

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

Report 2

Issued July 31, 2002



***CEMENTING SOLUTIONS, INC.***



**Cementing *Solutions, Inc.***



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## Executive Summary

### **Background**

The U.S. Department of the Interior, Minerals Management Service (MMS) has stated that, of the 14,000 producing wells offshore; some 11,000 exhibit sustained annular casing pressure. This annular pressure can be the result of a number of factors, some related to cement composition and some related to the downhole environment. The lithology of offshore formations (particularly in drilling deepwater wells) has recently been identified as the key element in well integrity. One of the most important factors when considering lithology of offshore formations in general is the stress exerted on the cement column during the life of the well. This stress can be thermally or hydraulically induced due to well intervention operations, or result from compaction. Stress gradients can be sufficiently large to cause mechanical failure of the cement.

Shallow formations penetrated in drilling deepwater wells often require extraordinary zonal isolation procedures to prevent shallow water flows. Severe operational and economic consequences resulting from the immediate flow of water from these shallow formations up to the sea floor demand that the surface casings penetrating these zones be adequately sealed. Significant effort has been devoted to development of cement compositions to alleviate shallow water flow. However, the long-term integrity of the seal provided by these special compositions has not been evaluated. Additionally, the lithology of deeper strata may increase the potential of subsidence at any depth as pore pressure is reduced with geopressured drawdown. Cement compositions used throughout construction of these wells must be able to withstand stresses exerted by subsidence while still providing an annular seal.

### **The MMS Project**

The MMS, in collaboration with representatives from AGIP, Anadarko, ARAMCO, BP Exploration, Conoco, DOE, ExxonMobil, ONGA, Petrobras, Saudi Aramco, and Unocal, is performing the MMS Project (Long-term Integrity of Deepwater Cement Systems Under Stress/Compaction Conditions) to evaluate the ability of cement compositions to provide well integrity and zonal isolation through zones in which subsidence, compaction, and excessive stresses can be long-term problems. Though the project's focus is on deepwater conditions, the well integrity issues hold for cementing in a variety of conditions, so the study has wide applicability. A significant number of wells drilled in deep water and other high-stress environments may not have adequate long-term zone isolation.

The MMS Project is challenging. A significant aspect of this project is to develop a correlation of the conventional cement tests with rock properties tests in conjunction with realistic annular seal model studies. This correlation will allow the prediction of the ability of various cement systems to seal under downhole stress conditions.



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A series of cement seal evaluation tests will be conducted in an apparatus designed to approximate the various stresses applied to the cemented annulus throughout the well's operating life. This apparatus (called an annular seal device) was developed as a standard means to measure the ability of a cementing system to provide sealing to water or gas in realistic *in-situ* conditions. The annular configuration allows realistic geometries and sealing conditions. Following are test parameters that will be evaluated:

- Cement compositions of varying densities from conventional normal weights to foamed cements
- Thermal cycling induced stress
- Pressure cycling induced stress
- Multiple cycles over six months duration
- Compaction conditions varying from no compaction to soft formations with significant compaction
- Mechanical properties of the cements

By rigorously and thoroughly applying these parameters to cement compositions, and by comparing the laboratory results to mathematical models developed by the University of Houston, the MMS Project team is confident of success in designing cement materials and systems that will withstand the extreme stress/compaction conditions that threaten well integrity.

### **Project Progress**

Thus far, Phase I of the project has yielded significant data to help address the well integrity issue. Data from the conventional, rock properties, and unconventional performance tests performed in Cementing Solutions, Inc.'s laboratory are provided in this paper. The mathematical modeling performed by the University of Houston revealed the cement material properties and cement thickness have negligible effect on the overall stress distribution in the Pipe-in-Pipe configuration, but that the material properties become significant for the Pipe-in-Soft configuration. In the Pipe-in-Soft configuration, thermal stresses lead to tensile stresses, which can result in tensile failures at high temperature variations. A very sharp stress contrast was observed in all cases at the casing-cement interface.

The project will continue with additional testing. Ongoing status reports will be provided to project participants. The final project report will summarize the project work and the test results. The final report will also present the decision matrix that will help guide the industry in how to design cement slurries that are best suited to withstand the problematic stress/compaction situations with deepwater and other high-stress environments and operations.



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### **Introduction**

The MMS Project pools the expertise of the United States Federal Government's Mineral Management Service (MMS) and several of the world's leading Oil & Gas production companies to investigate the long-term integrity of deepwater and other high-stress cement systems under stress/compaction conditions. The project's research will develop correlations between cement properties and seal performance under stress gradients that can be sufficiently large to cause mechanical failure of the cement.

The MMS Project consists of nine tasks:

1. Problem analysis
2. Property determination and test design
3. Mathematical analysis of stress
4. Testing baseline cement composition
5. Refine test procedure
6. Develop composition matrix
7. Conduct tests
8. Analyze results
9. Develop decision matrix

The University of Houston performed finite element analysis (FEA) of the laboratory models used in the project so the laboratory results can be compared to the mathematical modeling. The mathematical modeling was analyzed to determine if the stresses associated with the temperature and pressure cycling result in loss of annular seal.

Laboratory testing was performed on neat Type I cement at 15.6 lb/gal, foamed Type I cement, and Type I cement with lightweight beads. The neat Type I cement contains water at 5.2 gal/sk. The slurry with lightweight beads contains 13.2% BWOC 3M™ Scotchlite™ K46 Glass Bubbles and water at 6.9 gal/sk for a density of 12.0 lb/gal. The foamed cement contains Witcolate® 7093 (a foaming agent) at 0.03 gal/sk, Aromox® C/12 (a foam stabilizer) at 0.01 gal/sk, 1.0% BWOC calcium chloride, and water at 5.2 gal/sk for an unfoamed slurry density of 15.6 lb/gal; the slurry is then foamed to 12.0 lb/gal. The testing has helped to refine and confirm the test procedures that will be used for the remainder of the project

The following sections of this report provide data from the conventional testing, rock properties testing, and unconventional performance testing completed so far. The report concludes with a detailed explanation of the mathematical modeling procedures used in this project and the preliminary conclusions based on that modeling.



## **Conventional Testing**

### ***Thickening-Time Test***

Following the procedures (set forth in API RP 10B) thickening-time tests were performed on the three cement systems. The test conditions started at 80°F and 600 psi, and were ramped to 65°F and 5,300 psi in 48 minutes.

Some preparation and testing methods were modified to adapt for the lightweight bead and foamed slurries. The mixing procedures were modified for the bead slurry to minimize bead breakage that can occur because of high shear from API blending procedures. The following blending procedure was used for the bead slurry.

1. Weigh out the appropriate amounts of the cement, water, and beads into separate containers.
2. Mix the cement slurry (without beads) according to Section 5.3.5 of API RP 10B.
3. Pour the slurry into a metal mixing bowl and slowly add beads while continuously mixing by hand with a spatula. Mix thoroughly.
4. Pour this slurry back into the Waring blender and mix at 4,000 rev/min for 35 seconds to mix and evenly distribute the contents.

Testing methods for the foamed slurries were also modified. For example, thickening time is performed on unfoamed slurries only. Because the air in the foam does not affect the hydration rate, the slurry is prepared as usual per API RP 10B and then the foaming surfactants are mixed into the slurry by hand without foaming the slurry.

**Table 1** provides data from the thickening-time test.

### ***Free-Fluid Test***

The free-fluid testing that was performed on the Type I, Foamed Cement and Bead Slurries came from API RP 10B. The free-fluid procedure, also referred to as operating free water, uses a graduated cylinder that is oriented vertically. The free fluid for the slurry maintained at 65°F was measured by volume as shown in **Table 1**.



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**Table 1—Results from Thickening-Time and Free-Fluid Tests**

Slurry System	Thickening Time to 100 Bc (Hr:Min)	Percent Free Fluid
Neat	4:38	0.8
Foamed	3.42	0.0
Bead	5:04	0.8

## **Compressive Strength**

Table 2 presents compressive strength data for neat Type I, Foamed Cement, and Bead Cement. The compressive strengths were derived using the 2-in. cube crush method specified in API RP 10B. The samples were cured in an atmospheric water bath at 45°F. The reported values were taken from the average of three samples. Cells in Table 2 marked with “—” indicate that no compressive strength tests were performed for that time period.

**Table 2—Crush Compressive Strength**

Slurry System	Compressive Strength (psi) at Specified Number of Days							
	7	10	12	14	16	17	18	19
Neat	2735	4065	4385	4034	—	4471	—	—
Foamed	339	—	446	455	500	—	—	478
Bead	352	—	511	526	527	—	602	—

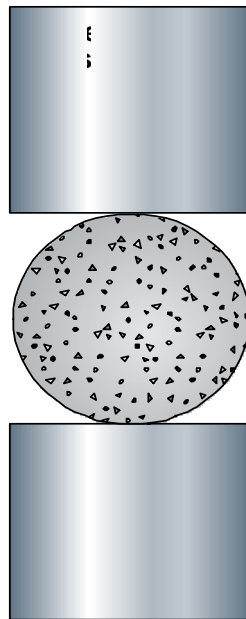


## Rock Properties Testing

### *Tensile Strength and Tensile Young's Modulus*

Mechanical properties of the neat Type I, Foamed Cement and Bead Cement were tested. Tensile strength was tested using ASTM C496 (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 1** shows 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 1—Sample Orientation for ASTM C496-90 Testing**



**Table 3** shows the 14-day tensile strength and tensile Young's modulus of the neat Type I cement. The samples were cured at atmospheric pressure in a water bath maintained at 45°F. The samples were cured under confined conditions (in the mold for the entire 14 days) and unconfined conditions (removed from mold after 24 hours and allowed to cure the remainder of the time outside of the mold). These were cured vertically with optimal conditioning time, and the top and bottom sections were removed. The tests were performed using a flat plate.





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**Table 3—Splitting Tensile Strength and Tensile Young’s Modulus Data**

Curing Condition	Splitting Tensile Strength (psi)				Tensile Young’s Modulus (10 <sup>4</sup> psi)			
	Sample			Average	Sample			Average
	1	2	3		1	2	3	
Confined	409	406	368	394	20.43	19.20	17.83	19.15
Unconfined	163	278	198	213	7.88	8.35	8.25	8.16

For this project, rock mechanics personnel from Westport and Conoco also incorporated the use of a test method from the International Society for Rock Mechanics (ISRM). The ISRM method calls for testing with a curved adapter or plate that gives more contact area between the testing surface and the test specimen and results in less variation in results.

**Table 4** presents data from tests using the traditional flat plates of ASTM C496 and tests using the curved plates from the ISRM test method. These tests were run with samples cured “in the mold” or confined. **Figures 2** and **3** show the data gathered during testing.

**Table 4—Splitting Tensile Strength and Tensile Young’s Modulus of 12.0 lb/gal Foamed Cement**

Plate Type	Failure Strength (psi)	Young’s Modulus (10 <sup>4</sup> psi)
Flat plate per ASTM	304	2.85
	276	3.99
	321	3.35
Curved plate per ISRM	206	3.66
	348	5.78
	204	3.26



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Figure 2—Tensile Young’s Modulus (Using Flat Plates) of 12.0 lb/gal Foamed Cement

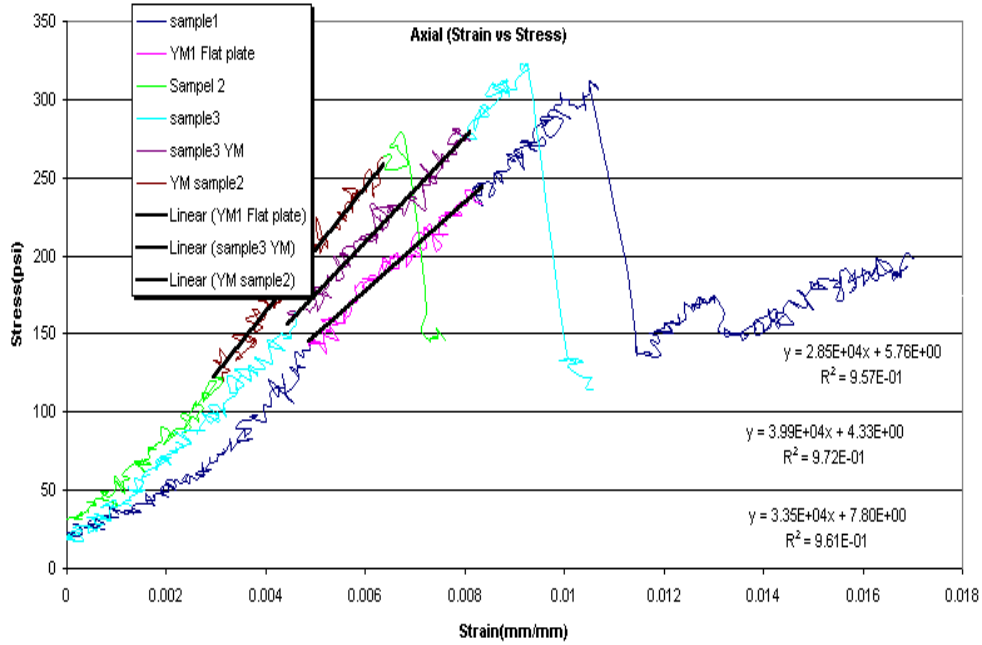
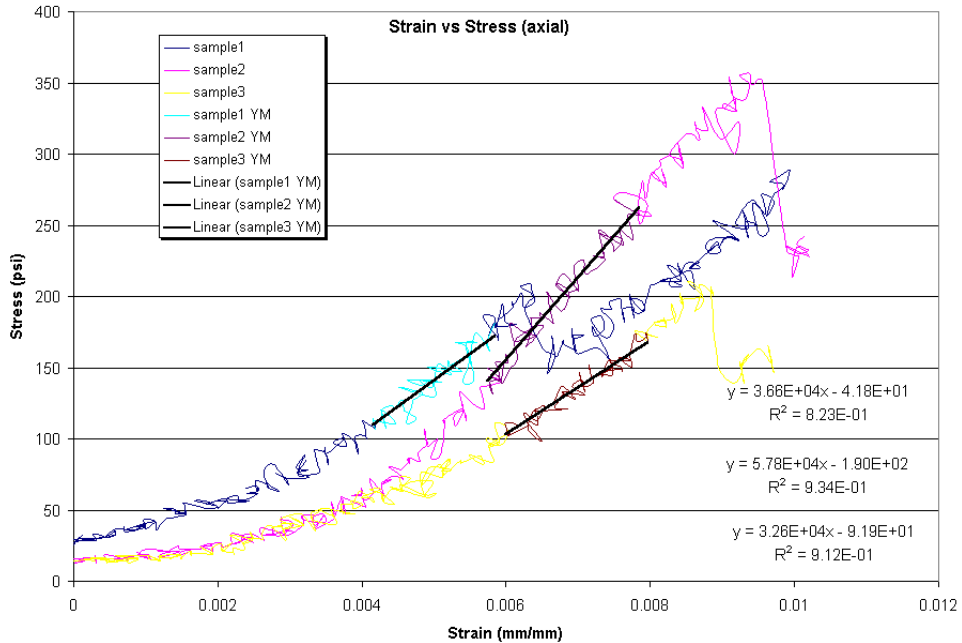


Figure 3—Tensile Young’s Modulus (Using Curved Plates) of 12.0 lb/gal Foamed Cement





### ***Compressive Young's Modulus***

Traditional Young's Modulus testing was also performed using ASTM C469, the Standard Test Method for Static Modulus of Elasticity (Young's Modulus) and Poisson's Ratio of Concrete in Compression. Young's Modulus and effective compressive-strength were tested. The effective compressive strength is the equivalent unconfined compressive strength, which eliminates the effect of confining pressure. The diameter of each test specimen was 1.5 in., and the length was 3.0 in.

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 minutes until stress and strain are at equilibrium. (In case of an unconfined test, only axial load is applied.)
8. The axial and confining stresses 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 the 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.

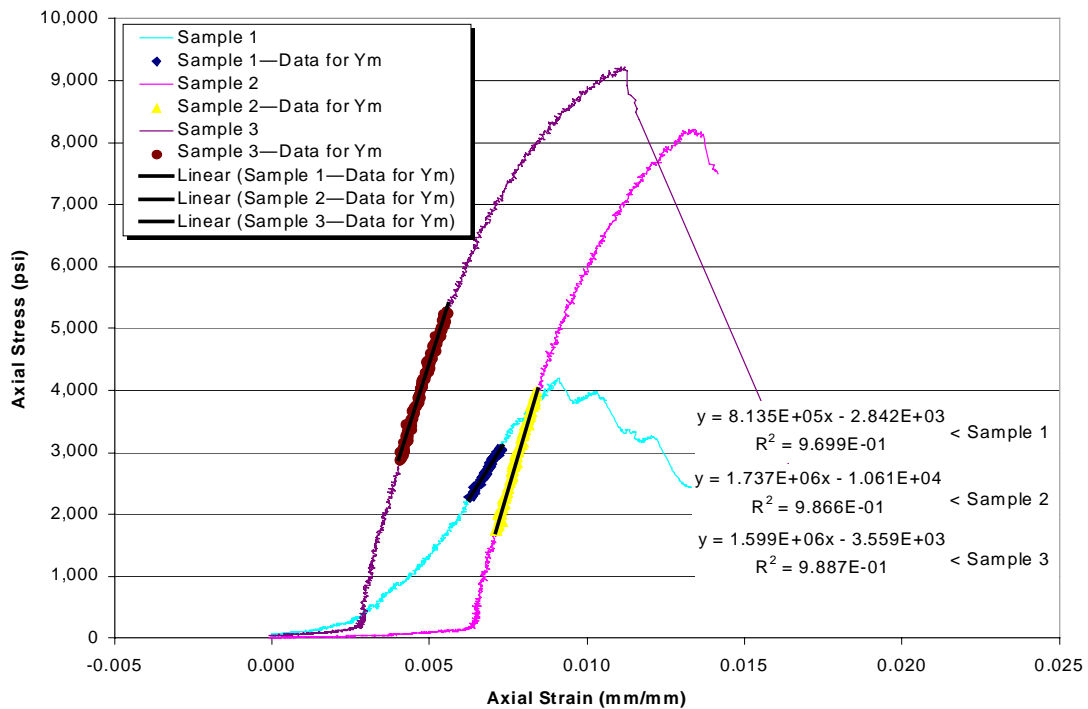
Samples that were cured in an unconfined condition (removed from mold after 24 hours and allowed to cure the remainder of the time outside of the mold) were tested at confining pressures of 0 (zero); 1,500; and 5,000 psi. Young's modulus data for neat Type I samples are presented in **Table 5**. Testing at 0 (zero) confining pressure was also performed on samples that were cured in a confined condition (in the mold for the entire 14 days). Results from testing on the confined, neat Type I samples are presented in **Table 6**. All samples were cured for 14 days at atmospheric pressure in a water bath maintained at 45°F.



