. 4, 5, and 7, respectively. In Test No. 4, brine flow did not occur until the internal brine pressure reached 1,000 psi. In Test Nos. 5 and 7, brine flow started as soon as the first increment of brine pressure was applied and continued throughout each test. The total brine flows in Test Nos. 4 and 7 were less than 200 milliliters. In contrast, the total brine flow in Test No. 5 was more than 3,000 milliliters. Although the duration of Test No. 5 was about four times that of Test No. 4 and three times that of Test No. 7, test duration alone does not explain the differences in the observed total flows. Some of the brine flow might be attributed to leakage around seals rather than through the cement and interfaces. Interestingly, Test No. 5 was the only test performed without a Phase 1 loading.

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Figure 4-8. Total Brine Flow and Brine Pressure Histories for Bench-Scale Test No. 4.

The flow rate for a particular time interval was estimated from the data shown in Figures 4-8 through 4-10 by fitting a straight line to three neighboring flow-time data pairs. Flow rate versus time relationships were then developed by making successive fits to data sets created by dropping the first data pair from the previous data set and adding the next successive data pair to the current data set. Figures 4-11 through 4-13 give flow rate and brine pressure as functions of time for Test Nos. 4, 5, and 7, respectively.

Figure 4-9. Total Brine Flow and Brine Pressure Histories for Bench-Scale Test No. 5.

Figure 4-10. Total Brine Flow and Brine Pressure Histories for Bench-Scale Test No. 7.

Figure 4-11. Flow Rate and Brine Pressure Versus Time for Bench-Scale Test No. 4.

Figure 4-12. Flow Rate and Brine Pressure Versus Time for Bench-Scale Test No. 5.

Figure 4-13. Flow Rate and Brine Pressure Versus Time for Bench-Scale Test No. 7.

Typically, the flow rate increases immediately following an increase in the internal brine pressure, but then decreases with time as the pressure is held constant. The reason for the decrease in the flow rate is not known; however, it is postulated the brine flow path becomes plugged over time because salt is precipitated out of the brine solution or because of autogenous healing³ [Wagner, 1974]. After several days of holding the brine pressure constant, the flow rate returns to the value it had before the brine pressure was increased, suggesting the flow rate is not dependent on the brine pressure. This observation suggests that brine may be “squeezed” out of the interfaces or the pores of the cement and/or salt through a process of compaction as the brine pressure is increased. The brine flow rates do appear to increase with brine pressure once the brine pressure approaches the applied external stress.

4.2.2.3 Maximum Brine Pressures

As described above in Section 4.2.2.1, the internal brine pressure was incrementally increased in each test while holding the external stress constant at 2,000 psi. Brine pressurization was terminated either when the test system malfunctioned or when the brine flow rates were so high, the buret could not be read accurately.

³ The precipitation of calcium carbonate in cement fissures both during flowing water and nonflowing water conditions.

Table 4-2 gives the maximum brine pressure observed during each test and provides some commentary about each test to aid in the interpretation of the results. Of the four tests conducted using the revised test procedure, only one (i.e., Test No. 6) was terminated prematurely because of a test system problem. In the other tests, the maximum brine pressures approached or even exceeded the external stress applied during the test. The lowest pressure measured was 1,600 psi (Test No. 4), or 80 percent of the external stress. This low pressure was traced to a "worm-hole" in the cement rather than a breakdown of the casing-cement-salt interfaces. In Test Nos. 5 and 7, the maximum brine pressures were approximately 2,100 psi and 2,200 psi, respectively, or about 105 percent and 110 percent of the applied external stress, respectively. The posttest diagnostic examination of the specimen used in Test No. 5 revealed that the casing-cement-salt interfaces were still intact and well bonded but that the seals located in the interface between the specimen and the lower platen failed, thereby allowing brine to escape from the internal bore. The posttest examination of the specimen used in Test No. 7 revealed a vertical fracture in the salt below the cemented casing rather than a breakdown of the casing-cement-salt interfaces. There was also evidence that the lower seals failed in this test as well.

Table 4-2. Maximum Brine Pressures Observed in the Bench-Scale Tests

Test	Applied External Stress (psi)	Maximum Brine Pressure (psi)	Brine Pressure To External Stress Ratio	Comments
4	2,000	1,600	0.80	Maximum brine pressure limited by a "worm-hole" extending through the cement and not a breakdown in casing-cement-salt interfaces.
5	2,000	>2,100	1.05	Possible leak in brine pressurization system. No brine flow paths were observed in the casing seal system or salt.
6	2,000	NA	NA	Test system malfunction. Test terminated prematurely before brine pressure could be applied.
7	2,000	>2,200	1.1	Maximum brine pressure attributed to a vertical fracture in the salt below the cemented casing. No breakdown in the casing-cement-salt interfaces was observed.

4.2.2.4 Specimen Deformations

Measurements of the salt specimen dimensions (i.e., length and internal and external diameters) were made after the specimen was initially machined and again at the end of both

the Phase 1 and Phase 2 testing. The length was measured at 30-degree intervals around the specimen perimeter. Both the inner and outer diameters were measured at orthogonal points every 1 inch along the length of the specimen, including the very ends of the specimen. During specimen preparation, the measurement points were labeled using a permanent marker and were used as landmarks for subsequent measurements. The measured specimen deformations are summarized below.

In general, the axial deformations of the specimens were uniform during both phases of testing, so the length measurements were simply averaged. Table 4-3 summarizes the three sets of length measurements made for the four specimens used in the production tests. With the exception of Specimen No. 6, the length of each specimen increased by a small amount both during Phase 1 and Phase 2 with the larger increase occurring during Phase 2. In contrast, the length of Specimen No. 6 decreased by 0.024 inch during Phase 1.

Table 4-3. Measured Specimen Length

Test No.	Length (in)			Displacement ^(a) (in)	
	Initial	After Phase 1	After Phase 2	After Phase 1	After Phase 2
4	15.947	15.958	15.998	0.011	0.051
5	16.004	(b)	16.064	(b)	0.060
6	16.035	16.011	(c)	-0.024	(c)
7	16.001	16.012	16.054	0.011	0.053

(a) Positive values indicated the specimen length increased.

(b) No Phase 1 was performed.

(c) No Phase 2 was performed.

The inner and outer specimen diameters for the four test specimens are plotted as functions of distance from the top of the specimen in Figures 4-14 through 4-21. The position of the steel casing is also shown for reference. The inner and outer diameters of the original specimens are nominally 6.5 inches and 12 inches, respectively. At the end of Phase 1, both the inner and outer diameters decrease slightly with larger decreases occurring at the midheight of the specimen and smaller decreases at the ends of the specimen. At the end of Phase 2, both the inner and outer diameters decrease, and these decreases are even larger than the ones observed at the end of Phase 1. In addition, the diameter profiles observed at the end of Phase 2 are less continuous than the profiles observed at the end of Phase 1. In particular, discontinuities are typically seen near the bottom of the casing with much larger deformations occurring below the bottom of the casing and relatively smaller deformations occurring above the bottom of the casing.

