CYCLIC LOADING OF FIBER-CONTAINING CEMENT SHEATHS IN HPHT CONDITIONS

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2014

Major Subject: Petroleum Engineering

ABSTRACT

A Chandler 7600 Ultra HPHT Viscometer was setup to imitate well bore conditions of high pressure, high temperature wells, and the research objective was to investigate the reaction of Class H cement with 35% silica and 0.5% nylon fiber to cyclic loading. This experimental setup facilitated the cyclic loading of the cement sheath by maintaining a constant confining pressure while the casing pressure was cycled. The fatigue endurance limit was found for 1,000 psi and 2,000 psi cyclic pressure differentials for the Class H with added fiber and the results were compared with that of Class H cement without fiber. At 1,000 psi pressure differentials, the cement with fiber remained intact until 15 cycles, whereas the cement without fiber failed at 14 cycles. At 2,000 psi pressure differentials the cement with nylon failed at 14 cycles, whereas the cement without nylon fiber failed at 13 cycles. These results clearly show that the cement with 0.5% nylon maintained integrity for one cycle longer for both 1,000 and 2,000 psi differentials tests when compared to the same cement without nylon fiber. The cement with added nylon therefore exhibits an increased tolerance to cyclic loading.

DEDICATION

To my parents who encouraged me

To God who gave me strength

To all my friends and family whom I cherish deeply

To all the loved ones I have lost, whom will never be forgotten

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Jerome Schubert, and my committee members, Dr. Samuel Noynaert, and Dr. Charles Aubeny, for their guidance and support throughout the course of this research.

Thanks also to Arash Shadraven who provided critical support to the experimental methodology and provided help in troubleshooting problems. In addition, thanks to John Maldonado with his assistance with troubleshooting and providing me with the tools necessary to fix the Chandler 7600.

I would also like to thank my good friend and classmate Omer Kaldirim for his assistance in the repair of the Chandler 7600 and his support and encouragement throughout the experiment.

NOMENCLATURE

HPHT	High Pressure High Temperature
SGS	Static Gel Strength
SCP	Sustained Casing Pressure
LWC	Loss of Well Control
S/N	Stress/Number of Cycles
PPE	Personal Protective Equipment
PSI	Pounds per square inch
PSIG	Pounds per square inch gauge pressure

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

In the past 10 years in North America, an emphasis has been placed on unconventional resources. Traditionally, unconventional plays were overlooked due to increased drilling time and low production rates in comparison with conventional fields. New drilling, completion, and production technology has decreased drilling time and allowed economical production of once ignored reservoirs. North American operating companies have bought, leased, and drilled various shale plays including the Bakken, Marcellus, and Haynesville.

Special consideration must be given to the Haynesville play due to its reservoir depth and temperature. The reservoir depth of the play ranges from 10,000 to 14,000 feet and the temperature averages around 300 °F. At total depth it is not uncommon for pressures to exceed 10,000 psi. This type of reservoir is known as a high pressure, high temperature (HPHT) formation. As shown in Figure 1, HPHT reservoirs exist in many parts of the world and have proven to be a challenge for operators to produce (Shadravan and Amani, 2012). At such extreme conditions well integrity problems can develop more readily during drilling, completion, and production operations.

Casing is cemented in place at certain depths depending on the need for zonal isolation and the pore and fracture gradients. The cement sheath bonds with the casing and the wellbore to effectively seal formation fluids from entering into the annular space. This cement sheath is subjected to cyclic stresses during drilling, hydraulic fracturing, and production which can lead to cement bond failure and subsequent compromised zonal isolation.