**Table 5—Young’s Modulus Data for Neat Type I Samples Cured “Out of the Mold”**

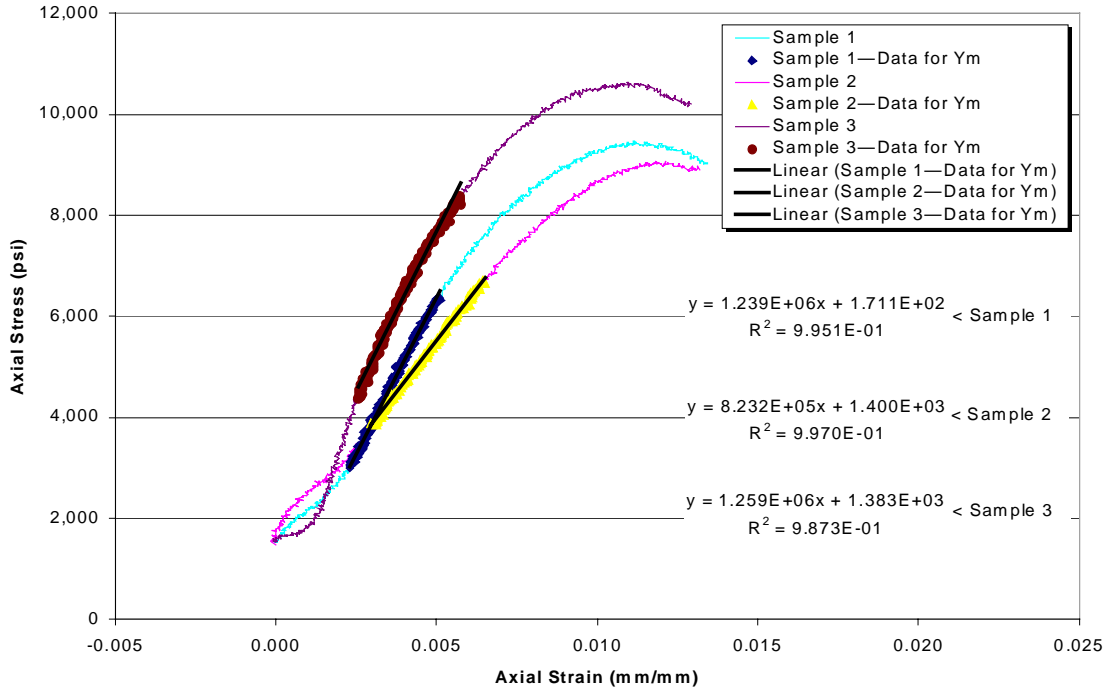
Confining Pressure (psi)	Young’s Modulus (10 <sup>5</sup> psi)	Effective Compressive Strength (psi)
0	8.13	4,118
	17.37	8,125
	15.99	9,166
1,500	12.39	7,912
	8.23	7,526
	12.59	9,046
5,000	8.22	8,553
	9.31	9,133
	9.67	9,007

**Figure 4—Young’s Modulus Testing for Neat Type I Samples Cured “Out of the Mold” and Tested at a Zero Confining Pressure**



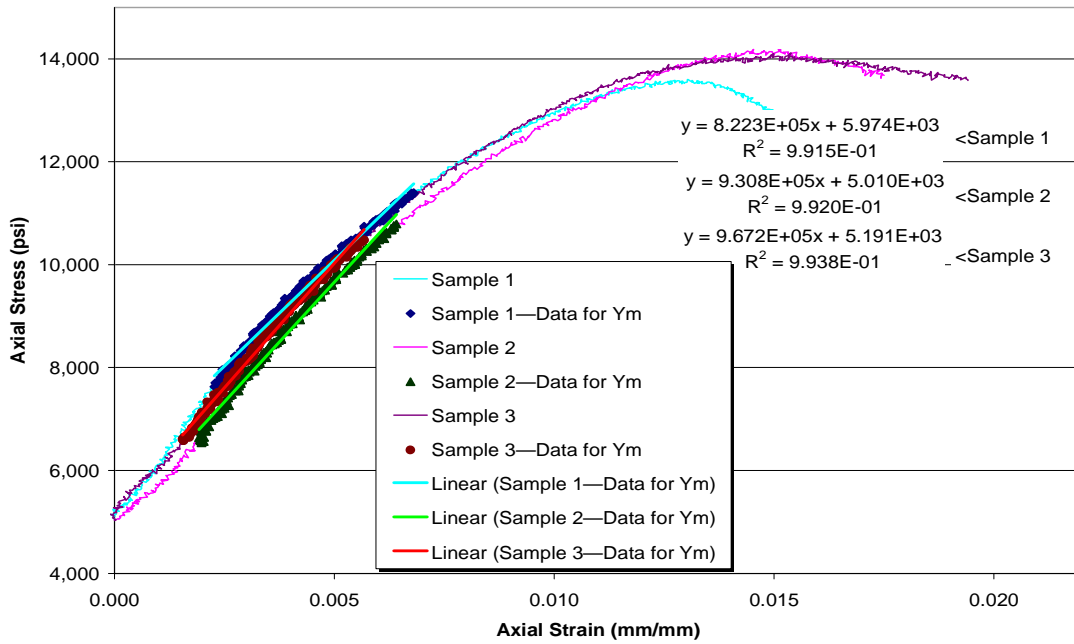


**Figure 5—Young’s Modulus Testing for Neat Type I Samples Cured “Out of the Mold” and Tested at a Confining Pressure of 1,500 psi**





**Figure 6—Young’s Modulus Testing for Neat Type I Samples Cured “Out of the Mold” and Tested at a Confining Pressure of 5,000 psi**

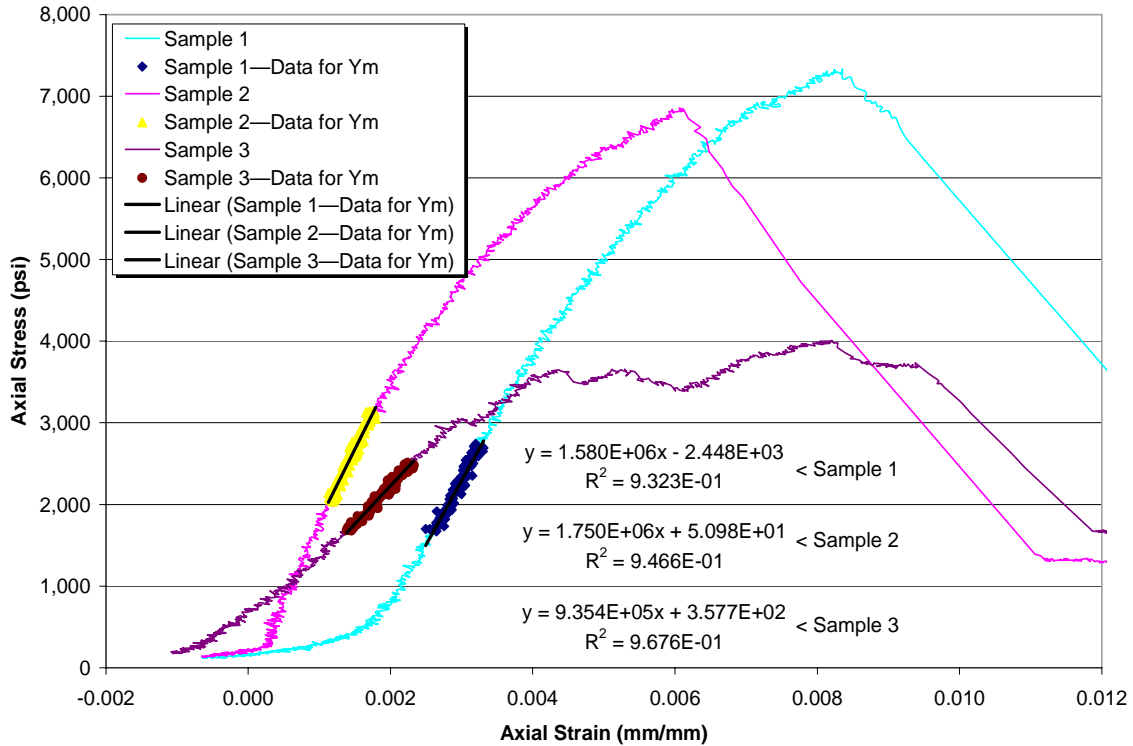


**Table 6—Young’s Modulus Data for Neat Type I Samples Cured “In the Mold”**

Confining Pressure (psi)	Young’s Modulus (10 <sup>5</sup> psi)	Effective Compressive Strength (psi)
0	15.80	7,330
	17.50	6,823
	9.35	4,000



**Figure 7—Young’s Modulus Testing for Neat Type I Samples Cured “In the Mold” and Tested at Zero Confining Pressure**



Tests were also conducted to determine the effect that temperature cycling has on Young’s Modulus. The temperature cycling procedure was 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 1 hour.
2. Samples are placed in 180°F water bath for 4 hours.
3. Samples are placed in 96°F water bath for 1 hour.
4. Samples are placed back in 45°F water bath.



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Table 7 presents data from neat Type I samples that were cured at 45°F in an unconfined condition (removed from mold after one day and allowed to cure the remaining 13 days outside of the mold) and that were then temperature-cycled for five days. Figures 6 and 7 present the Young’s Modulus data.

**Table 7— Young’s Modulus Data for Neat Type I Samples Cured in an Unconfined Condition and Then Temperature-Cycled for Five Days**

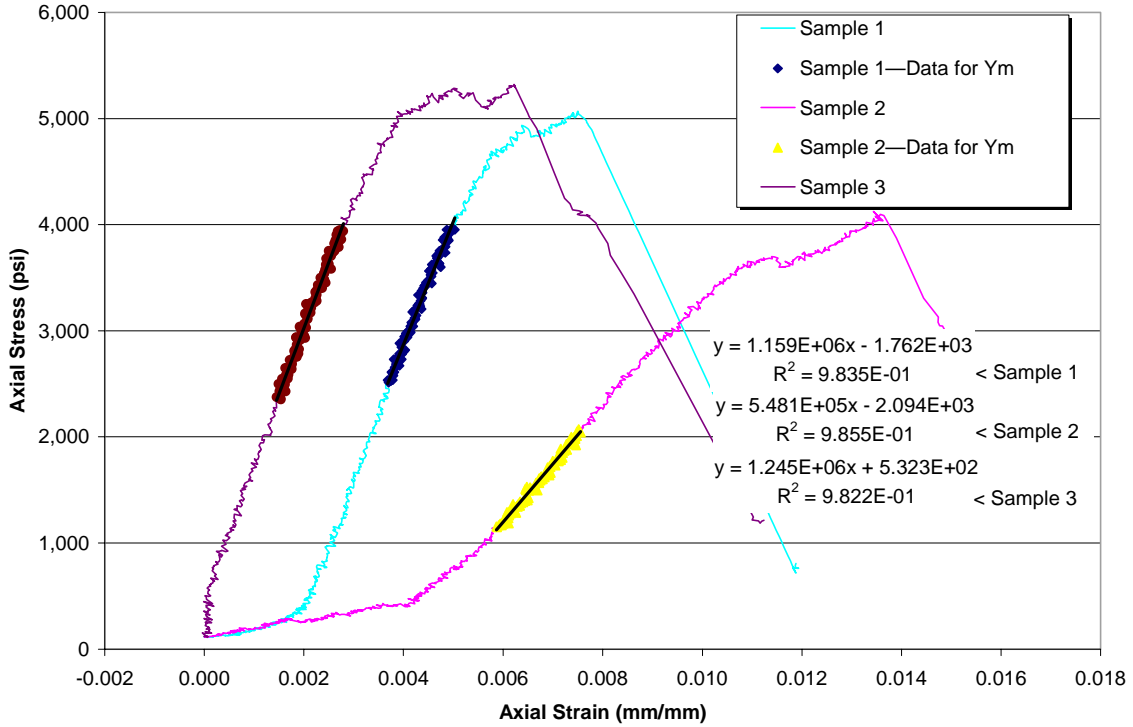
Confining Pressure (psi)	Young’s Modulus (10 <sup>5</sup> psi)	Effective Compressive Strength (psi)
0	11.59	5,014
	5.48	4,084
	12.45	5,243
1,500	8.92	6,975
	10.48	6,642
	11.09	7,022





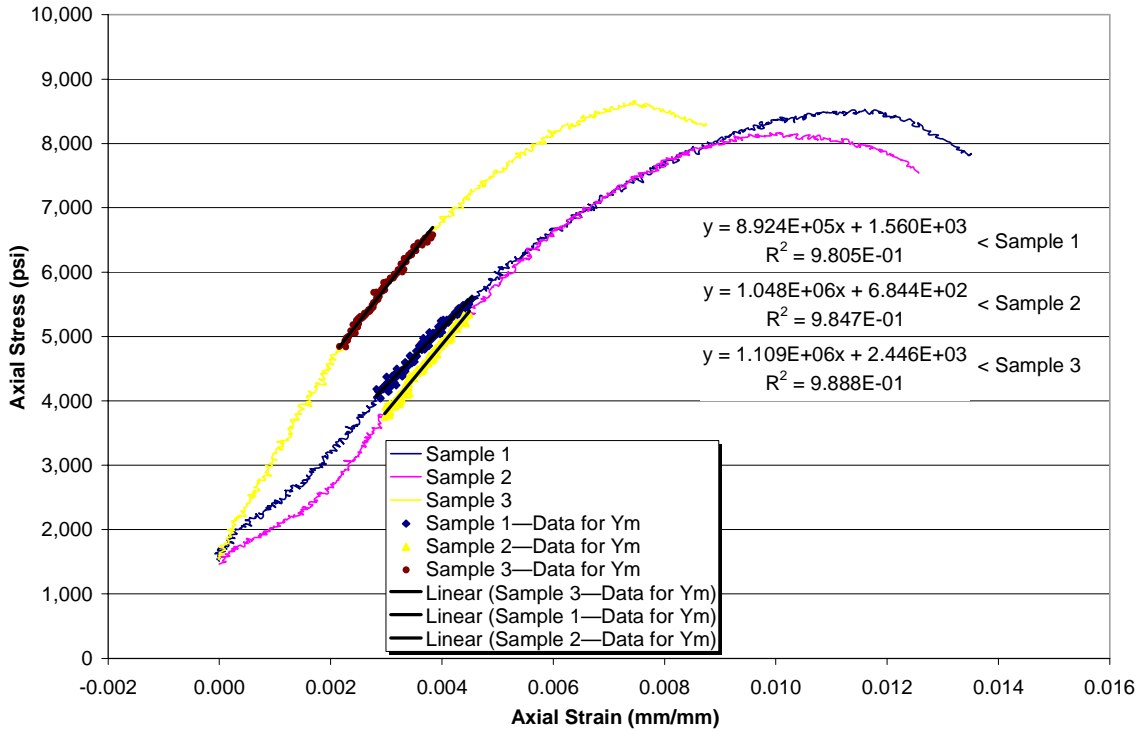
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**Figure 8—Young's Modulus Testing for Neat Type I Samples Cured in an Unconfined Condition**





**Figure 9—Young’s Modulus Testing for Neat Type I Samples Cured in an Unconfined Condition and Then Temperature Cycled for Five Days and Tested at a Confining Pressure of 1,500 psi**



Some of the variation in the Young’s Modulus data could be attributed to settling of the cement slurry. The samples were cured in molds that were 10 in. long, and the individual 3-in. samples were then cut from the 10-in. specimens. For future testing, to avoid potential slurry settling, the slurry will be preconditioned for 20 minutes in an atmospheric consistometer and then poured into individual, shorter molds so only one individual test sample will come from each mold.

**Table 8** and **Figures 10, 11,** and **12** present Young’s Modulus and Poisson’s Ratio data for a 12 lb/gal foamed cement.

