MMS Project

Long-Term Integrity of Deepwater Cement Systems Under Stress/Compaction Conditions

Report 3

Issued November 19, 2002

CSI

CEMENTING SOLUTIONS, INC.

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Objectives

The overall objective of this research project is to determine the properties that affect cement's capability to a produce fluid-tight seal in an annulus and to develop correlations between cement properties and sealing performance under downhole conditions. The testing reported previously in progress reports 1 and 2 has helped to refine and confirm the test procedures that will be used for the remainder of the project.

Research conducted during this project period focused on continued measurement and correlation of cement mechanical properties, mechanical bond integrity of a cemented annulus, and mathematical simulation of stresses induced in a cemented annulus. Mechanical property testing included measurement of tensile strength and Young's Modulus measurements under various confining loads. Mechanical integrity testing included shear bond and annular seal testing on specimens cured under various cyclic curing schedules. Mathematical simulation of casing and cement stress and strain induced by thermal and pressure cycling was also performed during this project period.

Conventional Performance Testing

Composition

The compositions tested in this project are detailed in **Table 1** below.

Table 1—Cement Compositions for Testing

Comp. No.	Description	Cement	Additives	Water Requirement (gal/sk)	Density (lb/gal)	Yield (ft^3/sk)
1	Neat slurry	TXI Type 1	—	5.23	15.6	1.18
2	Neat slurry with fibers					
3	Foam slurry	TXI Type 1	0.03 gal/sk Witcolate 0.01 gal/sk Aromox C-12 1% CaCl	5.2	12.0	1.19
4	Bead slurry	TXI Type 1	13.19% K-46 beads	6.69	12.0	1.81
5	Latex slurry	TXI Type 1	1.0 gal/sk LT-D500	4.2	15.63	1.17
6	Latex fiber slurry	TXI Type 1	1.0 gal/sk LT-D500 3.5% carbon milled fibers 0.50% Melkrete	4.09	15.63	1.20
7	Class H with silica	Class H	35% coarse silica 0.6% retarding fluid loss additive	5.38	16.4	1.40
8	Class H with silica and fibers	Class H	35% coarse silica 0.6% retarding fluid loss additive 3.2% milled fibers	5.38	16.4	1.43

Compressive Strength Testing

A summary of the compressive strength tests conducted was included in Report 2, and will not be repeated in this report. Please see Report 2 for a detailed description of these tests.

Report 2 discussed concerns about a possible discrepancy in compressive strength data provided by Westport and CSI. Compressive strength testing of representative compositions was conducted at Westport Laboratory to check the accuracy of CSI's test procedure. The results presented in **Table 2**, which represent the averages of three samples tested, indicate that data from the outside laboratory tracks closely with that of CSI.

Table 2—Comparison of Compressive Strengths

Location	Compressive Strength (psi) at 45°F	Compressive Strength (psi) at 80°F
Westport	1400	2015
CSI	1455	1920

Rock Properties Testing

Young's Modulus Testing

Composition 1 samples were cured in an unconfined condition (removed from mold after 24 hours and allowed to cure the remainder of the time outside of the mold) and tested at confining pressures of 0; 1,500; and 5,000 psi. The results are presented in **Table 3**.

Similar tests were conducted for Compositions 3 and 4 at confining pressures of 0, 500, and 1,000 psi, and for Composition 5 at confining pressures of 0, 250, and 500 psi. The results are presented in **Tables 4 through 6**.

Table 3—Composition 1, Compressive Young's Modulus

Confining Pressure (psi)	Effective Strength (psi)	Young's Modulus (psi)
0	8645	16.7 E 5
1500	8160	11.1 E 5
5000	8900	9.1 E 5

Table 4—Composition 3, Compressive Young's Modulus

Confining Pressure (psi)	Effective Strength (psi)	Young's Modulus (psi)
0	2885	5.8 E 5
500	3950	6.8 E 5
1000	4510	6.1 E 5

Table 5—Composition 4, Compressive Young's Modulus

Confining Pressure (psi)	Effective Strength (psi)	Young's Modulus (psi)
0	5150	9.5 E 5
500	6000	8.1 E 5
1000	6150	1 E 5

Table 6—Composition 5, Compressive Young's Modulus

Confining Pressure (psi)	Effective Strength (psi)	Young's Modulus (psi)
0	3500	5.6 E 5
250	5250	8.9 E 5
500	6000	9.4 E 5

Figure 1—Young's modulus testing of Composition 2 (neat Type 1 with fibers)

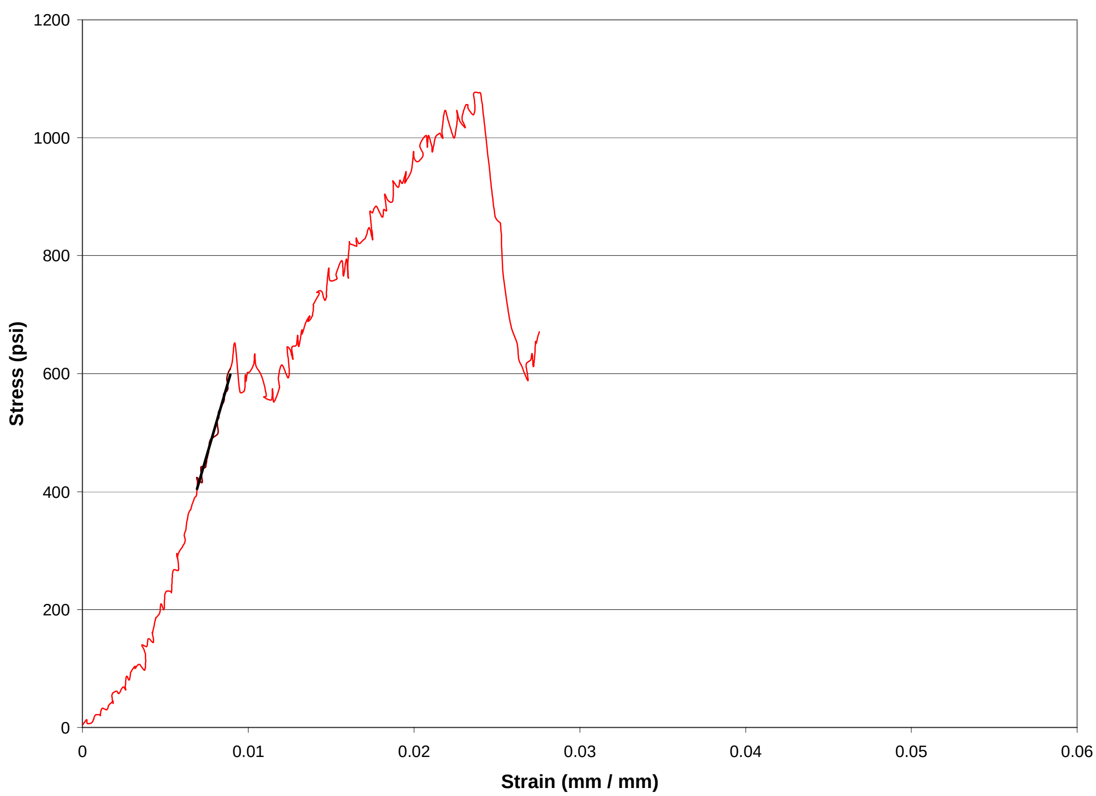


Figure 2—Young's modulus testing of Composition 5 (Type I latex without fibers)

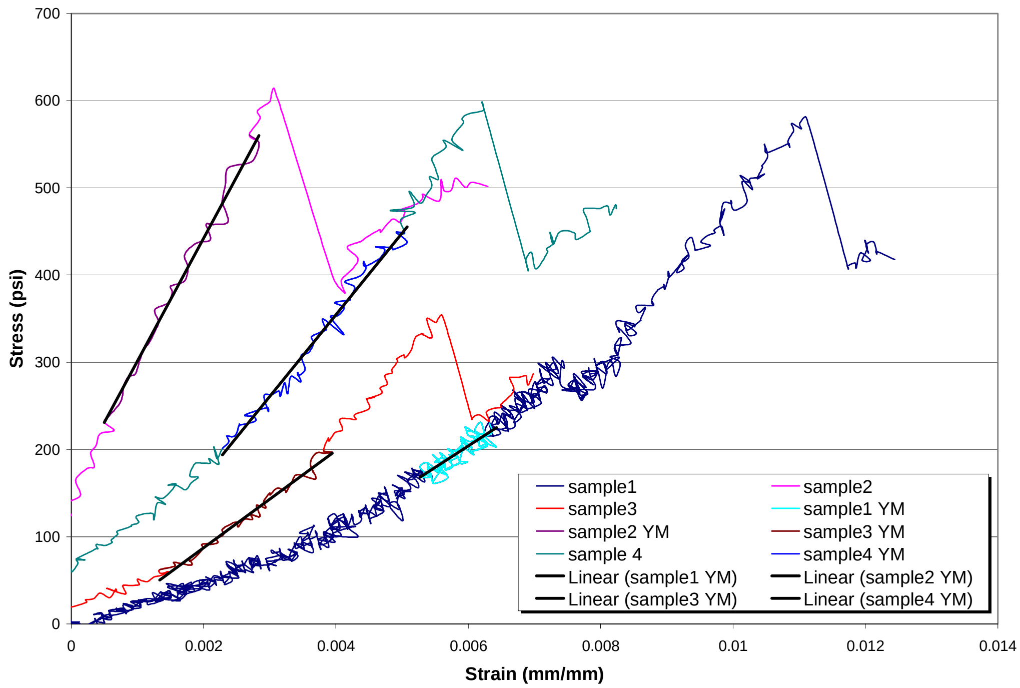
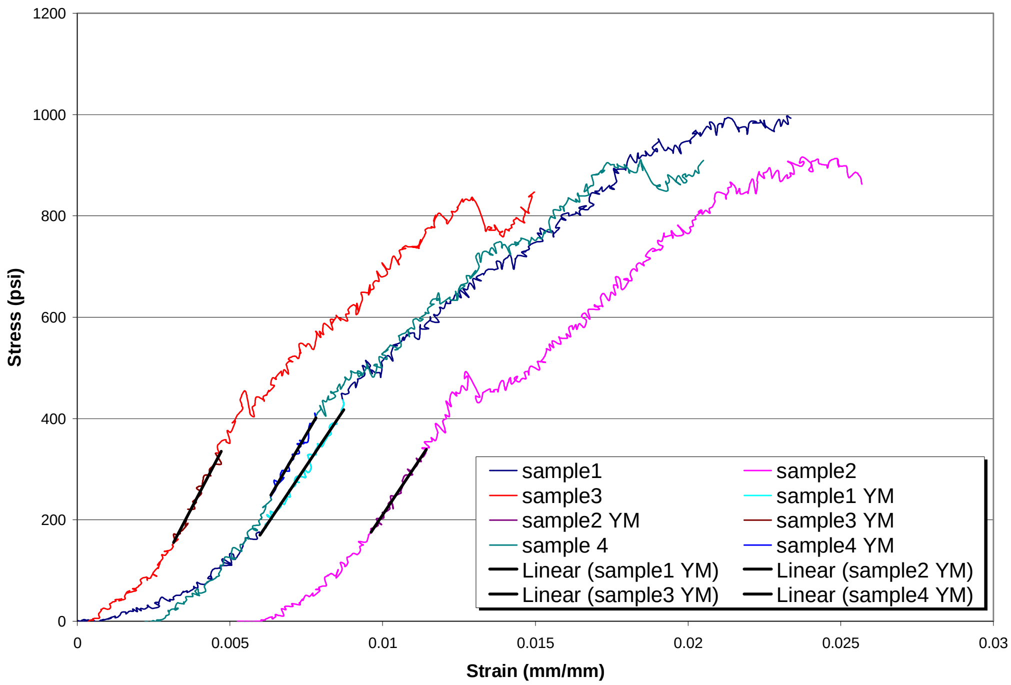


Figure 3—Young's modulus testing of Composition 6 (Type I latex with fibers)



Tensile Strength Testing

The data presented in **Table 7** indicate that the tensile strength of Composition 4 was significantly higher than that of the other compositions tested.

Table 7—Tensile Strength Comparison

Slurry	Tensile Strength (psi)
Composition 1	394* / 213**
Composition 3	253
Composition 4	1071
Composition 5	539
Composition 6	902

* Sample was cured outside the mold.

** Sample was cured in the mold.

Hydrostatic Pressure Testing

The first hydrostatic pressure tests performed on a 10 lb/gal slurry (**Table 8**) were discussed in Report 2, and is being included in Report 3 for comparison purposes, as we present results obtained with a 12-lb/gal slurry (**Table 9**).

In both sets of tests, the initial sample was tested to failure. Subsequent cycle tests were performed with separate samples. The results are shown in Figures 4 through 9.