Figure 4-14. Internal Diameter Profile for Bench-Scale Test No. 4.

Figure 4-15. External Diameter Profile for Bench-Scale Test No. 4.

Figure 4-16. Internal Diameter Profile for Bench-Scale Test No. 5.

Figure 4-17. External Diameter Profile for Bench-Scale Test No. 5.

Figure 4-18. Internal Diameter Profile for Bench-Scale Test No. 6.

Figure 4-19. External Diameter Profile for Bench-Scale Test No. 6.

Figure 4-20. Internal Diameter Profile for Bench-Scale Test No. 7.

Figure 4-21. External Diameter Profile for Bench-Scale Test No. 7.

The differences in the measured diameters at the end of Phase 1 and Phase 2 are plotted as functions of distance from the top of the specimen in Figures 4-22 and 4-23, respectively. By plotting differences rather than the actual measurements, comparisons among specimens can be made directly. Even though the deformation profiles shown at the end of Phase 1 (Figure 4-22) are highly nonlinear (i.e., less deformation at the ends of the specimens and more deformation at the midheight of the specimens), they are repeatable from test to test. The nonlinearity is attributed to frictional effects at the salt-platen interfaces which tend to constrain the salt near the metal platens. The repeatability of the deformation profiles at the end of Phase 1 implies the frictional properties of the interfaces as well as the material properties of the salt are homogeneous from test to test. The deformation profiles of the three specimens at the end of Phase 2 (Figure 4-23) are similar over the cemented portion of the specimens but then diverge below the bottom of the casing. The divergence is greatest between Test Specimen No. 4 and Specimen Nos. 5 and 7. This result was expected because the cemented length in Test No. 4 was 15.5 inches and was only 10 inches in Test Nos. 5 and 7.

The measurements of diameter shown in Figures 4-14 through 4-21 can be coupled with the length measurements shown previously in Table 4-3 to estimate specimen volume at the various stages of the tests. Based on simplistic assumptions related to geometry, the test specimens all dilated a small amount both during Phase 1 and Phase 2.

Figure 4-22. Change in Internal and External Specimen Diameters at the End of Phase 1.

Figure 4-23. Change in Internal and External Specimen Diameters at the End of Phase 2.

5.0 NUMERICAL ANALYSIS

5.1 TECHNICAL APPROACH

Analyses of Test Nos. 4, 5, and 7 were performed to predict both the kinematical (deformation) and statical (stress) quantities that evolved over time when the external stress and internal brine pressure histories described in Chapter 4.0 were applied to the test specimens. The numerical analyses (a joint effort by RESPEC and Terralog Technologies USA Inc.) were performed using the finite difference program **FLAC** [Itasca Consulting Group, Inc., 1996] and a different constitutive model for each of the materials (i.e., salt, cement, and steel) comprising the test specimen. Detailed descriptions of the finite difference program, the mesh configurations, the constitutive models, and the numerical results are provided below under separate heading.

5.1.1 Finite Difference Program

The finite difference program used in the numerical analyses was **FLAC**, Version 3.30, a two-dimensional explicit finite difference code developed by Itasca Consulting Group [1996]. Additional, confirmatory analyses were performed using **FLAC3D**, Version 2.00-008; however, since both versions of the code gave similar results, further discussion is limited to the two-dimensional version.

FLAC is designed to simulate the behavior of structures built of soil, rock, or other materials which may undergo plastic flow when their yield limit is reached. Materials are represented by elements, or zones, that form a grid and that can be adjusted to fit the shape of the object being modeled. Each element behaves according to a prescribed linear or nonlinear stress/strain law (constitutive model) in response to the applied forces or boundary restraints. If the stresses (or stress gradients) are high enough to cause the material to yield and flow, the grid can actually deform and move with the material represented in the model. **FLAC** is based on a "Lagrangian" calculation scheme that is well suited for modeling large distortions. Furthermore, **FLAC** has several built-in constitutive models that permit the simulation of highly nonlinear materials (e.g., salt).

Because **FLAC** was developed primarily for geotechnical applications, it embodies special features to accurately represent the mechanical behavior of geologic materials. **FLAC** has seven built-in material models ranging from the "null" model which represents holes (excavations) in the grid to the shear and volumetric yielding models which include strain hardening/softening behavior, nonlinear shear failure, and compaction. Three optional models are available to simulate time-dependent (creep) behavior. The **FISH** programming language is also available to create other constitutive models that are not built into the code. Additionally, an interface or slip-plane model is available to represent distinct interfaces between two or more portions of

the grid. The interfaces are planes upon which slip and/or separation are allowed, thereby simulating the presence of faults, joints, or frictional boundaries.

The basic formulation for **FLAC** assumes a two-dimensional, *plane-strain* state for use in analysis of long structures and excavations with constant cross section and acted on by loads in the plane of the cross section. In addition, **FLAC** offers a *plane-stress* option for elastic analysis of thin plates and an option for modeling an *axisymmetric* geometry (e.g., cylindrical test specimens and cylindrical and spherical holes in a continuum).

5.1.2 Mesh Configuration

Two different axisymmetric meshes or grids were assembled for use in the numerical modeling. One mesh was assembled specifically to analyze Bench-Scale Test No. 4 and the other was assembled to analyze both Bench-Scale Test Nos. 5 and 7. Two meshes were required because the lengths of the steel casing and cement annulus were 15.5 inches in Test No. 4 and only 10 inches in Test Nos. 5 and 7. With the exception of the casing and cement lengths, the two meshes were identical in all other aspects.

Figure 5-1 provides the two conceptual models developed to represent Specimen No. 4 and Specimen Nos. 5 and 7, respectively. The models are annotated to indicate the lines of axisymmetry, the material types, and the interfaces between dissimilar materials. A single line of axisymmetry is used in both models, and this line is coincident with the central axis of the test specimen. The materials included in the models are salt, cement, and steel (comprising both the casing and the steel platens used to apply the axial loads to the specimens during testing). Six interfaces are also represented, including two in the cemented region of the model (steel/cement (Interface 1) and cement/salt (Interface 2)), three near the top of the model (steel/steel (Interface 3), cement/steel (Interface 4), and salt/steel (Interface 5)), and one near the bottom of the model (salt/steel (Interface 6)).