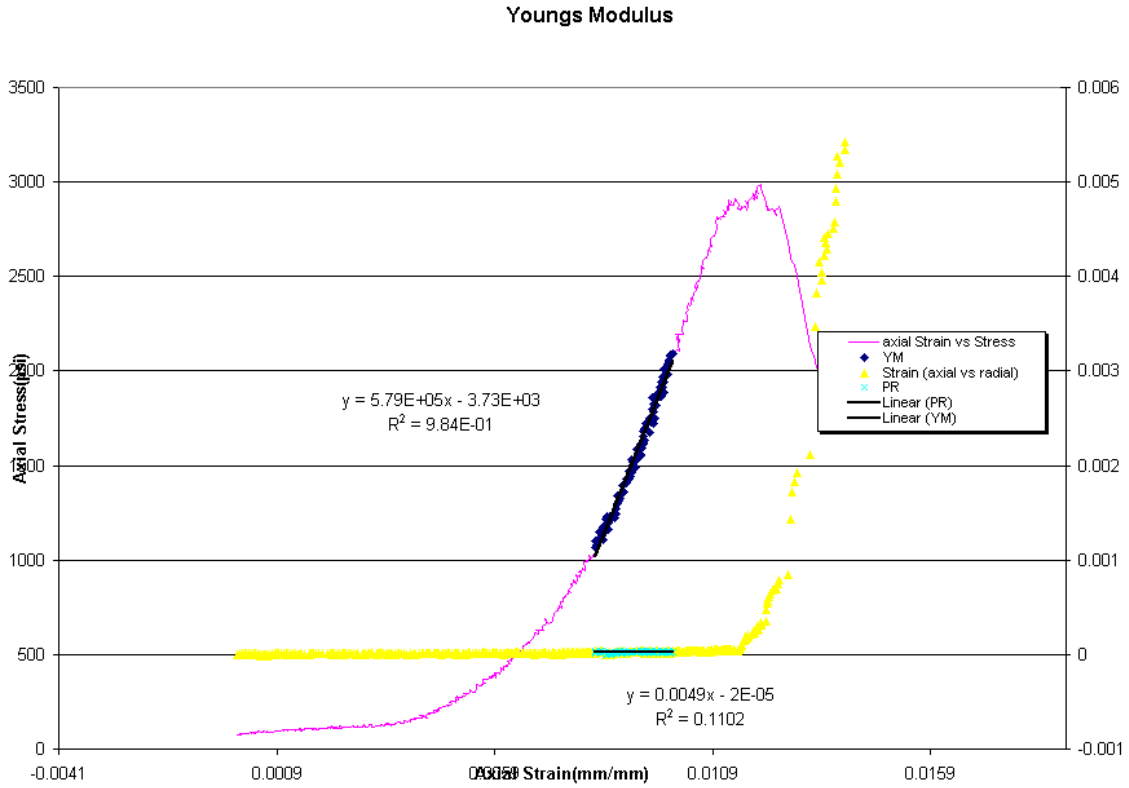
**Table 8—Young’s Modulus and Poisson’s Ratio for 12 lb/gal Foamed Cement**

Sample ID	Confining Stress (psi)	Failure Stress (psi)	Effective Failure Stress (psi)	Young’s Modulus (10 <sup>5</sup> psi)	Poisson’s Ratio (mm/mm)
1	0	2,885	2,885	5.79	0.0049
2	500	4,448	3,948	6.80	-0.0396
3	1,000	5,506	4,506	6.06	-0.0382



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Figure 10—Young's Modulus and Poisson's Ratio Testing for 12 lb/gal Foamed Cement Tested at Zero Confining Pressure



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Figure 11—Young's Modulus and Poisson's Ratio Testing for 12 lb/gal Foamed Cement Tested at 500 psi Confining Pressure

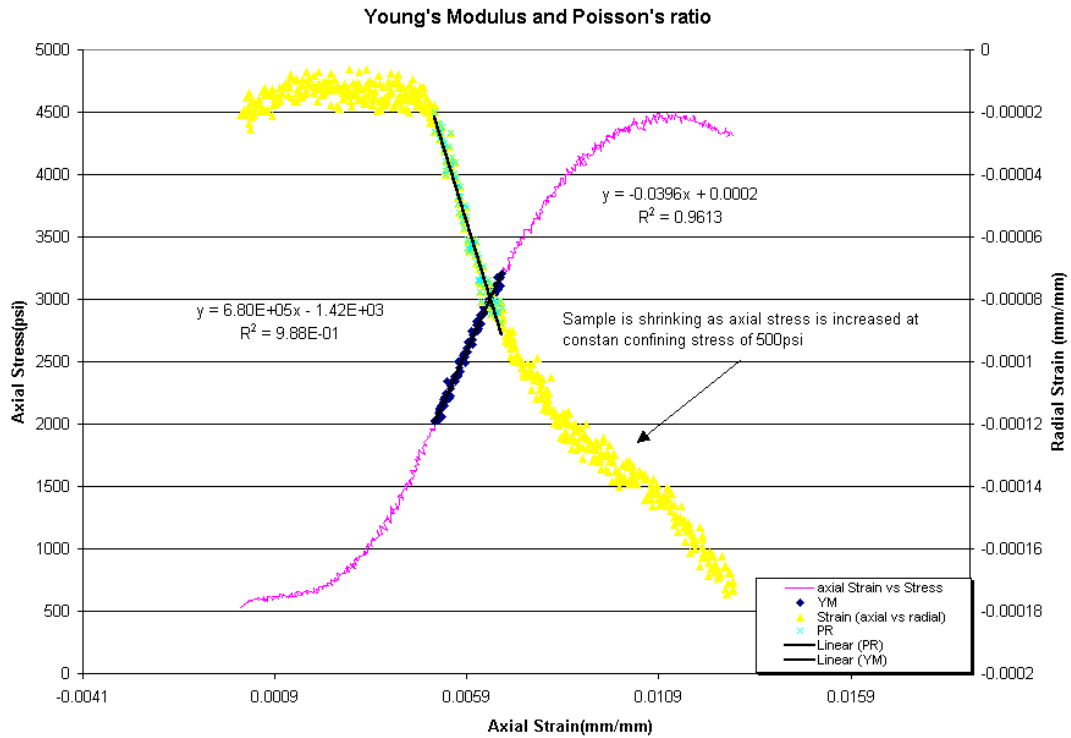
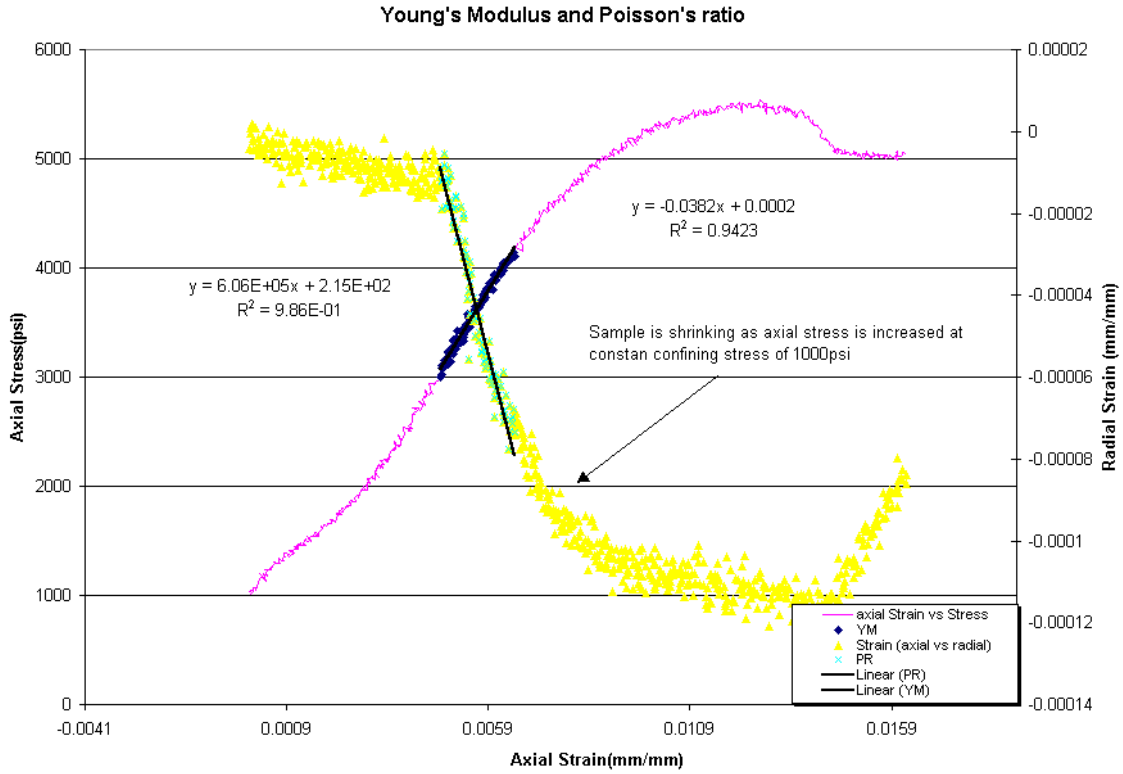




Figure 12—Young's Modulus and Poisson's Ratio Testing for 12 lb/gal Foamed Cement Testing at 1,000 psi Confining Pressure



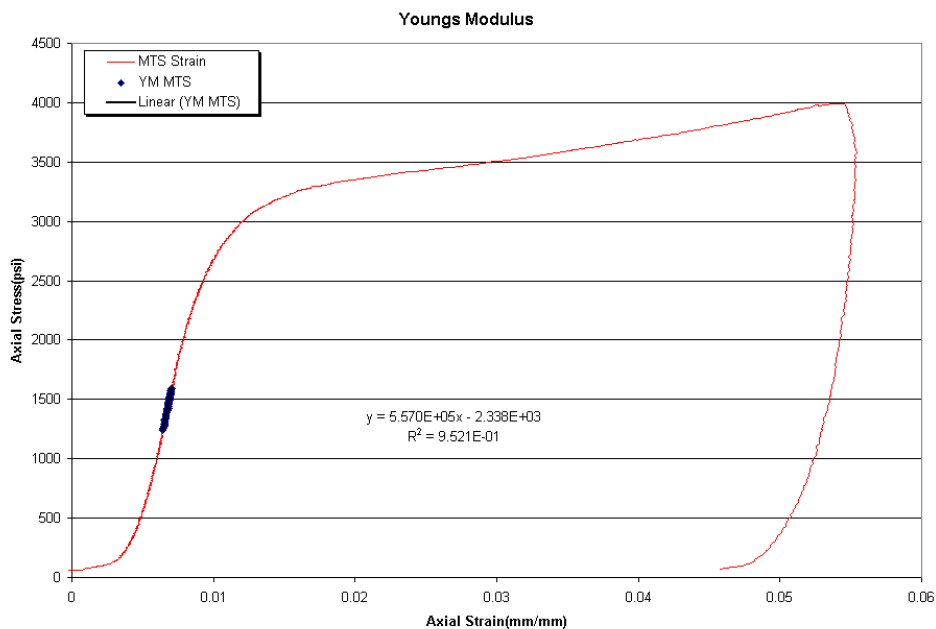


### **Hydrostatic Cycling Tests**

Additional Young's modulus testing was done to get a better understanding how cement responds to downhole pressure cycling. In this testing, a 10-lb/gal, Type I foamed cement was subjected to hydrostatic cycling.

**Figure 13** shows the hydrostatic Young's Modulus testing performed on the 10 lb/gal foamed cement. This testing was done to get an idea of how the cement sample responds under hydrostatic pressure conditions. It also gives an indication that other samples should be able to withstand at least 3,500-psi hydrostatic pressure. The last portion of the curve of **Figure 13**, where the curve is at a negative slope, is a misleading artifact associated with the ending of the test.

**Figure 13—Young's Modulus Testing of 10 lb/gal Foamed Cement**





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Hydrostatic cycling testing was then done on a different sample of the same 10 lb/gal foamed cement. For that testing, the hydrostatic pressure is cycled through the following ramping procedures.

- (1) Ramp up to 1,000 psi.
- (2) Ramp down to 100 psi.
- (3) Ramp up to 1,500 psi.
- (4) Ramp down to 100 psi.
- (5) Ramp up to 2,000 psi.
- (6) Ramp down to 100 psi.

Each ramp was conducted at a rate of 16.7 psi/min and the sample was held at the destination hydrostatic pressures (i.e., 100; 1,000; 1,500; and 2,000 psi) for no longer than two minutes before proceeding to the next ramp step. **Table 9** shows the Young's Modulus value for each ramp procedure. **Figure 14** shows the results of the hydrostatic cycling.

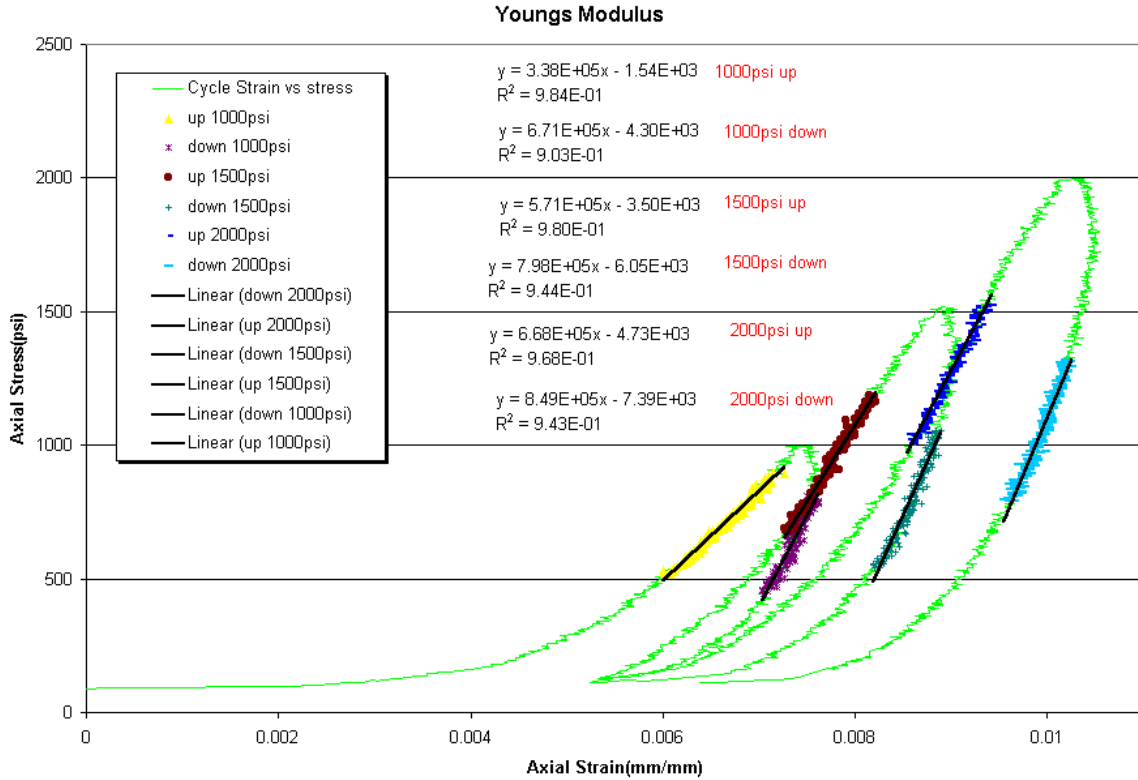
**Table 9—Young's Modulus Data for 10 lb/gal Foamed Cement Exposed to Hydrostatic Cycling**

Cycle #	Destination Hydrostatic Pressure (psi)	Young's Modulus ( $10^5$ psi)
1	1,000	3.38
1	100	6.71
2	1,500	5.71
2	100	7.98
3	2,000	6.68
3	100	8.49



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**Figure 14—Young’s Modulus Testing of 10 lb/gal Foamed Cement During Hydrostatic Cycling**



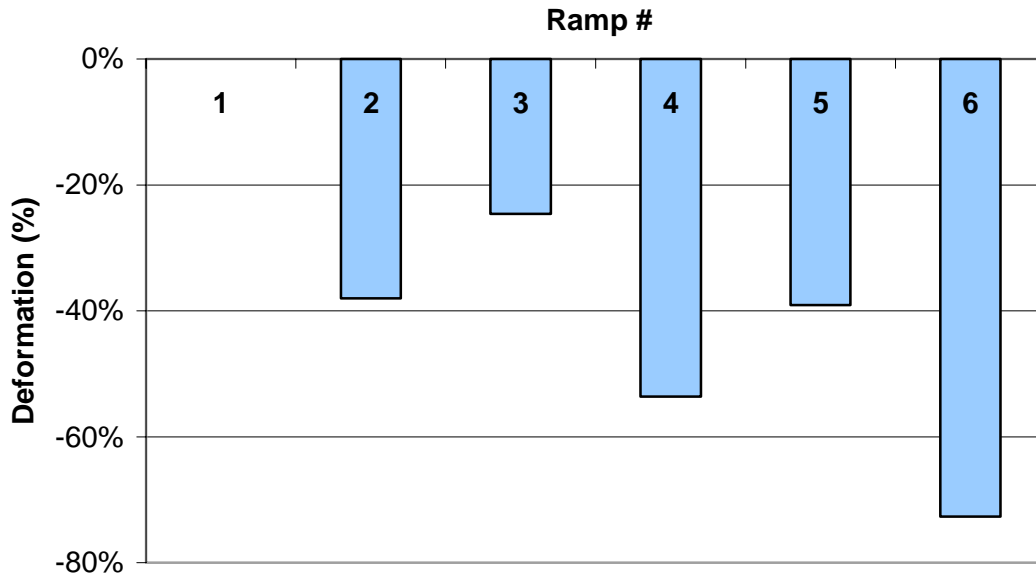
Further study of the hydrostatic cycling was done to examine the deformation that occurs during each of the ramps. **Figure 15** depicts the percentile deformation of each step of the ramps. The value (size) of the sample at 250 psi during the first ramp up to 1,000 psi is taken as the reference value for determining the percentile deformation. This size at 250 psi during Ramp 1 is compared to the sample size at 250 psi during each ramp step.