Table 8—Hydrostatic Cycles for 10-lb/gal Foam

Cycle No.	Hydrostatic (psi)	Young's Modulus (psi)
1 (initial)*	—	5.57E+05
2 (up)**	1000	3.38E+05
3 (down)**	100	6.71E+05
4 (up)**	1500	5.71E+05
5 (down)**	100	7.98E+05
6 (up)**	2000	6.68E+05
7 (down)**	100	8.49E+05***

* Initial sample taken to failure

** Tests performed on separate (not initial) samples

*** No deformation calculations performed for Cycle 7

Table 9—Hydrostatic Cycle for 12-lb/gal Foam

Cycle No.	Hydrostatic (psi)	Young's Modulus (psi)
1 (initial)*	—	8.24E+05
2 (up)**	600	1.30E+05

*Initial sample taken to failure

**Separate sample tested

Figure 4—Young's modulus testing of 10-lb/gal foamed cement

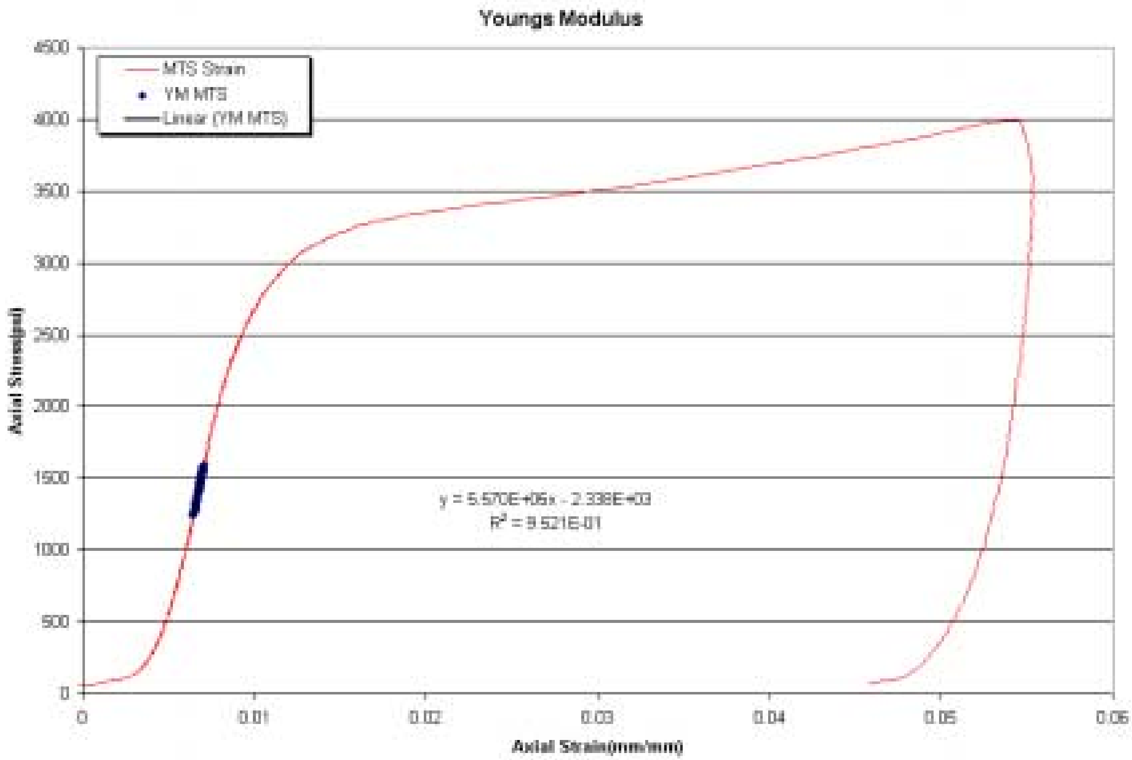


Figure 5—Young's modulus testing of 10-lb/gal foamed cement during hydrostatic cycling

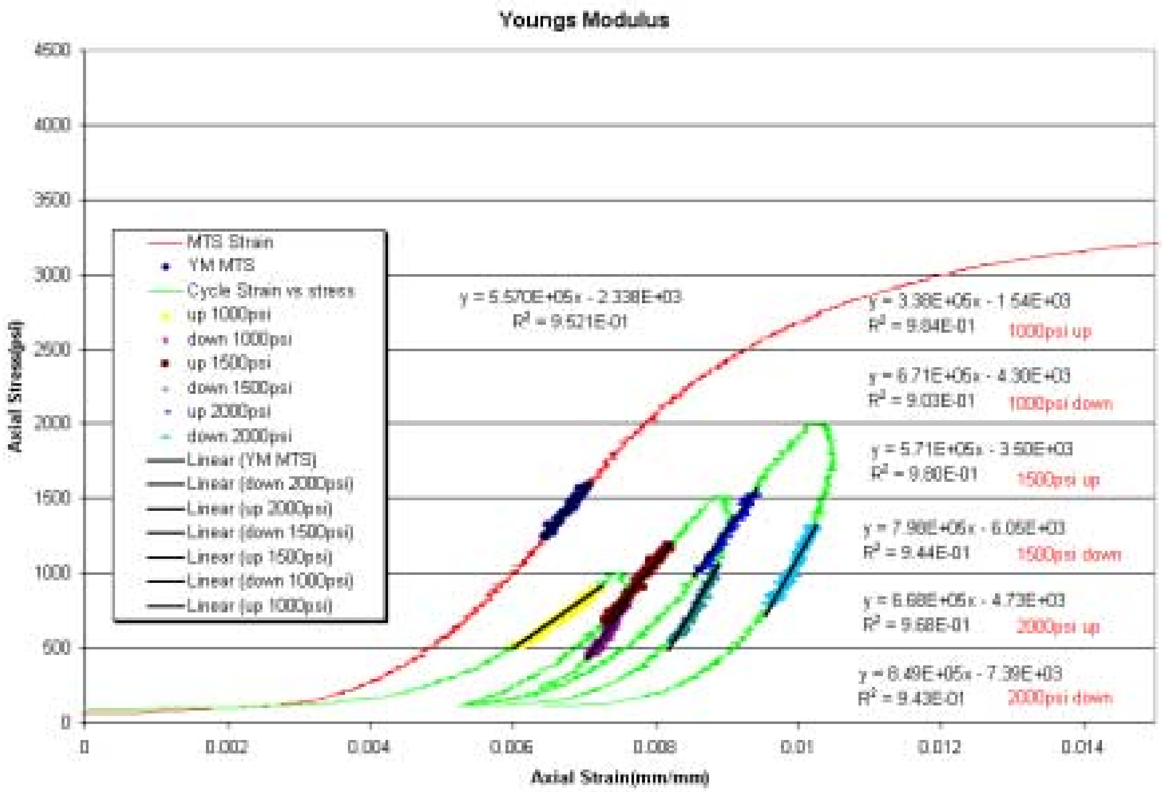


Figure 6—Deformation of 10 lb/gal foamed cement during hydrostatic cycling

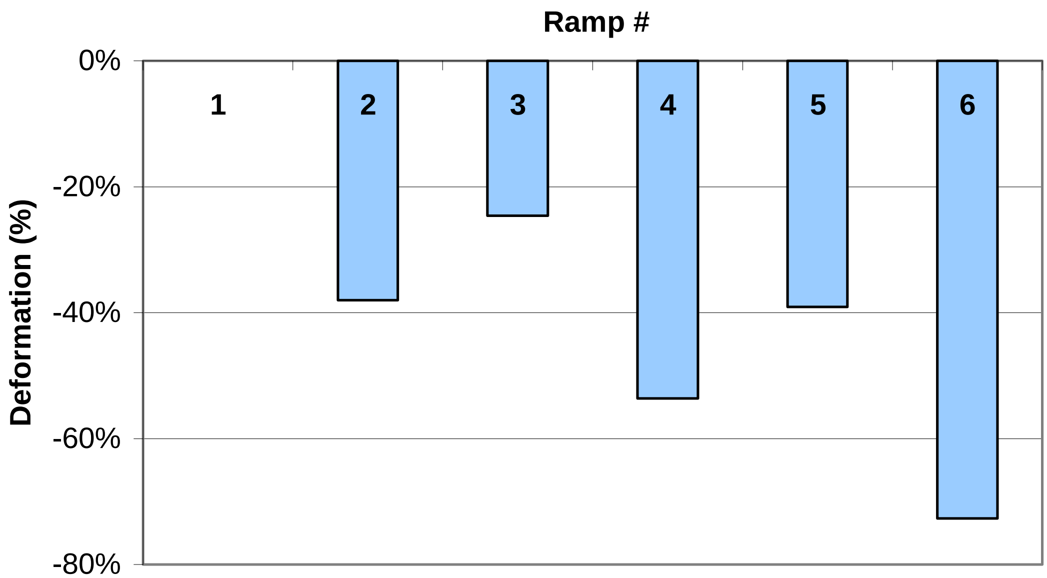


Figure 7— Young's modulus testing of 12-lb/gal foamed cement (Composition 2)

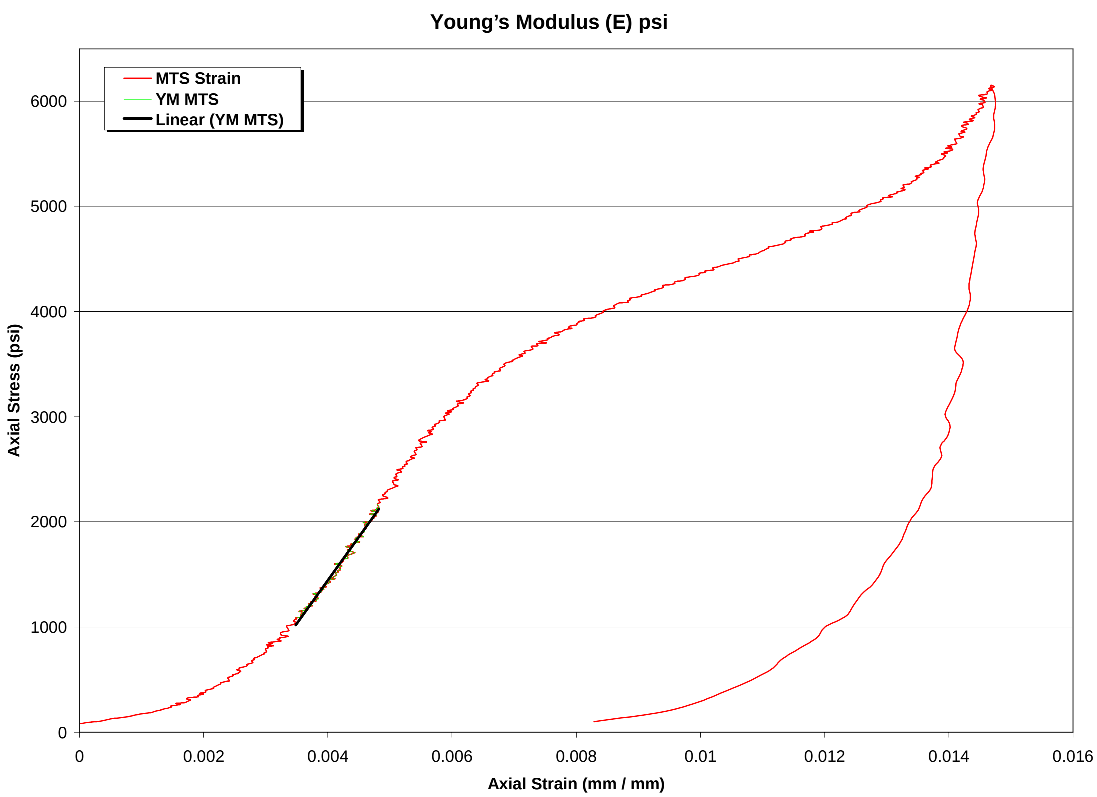


Figure 8—Young's modulus testing of 12-lb/gal foamed cement (Composition 2) during hydrostatic cycling