The finite difference axisymmetric grids for the two conceptual models are shown in Figure 5-2. The large grids are segregated into a steel casing segment, cement segment, salt segment, upper platen segment, and lower platen segment. Element sizes range from 0.0625 inch by 0.417 inch to 0.1875 inch by 1.0 inch. The interfaces are represented using zero-thickness interface or slip elements. The elements are fixed in the vertical direction at the bottom of the mesh and in the horizontal direction at the line of axisymmetry. Stress tractions are applied (1) at the top of the mesh to simulate axial load, (2) on the external radius of the salt and platens to simulate external pressure, and (3) on the inside radii of the salt and casing bores to simulate internal pressure. The loading sequence for these tractions are identical to the stress and pressure histories shown previously in Chapter 4.0.

Figure 5-1. Conceptual Models of Bench-Scale Test Specimen No. 4 and Bench-Scale Test Specimen Nos. 5 and 7.

Specimen No. 4

Specimen Nos. 5 and 7

Figure 5-2. Finite Difference Grids for Bench-Scale Test Specimen No. 4 and Bench-Scale Test Specimen Nos. 5 and 7.

5.1.3 Constitutive Models

A different constitutive model or material law was used for each material type represented in the conceptual models described above. Each constitutive model is defined by a set of model parameters that are typically determined from independent laboratory testing of the material being modeled. The model parameters for the salt and steel were obtained from the literature, while the model parameters for the cement were estimated from the strength testing conducted in this study. The models and parameters used in the analyses are presented below under separate headings.

5.1.3.1 Steel Casing and Platens

The mechanical behavior of the steel casing and the platens was assumed to be linear elastic. In addition, the steel was assumed to be homogeneous and isotropic so its elastic behavior could be characterized using only two elastic parameters. The elastic parameters selected were shear modulus, G , and bulk modulus, K . The values for these parameters are given in Table 5-1.

Table 5-1. Elastic Parameters for Steel Casing and Platens

Material Type	Shear Modulus G (psi)	Bulk Modulus K (psi)
Steel Casing	11.6×10^6	19.3×10^6
Steel Platens	11.6×10^6	19.3×10^6

5.1.3.2 Cement

As with the steel, the cement was also assumed to be a homogeneous, isotropic, linear elastic material; however, it was recognized that the elastic properties of the cement changed significantly during curing. The results of the laboratory tests conducted on the salt-saturated cement cylinders cast during the preparation of the eight batch mixes were used to develop a relationship between curing time and the elastic properties of the cement.

The two elastic parameters estimated from the test data were Young's modulus, E , and Poisson's ratio, ν . The elastic parameters used in the **FLAC** modeling were shear modulus, G , and bulk modulus, K . These two parameters were derived from the other two elastic parameters using the following two equations:

$$G = \frac{E}{2(1+\nu)} \quad (5-1)$$

$$K = \frac{E}{3(1-2\nu)} \quad (5-2)$$

The laboratory data clearly indicated that Young's modulus increased with curing time, but a similar correlation between Poisson's ratio and curing time could not be determined because Poisson's ratio was estimated in only a few tests. Therefore, Poisson's ratio was set at a constant value of 0.286 (the average value determined in the strength testing), and G and K were calculated from Equations 5-1 and 5-2 using the values of Young's modulus determined in the laboratory studies. Table 5-2 gives the time-dependent elastic parameters for the cement and the time intervals over which they apply.

Table 5-2. Time-Dependent Elastic Properties for Salt-Saturated Cement

Time Interval^(a) (days)	Shear Modulus G (psi)	Bulk Modulus K (psi)
0 to $t_1^{(b)}$	0 ^(c)	0 ^(c)
$t_1^{(b)}$ to 1	85,000	170,000
1 to 2	161,000	322,000
2 to 3	255,000	510,000
3 to 4	336,000	673,000
4 to 5	405,000	811,000
5 to 6	462,000	926,000
6 to 7	509,000	1,020,000
7 to 9	547,000	1,095,000
9 to 11	610,000	1,222,000
>11	622,000	1,246,000

(a) Elapsed time from the beginning of the cement pour.

(b) Variable to be established by trial and error. Typically, t_1 ranges from 0.3 to 0.9 day.

(c) In practice, the shear and bulk modulus values for the first time interval were 5 to 10 psi to prevent code instability.

The parameter, t_1 , shown in Table 5-2 represents the elapsed time between when the casing is cemented into the salt bore and when the cement had cured sufficiently to acquire some nonzero stiffness value. The parameter was treated as a variable because the true age of the cement was not known with complete certainty and because the curing conditions imposed on the cement in the bench-scale tests were different from the curing conditions used for the cement cylinders. Preliminary analyses suggested that the predicted deformations compared to the measured deformations would be too small if t_1 were set to zero but would be too large if t_1 were set greater than 1. Therefore, the value of t_1 was determined by trial and error during each individual analysis such that the predicted deformations matched the measured deformations at the end of Phase 2. Generally speaking, the value of t_1 was found to lie between 0.3 day and 0.9 day.

5.1.3.3 Salt

The salt used in the study was originally recovered from the Avery Island Dome, Louisiana, USA. As discussed in Section 2.1, a large database of mechanical properties is available for this salt and was used to derive an appropriate constitutive model. The model accounted for elastic deformations as well as time-dependent inelastic creep deformations.

The **FLAC** code can simulate the time-dependent material behavior of a creeping material using one of three material models: (1) a classical viscoelastic model, (2) a one- and/or two-component power law model, and (3) a reference baseline creep model [Senseny, 1983] developed for use in the nuclear waste isolation program. Preliminary analyses were performed with the simple one-component power law model, but this model was abandoned because it could not predict the deformations observed during the laboratory study. This deficiency was attributed to the inability of the simple power law model to predict transient creep deformations. Thus, the reference baseline creep model was used for all analyses.

In practice, the **FLAC** code uses another formulation of the baseline creep model, known as the WIPP reference creep law, because it is better suited for implementation in explicit computer codes. The WIPP reference creep law can be written as:

$$\dot{\epsilon} = \begin{cases} \dot{\epsilon}_s + (A - B\epsilon_p)\dot{\epsilon}_s & \dot{\epsilon}_s \geq \dot{\epsilon}_{ss}^* \\ \dot{\epsilon}_s + \left[A - B\left(\frac{\dot{\epsilon}_{ss}^*}{\dot{\epsilon}_s}\right)\epsilon_p \right]\dot{\epsilon}_s & \dot{\epsilon}_s < \dot{\epsilon}_{ss}^* \end{cases} \quad (5-3)$$

$$\dot{\epsilon}_s = D(\sigma)^n \exp\left(-\frac{Q}{RT}\right)$$

where:

$\dot{\epsilon}$ = strain rate

$\dot{\epsilon}_s$ = steady-state creep rate

ϵ_p = primary creep strain

σ = deviatoric stress

R = universal gas constant

T = absolute temperature

$A, B, D, Q, n, \dot{\epsilon}_{ss}^*$ = model parameters.