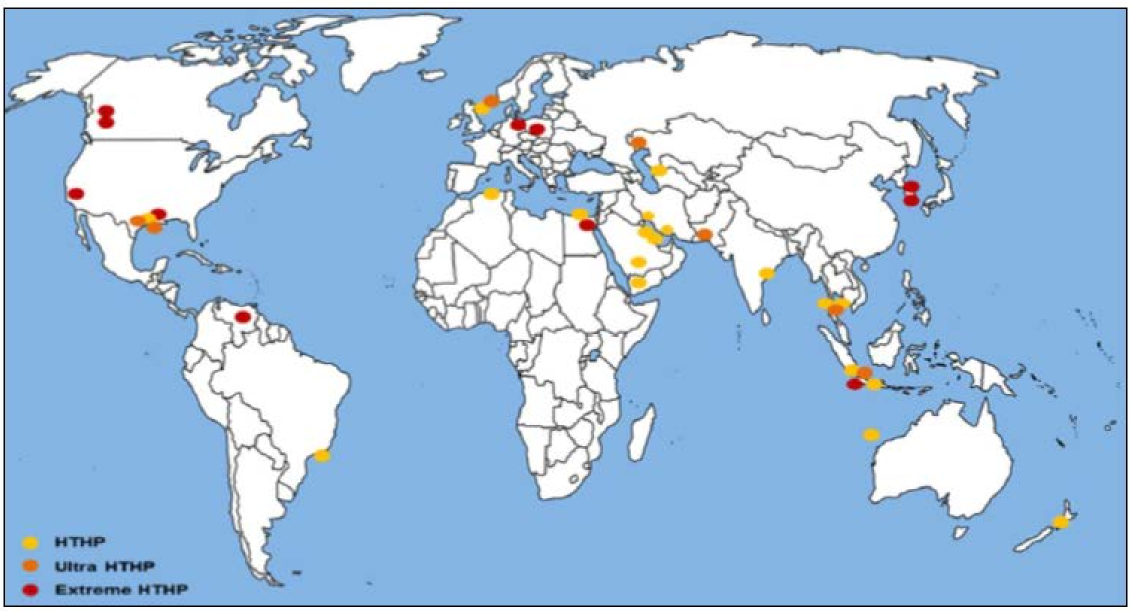


Figure 1: Global HPHT Reservoirs (Shadravan and Amani, 2012)

Short-term: Cement Slurry Complications

Cement is mixed into a slurry and exhibits Darcy flow while in its liquid state (Tinsley et al. 1980). As it cures, hydration causes the grains to expand and the cement becomes a poro-elastic grain-supported solid (Bois et al., 2012). This stat is shown in Figure 2. It is suggested by Saint-Marc et al. (2008) that the static gel strength (SGS) develops during the hydration of the cement and the slurry volume decreases. The SGS is equivalent to the shear resistance of the cement

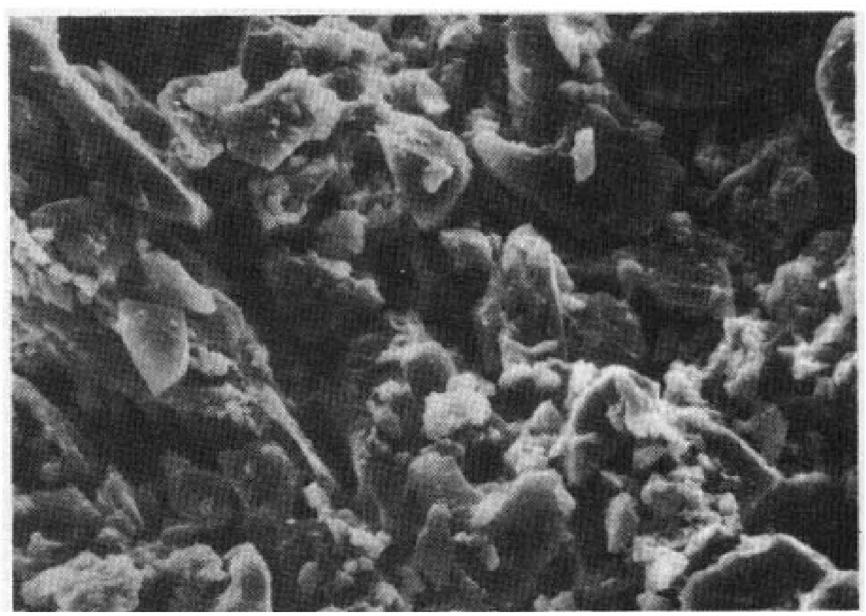


Figure 2: Cement Slurry in Liquid State - SEM 2000x (Bois et al., 2012).

and limits the hydrostatic pressure decrease that occurs in the cement column (Sabins and Wiggins, 1997). The volume decreases due to fluid loss and hydration; this causes a pressure drop in the slurry. If the slurry pressure drops below a gas zone pressure, gas will be able to migrate through the slurry and up the annulus. In addition Sabins and Wiggins (1997) suggested that the downhole fluid loss is significant to the influx of interstitial water and gas. These materials can remain trapped in the matrix of the cement and significantly affect the integrity of the sheath, leading to long-term problems with zonal isolation and sustained casing pressure (SCP).

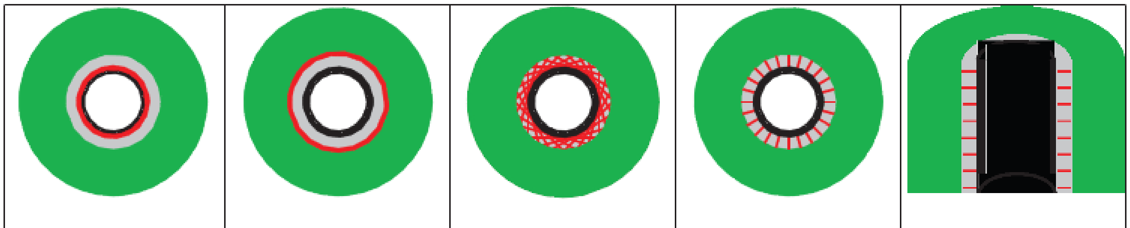
Long-term: Cement Sheath Failures

Bois et al. (2011) recognized that the cement sheath is the most important element in insuring well integrity. A seemingly small crack in the cement sheath can compromise zonal isolation, allow gas migration, and cause expensive well repairs or even loss of well control (LWC). Sustained casing pressure resulting from trapped formation gas between the casing-cement sheath boundary can cause casing collapse if the pressure exceeds the yield strength of the casing. Annular gas flow can upset packers and disrupt production operations. If the gas flow is not controlled, LWC will occur resulting in a well blowout and potential loss of life. Long term cement sheath complications can result from early-time cement slurry problems, mechanical loading of the casing and sheath during operations, or a combination of early-time malfunctions and late-time stress loading.