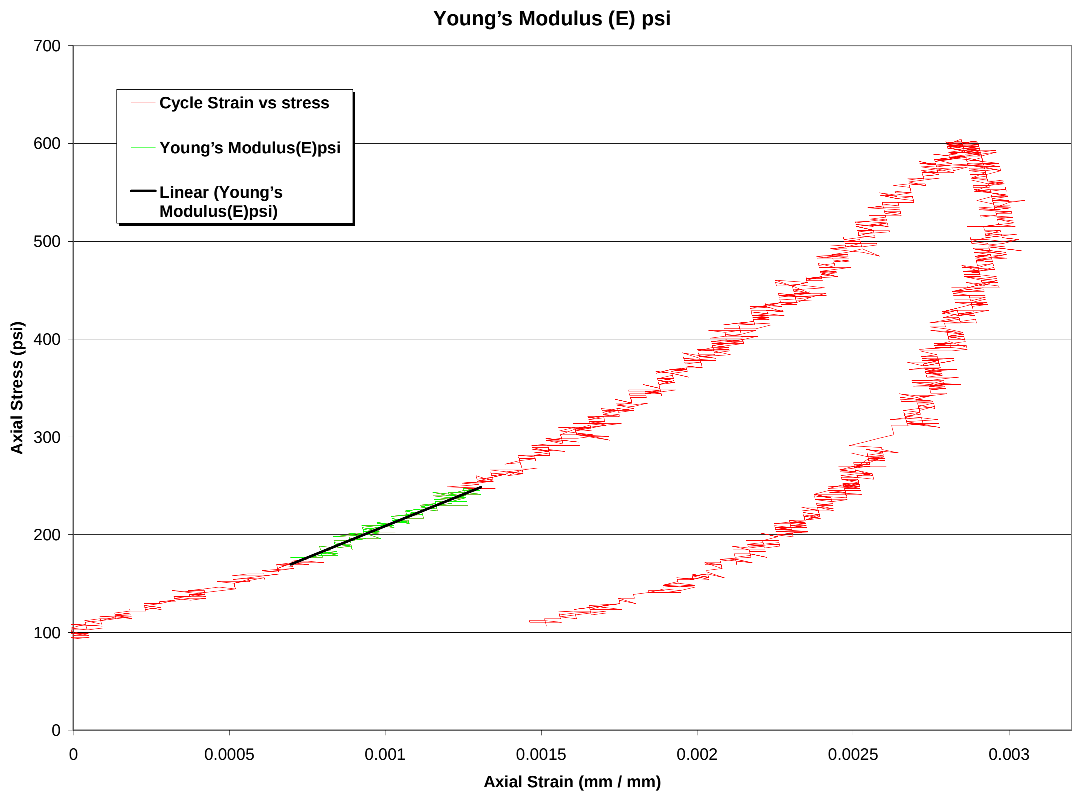
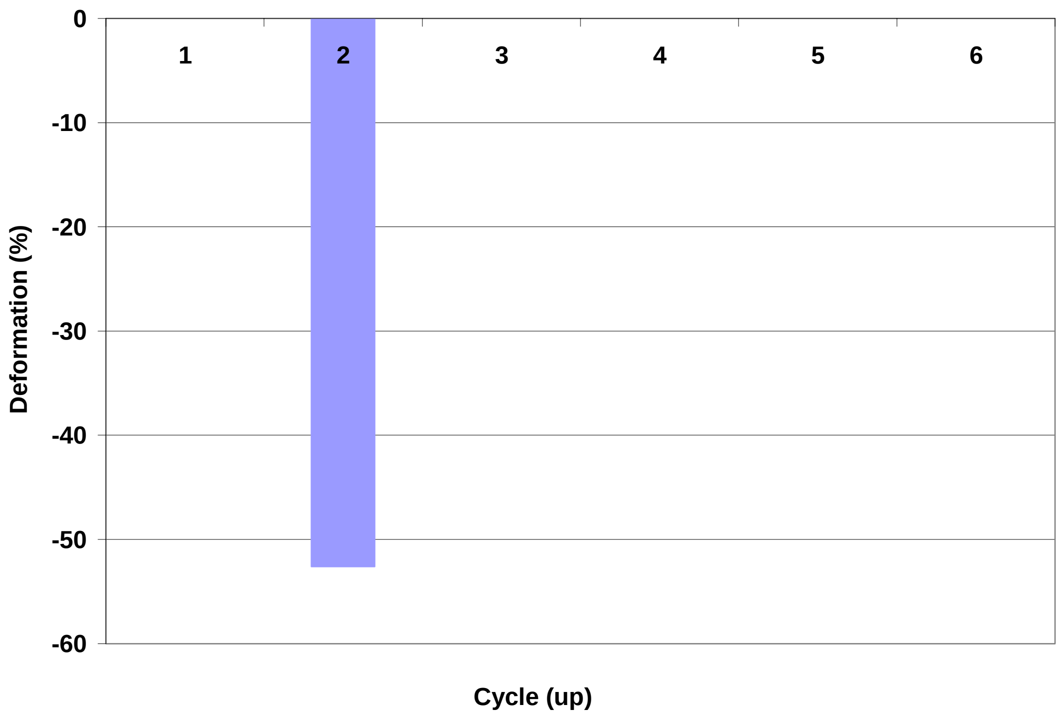


Figure 9—Deformation of 12-lb/gal foamed cement (Composition 2) during hydrostatic cycling



Chandler Engineering, Inc. Mechanical Properties Device

For comparison purposes, Chandler Engineering, Inc. and CSI have agreed to exchange data generated by two different systems – the rock mechanics system at Westport Laboratory and an acoustics-based system operated by Chandler. The same six slurries were tested in each device, and the comparative data is presented in **Tables 10 and 11**.

Initial results of Poisson's ratio testing on these lightweight cement compositions are not interpretable. The majority of tests yielded a negative Poisson's ratio, indicating a negative radial strain resulting from a positive axial strain. Several possible explanations for this phenomenon are under investigation. However, until the question is resolved, no Poisson's ratio data will be reported.

The Young's modulus values for latex cement with fibers, Class H cement, and Class H cement with fibers were not available at the time this report was prepared.

Like the UCA, Chandler's new analyzer measures the Young's modulus and compressive strength of a slurry as it cures at elevated temperatures and pressures, eliminating the potentially damaging effects of depressurization and cooling involved with traditional core testing. For more information on this device, see Appendix F.

Table 10—Chandler Device

Composition	Poisson's Ratio	Compressive Young's Modulus
1	0.20	2.3 E 6
4	0.31	1.5 E 6
5	0.39	1.4 E 6
6	0.19	2.5 E 6
7	0.24	2.2 E 6
8	0.25	2.3 E 6

Table 11—Rock Mechanics Data

Composition	Poisson's Ratio	Compressive Young's Modulus
1	—	1.7 E 6
4	—	9.5 E 5
5	—	5.6 E 5
6	—	—
7	—	—
8	—	—

Unconventional Performance Testing

Shear Bond Testing

Table 12 presents results of shear bond strength tests performed with temperature and pressure cycling on Compositions 1, 3, 4, and 5. For more information on test procedures, see Appendix C.

Table 12—Shear Bond Strengths (psi)

System	Simulated Formation	Comp. 1	Comp. 3	Comp. 4	Comp. 5
Baseline	hard	1194	127/98	109/78	—
	soft	198	233	143	223
Temperature-Cycled	hard	165	299/215	191/269	—
	soft	72	7	56	149
Pressure-Cycled	hard	194/106	276/228	294/170	—
	soft	23	22*	23*	11

* Visual inspection revealed samples were cracked.

Shrinkage Testing

Information on test procedures for shrinkage testing is provided in Appendix D.

Annular Seal Testing

Table 13 presents the results of annular seal tests performed on Compositions 1, 3, and 4. For information on test procedures for annular seal testing, see Appendix E.

Table 13—Annular Seal Tests

Condition Tested	Formation Simulated	Composition 1	Composition 3	Composition 4
Initial Flow	Hard	0 Flow	0 Flow	0 Flow
	Soft	0 Flow	0.5K (md)	0 Flow
Temperature-Cycled	Hard	0 Flow	0 Flow	0 Flow
	Soft	0 Flow	123K md / (2200 md)	43K (md)*
Pressure-Cycled	Hard	0 Flow	0 Flow	0 Flow
	Soft	27K (md)	0.19K (md)*	3K (md)

* Visual inspection revealed samples were cracked.

Pipe-in-Pipe Testing

A pipe-in-pipe test was designed to simulate the shrinkage of cement that can lead to fluid leakage when no external fluid is present outside the cement. Four models were tested:

- 6-in. flange
- 6-in. flange with 200-psi pressure
- 5-ft flange with vacuum
- 5-ft flange with 200-psi pressure

In all cases, no leaks were observed. The cement provided a tight seal to gas flow.

Mathematical Modeling

The graphs in this section represent an average of test results obtained in testing the performance of a neat cement (baseline), latex cement, and foamed cement. The compressive and tensile strengths and shear bond strength of the cements are shown in **Table 14**.

The abbreviations "PIP" and "PIS" are used in the following graphs to differentiate between test conditions that simulate hard formations (pipe-in-pipe) and those that simulate soft formations (pipe-in-soft).

Table 14—Compressive Strength

Cement	Compressive Strength After 10 Days (psi)	Tensile Strength (psi)	Shear Bond	
			PIP	PIS
Composition 3	3436	578	321	147
Composition 5	3630	504	432	237
Composition 1	4035	673	519.6	203

Compressive Failure

Figures 10 and 11 show the results of tests used to predict the effect of casing pressure and confining pressure on the radial stress experienced by the inner pipe, the cement sheath, and a hard formation.

The model showed that annular cement retains its integrity at high casing pressures and at high confining pressures in a hard formation.

When casing pressure was varied (**Figure 10**), and no confining pressure was applied, virtually no variation in the radial stress was observed for the cement or the formation. All variation, rather, was limited to the internal casing.

When confining pressure was varied (**Figure 11**), and casing pressure was fixed at 5,000 psi, the greatest variation in radial stress was observed in the inner casing and outer pipe (representing the formation), with very little variation observed in the cement. This is because of the differences in the Young's modulus properties of the cement vs. the Young's modulus of the steel pipe.

Figure 10—Compressive failure, simulated hard formation (1 of 2)

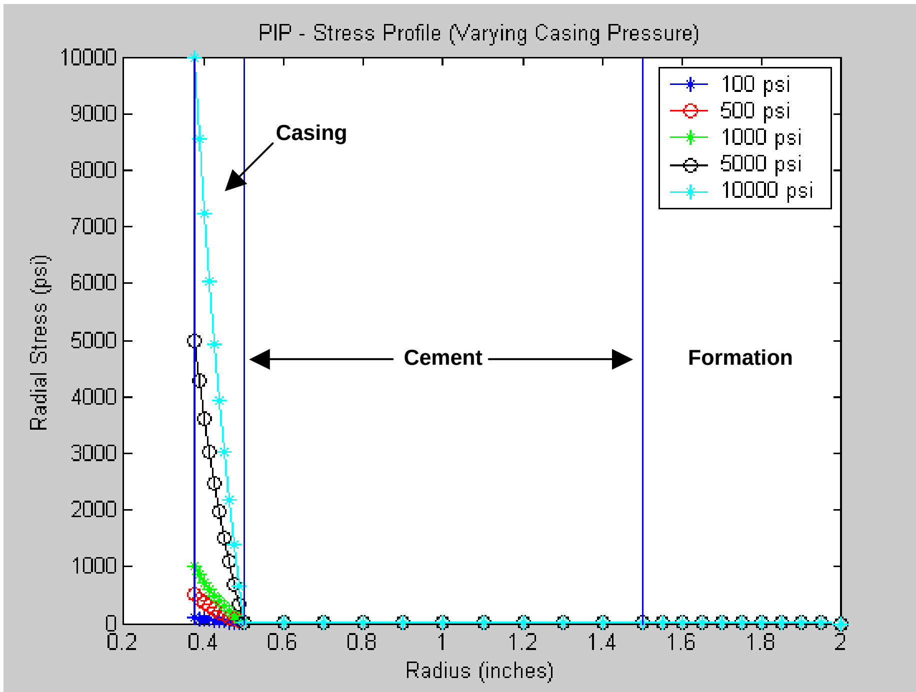
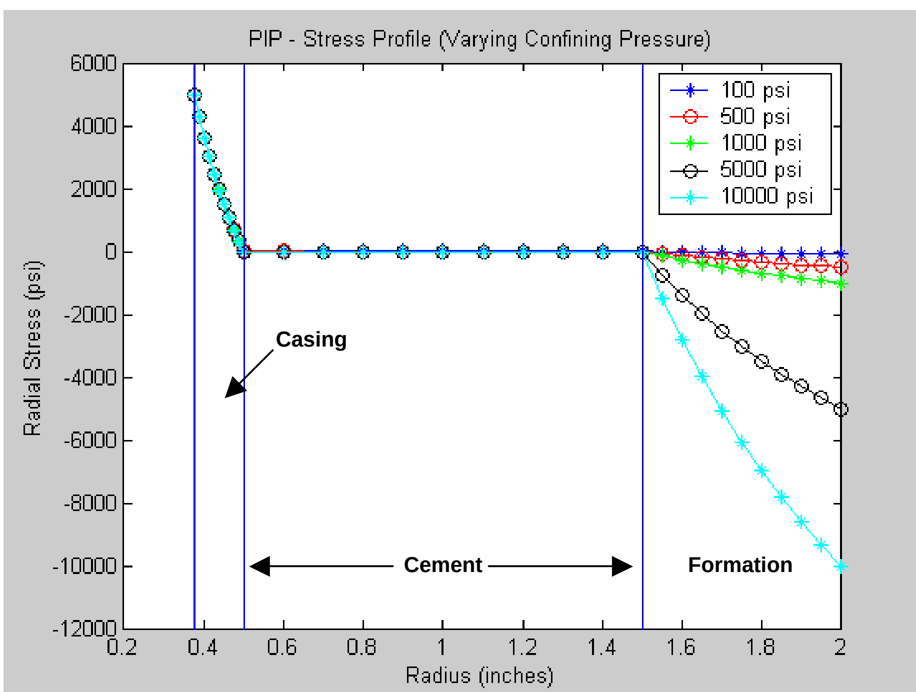


Figure 11—Compressive failure, simulated hard formation (2 of 2)



Cements were then tested to determine the effects of varying casing pressure and confining pressure in a soft formation scenario. Without confining pressure (**Fig. 12**), the cement and the formation experience no variation in radial stress as casing pressure increases. As in the test with the hard formation, the variation is limited to the inner casing.

However, when the casing pressure is fixed at 500 psi, and the confining pressure is increased from 100 psi to 10,000 psi (**Fig. 13**), the radial stress in the cement layer increases accordingly, to a point beyond which the sheath can withstand. At pressures of 5,000 psi and above, the cement sheath will almost certainly fail.

The positive and negative values shown in Figure 13 are used to differentiate radial stress (positive values) from the opposite of radial stress (negative values).