As shown in Equation 5-3, the expression governing the creep rate depends on the current value of the steady-state rate, $\dot{\epsilon}_s$. The WIPP reference creep model parameter values used in the analyses are summarized in Table 5-3.

Table 5-3. WIPP Reference Creep Law Parameters for Avery Island Salt

Parameter	Units	Value
Bulk Modulus, K	psi	4.83×10^6
Shear Modulus, G	psi	1.61×10^6
A	—	80.0
B	—	149
D	psi ⁻ⁿ /sec	6.89×10^{-14}
Q	J/gmole	31,200
n	—	2.99
$\dot{\epsilon}_{ss}^*$	1/sec	3.77×10^{-8}
R	J/gmole-K	8.413

5.1.3.4 Interfaces

The interfaces between dissimilar materials (e.g., steel/cement and cement/salt) and between identical materials but different test system components (e.g., casing/platen) were modeled with interface elements that allowed Coulomb sliding and tensile separation. The model parameters required for Coulomb sliding are as follows: (1) friction angle, ϕ ; (2) cohesion, c ; and (3) normal and shear stiffnesses (i.e., k_n and k_s). The parameter governing tensile separation is tensile strength, T .

Values for the four Coulomb parameters were not readily available from the literature, so instead, they were established by trial and error through two sets of numerical analyses of each bench-scale test. The first set of analyses was conducted to predict the internal and external salt specimen profiles at the end of the Phase 1 loading. In these analyses, only the salt/steel interfaces (i.e., Interfaces 5 and 6) were modeled because Phase 1 was conducted without the casing or the cement. The four Coulomb parameters for each salt/steel interface were varied in successive numerical runs until the predicted specimen profiles matched the measured specimen profiles at the end of Phase 1. In the second set of analyses, the salt/steel interface parameters were held constant at the values determined from Phase 1, and the steel/steel and cement/steel interface parameters were varied in successive numerical runs until the predicted specimen profiles matched the measured specimen profiles at the end of Phase 2. The interface parameters for the casing/cement and cement/salt were established based on experience.

Table 5-4 gives the interface parameters used in the analyses. Although Interfaces 5 and 6 both represent salt/steel interfaces, the friction and cohesion parameter values are different because of differences in the materials placed in the interfaces. For example, Interface 5 (salt/top platen) contains porous felt metal which has a rough surface, while Interface 6 (salt/bottom platen) contains a flexible rubber seal. The tensile strengths of all interfaces except the casing/cement (Interface 1) and the cement/salt (Interface 2) were set to high values to prevent separation of the interfaces during the simulations. The tensile strengths of the casing/cement and cement/salt interfaces were both set at 145 psi, which is the approximate tensile strength of cement and Avery Island salt.

Table 5-4. Interface Properties

Interface Number ^(a)	Interface Materials	Friction Angle ϕ (deg.)	Cohesion c (psi)	Stiffness (psi/inch)		Tensile Strength T (psi)
				Normal k_n	Shear k_s	
1	Steel/Cement	15	145	0.74×10^6	74×10^6	145
2	Cement/Salt	15	145	0.74×10^6	74×10^6	145
3	Steel/Steel	15	0	0.74×10^6	74×10^6	37×10^3
4	Cement/Steel	15	0	0.74×10^6	7.4×10^6	37×10^3
5	Salt/Steel	15	0.15	0.74×10^6	74×10^6	1.45×10^6
6	Salt/Steel	5	7.2	0.74×10^6	74×10^6	1.45×10^6

(a) Interface numbers are shown in Figure 5-1.

5.2 MODELING RESULTS

5.2.1 Displacements

The displacement profiles along the length of the test specimens were predicted for the internal diameter and the external diameter. Predictions were made both at the end of the Phase 1 loading and also at the end of the Phase 2 loading.

Figure 5-3 compares the measured and predicted displacements at the end of Phase 1 for Test Nos. 4, 6, and 7. The displacement profile predicted for the external diameter is in good agreement with the displacements measured in the three tests. The displacements along the inner bore of the salt are underpredicted slightly, but the nonlinear shape of the profile is captured well.

Figures 5-4 through 5-6 compare the measured and predicted displacements at the end of Phase 2 for Test Nos. 4, 5, and 7, respectively. The displacement profiles predicted for the inner and outer diameters match the measured displacement profiles extremely well, including the discontinuities at the bottom of the cemented casing.

5.2.2 Stresses

Radial stress was extracted as a function time from each of the **FLAC** simulations along two horizontal planes passing through the conceptual model. One plane was located just above the bottom of the steel casing and the other was located at the approximate midheight of the casing. The extraction points included: (1) the inner diameter of the cement annulus (Cement ID), (2) the outer diameter of the cement annulus (Cement OD), and (3) the inner diameter of the salt (Salt ID). Theoretically, the radial stresses at the Cement OD and the Salt ID should be identical; however, in **FLAC**, the stresses are calculated at the center of the elements so the Cement OD stresses will not match the Salt ID stresses because of spatial stress gradients. The radial stress histories for Test Nos. 4, 5, and 7 are summarized below under separate headings. Positive values of stress indicate compression.

5.2.2.1 Test No. 4

The predicted radial stress histories for the Test No. 4 simulation are shown in Figures 5-7 and 5-8 for the casing bottom and casing midheight, respectively. Also shown for reference is the internal brine pressure history. The external stress is held constant at 2,000 psi throughout Phase 2 of the simulation. The length of the cemented casing is 15.5 inches, leaving only about 0.5 inch of uncased hole below the bottom of the casing.

Figure 5-3. Measured and Predicted Displacements at the End of Phase 1 for Bench-Scale Test Nos. 4, 6, and 7.

Figure 5-4. Measured Versus Predicted Displacements at the End of Phase 2 for Bench-Scale Test No. 4.

Figure 5-5. Measured Versus Predicted Displacements at the End of Phase 2 for Bench-Scale Test No. 5.

Figure 5-6. Measured Versus Predicted Displacements at the End of Phase 2 for Bench-Scale Test No. 7.

Figure 5-7. Predicted Radial Stress Versus Time at the Casing Bottom, Test No. 4 Simulation.

Figure 5-8. Predicted Radial Stress Versus Time at the Casing Midheight, Test No. 4 Simulation.

Shortly after the casing was installed in the salt bore (~1 day), the radial stresses at the Cement ID, Cement OD, and Salt ID increase rapidly in the simulation. These high rates gradually decrease with time until pressurization of the internal bore of the salt and casing is initiated. In response to the incremental loading of the internal bore, the radial stresses at the casing bottom and midheight also increase incrementally, but the magnitude of the increase is less than the magnitude of the brine pressure increment. At the end of the simulation (~27 days), the radial stresses at the casing bottom are approximately 2,200 psi, 2,400 psi, and 2,850 psi at the Salt ID, Cement OD, and Cement ID, respectively, while at the casing midheight, the radial stresses are approximately 2,050 psi, 2,100 psi, and 2,400 psi at the Salt ID, Cement OD, and Cement ID, respectively.