Numerous studies have focused on understanding how cement sheath failure occurs. Goodwin and Crook (1992) and Jackson and Murphey (1993) independently showed that a microannulus can formed between the casing and cement sheath if casing pressure is increased and then decreased back to its initial pressure. Jackson and Murphey (1993) hypothesized that the increasing the casing pressure caused plastic strains in the sheath at the casing-cement boundary and decreasing the casing pressure back to its original value would result in formation of a microannulus. The Boukhelifa et al. (2005) experiment showed that increasing the cement expansion properties lead to a decreased risk in microannulus formation. Boukhelifa et al. (2005) further showed that cyclic loading of the casing increases the risk of cement sheath failure.

Cement Sheath Damage Indexes

Saint-Marc et al. (2008) and Bois et al. (2012) presents characterizations of cement sheath damage (Figure 3). Case A and B relates to the risk of the cement sheath debonding from the casing (inner) or formation (outer). Inner debonding can occur if the casing contracts and a gap forms between the casing and sheath. Outer debonding results from a contraction in the cement and separation from the formation.



a) Inner debonding	b) Outer debonding	c) Shear damage	d) Radial cracking	e) Disking
Casing is colored in black, cement sheath in grey, and formation in green - Failure surfaces are colored in red				

Figure 3: Cement Sheath Damage (Bois et al., 2012)

Case C represents the risk of damaging the sheath by shearing forces. This is due to the deviatoric state of stress caused when the sheath is between two casings or a casing and a rigid formation. Case D is the damage caused by radial cracks. Radial cracks form due to contraction of the cement sheath when inner pressure is larger than the outer pressure. Finally, Case E is the damage caused by axial disking or sliding. Disking can occur if the sheath axially contracts because it is unable to slide at its boundaries.

Fatigue

Damage to the cement sheath is the result of stress interactions with the casing and the formation. Many field studies and experiments have focused on single-loaded isotropic stress conditions and have not focused on cyclic loading and fatigue in the cement sheath. Fatigue is defined as the progressive and localized damage brought on by continuous loading and unloading of an object. These cyclic loads cause cracks to form at the molecular level. When additional loads are applied, the cracks propagate and the object can reach its failure point before its theoretical yield strength. The Stress/Number of Cycles (S/N) is a fatigue model that shows three regions (Figure 4). As the number of cycles increases, the amplitude of stress required to cause failure decreases. Zone K is10^0- 10^3cycles, Z is 10^3- 10^8cycles, and D is over 10^9cycles. This is significant because high amplitude stress translates to low cycle failure. In oilfield operations, cement sheaths are subjected to a wide range of stresses. Large differentials in stress magnitudes will cause failure within the low cycle region.

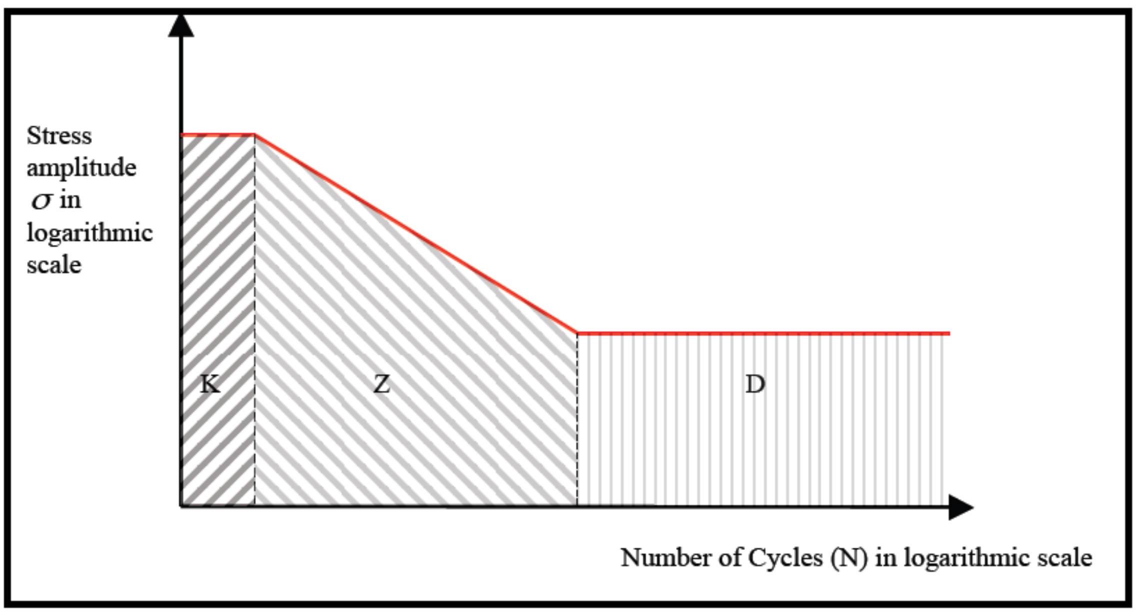


Figure 4: S/N Diagram (Ugwu, 2008)