Figure 12—Compressive failure, simulated soft formation (1 of 2)

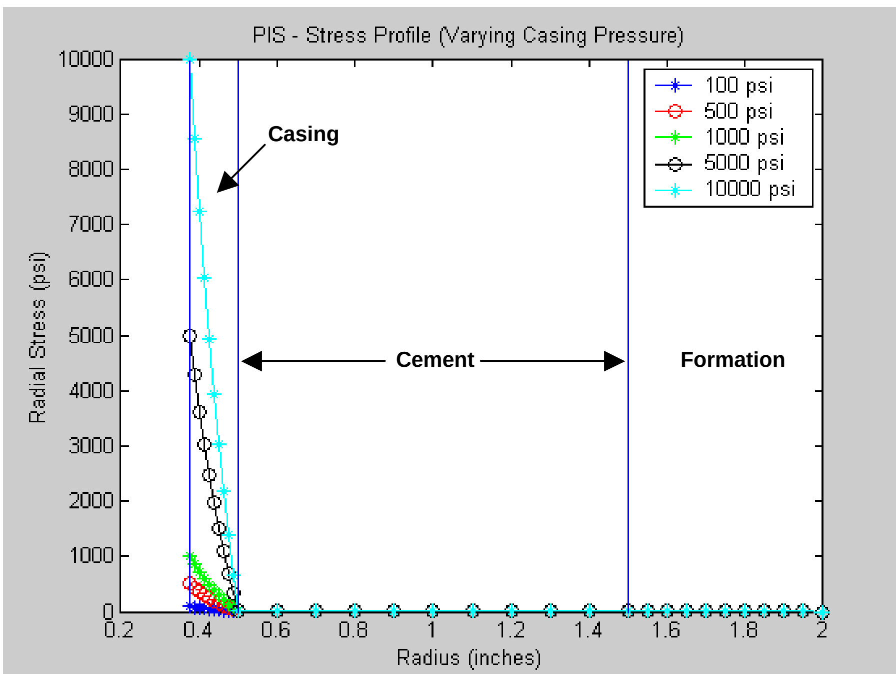
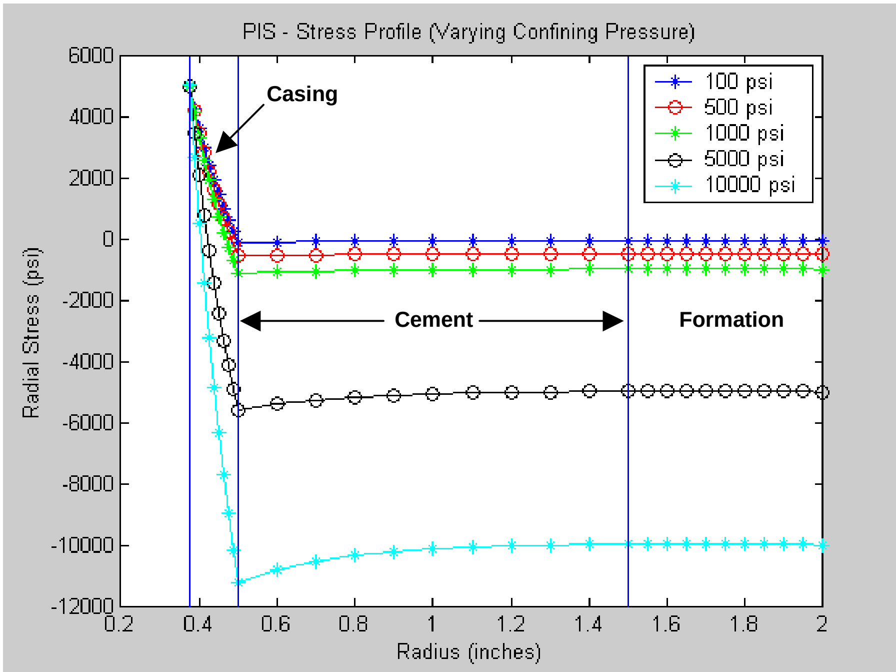


Figure 13— Compressive failure, simulated soft formation (2 of 2)



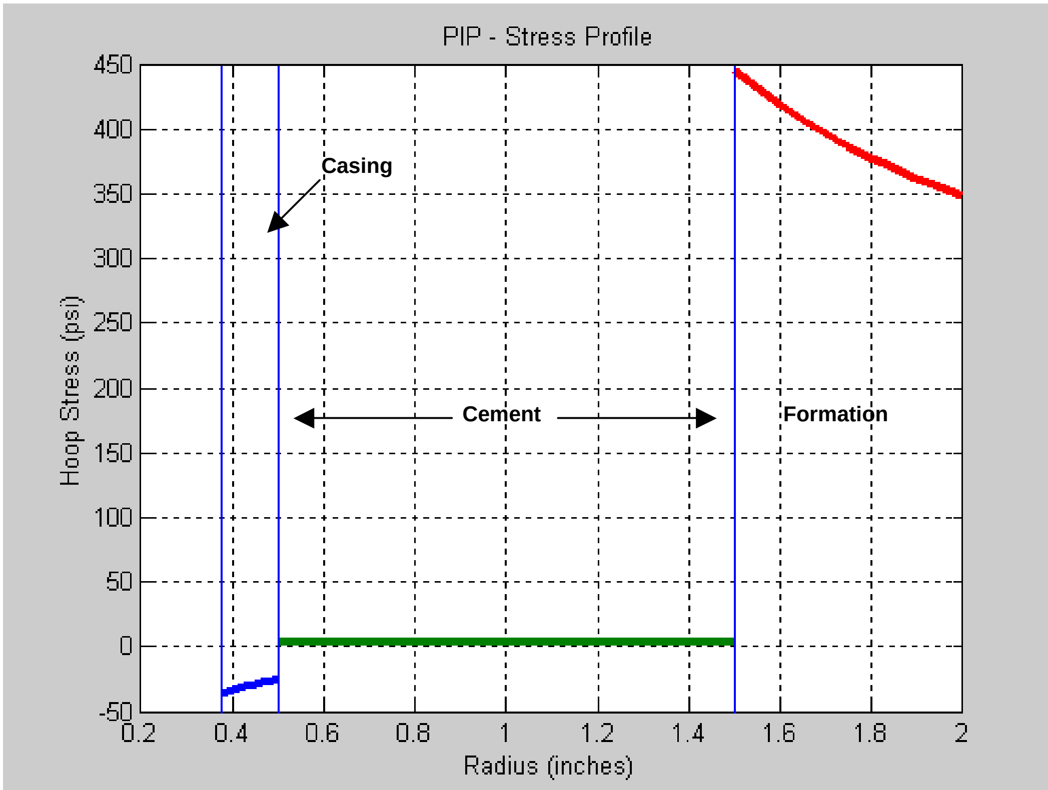
Shear Failure (Hoop Stress)

In a simulated hard formation (**Figure 14**), the variation in hoop stress at the pipe-cement interface is significantly less than that at the cement-formation interface. No significant variation in hoop stress is observed in the cement layer. Therefore, if failure occurs, it will most likely occur at the cement-formation interface.

In a simulated soft formation (**Figure 15**), there is almost no variation in the formation hoop stress, and there is slightly more variation in the hoop stress of the cement sheath. While the magnitude of variation between the pipe-cement interface and the cement-formation interface is significant, it is not as great as in the simulated hard formation shown in Figure 14. That is because the soft formation is more flexible and does not create the high stress contrast during displacement.

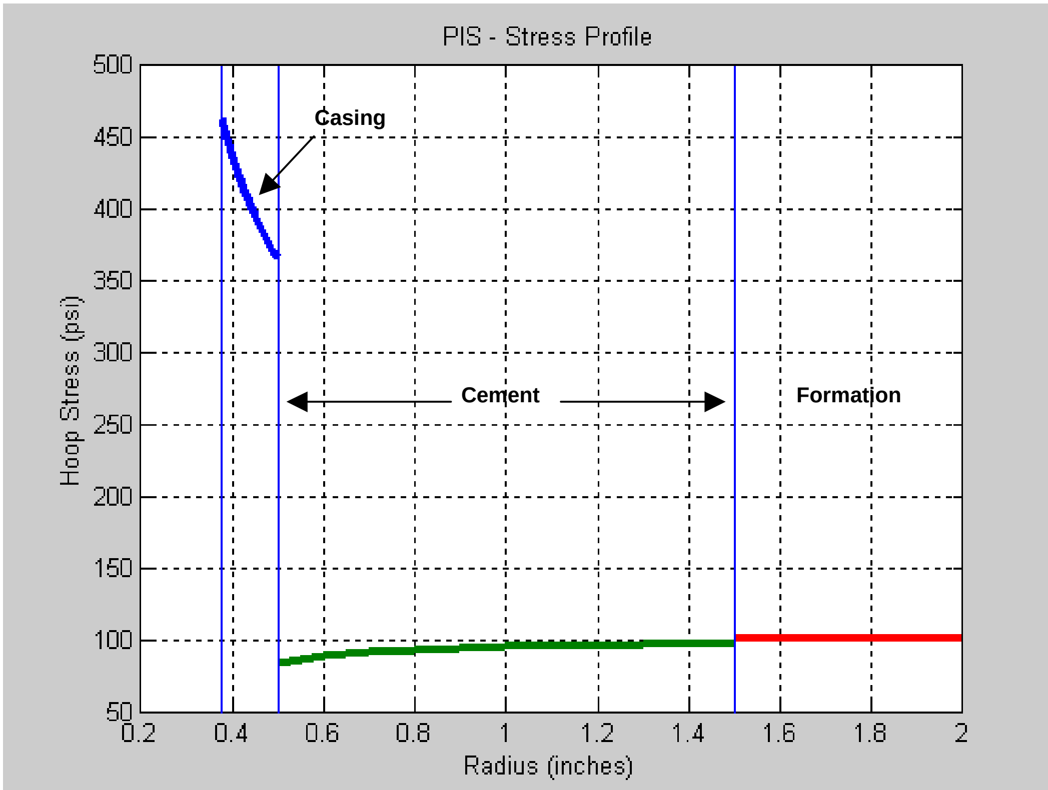
If failure occurs, it will most likely be at the pipe-cement interface.

Figure 14—Shear failure, simulated hard formation (1 of 2)



Casing Pressure	15 psi
Confining Pressure	100 psi
Hoop Stress Contrast	~ 450 psi

Figure 15—Shear failure, simulated soft formation (2 of 2)



Casing Pressure	15 psi
Confining Pressure	100 psi
Hoop Stress Contrast	~ 300 psi

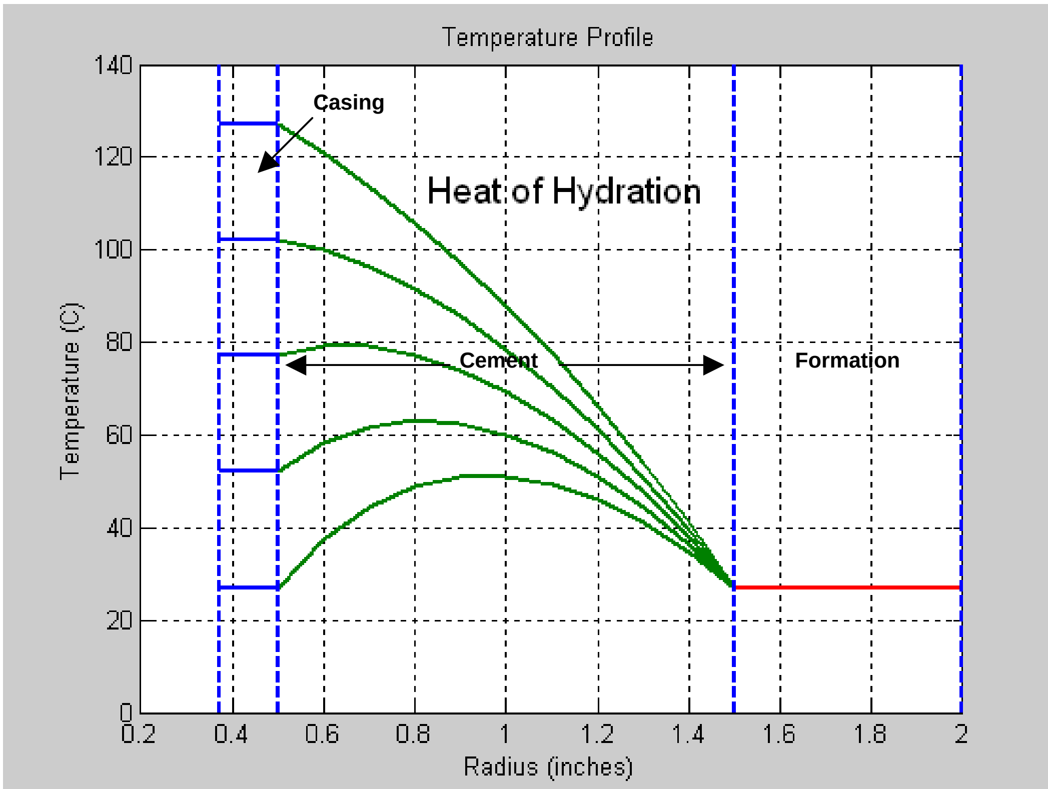
Heat of Hydration

Cements were tested for the effect of heat of hydration on the cement integrity. First, the borehole temperature was increased from 300K to 400K, and the heat of hydration rate was held constant (**Figure 16**). As the temperature increased, the peak temperature moves closer to the pipe-cement interface. Because the steel pipes conduct heat very well, little if any variation is seen in the inner casing or outer pipe.