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**Figure 15—Deformation of 10 lb/gal Foamed Cement during Hydrostatic Cycling**





## Unconventional Performance Testing

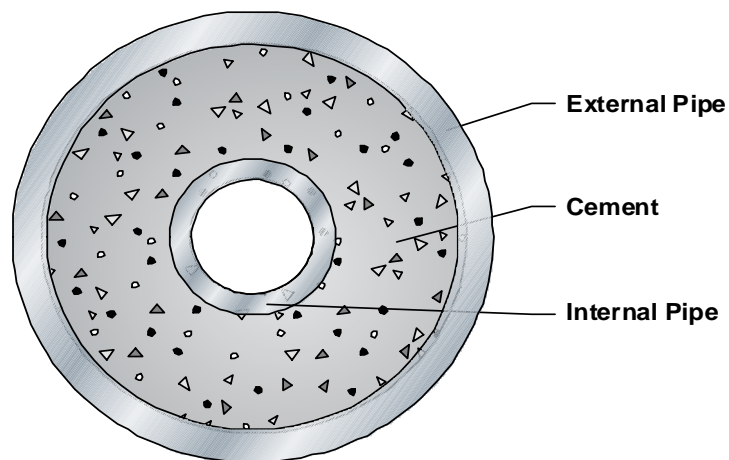
### *Shear Bond Strength*

Testing was also performed to evaluate shear bond strength of neat Type I cement, foamed cement and bead cement. These studies investigate the effect that restraining force has on shear bond. Samples were cured in a pipe-in-pipe configuration (**Figure 16**) and in a pipe-in-soft configuration (**Figure 17**). The pipe-in-pipe configuration consists of a sandblasted internal pipe with an outer diameter (OD) of  $1\frac{1}{16}$  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  $1\frac{1}{16}$  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  $1\frac{1}{16}$ -in. pipe. The top inch of annulus is filled with water.

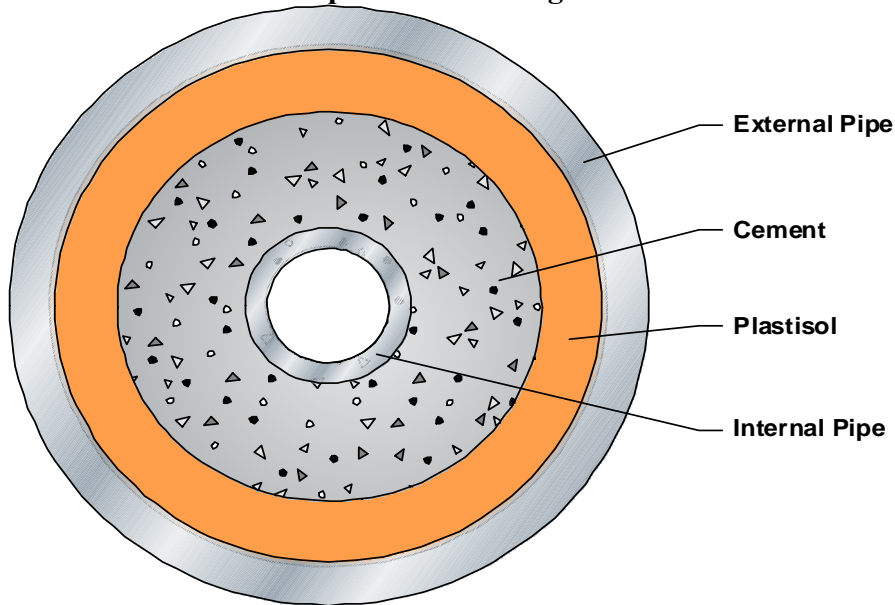
**Figure 16—Cross-Section of Pipe-in-Pipe Configuration for Shear Bond Tests**





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**Figure 17— Cross-Section of Pipe-in-Soft Configuration for Shear Bond Tests**

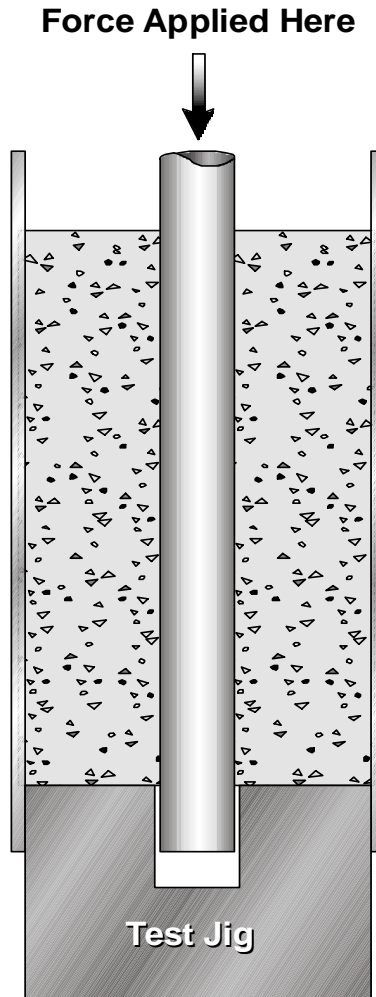


The shear bond measures the stress necessary to break the bond between the cement and the internal pipe. This was measured with the aid of a test jig that provides a platform for the base of the cement to rest against as force is applied to the internal pipe to press it through (**Figure 18**). The shear 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.



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**Figure 18—Configuration for Testing Shear Bond Strength**



**Table 10** presents the 14-day shear bond strengths of the cement samples in the pipe-in-pipe and pipe-in-soft configurations. They were cured at atmospheric pressure in a water bath maintained at 45°F. The † is used in the table to indicate samples that cracked during the pressure cycling. The ‡ is used in the table to indicate samples that were cured for some time other than 14 days; the number following the ‡ indicated the number of days the sample was cured.



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Table 10—Shear Bond Strengths

Slurry System	Shear Bond Strength (psi) at Different Conditions					
	Baseline		Temperature Cycled		Pressure Cycled	
	Pipe-in-Pipe	Pipe-in-Soft	Pipe-in-Pipe	Pipe-in-Soft	Pipe-in-Pipe	Pipe-in-Soft
Neat	1194	198	165	72	194/106	23
Foamed	127/98	233	299/215 <sup>‡26</sup>	7	276/228 <sup>‡24</sup>	22 <sup>†</sup>
Bead	109/78	143	191/269 <sup>‡27</sup>	56	294/170 <sup>‡24</sup>	23 <sup>†</sup>

<sup>†</sup> indicates cement cracked during pressure cycling.

<sup>‡</sup> indicates sample was cured for the number of days specified after the <sup>‡</sup>.

The effect that temperature cycling has on shear bond was tested. The temperature cycling procedure was 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 1 hour.
2. Samples are placed in 180°F water bath for 4 hours.
3. Samples are placed in 96°F water bath for 1 hour.
4. Samples are placed back in 45°F water bath.
5. Samples are conditioned for 20 minutes.

The effect that pressure cycling has on shear bond was also tested. The pressure cycling procedure was designed to simulate pressure conditions that might be encountered during production of a well. Because these samples will undergo 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 (zero) psi for 10 minutes.



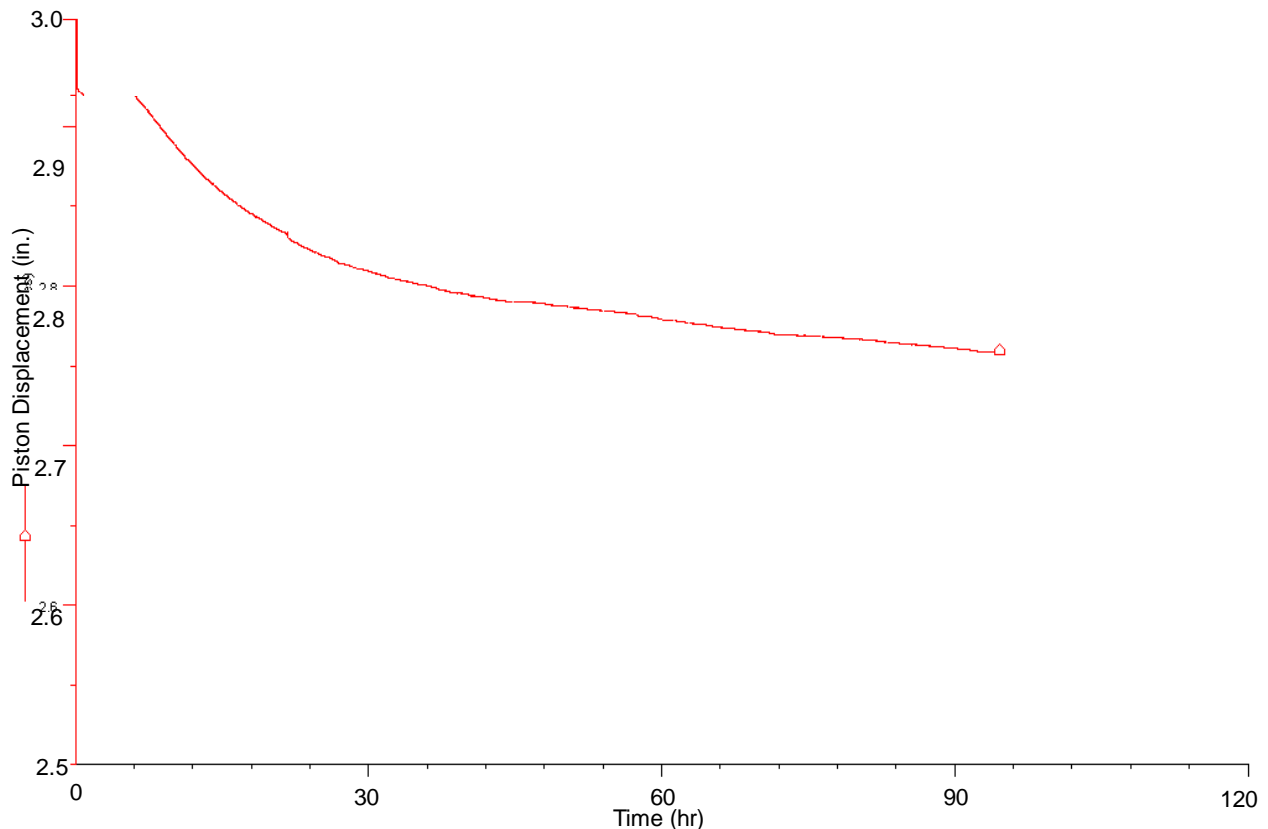
### ***Shrinkage Testing***

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

1. Fill the test cell with 180 cm<sup>3</sup> 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 the valve on top of the test cell cap. Purge the air out of the system.
6. Apply 1,000-psi hydrostatic piston pressure to the test cell and begin recording data (time, piston displacement, and pressure).
7. Run the test and gather data for the desired amount of time.

**Figure 19** shows the piston displacement recorded during the inner shrinkage testing. The piston displacement indicates the inner shrinkage of the cement.

**Figure 19—Piston Displacement during Inner Shrinkage Testing of Type I Cement**





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Changes in the cement volume are assumed to be overwhelmingly dominated by inner shrinkage, although any bulk shrinkage would also affect the volume. From the piston displacement data, the cement volume shrank by 6.8%.

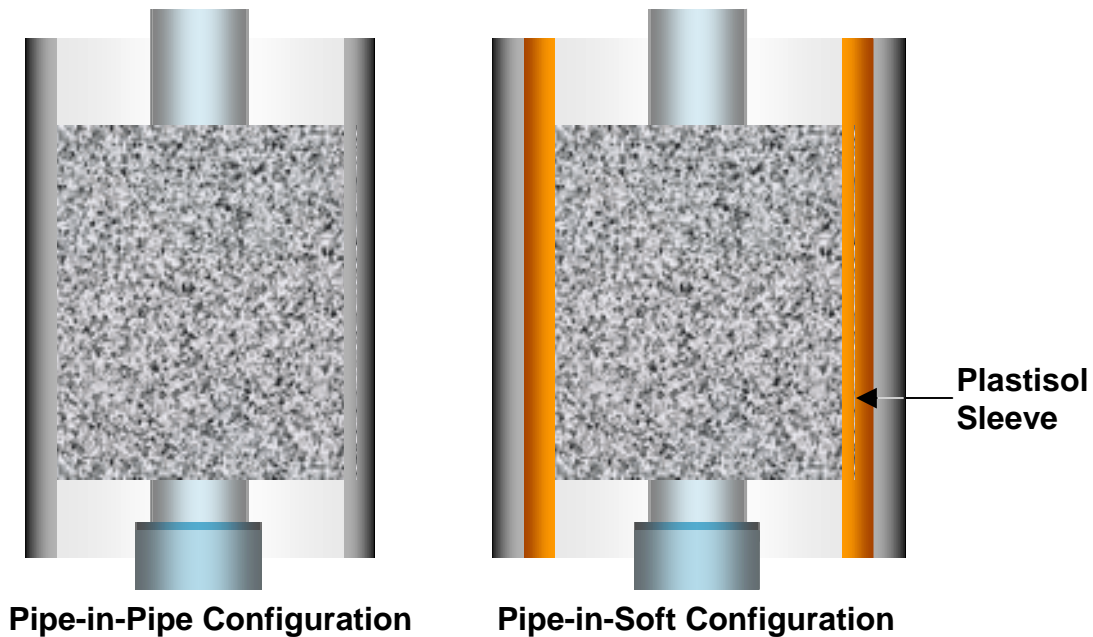
### **Annular Seal Testing**

#### **Casing Pressure Test**

These studies investigate the effect that casing pressure tests have on annular seal. Many people think that casing pressure tests expand the casing and create pressures on and increase the inner diameter of the surrounding cement. The stresses and physical changes can adversely strain the cement and potentially deform the cement irrecoverably.

A laboratory model has been developed to simulate casing pressure tests (**Figure 20**). The model can be made in two different configurations— pipe-in-pipe and pipe-in-soft. This is to simulate high-restraint and low-restraint formations. This can help identify differences between a hard formation and a loosely consolidated formation. The pressure testing will be initiated after different times of cement curing to determine the effects of curing time before pressure testing. Multiple cycles of pressure testing will be performed.

**Figure 20—The Two Configurations for the Casing Pressure Test**

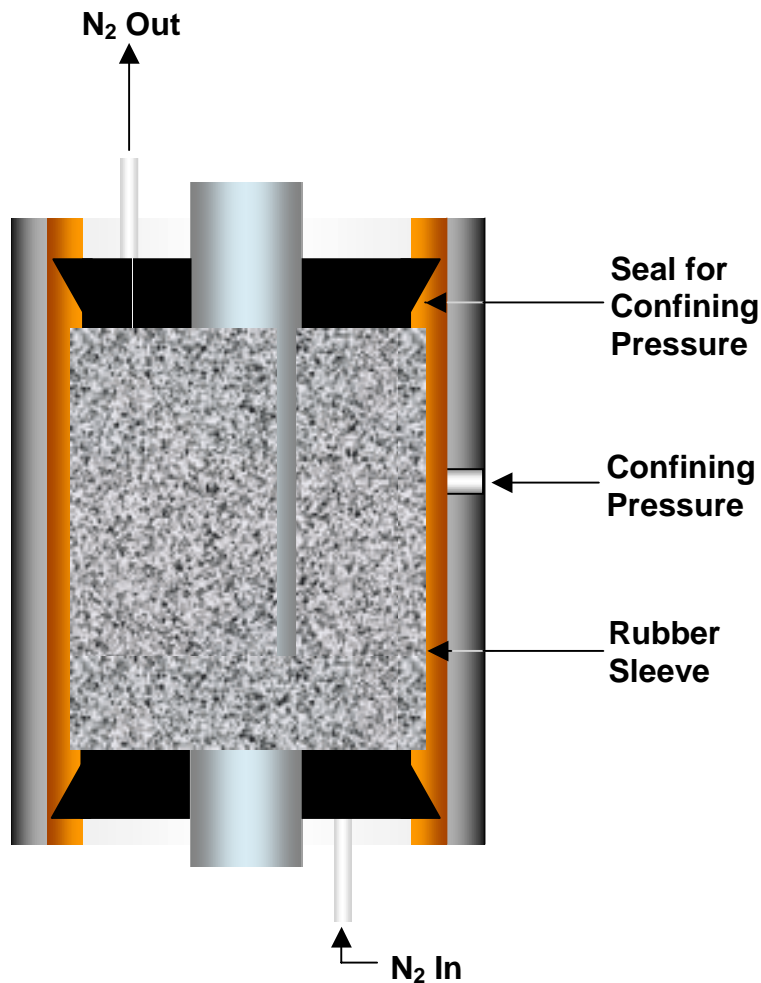




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A key component of this project is investigating cement's capability to maintain its seal under downhole stresses. An annular seal model has been developed that can measure bulk permeability across a cement system that has been stressed from temperature or pressure cycling. As with some of the other testing, the annular seal test model will have pipe-in-pipe and pipe-in-soft configurations to simulate high and low restraints, respectively. **Figure 21** shows the pipe-in-soft configuration of the annular seal model.

**Figure 21—Cross-Section of Annular Seal Model for Pipe-in-Soft Configuration**



The inner pipe of the model will be the main conduit for the stressing medium. For instance, the inner pipe can contain heated fluids while the remainder of the system is at a different temperature; this simulates the hotter formation fluids that can be experienced during production. The inner pipe of the model can also be pressured up to 5,000 psi, simulating casing pressure testing which is believed by many to lead to loss of annular seal because of the expanding and contracting casing.