Ugwu (2008) stated that increasing strength decreases a materials resistance to cyclic conditions, that is, a more ductile material performs better under cyclic loading than a high-strength brittle material. Kosinowski and Teodoriu (2012) experimented with cyclic loading in class G cement and found that longer curing times increased the brittleness of the cement which decreased the cement’s ability to withstand cyclic loading conditions. It is therefore advisable that any cement additives further add to the ductility of the cement if cyclic conditions are expected.

Cement-fiber Compound

Cement reinforced with fiber has been used extensively in the construction industry, but integration into the oil and gas industry has been unhurried.Vliet et al. (1995) studied the use of fiber containing cement as a borehole liner and stabilization plug, but very few have attempted to integrate this material in casing cement (Figure 5). Chung (2000) researched the mechanical properties of short fiber added to cement and found that the cement had a higher tensile strength, ductility, and flexural toughness. In addition cement reinforced with fiber also decreased the thermal conductivity of the cement, making it less receptive to temperature change.

Figure 5: Short Nylon Fiber

CHAPTER II

METHODOLOGY

Research Design

The experiment was to test the effect of short nylon fibers added to Class H cement and its performance at HPHT and cyclic loading conditions. The data collected will be compared in the following chapter with the results obtained from Shadravan (2013). The previous investigation was conducted with Class H cement with 35% silica by mass and multiple cyclic tests were conducted at various temperatures and pressure differentials.

The current experiment involved similar temperature and pressures, but the key difference was the composition of the cement consisted of 0.5% by mass of short nylon fibers. The precise mixture is found in Table 1 in Chapter III. The cement samples were subjected to cyclic differential pressures of 1,000 psi and 2,000 psi with the initial pressure of 15,000 psi. The samples were then removed from the Chandler 7600 Viscometer and visually inspected for cracks. Any visible cracks corresponded with cement integrity failure, and any samples that showed cracking were assumed to have failed due to fatigue caused by cyclic loading. The purpose of the experiment was to determine the fatigue endurance limit for Class H cement with 0.5% nylon fibers and 35% silica. The endurance limit provides an idea how well the cement composition fared in cyclic loading conditions, and it was the hypothesis of the author that the cement containing the nylon fiber would have a higher endurance limit than the conventional cement because the nylon fiber adds to the tensile strength to the mechanical properties of the cement.

Area of Study

The scope of this experiment is casing cementing. Although the experiment is small-scale, the results may provide useful insights into the nature of sheath failure in HPHT wells. It is the sincere hope of the author that the research conducted will help decrease the incidence of annular gas flow and other cement sheath related complications.

Equipment and Experimental Setup

The experiment utilized a variety of specialized equipment including the high pressure, high temperature (HPHT) cell and Chandler 7600 Ultra HPHT Viscometer. The HPHT cell was designed at Clausthal University of Technology in Clausthal, Germany, and was integrated with the Chandler 7600 hardware and rheological software (RHEO). This experimental setup allowed the operator to apply a confining pressure and casing pressure (Figure 6 and Figure 7). Referring to Figure 7, the HPHT cell has a valve along the confining pressure line that can be closed in order to vary the casing pressure without changing the confining pressure. This is an important feature that facilitates the testing of cyclic loading on the cement sheath due to varying casing pressures (Teodoriu 2013).