5.2.2.2 Test No. 5

The predicted radial stress histories for the Test No. 5 simulation are shown in Figures 5-9 and 5-10 for the casing bottom and casing midheight, respectively. Also shown for reference is the internal brine pressure history. As in the simulation of Test No. 4, the external stress is held constant at 2,000 psi throughout Phase 2; however, in the simulation of Test No. 5, the Phase 1 loading was intentionally omitted. The length of the cemented casing is 10 inches, leaving about 6 inches of uncased hole below the bottom of the casing.

The radial stresses at the casing bottom increase rapidly with time after the installation of the casing is simulated. In fact, the radial stresses at the Cement OD and Salt ID both reach approximately 3,000 psi, and the radial stress at the Cement ID reaches approximately 3,800 psi within the first 7 days of the simulation. However, as soon as the internal brine pressure is applied at 7 days, all of the radial stresses drop to about 2,000 psi. The radial stresses then remain at approximately 2,000 psi throughout the simulation period but do decrease slightly with each increment of internal pressure (or increase slightly with each decrement of internal pressure).

At the casing midheight, the radial stresses also increase rapidly with time following the installation of the casing; however, the stresses reach a plateau (~600 to 700 psi) after only 2 or 3 days. When the internal pressure is applied in the simulation, the radial stresses at the Cement ID, Cement, OD, and Salt ID instantaneously increase but again by a smaller magnitude than the applied pressure increment. The radial stresses also increase slightly with each successive brine pressure increment. At the end of the simulation, the radial stresses at the Cement OD and Salt ID are about 1,100 psi and the radial stress at the Cement ID is about 1,400 psi.

5.2.2.3 Test No. 7

The predicted radial stress and brine pressure histories for the Test No. 7 simulation are shown in Figures 5-11 and 5-12 for the casing bottom and casing midheight, respectively.

Figure 5-9. Predicted Radial Stress Versus Time at the Casing Bottom, Test No. 5 Simulation.

Figure 5-10. Predicted Radial Stress Versus Time at the Casing Midheight, Test No. 5 Simulation.

Figure 5-11. Predicted Radial Stress Versus Time at the Casing Bottom, Test No. 7 Simulation.

Figure 5-12. Predicted Radial Stress Versus Time at the Casing Midheight, Test No. 7 Simulation.

Similar to the other two simulations, the external stress is held constant at 2,000 psi throughout Phase 2. In contrast to the simulation of Test No. 4, the length of the cemented casing is 10 inches rather than 15.5 inches, while in contrast to the simulation of Test No. 5, the Phase 2 loading of Test No. 7 was preceded by a Phase 1 loading.

The radial stresses at both the casing bottom and casing midheight respond nearly identically to the radial stresses predicted in Test No. 5. For example, at the casing bottom, the radial stresses increase rapidly after the casing installation is simulated and reach values in excess of the external stress (the radial stresses at the Cement OD and Salt ID both reach approximately 2,900 psi, while the radial stress at the Cement ID reaches approximately 3,500 psi). As soon as the internal brine pressure is applied, all of the radial stresses drop dramatically (to about 1,800 psi) and then remain nearly constant even when the internal pressure is changed (as before the stresses decrease slightly as the internal pressure is increased). At the end of the simulation, the radial stresses at the Cement ID, Cement OD, and Salt ID of the casing bottom are approximately 1,700 psi, 1,500 psi, and 1,500 psi, respectively. At the casing midheight, the radial stresses increase rapidly to about 500 to 600 psi and then plateau at this level until the internal pressure is applied. As in the simulation of Test No. 5, the radial stresses at the casing midheight increase slightly with each brine pressure increment. At the end of the simulation, the radial stresses at the Cement OD and Salt ID are about 750 psi and the radial stress at the Cement ID is about 1,100 psi.

5.3 DISCUSSION OF NUMERICAL RESULTS

The FLAC simulations were able to predict both the displacements of the test specimens at the end of Phase 1 and Phase 2 and the displacement profiles along the length of the specimens at the end of the same two phases. This good agreement was primarily a result of the trial-and-error modeling performed to establish the salt/steel, steel/steel, and cement/steel interface properties.

The high radial stresses predicted in the interfaces at the bottom of the casing are attributed to the inward bending of the bottom of the salt specimen under the externally applied external stress. Under this assumption, the radial stresses should be the largest when the cemented casing length is the smallest. A comparison of results from the Test No. 4 simulation with the results from the Test Nos. 5 and 7 simulations supports this conclusion. In Test No. 4, the radial stresses reach nominal values of about 2,000 psi just before the internal pressure is applied, while in Test Nos. 5 and 7, the radial stresses exceed 3,000 psi just before the internal pressure is applied. Based on similar arguments, the internal pressurization should have a more significant effect on the radial stresses predicted in Test Nos. 5 and 7 than in Test No. 4. Again, this hypothesis is borne out by the large decreases in the radial stresses predicted in Test Nos. 5 and 7 immediately following the application of the internal pressure, while the radial stresses predicted in Test No. 4 increase slightly.

The radial stresses predicted at the casing midheight are similar in all simulations in that the stresses increase both immediately following the installation of the casing and after the internal brine pressurization is initiated. The most significant difference in the predicted radial stresses at the casing midheight is the magnitude of the stresses relative to the casing length. In Test No. 4, the radial stresses at the casing midheight plateau at approximately 1,900 psi just before the internal pressure is applied and then increase to between 2,100 psi and 2,400 psi at the end of the simulation. In Test Nos. 5 and 7, the initial plateau is about 500 or 600 psi and the radial stresses are less than 1,400 psi at the end of the simulation. This difference may also be explained by the flexural behavior of the salt wall. For example, Test No. 4 nearly simulates a wellbore interval that is cased throughout its full length, so bending or flexure is likely to have little effect because there is no "pivot point" (stress concentrator such as the bottom of a rigid steel casing) along the interval. In contrast when a pivot point exists, such as in Test Nos. 5 and 7, and when the ends of the salt are restrained by the friction in the salt-platen interfaces, it is highly likely that the salt wall will take on the complex shape of a compound flexure along the cased interval. In this case, the casing-cement-salt interfaces may experience relatively high or relatively low compressive radial stresses, depending on the position of the inflection point (or points) in the salt wall.

The effect of including a Phase 1 loading on the radial stresses predicted during Phase 2 is relatively small, as shown in a comparison between the radial stresses predicted in Test No. 5 (no Phase 1) and Test No. 7 (with Phase 1). The radial stresses predicted in Test No. 5 do appear to build more quickly than do the radial stresses in Test No. 7. This result might be expected, particularly after the casing is installed, because the salt in Test No. 5 will exhibit higher creep rates than the salt in Test No. 7. The higher creep rates for the salt in Test No. 5 are manifestations of the combined affect of both transient creep and steady-state creep. The salt in Test No. 7 also exhibits transient creep, but much of the transient creep occurs during Phase 1 before the casing is installed.