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For the temperature and pressure cycling, the model will be subjected to five complete temperature and pressure cycles and then annular seal testing will be done.

In the pipe-in-soft configuration, the rubber sleeve surrounding the cement is able to withstand 25 psi. During the annular seal test, pressure can then be applied to the outside of the rubber sleeve, allowing the sleeve to make a fluid-tight seal on the outside of the cement. Pressurized nitrogen gas (<25 psi) can then be applied axially across the cement and the only paths for fluid flow is through cement or along the interface between the cement and the inner pipe. Any exiting nitrogen flow rate can be monitored and measured. In the pipe-in-pipe configuration, there is no need for the rubber sleeve or the exterior confining pressure.

### **Annular Seal Testing Procedure**

These procedures are for the use of the Pipe-in-Soft annular seal apparatus and the Pipe-in-Pipe annular seal apparatus. These procedures are organized by apparatus and are to be used specifically for that type of apparatus. 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 those cores that were made inside iron pipes, giving the cement slurry a restricting force outside of the core.

#### Testing Procedure for Pipe-in-Soft:

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<sub>2</sub> 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 out of the out-line using flowmeters.



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Testing Procedure for Pipe-in-Pipe:

1. After the core is cured inside the iron pipe, using iron 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 out of the out-line using flowmeters.

As with the shear bond tests, temperature and pressure cycling were also performed with the annular seal tests. **Table 11** shows the results of the annular seal testing.

**Table 11—Annular Seal Tests**

<b>Annular Seal</b>	<b>Type I</b>	<b>Foamed</b>
Initial Flow — Pipe-in-Pipe	0 Flow	0 Flow
Initial Flow — Pipe-in-Soft	0 Flow	0.9K(md)Liquid(retesting)
Temperature Cycled — Pipe-in-Pipe	0 Flow	0 Flow
Temperature Cycled — Pipe-in-Soft	0 Flow	123K(md)(retesting)
Pressure Cycled — Pipe-in-Pipe	0 Flow	0 Flow
Pressure Cycled — Pipe-in-Soft	27K(md)	0.19K(md)(cracked during cycling)



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## **Mathematical Modeling**

The University of Houston performed finite element analysis (FEA) of the laboratory models used in the project (temperature and pressure cycling models) so the laboratory results can be compared to the mathematical modeling. The mathematical modeling was analyzed to determine if the stresses associated with the temperature and pressure cycling result in loss of annular seal. These studies will then be compared with other FEA work.

The mathematical simulations reveal that the Pipe-in-Pipe configuration is very stable and retains its integrity even at sufficiently large loading conditions. This is mainly due to the order of magnitude difference in the Young's Modulus of the steel pipe and the cement sheath. However, for the Pipe-in-Soft configuration, large deformations are observed in the cement and the plastisol layer, which suggests potential loss in integrity of cement-casing bonding and hence the annular seal. This result must be confirmed by experiments and further analysis to account for the interfacial bonding.

The cement material properties and cement thickness have negligible effect on the overall stress distribution in the Pipe-in-Pipe configuration. However, for the Pipe-in-Soft configuration, the material properties become significant. Thermal stresses lead to tensile stresses, which can result eventually in tensile failures at high temperatures. A very sharp stress contrast is observed in all cases at the casing-cement interface.

Details of the mathematical modeling procedure, results, and conclusions are contained in the Mathematical Modeling appendix to this report.



## **Appendix: Mathematical Modeling**

### **Introduction**

In understanding the long-term integrity of cement in deepwater systems and determining the properties that affect the ability of cement to seal fluids, a principal step is to mathematically model the system to study different stress-causing phenomena. Besides enabling researchers to theoretically predict the effect of various stress conditions such as temperature cycling, pressure cycling, etc., mathematical modeling will also provide a means of justification to test the designs and steer the direction of laboratory testing. The results of these models will be analyzed to determine if the stresses associated with the stress-causing conditions will result in loss of annular seal of cement.

Further, in the presence of asymmetrical far-field stresses, internally pressurized and cemented wells can experience both tensile and compressive stresses. As a result, fracture initiation (if the internal pressure is sufficiently high) is a function of the cement's tensile strength and the tensile stresses induced within the cement sheath. This makes some portions of the cement sheath particularly vulnerable to fracture initiation. The stress distribution in casing-cement-rock system needs to be estimated as a single continuous problem over disjointed domains. It is presumed that a fundamental study of such systems will provide valuable clues on the selection of choice of well completion and appropriate cement properties.

Two main configurations have been considered for modeling purposes: Pipe-in-Pipe and Pipe-in-Soft (see **Figure 1**). The focus will be on establishing a mathematical framework for analysis of different loading conditions, temperature gradients and material properties and their effect on the induced stress distribution. Long term effects such as subsidence and compaction may also be interpreted and incorporated through appropriate changes to loading conditions. A parametric variation of cement's material properties and thickness has been studied to determine the role of each variable toward the overall stress and strain distributions.

The following sections describe briefly the mathematical model and discuss the main results of the analysis.



## Mathematical Model

In practice, the magnitude and orientation of the *in situ* stress field is altered locally, as a result of the drilling of a well. In addition, when internal wellbore pressure and temperature gradients are present, the pre-existing stress fields are distorted significantly to give rise to new induced stresses. The following equation summarizes the regular elasticity problem, with internal wellbore pressure and far-field boundary conditions:

$$\begin{aligned}\nabla \cdot \sigma &= 0 && \text{on } B \\ \varepsilon &= \frac{1}{2}(\nabla u + \nabla u^T) \\ \sigma &= L\varepsilon \\ e_i \cdot (\sigma \cdot n) &= \hat{\sigma}_1 && \text{on } \partial B_{1i}\end{aligned}\tag{1}$$

where  $\sigma$  is the stress tensor,  $\varepsilon$  is the strain tensor,  $u$  is the displacement vector and  $L$  is the elasticity tensor. Equation 1 represents the traction boundary condition specified on the internal and external boundary.

In deepwater conditions, the subsea temperature will be lower ( $< 5^\circ\text{C}$ ) than the surface temperature. However, after prolonged production, the pipelines can reach much higher temperature (about  $100^\circ\text{C}$ ). As a result, there is a temperature gradient present across the annular cylinders (casing and cement sheath).

When the temperature rise in a homogeneous body is not uniform, different elements of the body tend to expand at different rates, and the requirement that the body remain continuous conflicts with the requirement that each element expand by an amount proportional to the local temperature rise. Thus the various elements exert upon each other a restraining action resulting in continuous unique displacements at every point. The system of strains produced by this restraining action cancels out all, or part of, the free thermal expansions at every point so as to ensure continuity of displacement. This system of strains must be accompanied by a corresponding system of self-equilibrating stresses. These stresses are known as thermal stresses. A similar system of stresses may be induced in a structure made of dissimilar materials even when the temperature change throughout the structure is uniform. Also, if the temperature change in a homogeneous body is uniform and external restraints limit the amount of expansion or contraction, the stresses produced in the body are termed as thermal stresses.

In a completed wellbore system, all these three conditions are present and contribute toward thermal stresses, namely non-uniform temperature distribution, dissimilar materials (casing, cement, etc.), and external restraints.



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The desired energy equation for an isotropic, elastic solid is

$$k\nabla^2 T = C_{e=0} \frac{\partial T}{\partial t} + \beta T_0 \frac{\partial e'}{\partial t} \quad (2)$$

where  $k$  is the thermal conductivity,  $T$  is the temperature rise from the initial uniform temperature  $T_0$ , of the stress-free state,  $\beta = E\alpha/(1-2\nu)$ ,  $C_{e=0}$  is the heat capacity per unit volume at zero strain and  $e'$  is the dilatation.

This equation is based on the Fourier law of heat condition and the linear thermoelastic stress-strain relations, and it shows that the temperature distribution in a body depends upon the dilatations through out the body. Thus, the temperature and strain (and hence, stress) distributions are coupled and an exact analysis would require the simultaneous determination of the stress and temperature profiles.

For numerical modeling purposes, the casing-cement-rock system is considered as concentric cylindrical structures, in continuous contact with each other. The Pipe-in-Pipe configuration represents a hard formation, while the Pipe-in-Soft configuration represents a soft formation. A generic, 3D finite element model is developed for this composite system using Abaqus 5.7 and Matlab 6.0 (see **Figure 2**). Pure elastic stress-strain analysis is performed using customized Matlab programs, while thermal stress analysis is handled using Abaqus. For laboratory tests involving homogeneous casing and confining pressures, the system is axi-symmetric and hence only a quadrant of the annular structure is studied.

### Assumptions

1. The system can be modeled using linear elastic theory.
2. The composite system retains continuity at the interfaces.
3. The system is axi-symmetric because of the boundary conditions.
4. All materials are homogeneous and continuous.
5. Plastisol has the same material properties as that of rubber.
6. Plane stress condition is valid.



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## **Stress Conditions**

The following stress-causing conditions have been considered for mathematical modeling purposes:

- Normal production operation
- Pressure cycling (casing pressure)
- Subsidence, compaction (confining pressure)
- Temperature cycling (thermal stress)

The normal production operation includes an operating casing pressure and an external confining pressure (*in situ* stresses), along with a steady thermal gradient. All elastic and thermoelastic simulations represent steady state conditions. A fully rigorous coupled thermoelastic equation is considered for numerical modeling purposes. However, the effect of dilatation is negligible when the system is allowed to evolve up to steady state.



## Parametric Studies

The following parameters and cement properties have been varied to study their influence on stress distribution in the cement:

- Casing pressure (100 to 10,000 psi)
- Confining pressure (100 to 1000 psi)
- Temperature gradient (80 to 180° F)
- Young's modulus (1000 to 7000 psi)
- Poisson ratio (0.15 to 0.45)
- Cement thickness (1 to 7 inches)

All numerical simulations are representative of the laboratory testing conditions, with the parameter ranges provided by CSI from their experimental results. All parametric studies are with respect to the following reference case:

Parameter	Value
Casing pressure	500 psi
Confining pressure	500 psi
Young's modulus	5000 psi
Poisson ratio	0.35
Cement thickness	1 inch
No thermal gradient	

## Results and Discussion

Stress, displacement and temperature profiles for both the configurations are computed using a 3D finite element model, with quadratic elements. **Figure 3** shows the first principal stress and horizontal displacement profiles for a representative case (Pipe-in-Pipe), with an internal casing pressure of 500 psi and no confining pressure or thermal gradient. A Young's Modulus of 5,000 psi and a Poisson ratio of 0.35 were used for the cement sheath. It may be observed that most of the stress variation is arrested within the inner pipe (made of steel), with a relatively high Young's Modulus ( $3.05 \times 10^7$  psi). As a result, very little stress is transferred across to the cement sheath. The outer pipe experiences hardly any load in the absence of a direct confining pressure, as is evident from the negligible stresses and displacements.





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### ***Casing Pressure***

The casing pressure is varied from 100 to 10,000 psi for the Pipe-in-Pipe configuration, in the absence of any confining pressure or thermal gradient. The first principal stress and horizontal displacement along the x-axis is plotted in **Figure 4**. Clearly, the inner steel pipe limits the transfer of any load across to the cement sheath, because of its high Young's Modulus. A sharp stress contrast is observed at the casing-cement interface, while the continuity requirement of displacement at the interface manifests itself as differing gradients in the two materials and reaching zero at the external boundary. Since the inner steel pipe is the dominant material as far as the load distribution is concerned, very little effect is felt by the cement sheath.

The same result is observed for the stress distribution, even more pronounced, in the Pipe-in-Soft configuration (see **Figure 5**) in the absence of confining pressure. However, larger displacements are observed in comparison to the Pipe-in-Pipe case. This suggests that the cement sheath can displace more from its set position and can potentially lose its annular seal in a soft formation.

### ***Confining Pressure***

In addition to base casing pressure of 500 psi, a confining pressure is applied on the outside ranging from 100 to 1000 psi. All other conditions are held constant as before. The stress profile (shown in **Figure 6**) shows a similar result as before, since both the inner and outer pipes are assumed to be of the same material (steel). The cement sheath has a reduced and almost uniform stress distribution, while the steel pipes arrest most of the variation.

For the Pipe-in-Soft configuration, when a confining pressure is present, both the cement and the plastisol layer undergo relatively larger deformations. However, increasing the confining pressure from 100 to 1000 psi has little effect on the magnitude of displacements in all the three materials (see **Figure 7**).

### ***Young's Modulus and Poisson Ratio***

The cement material properties (Young's Modulus and Poisson Ratio) are varied to study their effect on stress distribution in the Pipe-in-Pipe configuration. The Young's modulus is varied between 1000 and 7000 psi, and the Poisson ratio is varied from 0.15 to 0.45. Since the steel pipe transfers very little stress to the cement sheath, there is a negligible influence on the stress and strain distribution in the cement sheath (see **Figure 8** and **Figure 9**).



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### ***Cement Thickness***

The thickness of the cement layer is varied between 1 to 7 inches for the Pipe-in-Pipe configuration. As the thickness increases, a larger portion of the cement is under compression, which results in an increased horizontal displacement for the same casing and confining pressure, as shown in **Figure 10**. It may be observed that the same amount of net displacement is experienced by the inner and outer steel pipes, in comparison to the more flexible cement sheath.

### ***Temperature Gradient***

In addition to a casing pressure of 500 psi and a confining pressure of 500 psi, a thermal gradient is applied across the concentric cylinders for the Pipe-in-Pipe configuration. The external temperature on the outer pipe is held constant at 68°F, and the temperature at the inner surface of the inner pipe is varied between 80°F and 180°F. The temperature profile is symmetric, and varies only along the radial direction (shown in **Figure 11**). While the elastic stress acts in compression, the thermal stress arising due to non-uniform and dissimilar expansion of the composite system can lead to tensile stresses. As a result, the net stress experienced by the system is controlled by the dominant stress source. It may be observed from the displacement profile (**Figure 12**) that the thermal stresses tend to expand the concentric cylinders. At high temperatures and low external loads, the thermal stress can be controlling the net displacement and vice versa at low temperatures and high external loads.



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## **Conclusions**

In summary, from the above simulations performed to verify and complement the laboratory testing, it is observed that the Pipe-in-Pipe configuration is very stable and retains its integrity even at sufficiently large loading conditions. This is mainly due to the order of magnitude difference in the Young's Modulus of the steel pipe and the cement sheath. It is suggested to study the behavior of these systems at higher cement Young's Modulus. However, for the Pipe-in-Soft configuration, large deformations are observed in the cement and the plastisol layer, which suggests potential loss in integrity of cement-casing bonding and hence the annular seal. This, however, must be confirmed by experiments and further analysis to account for the interfacial bonding.

The cement material properties and cement thickness have negligible effect on the overall stress distribution in the Pipe-in-Pipe configuration. However, for the Pipe-in-Soft configuration, the material properties become significant. Thermal stresses lead to tensile stresses, which can result eventually in tensile failures at high temperatures. A very sharp stress contrast is observed in all cases at the casing-cement interface.

The mathematical model framework is generic and can be easily extended to include several other scenarios such as heat generation (due to heat of hydration) in the cement layer, multi-layered formation, pressure transmission of gas flow, etc.