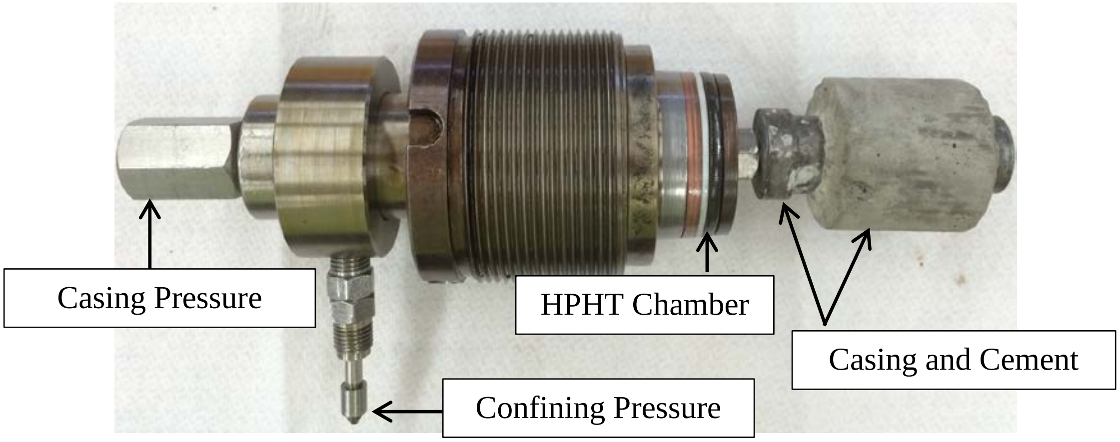


Figure 6: HPHT Cell

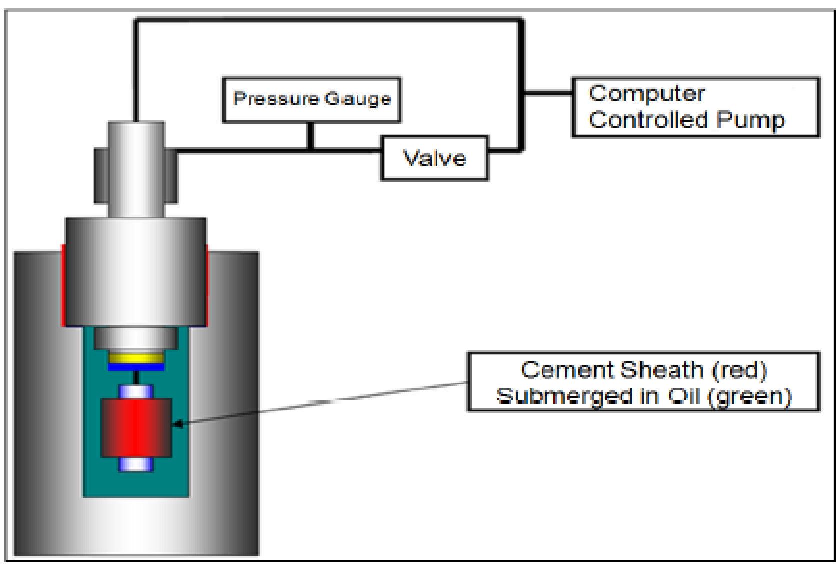


Figure 7: Experimental Setup (Shadravan, 2013)

As shown in Figure 8, the lower part of the HPHT cell consists of small metal cell that simulates the casing in a wellbore. As mentioned in the Literature Review, casing is cemented in the well to establish complete zonal isolation, and it is of paramount importance that the annular space is isolated from formation fluids. In this experiment, a cement sheath is molded around the “casing” and the sheath is cured for 12 hours at 330°F and 15,000 psi. The preparation of the sample will be mentioned in further detail in the Procedures section.

Figure 8: Casing Cell and Cement Sheath

The Chandler 7600 incorporates a temperature and pressure controller, along with a motor controller. The motor controller is utilized for rheological research and is not used in this experiment. The temperature and pressure controller allows the operator to both manually set a pressure and temperature or automatically schedule a temperature/pressure at a defined time using the RHEO software interface. The temperature/pressure controller insures that pressure and temperature remains at a defined value and uses a feedback loop to constantly monitor and adjust conditions if needed.

The cement was mixed using an OFITE constant speed blender controller paired with a commercial waring blender. This equipment is preprogrammed and allows the user to easily mix cement according to API standards. In addition, a Mettler Toledo precision scale was used to measure the cement components and was accurate to ± 0.01 grams.

CHAPTER III

EXPERIMENTAL PROCEDURES

The following section describes in detail how the author conducted the experiment using the aforementioned equipment. It describes how the author operated the Chandler 7600 using the automatic schedule method and is not intended to replace the manufacturer's recommendations and instructions. It is recommended that PPE be donned throughout the experiment to insure the safety of the individual.

Preparing the Mold

The first step in conducting the experiment was to prepare the samples. A ½ inch thick board with 1 inch drilled holes was used to hold the cells in place. The cells were cleaned with acetone and scrubbed with a steel wire brush. It was important that the cells were free of oil as it would interfere with the bonding between the cement and metal cell. Clear 2 ½ inch PVC pipe was cut into 2 inch sections and glued with silicone caulk around the cells. A seam was cut across the PVC pipe to facilitate removal of the completed sheath. The caulk prevents cement from flowing out of the PVC mold. The mold insures the consistency of cement sheaths and facilitates the creation of sheaths that are compatible with the HPHT cell and the Chandler 7600 (Figure 9). Once the mold was prepared and the silicone caulk was dry, the cement slurry was mixed.