Interestingly, the casing-cement-salt interfaces did not debond or open at the bottom of the casing even though the applied brine pressure exceeded the predicted radial stresses in two of the three tests. However, because the internal pressure below the casing is higher than the radial stress in the interfaces, the interfaces might ratchet open if vertically oriented voids or defects in the cement or interfaces were to connect with the open wellbore below the cemented casing allowing brine to fill the voids and/or defects.

Finally, the numerical analyses indicated no slippage or tensile separation along the casing-cement-salt interfaces in any of the simulations. This result implies that (1) the shear stresses induced in the interfaces were below the Coulomb strength of the interfaces and (2) the stresses normal to the interfaces were all compressive or at least below the tensile strength of the interfaces.

6.0 SUMMARY AND CONCLUSIONS

6.1 SUMMARY

In response to the SMRI CS&A Research Program, seven bench-scale tests were performed to investigate the integrity of well casings set in natural rock salt. The specific objectives of the testing were to:

- Develop and validate an appropriate test method and test configuration for simulating the physical characteristics of a casing shoe set in salt as well as the state of stress in the vicinity of the casing shoe.
- Conduct tests to investigate the hydraulic and mechanical integrity of the casing seal (including casing-cement-salt interfaces) at fluid pressures approaching and even exceeding lithostatic stress.
- Develop diagnostic techniques to assess the condition of the casing-cement-salt interfaces and the leakage rates through these interfaces.
- Perform numerical analyses of the tests to predict deformations and stress states in the vicinity of the casing shoe.

All bench-scale and diagnostic testing was performed at RESPEC's Materials Testing Laboratory located in Rapid City, South Dakota, USA. The numerical analyses were a joint effort by RESPEC and Terralog Technologies USA Inc., Arcadia, California, USA.

Test Method and Configuration

The testing made use of large (13-inch-diameter) salt cores recovered from the Avery Island Dome, Louisiana, USA. These cores were machined to produce thick-walled, hollow cylinder test specimens with nominal lengths of 16 inches and nominal external and internal diameters of 12 inches and 6.5 inches, respectively. A steel casing was cemented (using a salt-saturated cement) into the internal bore of each salt specimen and the specimen was placed in a large special-purpose test system capable of simultaneously applying load to all external surfaces of the test specimen and pressurizing the internal salt bore. The external stress and internal pressure simulated the in situ lithostatic stress and cavern pressure, respectively. The external stress was 2,000 psi for all tests. The internal pressure was increased in a step-wise manner, while a leak detection system monitored brine flow rates through the casing seal. The tests were terminated when the observed leakage rates were so high they could no longer be measured accurately.

Cement Testing

Cement cylinders were cast from each batch mix used in the installation of the casings and also from a trial batch prepared at the beginning of the study. The cylinders were subsequently used to determine the mechanical properties of the cement as it cured. The mechanical properties measured in the cement tests included: (1) unconfined and triaxial compressive strengths, (2) Young's modulus of elasticity, and (3) Poisson's ratio. Typically, unconfined compressive strength tests were conducted on cylinders from each batch following curing times of 1, 3, 7, 14, and 28 days. Limited triaxial compression testing was performed at a confining pressure of 2,000 psi to investigate the effect of pressure on cement strength. A total of 24 tests was completed, including 22 unconfined compressive strength tests and 2 triaxial compressive strength tests. The data from the tests were used directly in the numerical analyses and also in establishing the curing time required before the internal bore of the bench-scale specimens could be safely pressurized.

Bench-Scale Testing

Initially, three bench-scale tests were performed to develop and validate an appropriate test procedure and test configuration. In these tests, the casings were cemented into the internal bore of the salt and the cement was allowed to cure for 28 days at normal room temperature (68°F) and ambient pressure conditions. Following the 28-day curing time, the test specimens were placed in the test system and proportionally loaded with an external stress and internal brine pressure. During the proportional loading, the external stress was applied at a rate twice that of the brine pressure. Loading continued until high brine flow rates were observed. High flow rates were measured at low internal brine pressures (i.e., 1,000 psi or lower) for all three tests, which was attributed to deficiencies in the test procedure and test configuration rather than the casing integrity. These deficiencies were remedied before any production testing was performed.

Four production bench-scale tests were conducted according to a revised test procedure and test configuration. The most significant revision to the original test procedure was the method used to cure the cement after the steel casing was installed in the inner bore of the salt specimen. Instead of curing the cement under ambient pressure conditions, the cement was cured while the stress was applied to the external surfaces of the salt specimen. This change required the installation of the casing with the specimen mounted in the test system and the immediate loading of the specimen following assembly.

The internal brine pressure and the external stress were not applied simultaneously in the revised procedure because the "green" cement would likely be displaced by the brine during pressurization. Instead, the brine was pressurized only after the cement achieved an unconfined compressive strength of 3,500 psi (based on cement cylinder test results). Once the cement strength had been achieved (typically requiring 7 days), the internal brine pressure was

increased in a load-hold manner. The hold time was typically several days, during which time, the brine flow rate was monitored.

One of the four production tests was aborted prematurely because of a test system malfunction; however, the other three tests were considered successful. In two of the successful tests, the internal brine pressure reached 2,100 psi and 2,200 psi, or 105 percent and 110 percent of the applied external stress, respectively. In the other successful test, the maximum brine pressure was only 1,600 psi (or 80 percent of the external stress). This low pressure was attributed to a "worm-hole" in the cement rather than a breakdown of the casing-cement-salt interfaces.

Diagnostic Techniques

Several diagnostic techniques were developed during the study to assess the integrity of the cemented casing, including the casing-cement-salt interfaces. In some cases, the techniques were used in combination with one another to improve the results. Visual inspection was used whenever possible to look for voids in the cement and macroscopic fractures and separations along the interfaces. The brine used to pressurize the internal bore was doped with a fluorescent dye that could be viewed using a black light to facilitate the visual inspection. In addition, the test specimens were sawn into 1-inch-thick disks so the casing-cement-salt interfaces could be examined along the full length of the cemented portion of the test specimen. Other diagnostic techniques included the use of compressed air and liquid soap and a vacuum pump/manometer system used to measure vacuum loss through the thickness of the individual 1-inch-thick disks.