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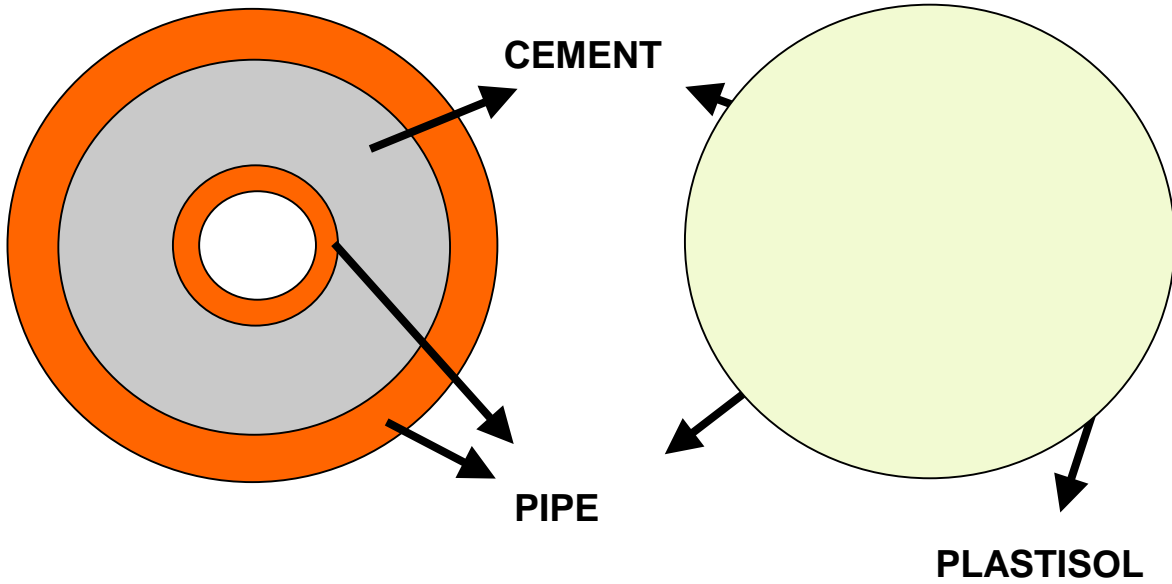


Figure 1 — Pipe-in-Pipe and Pipe-in-Soft Configurations

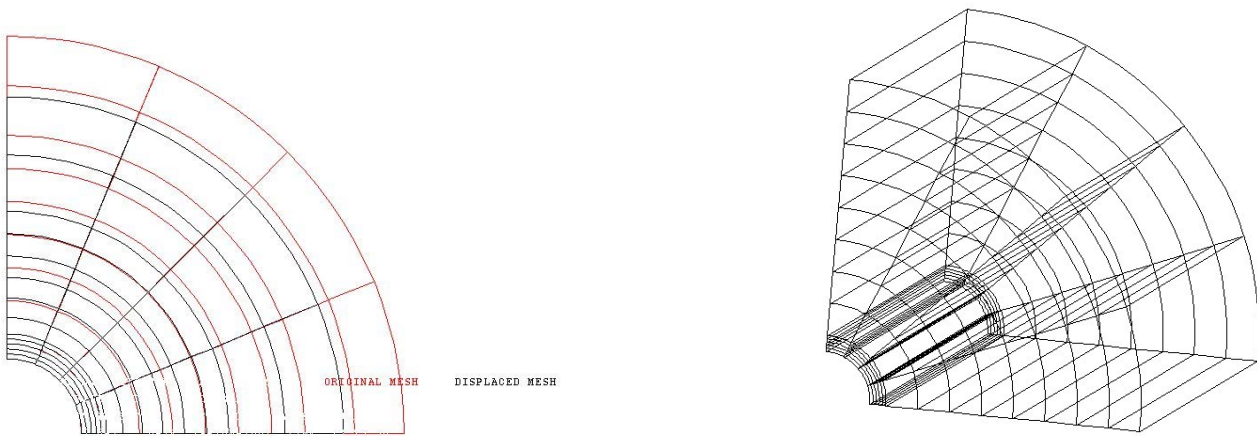


Figure 2—3D Finite Element Model Grid



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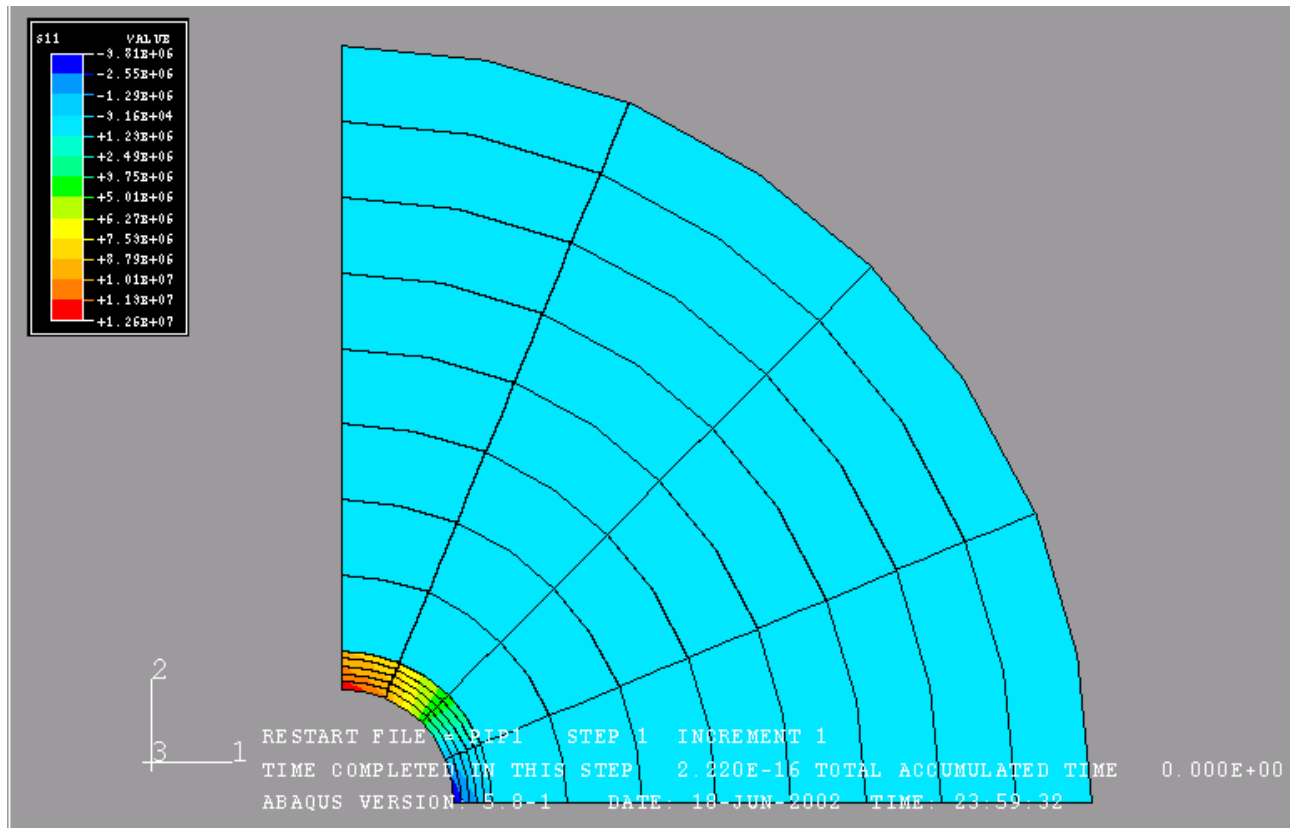


Figure 3a—First Principal Stress Profile (PIP; No Confining Pressure)



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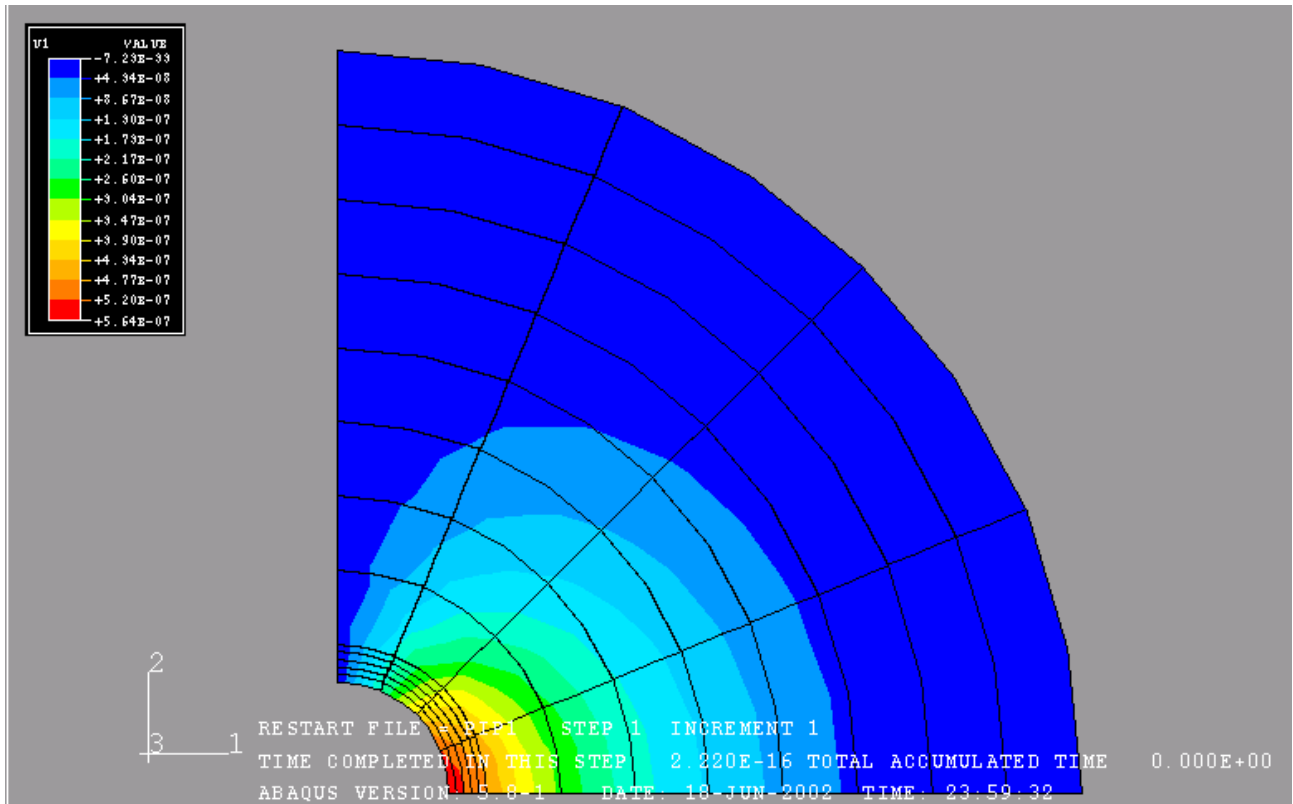


Figure 3b—Horizontal Displacement Profile (PIP; No Confining Pressure)



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**Young's Modulus**            **5000 psi**  
**Poisson Ratio**            **0.35**  
**Confining Pressure**       **None**  
**Cement Thickness**        **1 inch**  
**Temperature Gradient**    **None**

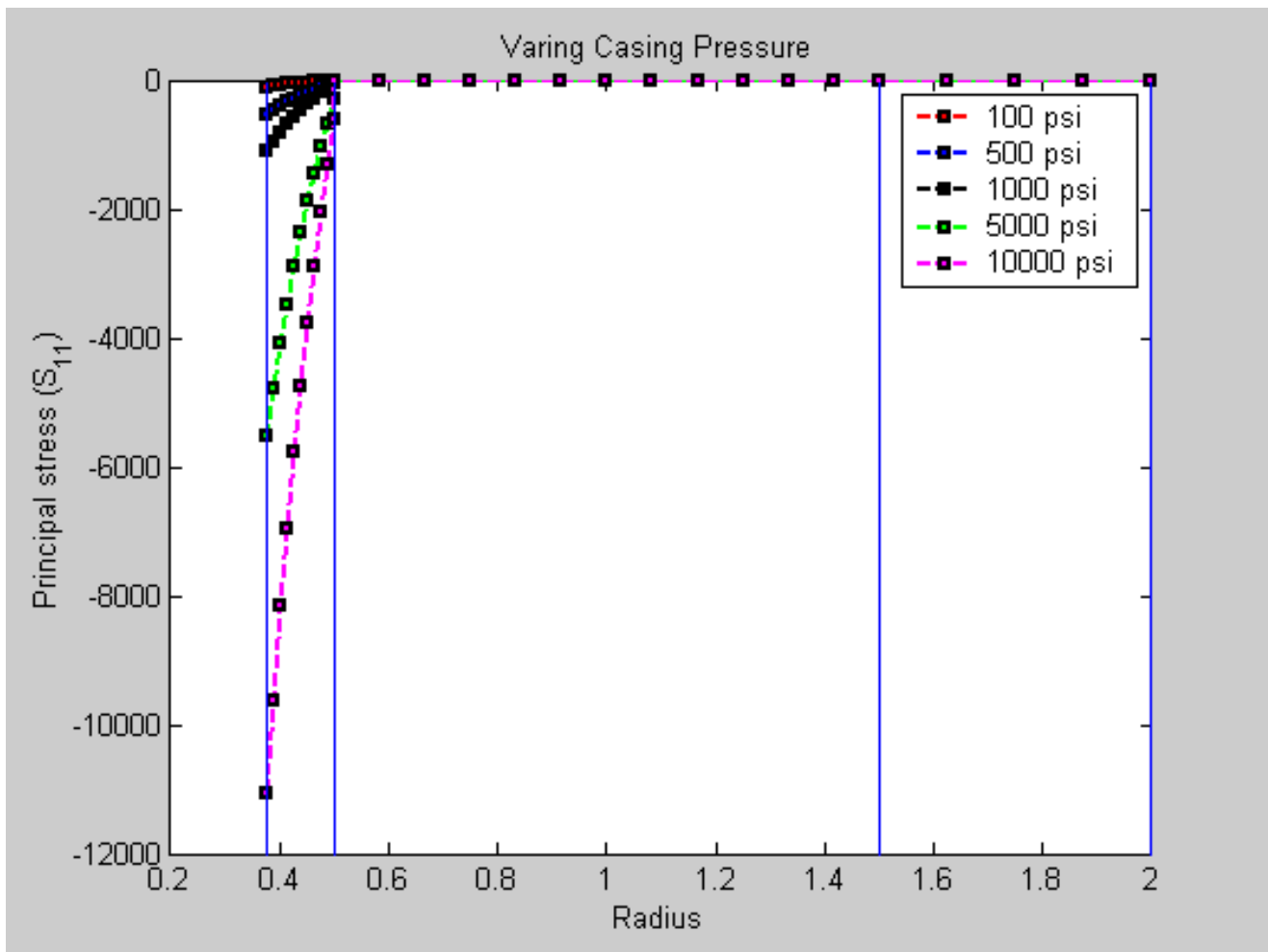


Figure 4a—First Principal Stress Profile along X-Axis (PIP)



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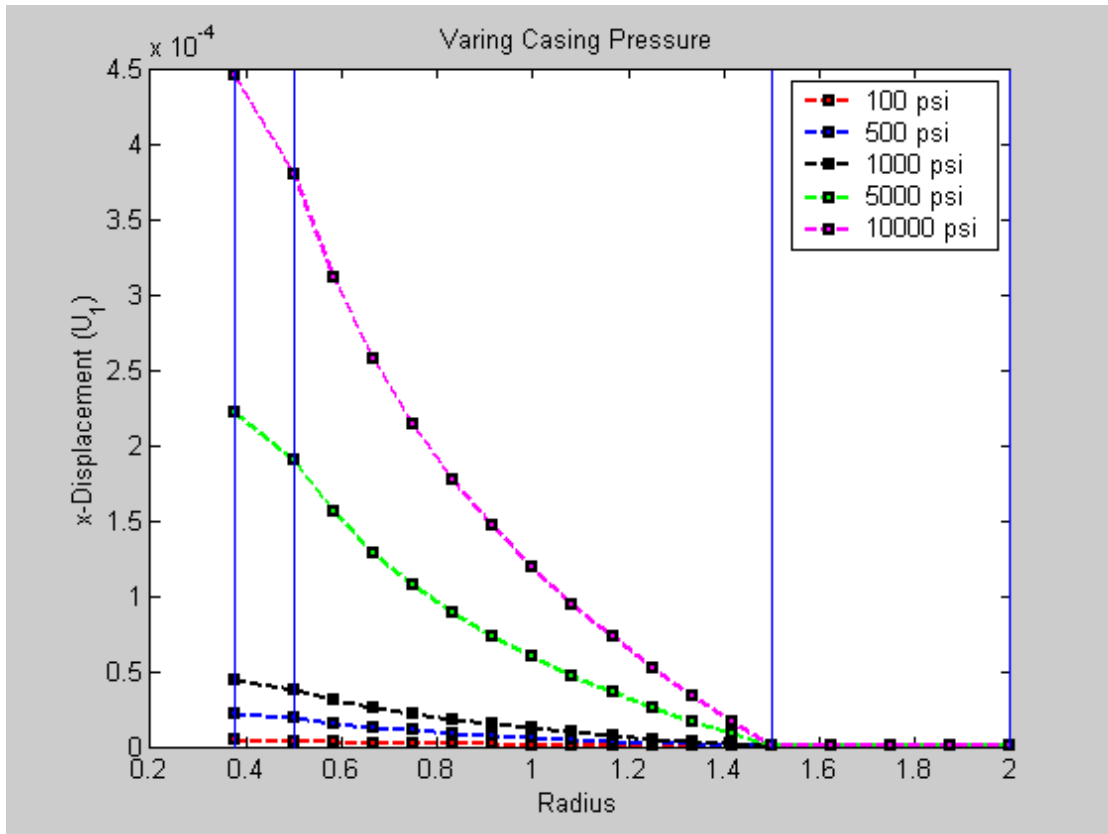


Figure 4b—Horizontal Displacement Profile along X-Axis (PIP)





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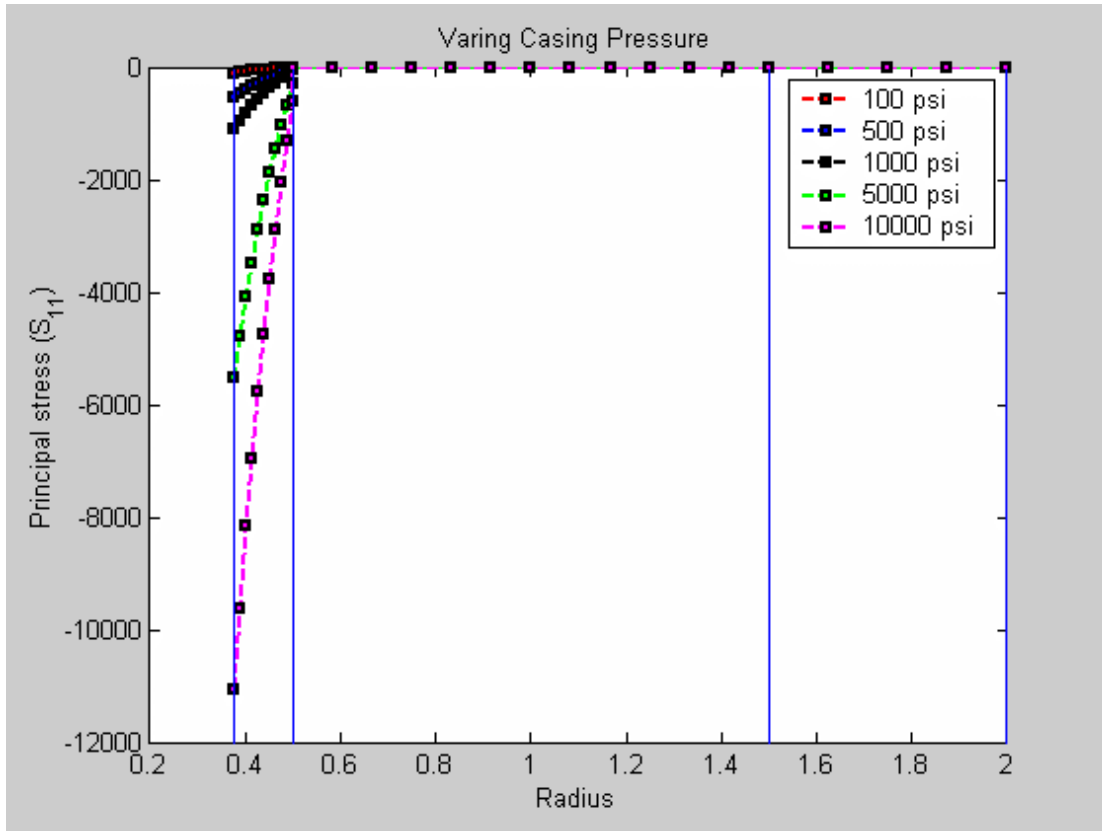