Figure 9: Cement Sheath Mold

Mixing the Cement

The cement slurry was designed based on API and industry standards for Class H cement. A 150 mL slurry was prepared with 35% silica by mass and 0.5% short nylon fiber by mass. Different classes of cement have different water requirements. This is due to the grain size and reactivity of the components. Initially the recommended water to cement ratio for Class H cement of 0.38 was used, but it was discovered that the added fiber absorbs water and prevents the slurry from adequately mixing, and the slurry had a thick, semi-solid state which was not ideal for this experiment. The water was increased until the slurry had the proper consistency. The mass of each component is shown in Table 1.

Slurry Volume (mL)	150
Class H Cement (grams)	212.75
Water (grams)	102
Nylon 0.5% by mass (grams)	1.47
Silica 35% by mass (grams)	103.16

Table 1: Experiment Cement Mixture

Once the components were measured to the proper weight, the cement and silica were dry mixed in a constant speed mixer at low shear. This insured that the cement and silica were adequately distributed prior to mixing in the waring blender. Water was the first component added to the waring blender, which was initially programed to run at a low shear rate of 4000 RPM for 15 seconds. The whole cement and silica mixture and nylon fiber was added in the first 15 seconds of blending. Afterwards, the blender was set to high shear at 12000 RPM for 35 seconds. After the total blending time of 50 seconds passed, the cement slurry was ready to be poured in the mold.

Surface Curing

After mixing was complete, the cement slurry was poured into the mold and placed underwater at 72°F (Figure 10). It was important to insure that the casing cell nozzle remained above the surface of the water, as oxidation of the interior of the cell would weaken its integrity. It was also imperative to clean the nozzle threads of any debris so that the glands and collar could be installed once surface curing was complete. The cement was cured for 12 hours at surface conditions and then removed from the mold.

Figure 10: Curing at Surface Conditions

Figure 11: Cell Glands and Collar: Correct Positioning

Removing the Cement Sheath

Removing the sample from the mold took practice and the author found the simplest way to achieve this was to first scrape excess cement from the edges of the PVC mold. Once the excess cement was removed, a standard screw driver was wedged in the seam of the PVC pipe and the cement sheath was gently removed from the mold.

Installing the Cement Sheath in the HPHT Cell

Once removed from the mold, the cement sheath and cell were assembled with the HPHT cell. This required a gland and collar to be installed on the cell, and then the gland was threaded into the HPHT cell. It is critical to insure that the collar is threaded at least half way down the cell shaft; otherwise the cell nozzle will not make an adequate seal when the cell gland is tightened (Figure 11). A quick way to determine if the cell is sealed properly with the HPHT cell is to place the bottom of a casing cell against a surface and rotate the top of the HPHT cell. If the assembly moves as one, the casing cell is adequately sealing, otherwise additional tightening and repositioning of the cell collar is required.

Once the cement sheath and cell was installed into the HPHT cell, the HPHT cell was fitted into the Chandler 7600 confining chamber. It was important to position the HPHT confining pressure inlet toward the isolation valve before tightening the threaded collar with a spanner wrench. The next step was to slip the free-floating collar over the HPHT cell and tighten the connection. The author found it was easiest to disassemble the tubing connection between the isolation valve and confining pressure inlet before installing the collar. The connection was then tightened on the isolation valve side before the confining inlet side. It was crucial to insure that tubing nozzle was properly sealed against the HPHT cell confining pressure inlet, otherwise the system would leak extensively. The last step was to tighten the casing pressure inlet. Additional tightening and repositioning of the internal collars was needed in some cases in order to prevent the assembly from leaking.

Pre-test Checks

After the HPHT cell was installed in the Chandler 7600, the assembly was ready for pressurization. It was important to check the hydraulic fluid supply and insure that the fluid level was at least at the half way mark. In addition it is advised that any discharge fluid be disposed of properly. The next step was to power on the Chandler 7600. There were two power switches, one on the main control panel, and the other is behind the machine near the COMM ports. In order to operate correctly, the supply pressure must be at least 90 psi. This was verified by looking at the lowest gauge shown in Figure 12. In addition, the pressure release valve shown in Figure 12 had to be closed fully in order to establish a confining pressure.

The Chandler 7600 control panel allows an operator to either manually or automatically establish a desired temperature and pressure. In this experiment, the automatic schedule function in the RHEO 7000 software was utilized. Figure 13 shows the correct switch orientation where an arrow pointing up denotes the switch must be toggled “UP”, an arrow pointing down denotes the switch must be toggled “DOWN”, and switches with no markings must be in the neutral position. Note that in this experiment no coolant system was used in conjunction with the heater. It was also crucial that the controllers for the temperature and pressure were set to “AUTO” mode, and that the “RUN/HOLD” feature was toggled off and not illuminated (Figure 13).

Figure 12: Pressurized System

Figure 13: HPHT Viscometer Control Panel

Once powered on with the switches in the proper orientation, the Chandler 7600 could be controlled by the RHEO 7000 software on a Windows 7 based operating system. It was paramount to insure that COMM ports were plugged into the USB serial hub, which was in turn connected to the PC. Once opened, the software required the user to start and save a new instrument in the "File" options before going to the main screen seen in Figure 14.