With a fixed borehole temperature (**Figure 17**), increasing the heat of hydration rate causes an increase in the temperature of the cement sheath. At the peak heat of hydration rate, the temperature is increased by nearly 30C, which can cause considerable stress on the cement system.

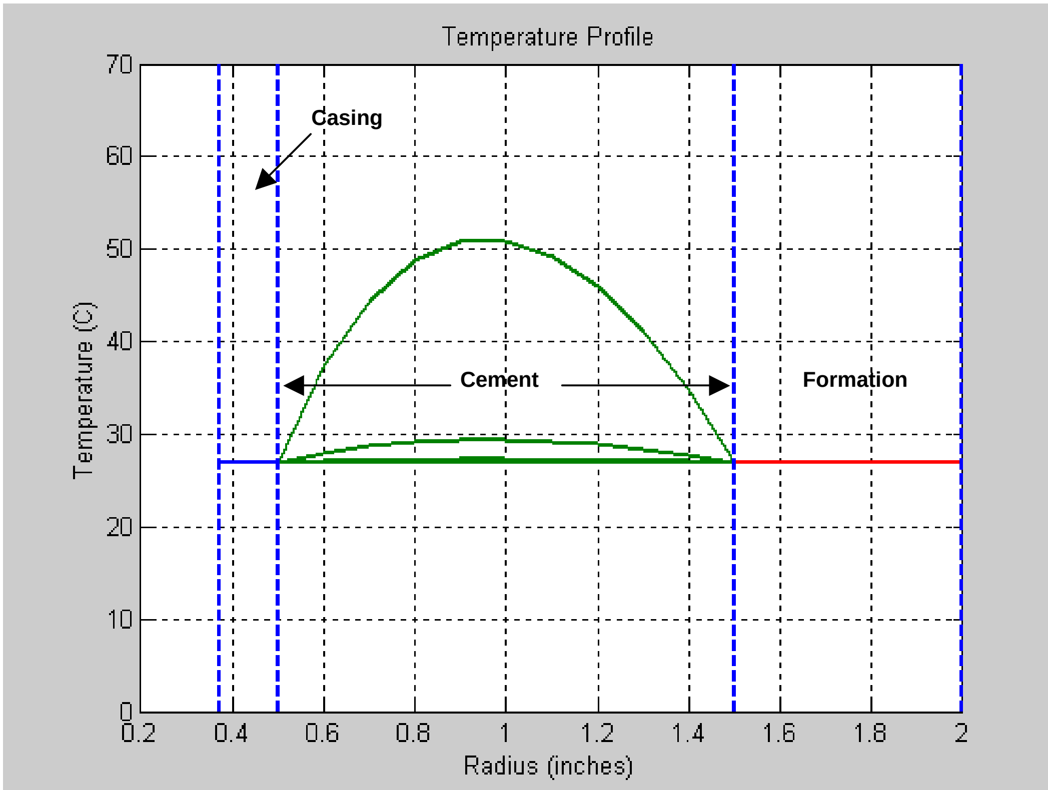
When viewed as a radial stress profile (**Figure 18**), the highest heat of hydration rate creates a radial stress of 600 psi on the cement sheath, but little variation of radial stress is observed within the cement.

Figure 16—Heat of hydration, temperature profile (1 of 2)



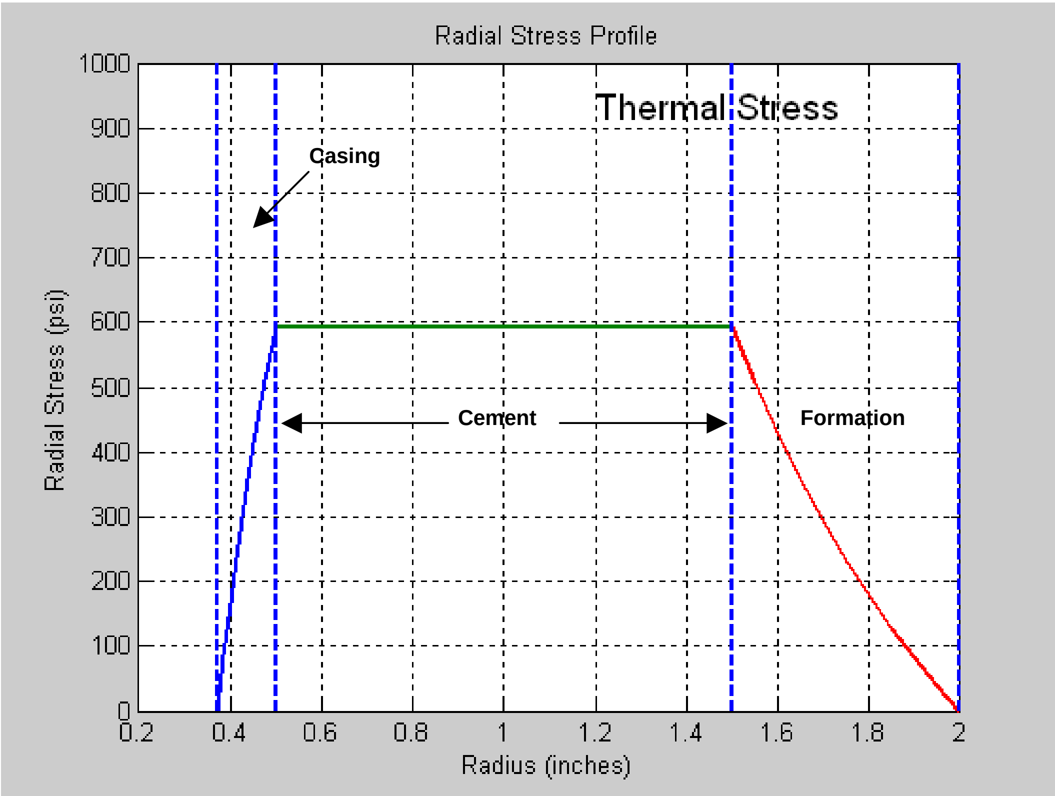
Borehole Temperature	300 K to 400 K
Heat of Hydration Rate	3.5 KJ/Kg.sec

Figure 17—Heat of hydration, temperature profile (2 of 2)



Borehole Temperature	300 K
Heat of Hydration Rate	3.5 KJ/Kg.sec - 3.5 KJ/Kg.sec

Figure 18—Heat of hydration, radial stress profile



Borehole Temperature	300 K
Reservoir Temperature	300 K

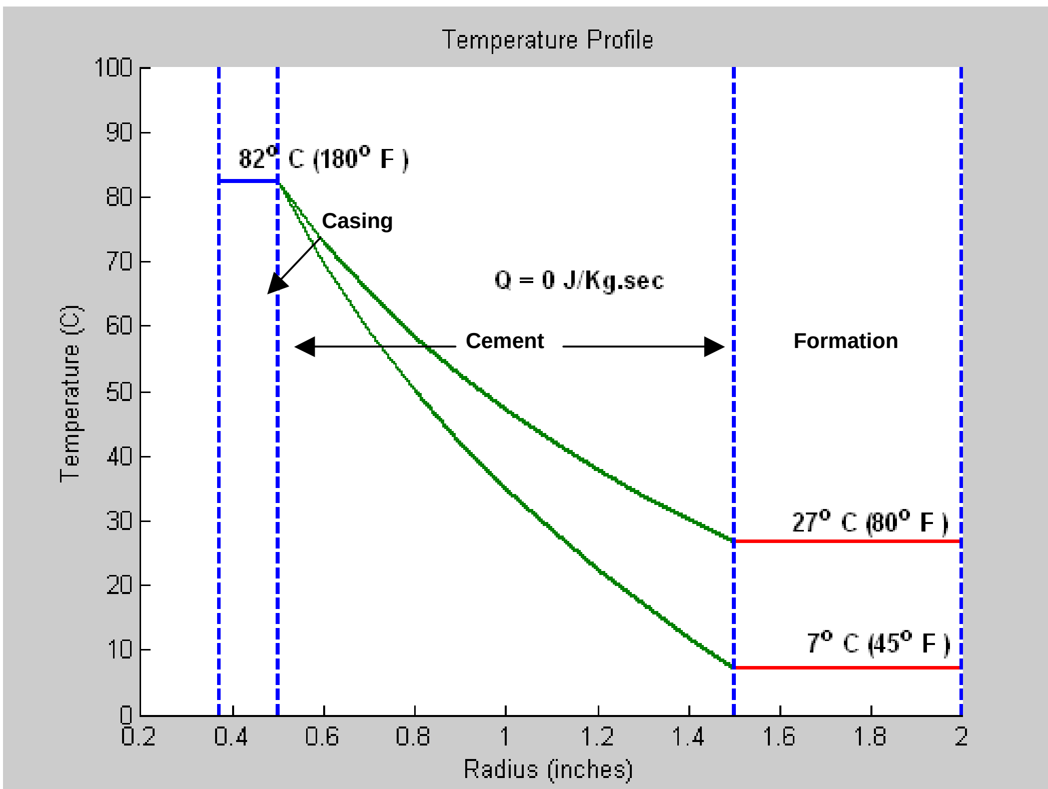
Linear Superposition with Elastic Stress

Thermal Stress

Thermal stress tests were performed to evaluate the effect of thermal stress on the cement. **Figure 19** plots the differences between the borehole temperature and two different reservoir temperatures.

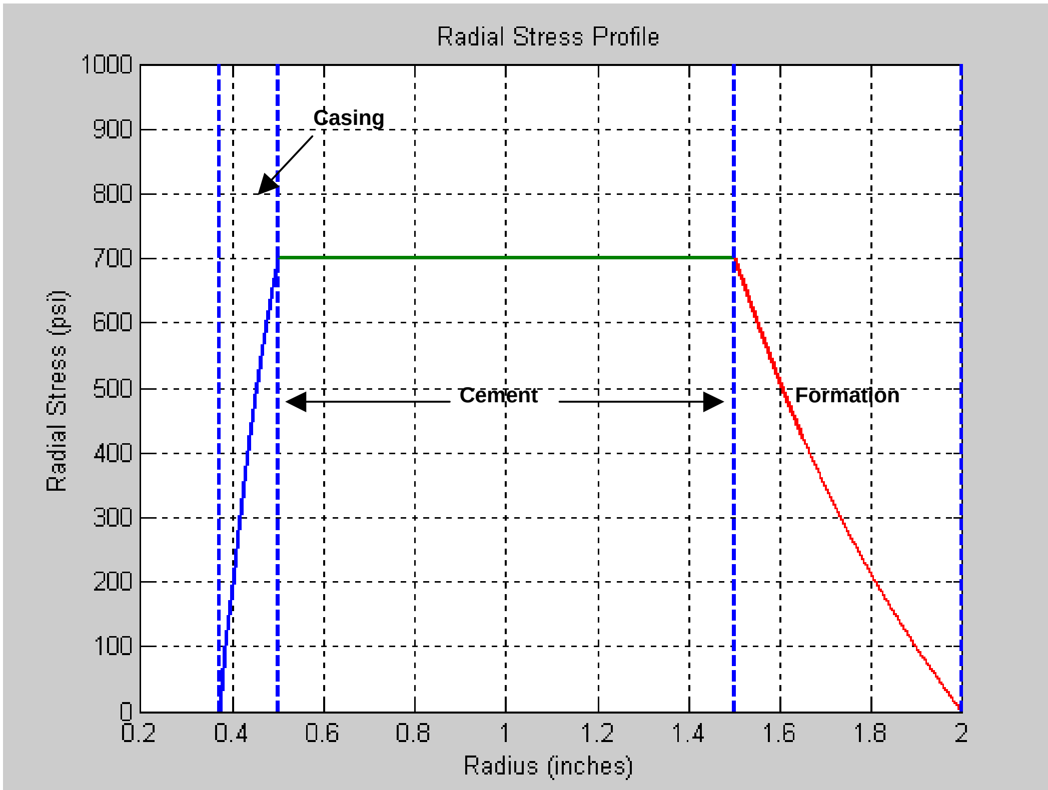
The large temperature contrast between the inner casing and formation can cause significant radial stress (as much as 700 psi in **Figure 20**), which can affect the integrity of cement. However, the radial stress does not vary greatly within the cement.

Figure 19—Thermal stress, temperature profile



Borehole Temperature	180°F
Reservoir Temperature	45°F, 80°F
Heat of Hydration Rate	0 J/Kg.sec

Figure 20—Thermal stress, radial stress profile



Borehole Temperature	180°F
Reservoir Temperature	45°F, 80°F
Heat of Hydration Rate	0 J/Kg.sec

- Higher thermal stress
- No significant variation within cement

Hoop Stress (Tensile) without Confining Pressure

Cements were tested to determine how hoop stress would affect the cement, given a specific casing pressure. No hoop stress variation was observed in either the cement or the outer pipe in simulated hard formations (**Figure 21**) and soft formations (**Figure 22**). The only contrast in hoop stress was apparent at the pipe-cement interface. This can be attributed to the difference in the elastic Young's modulus properties of the pipe and the cement.