Numerical Analyses

Numerical analyses of the three successful tests were performed using the finite difference program **FLAC**. The analyses predicted (1) the displacement profiles of the internal and external diameters of the salt at the end of both the Phase 1 and Phase 2 loading and (2) the radial stress histories at relevant locations within the finite difference model; e.g., at the casing-cement-salt interfaces located near the casing midheight and the casing bottom. A separate constitutive model or material law was used for each of the materials comprising the bench-scale test specimens. The steel components (i.e., casing and platens) and the cement in the annulus between the casing and salt were treated as homogeneous and isotropic materials and were simulated using linear elastic models. The elastic properties of the cement were made time-dependent to account for the stiffening of the cement as it aged. The WIPP reference creep model was used for the salt and was capable of simulating both transient and steady-state creep deformation.

The displacement profiles of the internal and external diameters were predicted reasonably well both at the end of Phase 1 and the end of Phase 2. The good agreement was a result of the

trial-and-error numerical modeling process used to establish the frictional properties of the interfaces between the test specimen and the loading platens.

In response to the application of the external stress and the subsequent curing of the cement and inward creeping of the salt, high compressive radial stresses (in excess of the applied external stress) were predicted for the casing-cement-salt interfaces at the bottom of the casing. The application of the internal brine pressure had significant consequences for the radial stresses, and these consequences depended on the cemented casing length. In the simulation conducted with the longer cemented casing (i.e., 15.5 inches), the radial stresses increased only moderately as the brine pressure was incremented. However, in the simulations conducted for the shorter cemented casings (i.e., 10 inches), the radial stresses dropped instantaneously to the value of the lithostatic stress when the brine pressure was initially applied and then continued to decrease by small amounts as each new brine pressure increment was applied.

The radial stresses predicted at the casing midheight interfaces were similar in all numerical simulations in that the stresses increased immediately following the installation of the casing and also after the internal bore pressure was applied and subsequently incremented. The cemented casing length again affected the radial stress predictions, primarily in terms of the stress magnitude. In the simulation of the longer cemented casing, the radial stress increased and ultimately reached the value of the applied external stress. Then, as the internal salt bore was pressurized, the radial stresses continued to rise until they exceeded the external stress by as much as 20 percent. In the simulations of the shorter cemented casings, the radial stresses initially rise to only about 30 percent of the applied external stress and ultimately reach values that are only about 50 percent of the external stress, even after the internal bore pressure approaches and exceeds the external stress.

The effect of cemented casing length on the predicted radial stresses at the casing midheight and casing bottom is attributed to the differences in the flexural bending of the salt wall caused by the external stress, the internal brine pressure, and the position of the casing bottom relative to the loading platens. These differences arise from differences in the position of the flexure points in the salt as well as the frictional constraints at the ends of the test specimen.

Although the effect of including a Phase 1 loading on the radial stresses predicted during Phase 2 is small, the radial stresses in the casing-cement-salt interfaces build more quickly and reach higher values in the simulation that omits the Phase 1 loading when compared to the simulations that retain the Phase 1 loading. This difference is attributed to the higher transient deformation rates that occur in the salt when the Phase 1 loading is omitted from the Phase 2 simulation.

6.2 CONCLUSIONS

During the course of the bench-scale testing and subsequent numerical analyses, several observations and conclusions were made relative to the test method/configuration and the application of the results in practice. The observations and conclusions are summarized below.

Observations

- As expected, the unconfined compressive strength and Young's modulus (stiffness) of the salt-saturated cement increase with curing time. The maximum unconfined strength is achieved in approximately 30 days, while the maximum value of Young's modulus is achieved after only 14 days. The time-dependent properties of the cement (particularly Young's modulus) need to be accounted for in the numerical analyses in order to predict accurately the specimen deformations.
- The unconfined compressive strength of a 5.2 gallons/sack cement mix is only about 60 percent of the strength of a 4.3 gallons/sack cement mix at comparable curing times (~28 days). The effect of water-to-cement ratio on Young's modulus is negligible for the two ratios investigated in the study.
- Based on limited testing, Young's modulus of cement is not affected by confining pressure provided the curing time is a constant. Therefore, the values of Young's modulus determined from the unconfined compression tests can be used in modeling cement subjected to compressive stress states.
- The curing of the cemented casings under ambient pressure conditions produces reasonably good bonds between the casing and cement and cement and salt in the bench-scale tests, but does not simulate either the creeping of the salt into a wellbore or the pressure induced in the cement by the weight of the cement column placed in the field. The inward creeping of the salt can be simulated in the bench-scale tests by applying external stress to the test specimen while the cement is curing.
- When the cement is allowed to cure under ambient pressures, the subsequent external loading of the test specimen results in the cracking of the cement and debonding of interfaces because of mismatches in material stiffness. In practice, this condition seldom occurs in the field.
- The length of the casing and the frictional end effects of the loading platens influence the deformation profiles of the bench-scale specimens. In general, the applied external stress induces the inward displacement of both the external and internal surfaces of the hollow cylinder. This inward movement is restrained at the ends of the specimen by the friction between the specimen and the loading platens. The deformation profile is discontinuous near the bottom of the casing with larger deformations occurring below the casing bottom and smaller deformations occurring above the casing bottom.

- Brine flow or leakage was observed in all the bench-scale tests, even at low internal brine pressures. The flow rates increased instantaneously with each increment of the internal brine pressure but then decayed to constant values. The flow rates were not correlated to the magnitude of the internal brine pressure except at brine pressures approaching the applied external stress.
- The total brine flow was less than 150 milliliters in two tests and nearly 3,500 milliliters in a third test. The higher flow could be a result of brine seeping around the seals used to isolate the internal bore rather than flow through the cement or interfaces.
- Based on simplistic assumptions regarding the deformed geometry of the test specimens, the salt may have dilated a small amount during testing.
- Diagnostic techniques can be developed and used to assess casing-cement-salt interface damage and to identify leakage paths. In addition to visual inspection, the diagnostic techniques included (1) doping of the brine with fluorescent dye, (2) injecting air into the internal bore followed by the application of liquid soap to the cement and interfaces, (3) sectioning of the specimen into thin disks, and (4) inspecting the thin disks using a vacuum/manometer system. The fluorescent dye was ineffective in identifying flow paths relative to the other methods developed.
- The deformation profiles of both the internal bore and the external diameter of the bench-scale specimens can be predicted from numerical analyses provided the interface friction at the ends of specimen is well defined.
- The radial stresses predicted at the casing bottom and casing midheight indicate flexural bending of the salt wall, and therefore, are strongly influenced by the casing length and frictional effects of the platens at the ends of the specimen.
- Based on the predictions from the analyses, the radial stresses will develop more quickly and reach higher values when the casing is cemented into the salt bore immediately following the application of the external stress rather than waiting several days before the casing is installed.