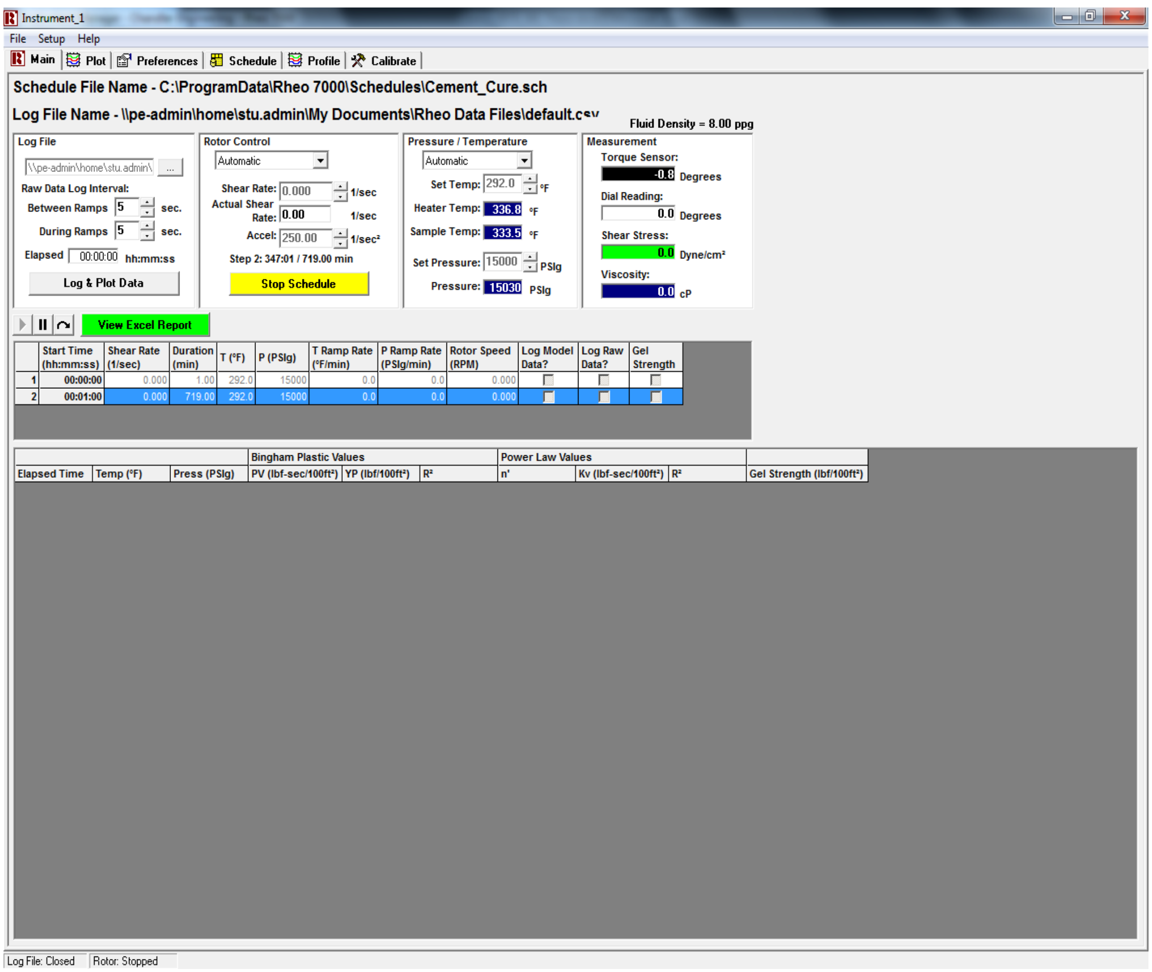


Figure 14: RHEO 7000 Main Operation Screen

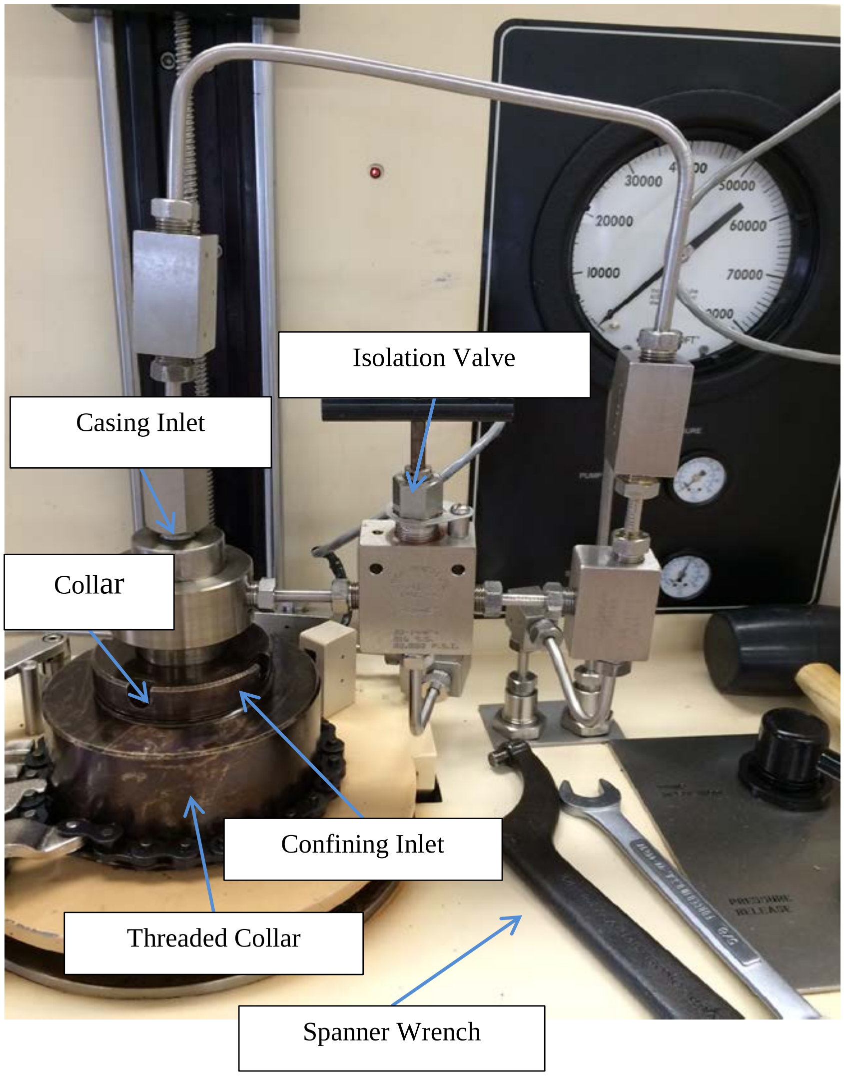


Figure 15: Complete Assembly

The RHEO 7000 “SCHEDULE” option was used to automatically set pressure and temperature for certain times. For instance, one schedule file was used for curing the sample for 12 hours at 15,000 psi and 330°F. Another was used to cyclically load the cement sheath for the desired number of cycles. While active, the Chandler 7600 pressure and temperature controller maintained the programmed set point for the desired time period. Communication between the serial COMM ports and the software was verified by the retrieval of temperature and pressure data in the “MAIN” screen in RHEO. If data was not retrieved from the Chandler 7600, there was either a loose connection between the USB Serial Hub and PC, or the 7600 serial ports were incorrectly assigned. By default, the pressure and temperature I/O ports were set to COMM 6. These options were defined in the “SETUP” tab of the RHEO software. As a function test, the author would create a pressure set point and observe the pressure controller (Figure 13). As the 7600 automatically increased the pressure, the controller would display “OP1” to denote pump activation. As the pressure set point was reached, the controller would display “OP2” to denote discharge valve operation. If there was no change after the pressure set point was defined, and the controller remained static, there was a communication error between the RHEO 7000 and Chandler 7600 COMM port interface, or the control panel switches were in the improper configuration.

Cyclic Testing