Figure 21—Hoop stress (tensile), simulated hard formation, 0-psi confining pressure

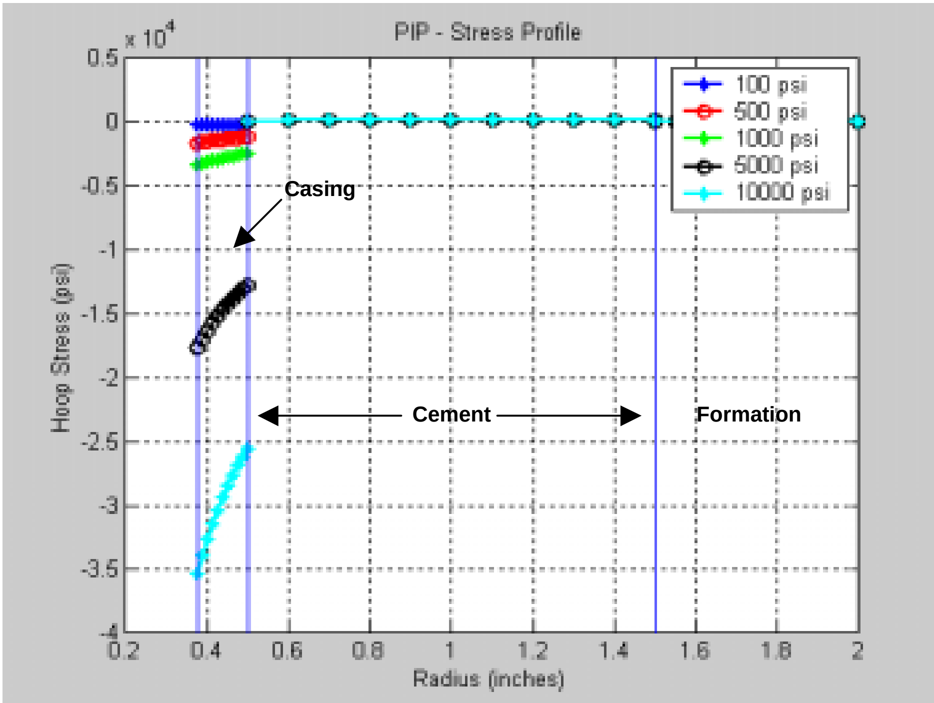
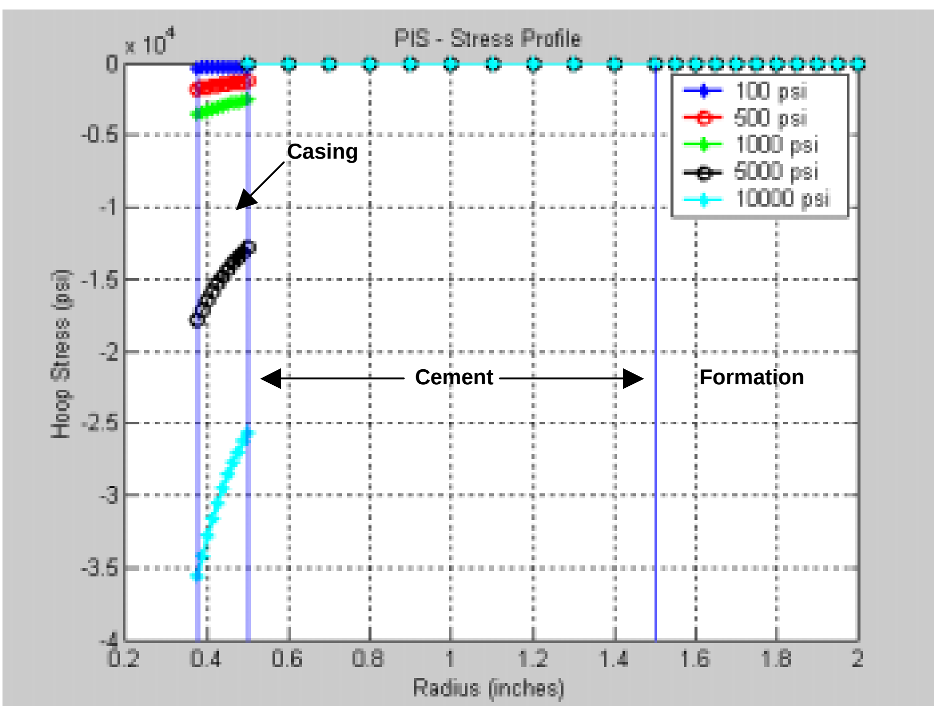


Figure 22— Hoop stress (tensile), simulated soft formation, 0-psi confining pressure



Displacement (No Confining Pressure)

The next set of simulations was conducted to determine the effect of varying casing pressures on displacement, in both hard and soft formations with no confining pressure. In hard formation tests, a larger displacement, and incidentally, a larger variation in displacement, was observed within the cement (**Figure 23**). The displacement of the cement is significantly large to absorb the load.

In simulated soft formations (**Figure 24**), a large displacement (and variation in displacement) was observed for both the cement and the formation.

Figure 23—Displacement profile, simulated hard formation, 0-psi confining pressure

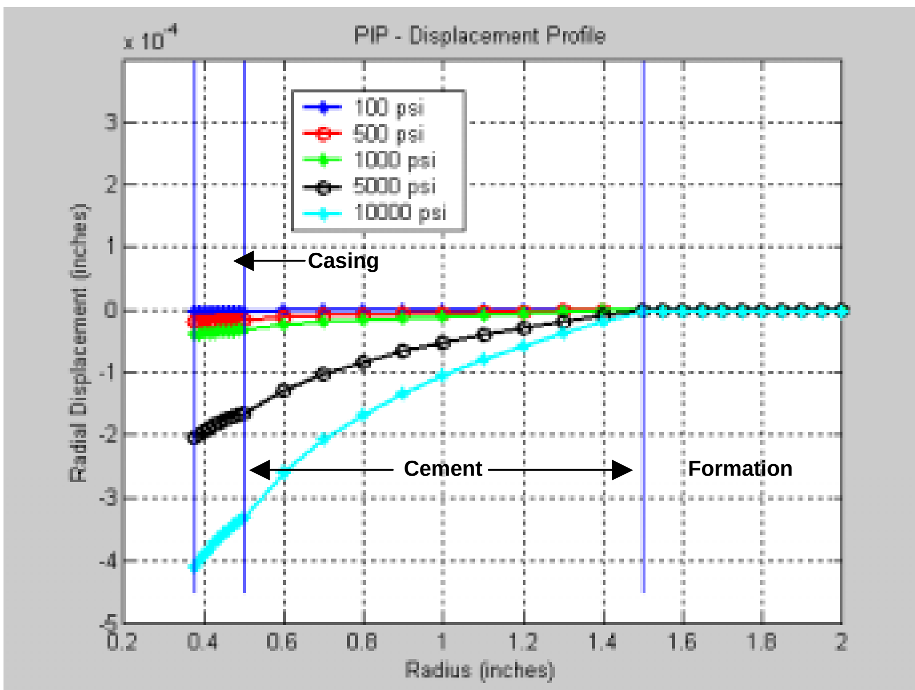
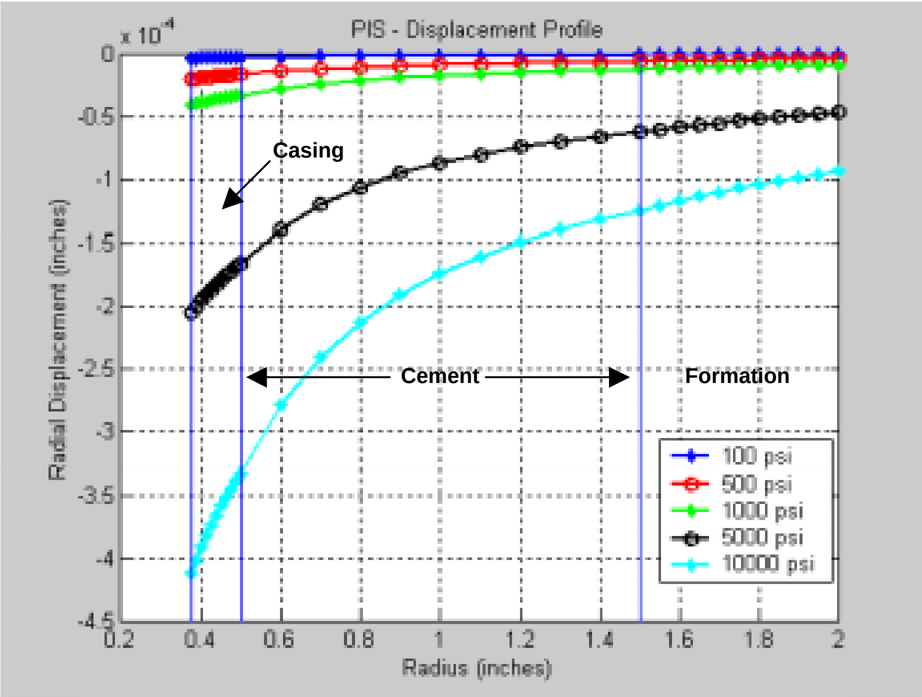


Figure 24—Displacement profile, simulated soft formation, 0-psi confining pressure



Hoop Stress (Tensile) with Confining Pressure

Tests were also performed to determine the effect of varying casing pressures on hoop stress with 500-psi confining pressure.

When applied to a simulated hard formation configuration (**Figure 25**), the test indicated that increasing casing pressures result in an increase in hoop stress at the cement-outer pipe interface; yet, the cement itself does not experience much hoop stress.

Increasing casing pressures in the simulated soft formation test (**Figure 26**) revealed a slightly higher hoop stress in the cement and the formation, but no significant contrast in hoop stress at the cement-formation interface.

Figure 25—Hoop stress (tensile), simulated hard formation, 500-psi confining pressure

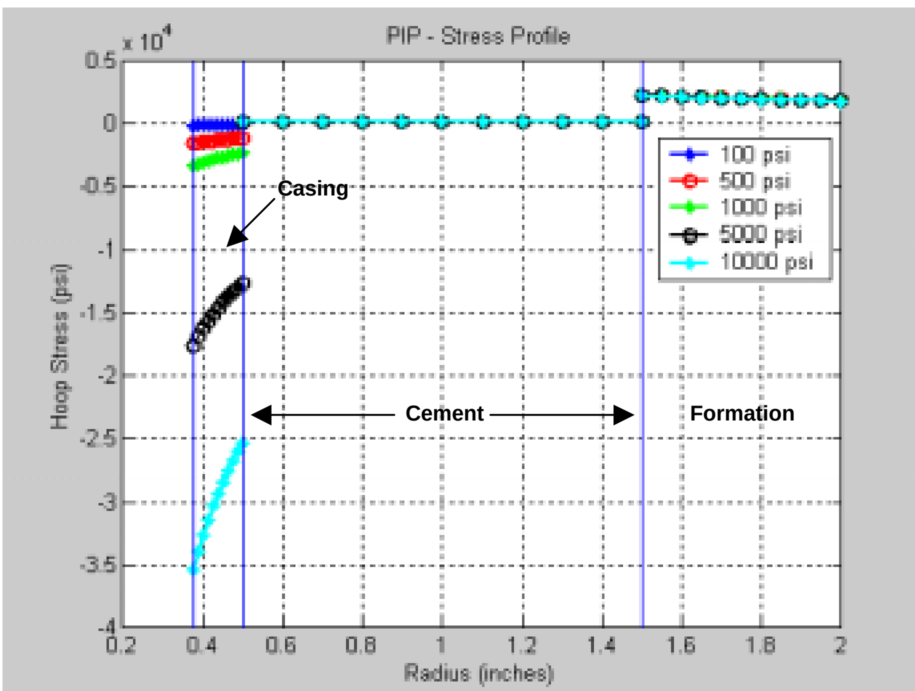
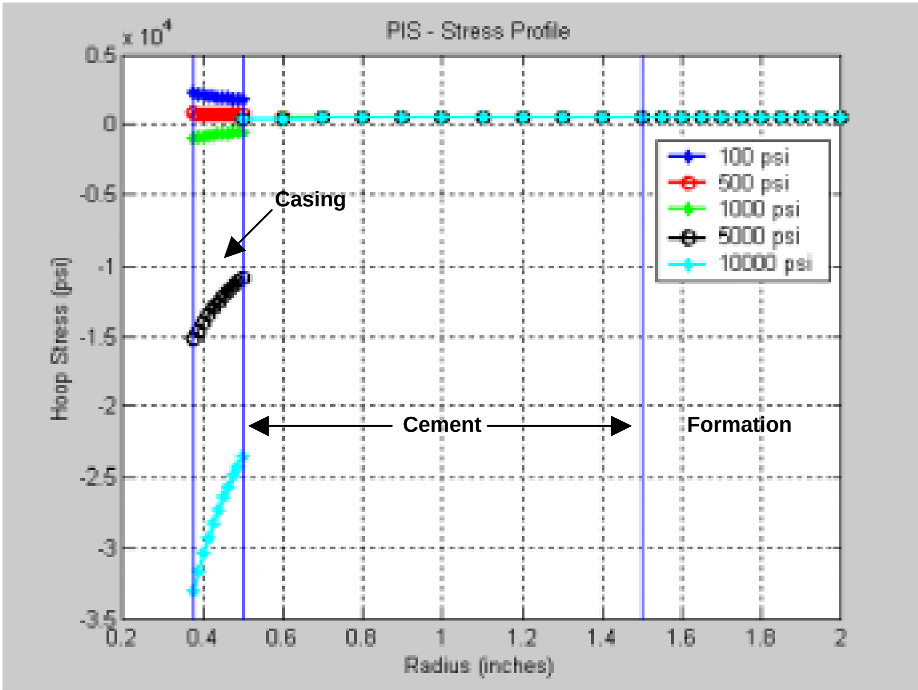


Figure 26—Hoop stress (tensile), simulated soft formation, 500-psi confining pressure



Displacement with Confining Pressure

As casing pressures vary and confining pressure is held constant in a hard formation, hoop stress increases in the formation, and stays constant in the cement. Displacement, rather, varies within the cement, and is almost constant in the formation (**Figure 27**).