Figure 5a—First Principal Stress Profile along X-Axis (PIS)



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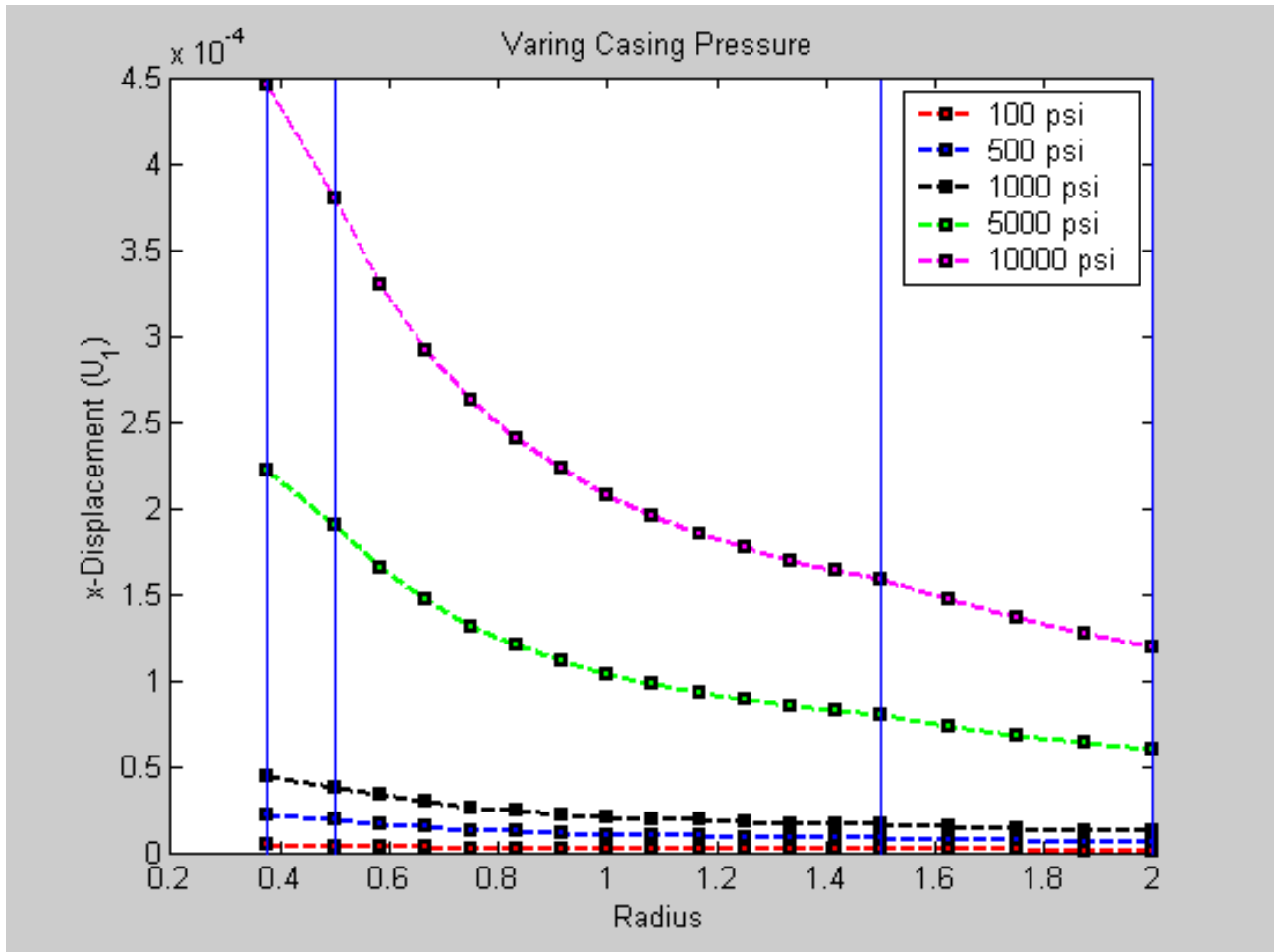


Figure 5b—Horizontal Displacement Profile along X-Axis (PIP)



**Cementing Solutions, Inc.**

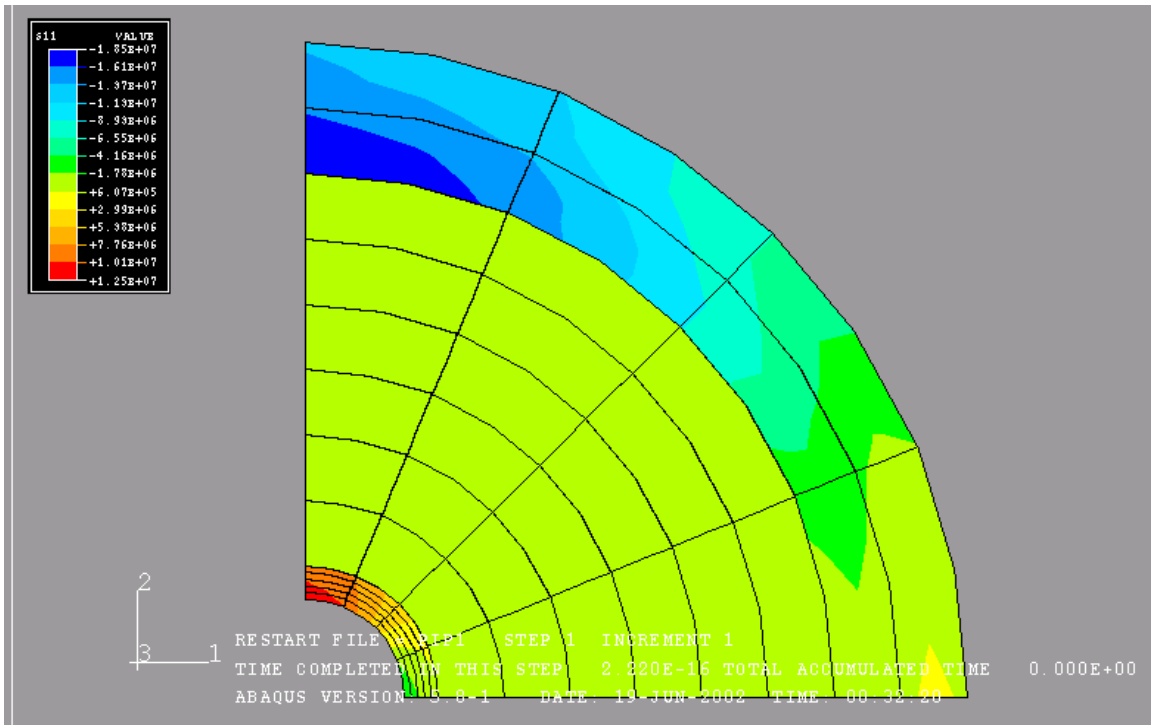


Figure 6a—First Principal Stress Profile (PIP; with Confining Pressure)



**Cementing Solutions, Inc.**

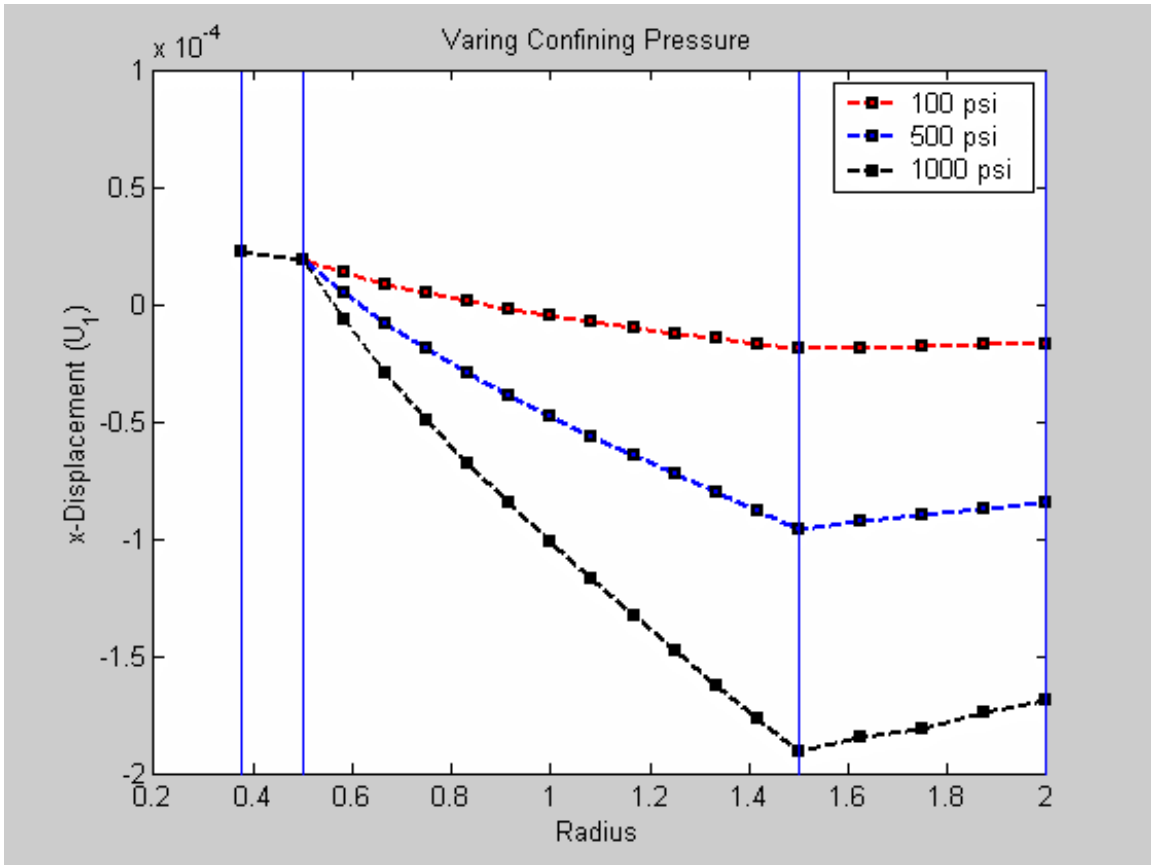


Figure 6b—Horizontal Displacement Profile (PIP; with Confining Pressure)



**Cementing Solutions, Inc.**

**Young's Modulus**            **5000 psi**  
**Poisson Ratio**            **0.35**  
**Confining Pressure**        **500 psi**  
**Cement Thickness**         **1 inch**  
**Temperature Gradient**    **None**

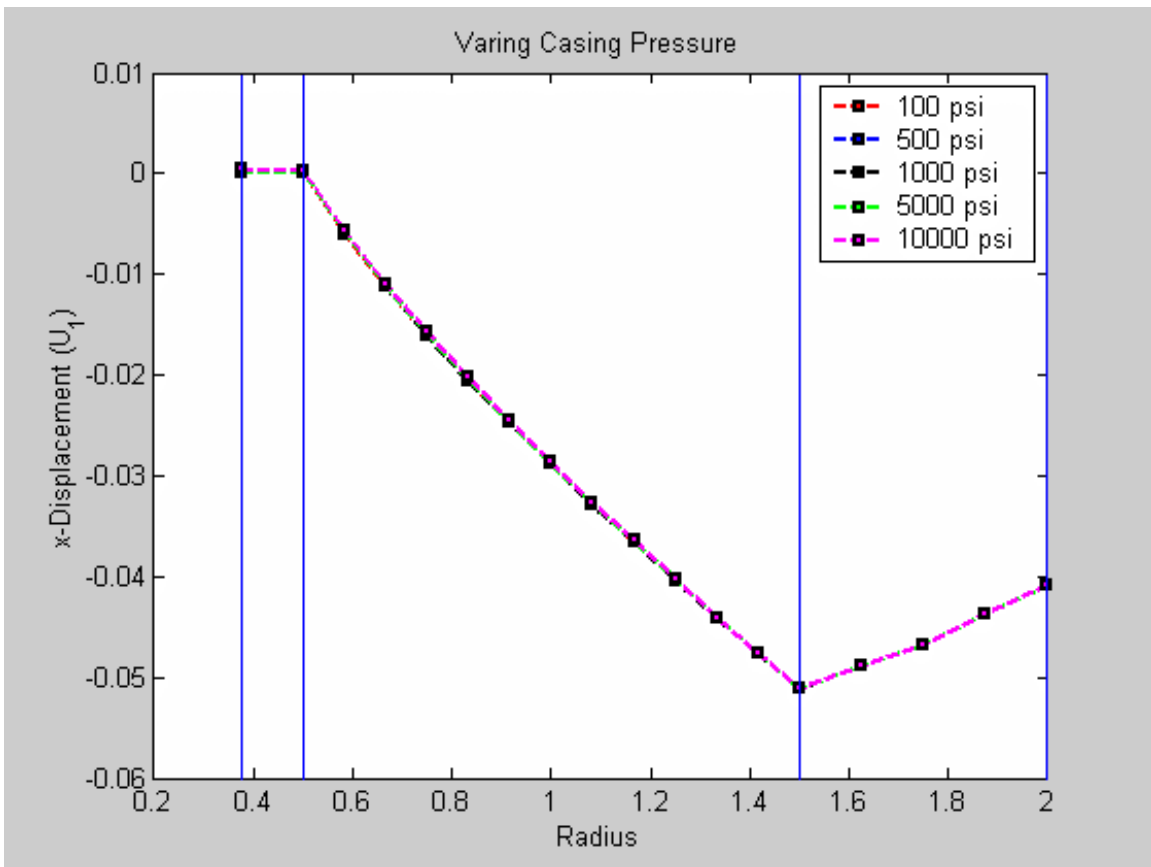


Figure 7—Horizontal Displacement Profile (PIS; with Confining Pressure)



**Cementing Solutions, Inc.**

**Confining Pressure**      **500 psi**  
**Poisson Ratio**          **0.35**  
**Casing Pressure**        **500 psi**  
**Cement Thickness**      **1 inch**  
**Temperature Gradient**   **None**

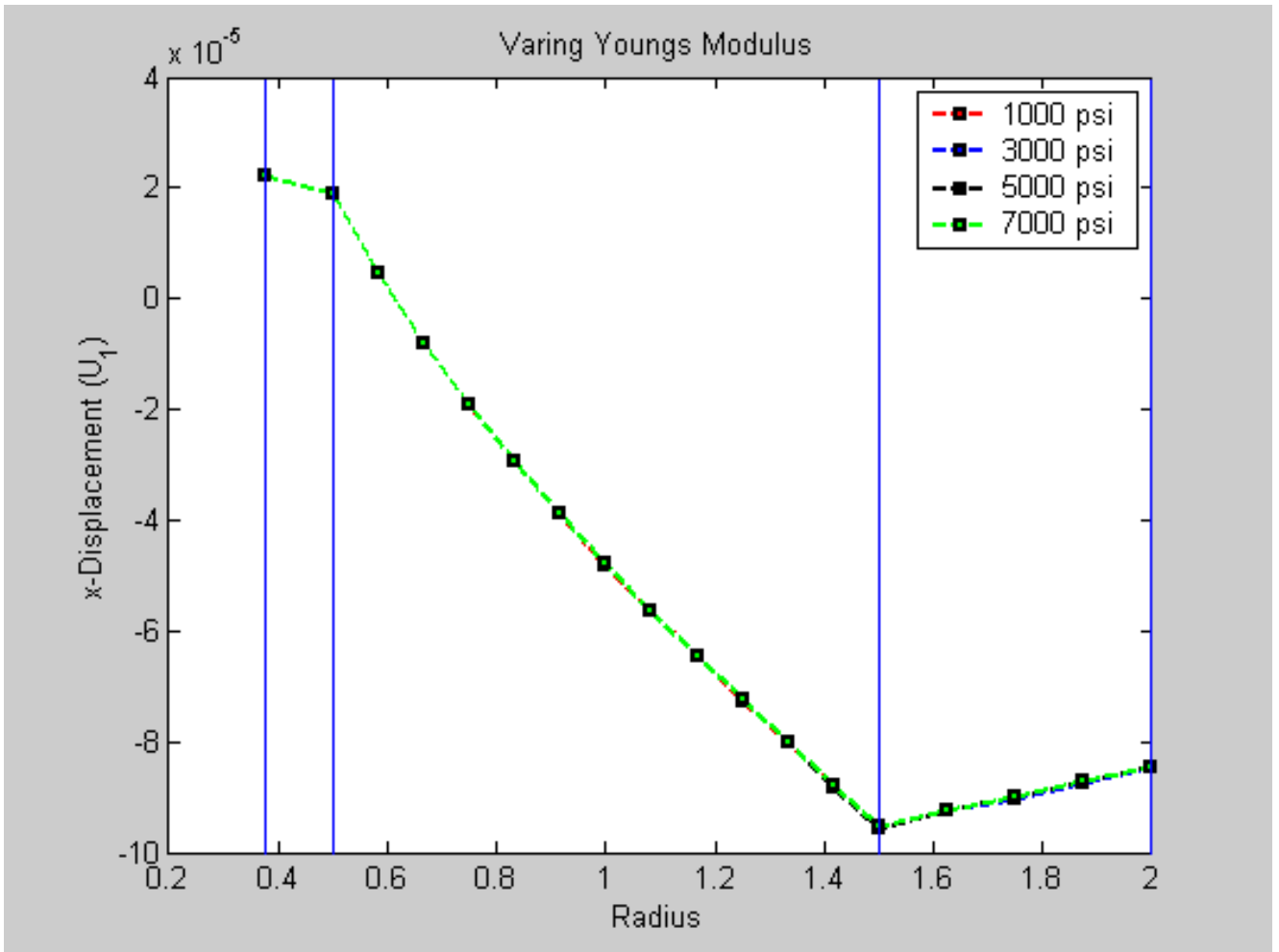


Figure 8—Horizontal Displacement Profile (PIP; Varying Young's Modulus)