Conclusions

- The bench-scale test can adequately simulate the loading conditions and cross-sectional geometry along a horizontal plane of a cemented casing shoe set in salt. Lithostatic stresses and internal brine pressures as high as 2,000 psi can be simulated in the test. In addition, the diameter of the casing and the thickness of the cemented annulus used in the tests approximate what is used in the field. Limitations of the bench-scale test include: (1) inability to simulate the pressure in the cement induced by the weight of a tall column of cement and (2) significant frictional effects in the platen-specimen interfaces which induce deformations and stress states that may not simulate the deformations and stresses in the vicinity of an actual casing shoe.

- Leakage of brine through the cemented seal system will occur even at low brine pressures; however, the leakage rates do not appear to be proportional to the applied brine pressure so Darcy flow is probably not a valid assumption for explaining the leakage. The flow could be a result of the “squeezing” of brine out of the pore spaces of the cement, interfaces, and salt immediately following the application of the brine pressure increment.
- Internal brine pressure can exceed the applied external stress by as much as 10 percent (i.e., a brine pressure-to-external stress ratio of 1.1) without a breakdown of the casing-cement-salt interfaces. However, these high pressures may cause a breakdown of other casing seal components (e.g., the salt below the casing may fracture).
- Based on the numerical analyses, the radial stresses in the casing-cement-salt interfaces develop more quickly and reach higher values when the casing is cemented into the salt bore immediately following the application of the external stress rather than waiting several days before the casing is installed. This result implies that the maximum radial stress in the vicinity of an actual casing shoe could be reduced if the hole is left open for a period of time before the casing is installed to complete the well.

7.0 REFERENCES

Carter, N. L. and F. D. Hansen, 1980. *Mechanical Behavior of Avery Island Halite: A Preliminary Analysis*, ONWI-100, prepared by RE/SPEC Inc., Rapid City, SD, for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Fokker, P. A., C. J. Kenter, and H. P. Rogaar, 1993. "The Effect of Fluid Pressures on the Mechanical Stability of (Rock) Salt," *Proceedings, 7th Symposium on Salt*, Kyoto International Conference Hall, April 6–9, Kyoto, Japan, H. K. Kakihana; H. R. Hardy, Jr.; T. Hoshi; and K. Toyokura (eds.), Elsevier Science Publishers B.V., Amsterdam, The Netherlands, Vol. 1, pp. 75–82.

Halliburton Company, 1994. *Halliburton Redbook (Cementing Tables Handbook)*, Halliburton Company, Dallas, TX.

Hansen, F. D. and N. L. Carter, 1981. "Creep of Avery Island Rocksalt," *Proceedings, First Conference of The Mechanical Behavior of Salt*, Pennsylvania State University, University Park, PA, November 9–11, H. R. Hardy Jr. and M. Langer (eds.), Trans Tech Publications, Clausthal, Germany, 1984, pp. 53–69.

Hansen, F. D. and K. D. Mellegard, 1980a. *Quasi-Static Strength and Deformational Characteristics of Dome Salt from Avery Island, Louisiana*, ONWI-116, prepared by RE/SPEC, Inc. for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Hansen, F. D. and K. D. Mellegard, 1980b. *Creep of 50-mm-Diameter Specimens of Dome Salt from Avery Island, Louisiana*, ONWI-104, prepared by RE/SPEC, Inc. for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Hansen, F. D., K. D. Mellegard, and P. E. Senseny, 1981. "Elasticity and Strength of Ten Natural Rock Salts," *Proceedings, First Conference of The Mechanical Behavior of Salt*, Pennsylvania State University, University Park, PA, November 9–11, H. R. Hardy Jr. and M. Langer (eds.), Trans Tech Publications, Clausthal, Germany, 1984, pp. 71–83.

Itasca Consulting Group, Inc., 1996. *FLAC: User's Manual*, Minneapolis, MN.

Mellegard, K. D. and P. E. Senseny, 1983. *Exponential-Time Creep Law for Avery Island Salt*, ONWI-329, prepared by RE/SPEC Inc., Rapid City, SD, for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Mellegard, K. D., P. E. Senseny, and F. D. Hansen, 1983. *Quasi-Static Strength and Creep Characteristics of 100-mm Diameter Specimens of Salt From Avery Island, Louisiana*,

ONWI-250, prepared by RE/SPEC Inc., Rapid City, SD, for Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Ratigan, J. L., 2000. "A Status Report on the Solution Mining Research Institute Cavern Sealing and Abandonment Program," *Solution Mining Research Institute Fall Meeting*, San Antonio, TX, October 15–18.

Senseny, P. E., 1983. *Review of Constitutive Laws Used to Describe the Creep of Salt*, ONWI-295, prepared by RE/SPEC Inc., Rapid City, SD, for the Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, OH.

Wagner, E. F., 1974. "Autogenous Healing of Cracks in Cement-Mortar Linings for Gray-Iron and Ductile-Iron Water Pipe," *Journal of the American Water Works Association (AWWA)*, Denver, CO, June, pp. 358–360.

APPENDIX A

**STRESS-STRAIN CURVES FOR UNCONFINED AND
TRIAxIAL COMPRESSIVE STRENGTH TESTS
OF SALT-SATURATED CEMENT**

Figure A-1. Stress Difference Versus Axial Strain for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G1 (Trial Batch, 5-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-2. Stress Difference Versus Axial Strain for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G2 (Trial Batch, 28-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-3. Stress Difference Versus Axial and Radial Strains for a Triaxial Compression Test of Salt-Saturated Cement, Specimen G3, at a Confining Pressure of 2,000 psi (Trial Batch, 42-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-4. Stress Difference Versus Axial and Radial Strains for a Triaxial Compression Test of Salt-Saturated Cement, Specimen G4, at a Confining Pressure of 2,000 psi (Trial Batch, 45-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-5. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G5 (Trial Batch, 47-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-6. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G7 (Batch 1, 43-Day Cure, 5.2 Gallons/Sack Mix).

Figure A-7. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G22 (Batch 4, 1-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-8. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G23 (Batch 4, 3-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-9. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G25 (Batch 4, 7-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-10. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G26 (Batch 4, 14-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-11. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G27 (Batch 4, 28-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-12. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G28 (Batch 5, 1-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-13. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G29 (Batch 5, 3-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-14. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G30 (Batch 5, 7-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-15. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G31 (Batch 5, 14-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-16. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G32 (Batch 5, 28-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-17. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G33 (Batch 6, 1-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-18. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G35 (Batch 6, 3-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-19. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G36 (Batch 6, 7-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-20. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G40 (Batch 7, 1-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-21. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G41 (Batch 7, 3-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-22. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G42 (Batch 7, 7-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-23. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G43 (Batch 7, 14-Day Cure, 4.3 Gallons/Sack Mix).

Figure A-24. Stress Difference Versus Axial and Radial Strains for an Unconfined Compression Test of Salt-Saturated Cement, Specimen G44 (Batch 7, 28-Day Cure, 4.3 Gallons/Sack Mix).