As casing pressures are varied and confining pressure is held constant in a soft formation, hoop stress is slightly greater than that of the hard formation, and remains constant through the cement-formation interface. Displacement varies significantly in both the cement and the formation (**Figure 28**). This variation helps explain why no significant difference in hoop stress values is seen at the cement-formation interface in Figure 26.

Figure 27—Displacement profile, simulated hard formation, 500-psi confining pressure

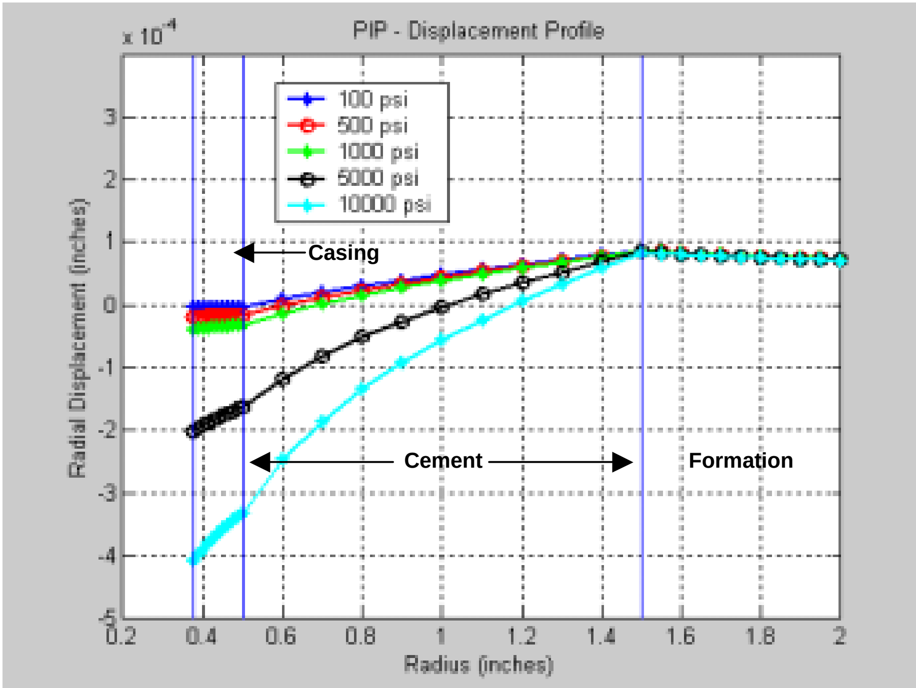
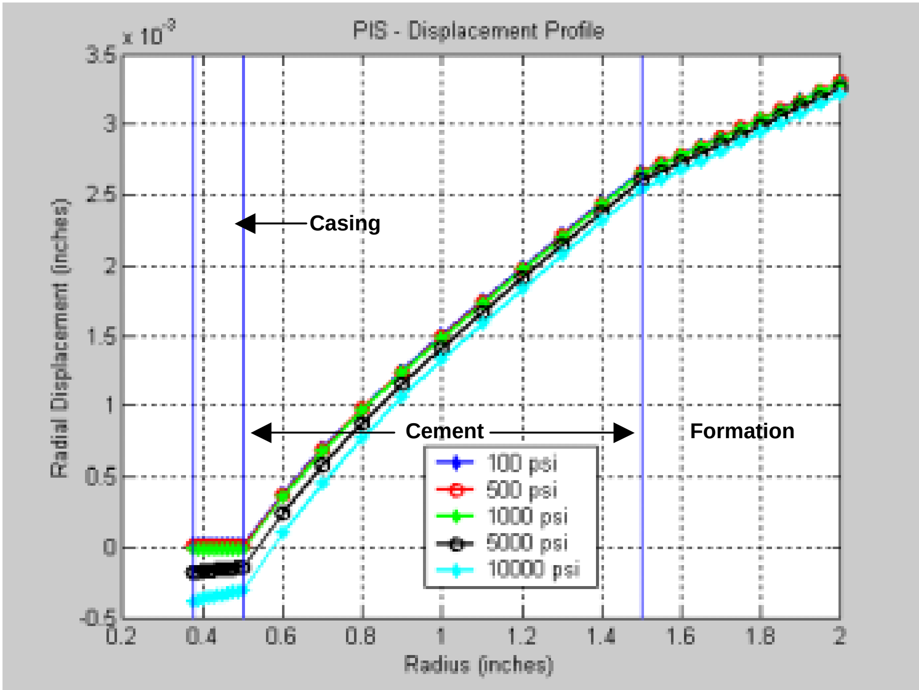


Figure 28— Displacement profile, simulated soft formation, 500-psi confining pressure



Appendix A—Young's Modulus Testing

Traditional Young's modulus testing was performed using ASTM C469[1], Standard Test Method for Static Modulus of Elasticity (Young's Modulus) and Poisson's Ratio of Concrete in Compression.

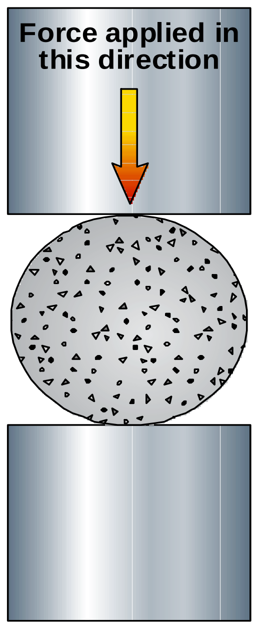
The following procedure is used for the Young's modulus testing.

1. Each sample is inspected for cracks and defects.
2. The sample is cut to a length of 3.0 in.
3. The sample's end surfaces are then ground to get a flat, polished surface with perpendicular ends.
4. The sample's physical dimensions (length, diameter, weight) are measured.
5. The sample is placed in a Viton jacket.
6. The sample is mounted in the Young's modulus testing apparatus.
7. The sample is brought to 100-psi confining pressure and axial pressure. The sample is allowed to stand for 15 to 30 min until stress and strain are at equilibrium. (In case of an unconfined test, only axial load is applied.)
8. The axial and confining stress are then increased at a rate of 25 to 50 psi/min to bring the sample to the desired confining stress condition. The sample is allowed to stand until stress and strain reach equilibrium.
9. The sample is subjected to a constant strain rate of 2.5 mm/hr.
10. During the test, the pore-lines on the end-cups of the piston are open to atmosphere to prevent pore-pressure buildup.
11. After the sample fails, the system is brought back to the atmospheric stress condition. The sample is removed from the cell and stored.

Appendix B—Tensile Strength Testing

Tensile strength was tested using ASTM C496[2] (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens). For this testing, the specimen dimensions were 1.5 in. diameter by 1 in. long. **Figure B1** shows a general schematic of how each specimen is oriented on its side when tested. The force was applied by constant displacement of the bottom plate at a rate of 1 mm every 10 minutes. Change in the specimen diameter can be calculated from the test plate displacement. The (compressive) strength of the specimen during the test can be graphed along with the diametric strain (change in diameter/original diameter) to generate the tensile Young's modulus.

Figure B1—Sample Orientation for ASTM C496-90 Testing



Appendix C—Shear Bond Strength Testing

Shear bond strength tests are used for investigating the effect that restraining force has on shear bond. Samples are cured in a pipe-in-pipe configuration (**Figure C1**) and in a pipe-in-soft configuration (**Figure C2**). The pipe-in-pipe configuration consists of a sandblasted internal pipe with an outer diameter (OD) of $1\ ^{1}/_{16}$ in. and a sandblasted external pipe with an internal diameter (ID) of 3 in. and lengths of 6 in. A contoured base and top are used to center the internal pipe within the external pipe. The base extends into the annulus 1 in. and cement fills the annulus to a length of 4 in. The top 1 in. of annulus contains water.

For the pipe-in-soft shear bonds, plastisol is used to allow the cement to cure in a less-rigid, lower-restraint environment. Plastisol is a mixture of a resin and a plasticizer that creates a soft, flexible substance. This particular plastisol blend (PolyOne's Denflex PX-10510-A) creates a substance with a hardness of 40 duro.

The pipe-in-soft configuration contains a sandblasted external pipe with an ID of 4 in. A molded plastisol sleeve with an ID of 3.0 in. and uniform thickness of 0.5 in. fits inside this external pipe. With the aid of a contoured base and top, a sandblasted internal pipe with an OD of $1\ ^{1}/_{16}$ in. is then centered within the plastisol sleeve. The pipes and sleeve are 6 in. long. The base extends into the annulus 1 in. and cement fills the annulus to a length of 4 in. between the plastisol sleeve and the inner $1\ ^{1}/_{16}$ -in. pipe. The top inch of annulus is filled with water.

Figure C1—Cross-Section of Pipe-in-Pipe Configuration for Shear Bond Tests

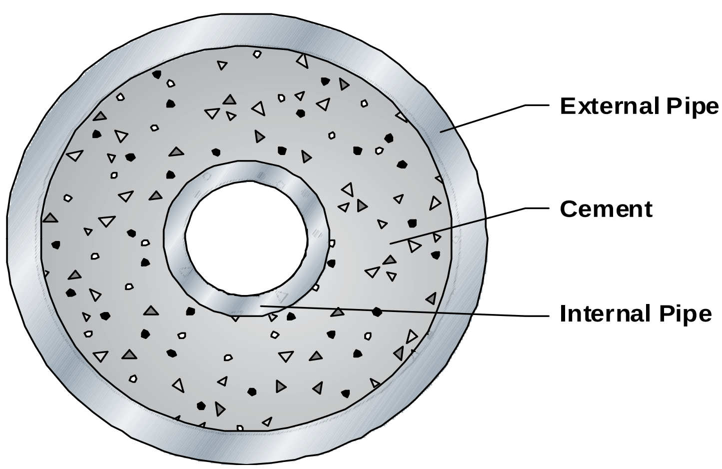
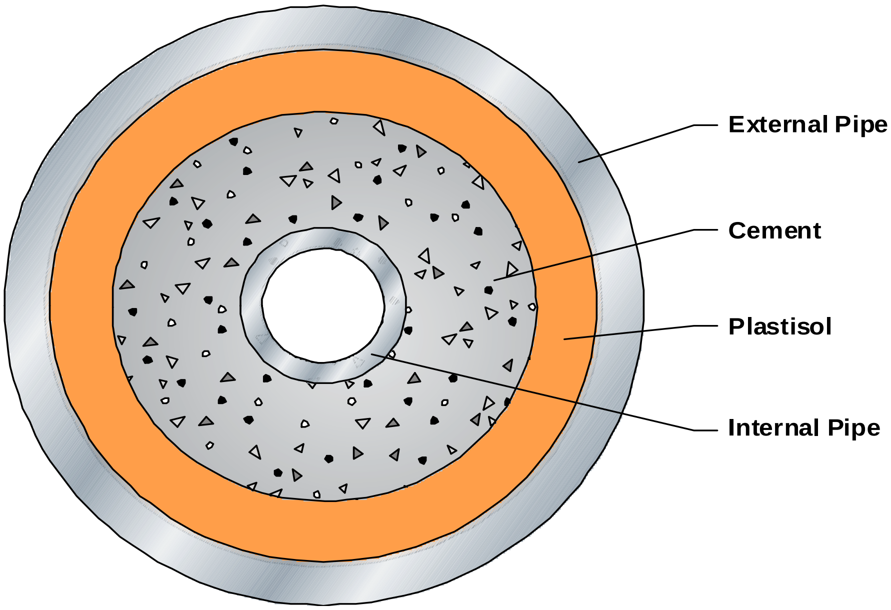
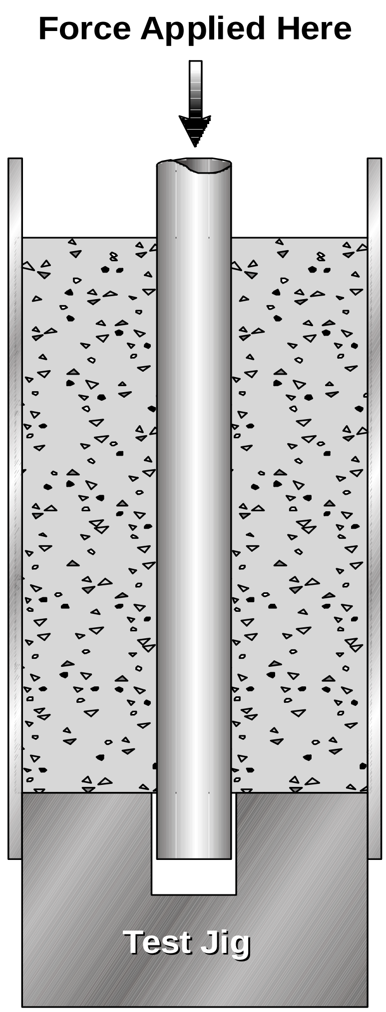


Figure C2— Cross-Section of Pipe-in-Soft Configuration for Shear Bond Tests



The shear bond measures the stress necessary to break the bond between the cement and the internal pipe. This was measured with the aid of a test jig that provides a platform for the base of the cement to rest against as force is applied to the internal pipe to press it through. (**Figure C3**) The shear bond force is the force required to move the internal pipe. The pipe is pressed only to the point that the bond is broken; the pipe is not pushed out of the cement. The shear bond strength is the force required to break the bond (move the pipe) divided by the surface area between the internal pipe and the cement.