**Cementing Solutions, Inc.**

<b>Confining Pressure</b>	<b>500 psi</b>
<b>Young's Modulus</b>	<b>5000 psi</b>
<b>Casing Pressure</b>	<b>500 psi</b>
<b>Cement Thickness</b>	<b>1 inch</b>
<b>Temperature Gradient</b>	<b>None</b>

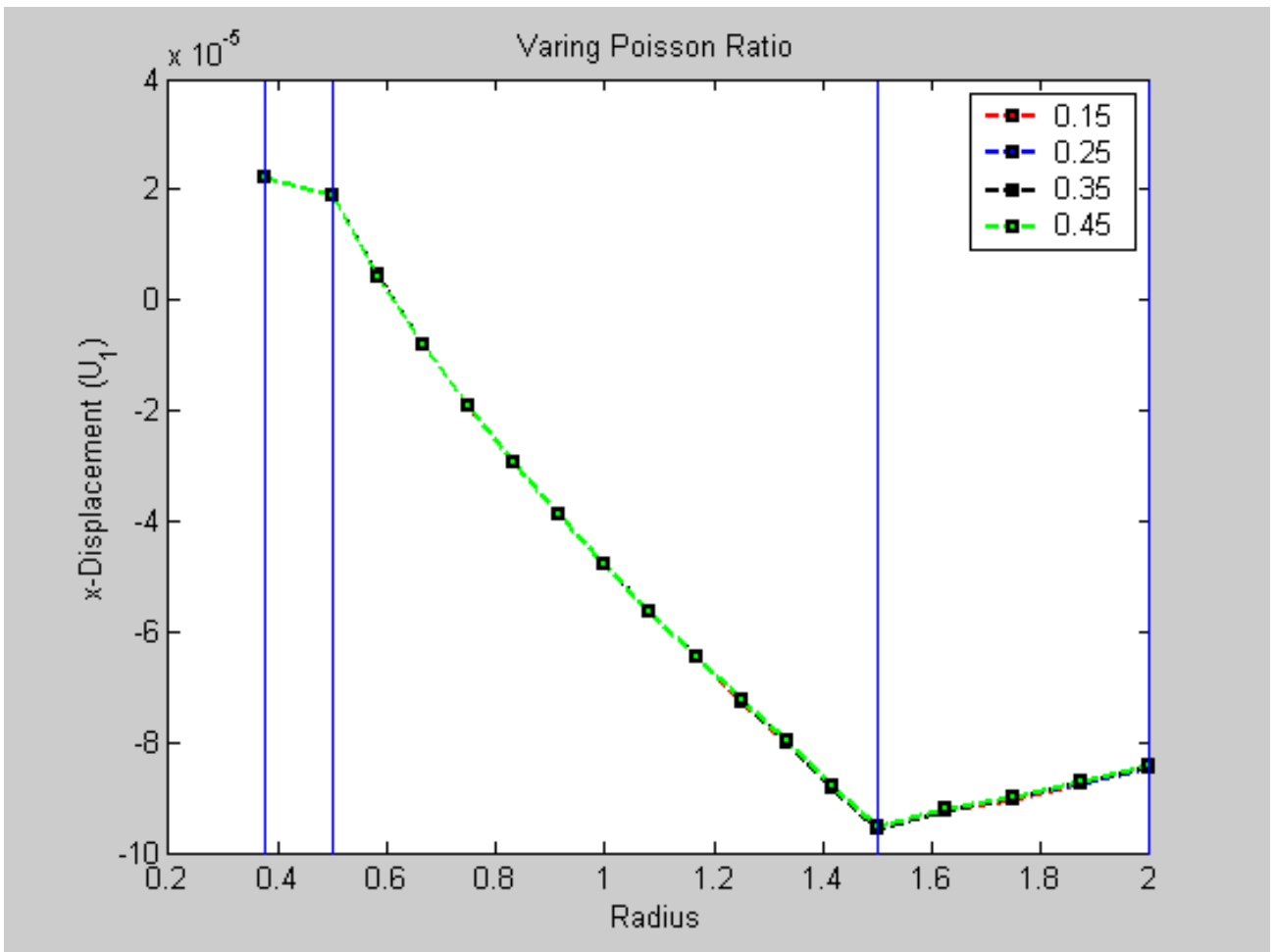


Figure 9—Horizontal Displacement Profile (PIP; Varying Poisson Ratio)



**Cementing Solutions, Inc.**

<b>Confining Pressure</b>	<b>500 psi</b>
<b>Young's Modulus</b>	<b>5000 psi</b>
<b>Casing Pressure</b>	<b>500 psi</b>
<b>Poisson Ratio</b>	<b>0.35</b>
<b>Temperature Gradient</b>	<b>None</b>

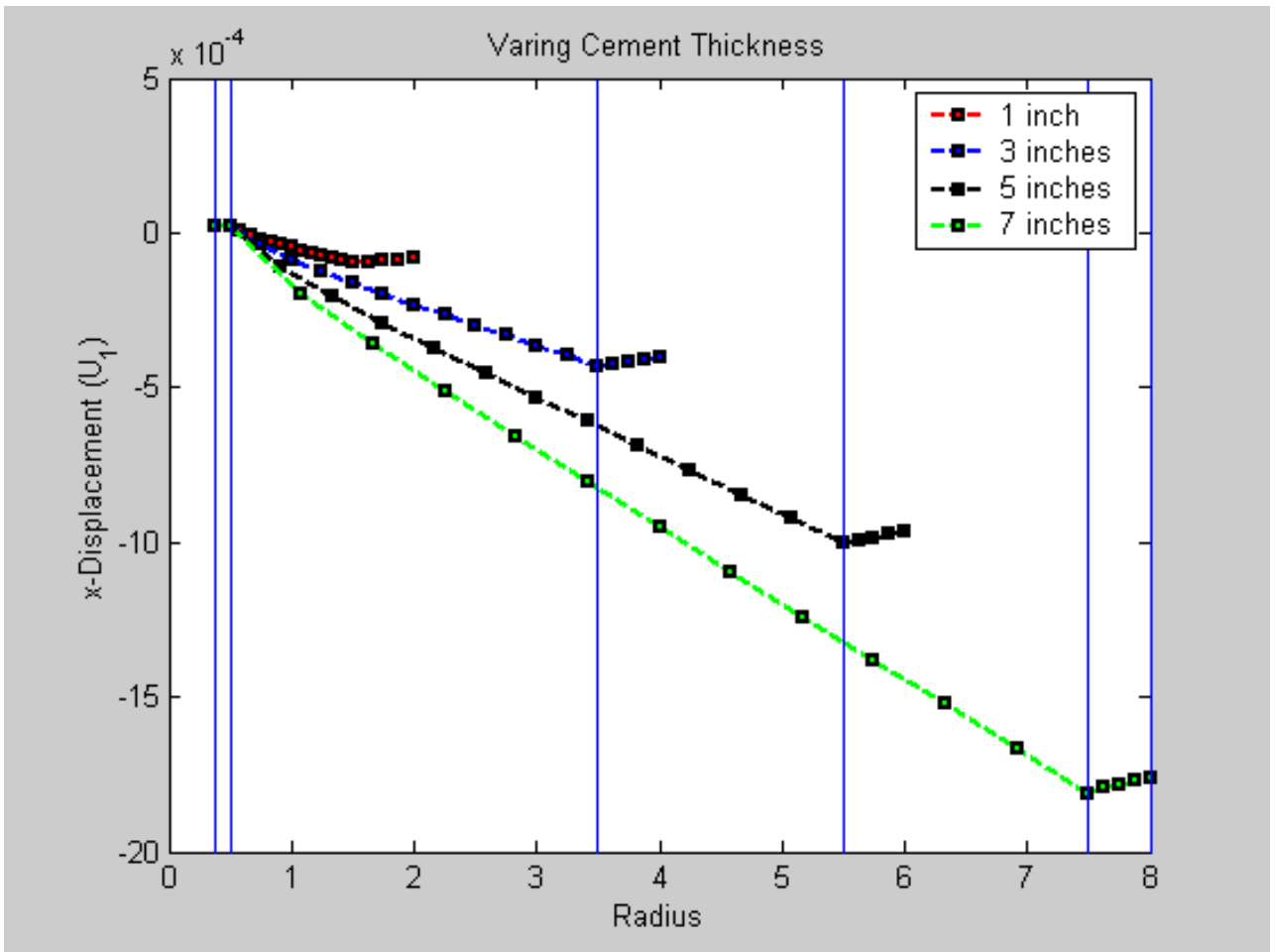


Figure 10—Horizontal Displacement Profile(PIP; Varying Cement Thickness)





**Cementing Solutions, Inc.**

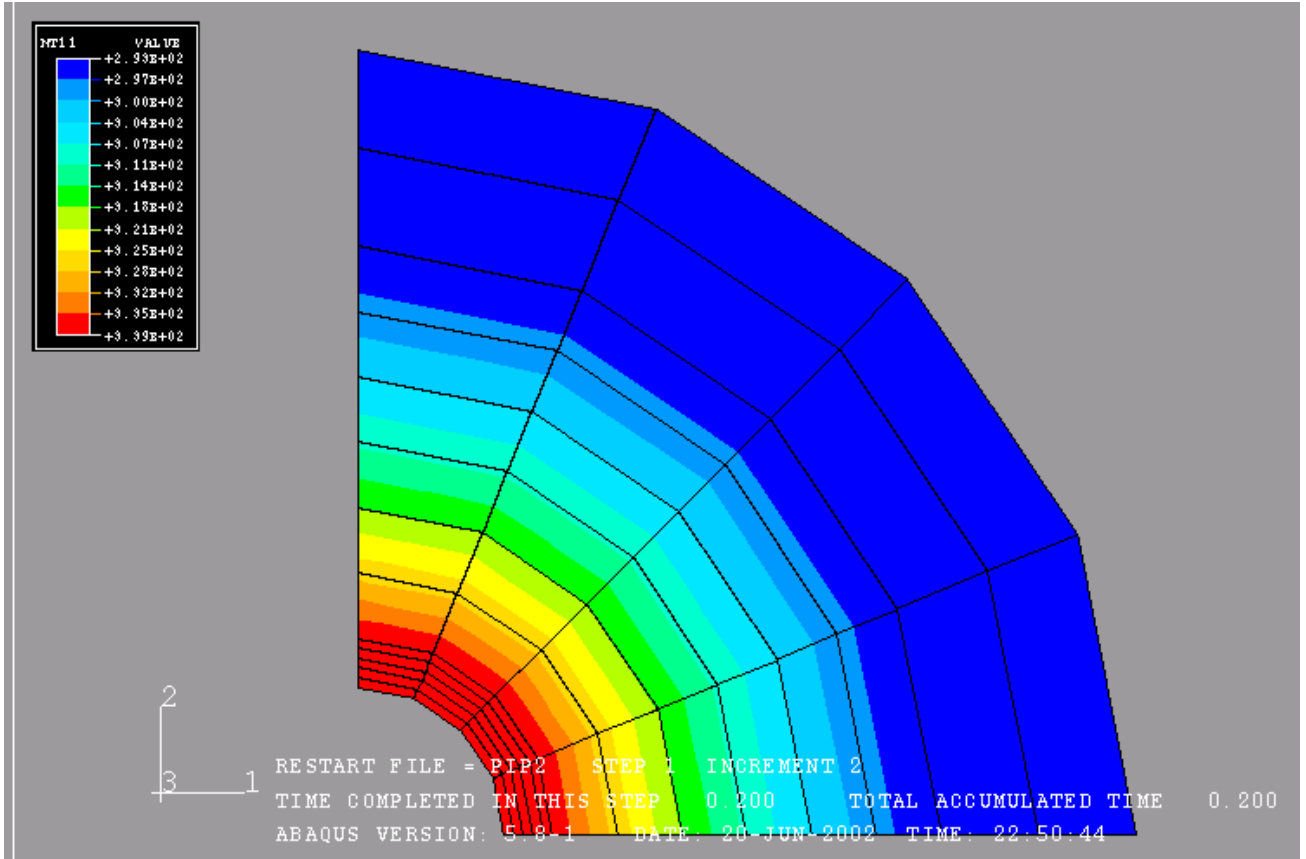


Figure 11—Temperature Profile (PIP)



**Cementing Solutions, Inc.**

<b>Young's Modulus</b>	<b>5000 psi</b>
<b>Poisson Ratio</b>	<b>0.35</b>
<b>Confining Pressure</b>	<b>None</b>
<b>Cement Thickness</b>	<b>1 inch</b>
<b>Casing Pressure</b>	<b>500 psi</b>

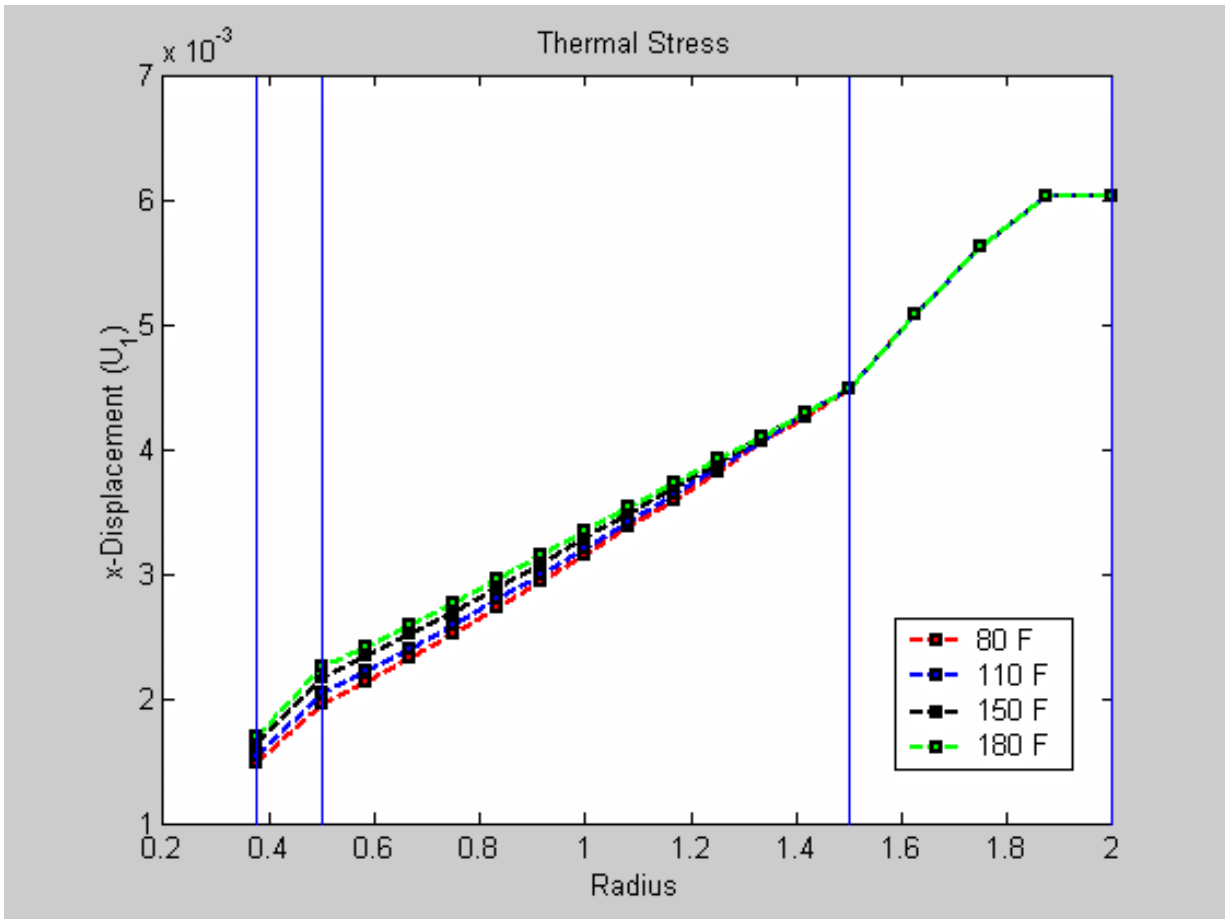


Figure 12—Horizontal Displacement Profile (PIP; Varying Internal Temperature)