Figure C3—Configuration for Testing Shear Bond Strength



Temperature Cycling

The effect that temperature cycling has on shear bond is tested as follows.

The temperature cycling procedure is designed to simulate temperature conditions that might be encountered during production of a well. The samples are first cured for 14 days in a 45°F water bath at atmospheric pressure. They are then subjected to five days of temperature cycling. During each of these five days of temperature cycling, the cured samples are cycled as follows.

1. Samples are removed from 45°F water bath and placed in 96°F water bath for one hour.
2. Samples are placed in 180°F water bath for four hours.
3. Samples are placed in 96°F water bath for one hour.

4. Samples are placed back in 45°F water bath.

Pressure Cycling

The effect that pressure cycling has on shear bond is tested as follows.

The pressure cycling procedure is designed to simulate pressure conditions that might be encountered during production of a well. Because these samples will be dealing with high pressures, the interior pipe of each sample was made from 1-in. diameter, 40/41 coiled tubing pipe that can withstand 10,000 psi. Each end of the pipe is threaded. One end will have a pressure-tight cap on it during pressure cycling and the other end of the pipe will be connected to the pressure source.

The samples are first cured for 14 days in a 45°F water bath at atmospheric pressure. They are then subjected to five periods of pressure cycling in which the interior pipe is pressured to 5,000 psi for 10 minutes and then allowed to rest at 0 psi for 10 minutes.

Appendix D—Shrinkage Testing

Using a modified Chandler Model 7150 Fluid Migration Analyzer, tests are performed to determine shrinkage of the neat Type I cement. The following procedures are used for performing the shrinkage testing.

1. Fill the test cell with 180 cm^3 of the cement slurry.
2. Place 40 mL of water on top of cement slurry.
3. Place the hollow hydraulic piston into the test cell and on top of the water.
4. Close off the test cell and attach the pressure lines and piston displacement analyzer.
5. Close all valves except valve on top of test cell cap. Purge air out of system.
6. Apply 1,000-psi hydrostatic piston pressure to the test cell and begin recording data (time, piston displacement, and pressure).
7. Run test and gather data for desired amount of time.

Appendix E—Annular Seal Testing

The following procedures are for the use of the Pipe-in-Soft annular seal apparatus (for simulating soft formations) and the Pipe-in-Pipe annular seal apparatus (for simulating hard formations). The Pipe-in-Soft apparatus is to be used with cores that were formed using a soft gel mold surrounding the cement slurry to form a core that was cured to set by using a semi-restricting force on the outside of the core. The Pipe-in-Pipe apparatus is to be used with cores that were made inside steel pipes, giving the cement slurry a restricting force outside of the core.

Simulated Soft Formation Test Procedure

1.) After the core is cured, place the core inside the gel mold sleeve.
2.) Place the core and sleeve inside the Pipe-in-Soft steel cell.
3.) Once inside, both ends of the core are supported with o-rings.
4.) The o-rings are then tightened to close off air-leaks that might be present.
5.) Using water, pressurize the exterior circumference of the sleeve to 25 psi. Once the pressurized water is applied to the cell, check for leaks on the ends of the cell.
6.) Using the cell's end caps, cap off both ends of the steel cell. One end cap has a fitting that allows for N_2 gas to be applied into the cell, and the other end cap allows for the gas to exit the cell.
7.) Attach the pressure in-line to one end and then attach the pressure out-line to the other end.
8.) Apply pressure to the in-line. (Do not exceed 20 psig.) Measure the output of the out-line with flowmeters.

Simulated Hard Formation Test Procedure

1.) After the core is cured inside the steel pipe, using steel end caps, cap off each end of the pipe. Each end cap has a fitting that allows for gas to be applied into the pipe on one end, and also allows for the gas to exit the pipe on the other end.
2.) Attach the pressure in-line to one end, and then attach the pressure out-line to the other end.
3.) Apply pressure to the in-line. (Do not exceed 20 psig.) Measure the pressure output of the out-line with flowmeters.

Appendix F—Chandler Engineering Mechanical Properties Analyzer

See the attached brochure for a detailed description of the Chandler Engineering Mechanical Properties Analyzer, its applications, and its benefits.

MECHANICAL PROPERTIES ANALYZER

In recent years the oil/gas industry has begun to understand the implication of cement sheath mechanical properties on the ability of the cement to perform its zonal isolation function long term. With computer modeling capabilities, the mechanical compliance of the cement sheath relative to the deformation of the contacting rock and casing can be optimized to improve wellbore sealing. Cement formulations are being developed to address the need for flexure of the cement, rather than say the need for high compressive strength. However, the measurement of cement mechanical properties at elevated pressure and temperature has limited the implementation of cement mechanical properties as a design protocol.

With a technological breakthrough (patent applied), Chandler Engineering has developed the first high-pressure, high-temperature instrument designed specifically to measure the mechanical properties (elastic moduli and compressive strength) of oil/gas-well cements. Like the Ultrasonic Cement Analyzer (UCA), testing with the new Mechanical Properties Analyzer (Model 6265 MPro) begins with a cement slurry, which is placed into a pressure vessel. Measurements are then taken directly from this sample as it cures at elevated temperature and pressure.

The ***CHANDLER*** Model 6265 MPro has several advantages over routine mechanical properties testing. First, by providing continuous measurements, a single test with the MPro can provide more information about the cement properties than one would get from a series of routine tests. Second, samples for routine testing are typically cured in one vessel returned to room conditions, and then cored and/or cut, before testing begins in a different pressure vessel. With the MPro the sample conditions and integrity are maintained for the duration of the test (which may be days, weeks, or even months). Thus,

MODEL 6265 MPro

the MPro samples are neither subjected to damage from preparation, and handling, nor from unrealistic cooling and depressurization.

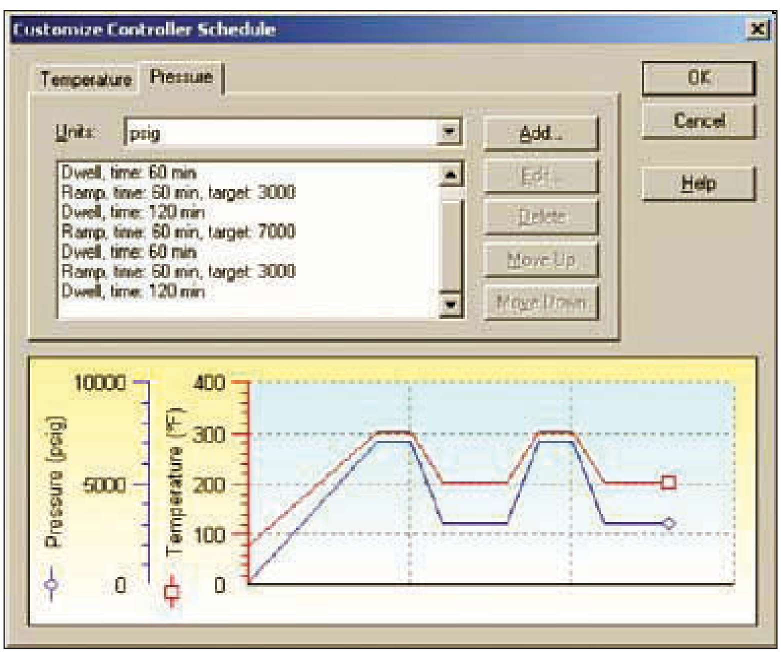
The ***CHANDLER*** Model 6265 MPro is optionally configured to perform UCA (compressive strength) Analyses in addition to the elastic mechanical properties measurements - thus providing a suite of information from a single sample and single test, and optimizing laboratory efficiency.

The new Model 6265 MPro includes programmable temperature control which provides the capability to investigate the impact of temperature variations on the cement mechanical properties. With the Chandler Model 6265P programmable pressure control module, the user can simulate realistic pressure conditions to evaluate the impact on the mechanical properties of the cement sample.

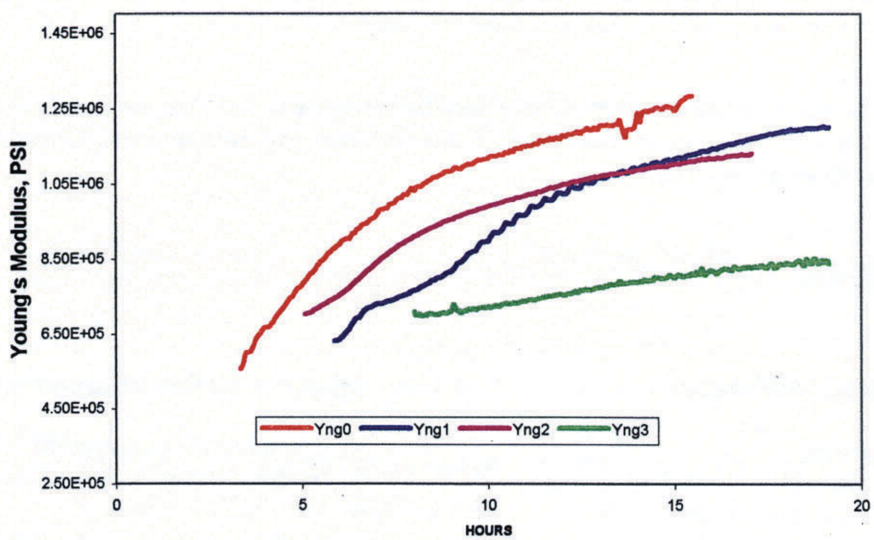
Combining the programmable pressure control module with programmable temperature control, will allow the investigator to replicate realistic pressure and temperature conditions.

Using Chandler Engineering's state-of-the-art 5270 Automation System, complex-testing protocols can be easily set up and run using a standard PC. The 5270 System can be optionally configured to control and collect/display/analyze data from several Model 6265 MPro's.

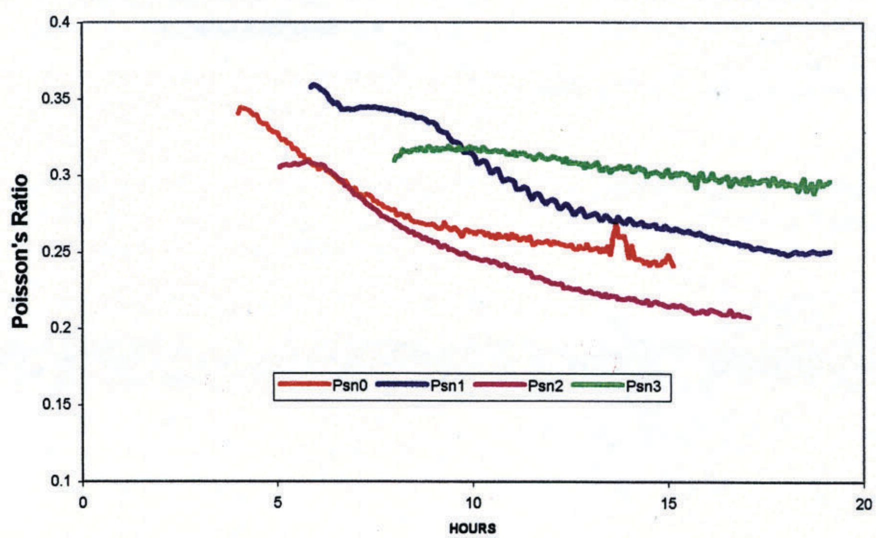
MODEL 6265P
PROGRAMMABLE PRESSURE
CONTROL MODULE



Cement Mechanical Properties Testing
Chandler Engineering Model 6265 Data
Young's Modulus vs Time



Cement Mechanical Properties Testing
Chandler Engineering Model 6265 Data
Poisson's Ratio vs Time



All Chandler Engineering products are covered by a full one-year warranty against defects in materials and workmanship. Sales terms, conditions and warranty statements are included with each quotation or confirmation of order.

More than 50 years ago, Chandler Engineering pioneered High Pressure and High Temperature Equipment. Today, Chandler Engineering is the leading manufacturer of a broad range of innovative and extremely reliable Measurement Instruments for the Energy Industry.

Chandler Engineering specializes in outfitting laboratories designed for testing cement, drilling muds and stimulation fluids. Through Research & Development, experienced manufacturing and worldwide logistic operations, Chandler Engineering provides for your complete laboratory requirements.

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