The cyclic testing of the cement sheath samples were conducted after curing at surface conditions and 72°F for 12 hours and 15,000 psi and 330°F for an additional 12 hours.

The cyclic test involved the continuous loading and unloading of the casing pressure while the confining pressure was held constant. The isolation valve shown in Figure 15 was closed before the cyclic test was conducted. This valve isolated the confining pressure from the pump supply pressure and allowed the operator to create a pressure differential between casing and confining pressure. It was crucial to insure that all high pressure lines were sealed and that all connections were tightened to the proper specification. Under high pressure, any unsecure lines could have ruptured and caused serious injury to the operator.

CHAPTER IV

EXPERIMENTAL RESULTS

The previous trials conducted by Shadraven (2013) found the fatigue endurance limit for Class H cement with 35% silica at various pressure differentials. These results are notated in Table 2. The table below also shows the curing and testing conditions used in the current trials. The only difference between the two separate studies conducted by Shadraven (2013) and Johns (2014) was the addition of short nylon fibers and the slight difference in curing times at HPHT conditions.

Set		A	B	C
HPHT Curing	Time, hours	12	12	12
	Pressure, psi	15,000	15,000	15,000
	Temperature, °F	330	330	330
Testing	Confining Pressures, psi	15,000	15,000	15,000
	Casing Pressures, psi	15,000 - 16,000	15,000 - 17,000	15,000 – 20,000
	Sample Temperature, °F	330	330	330
	Previous Failure Cycle # for Class H NO FIBER	14	13	11
	Previous Failure Type for Class H NO FIBER	Radial Crack	Radial Cracking And Disking	Radial Cracking, Disking, and Combination of Both

Table 2: Test Parameters and Previous Testing Results

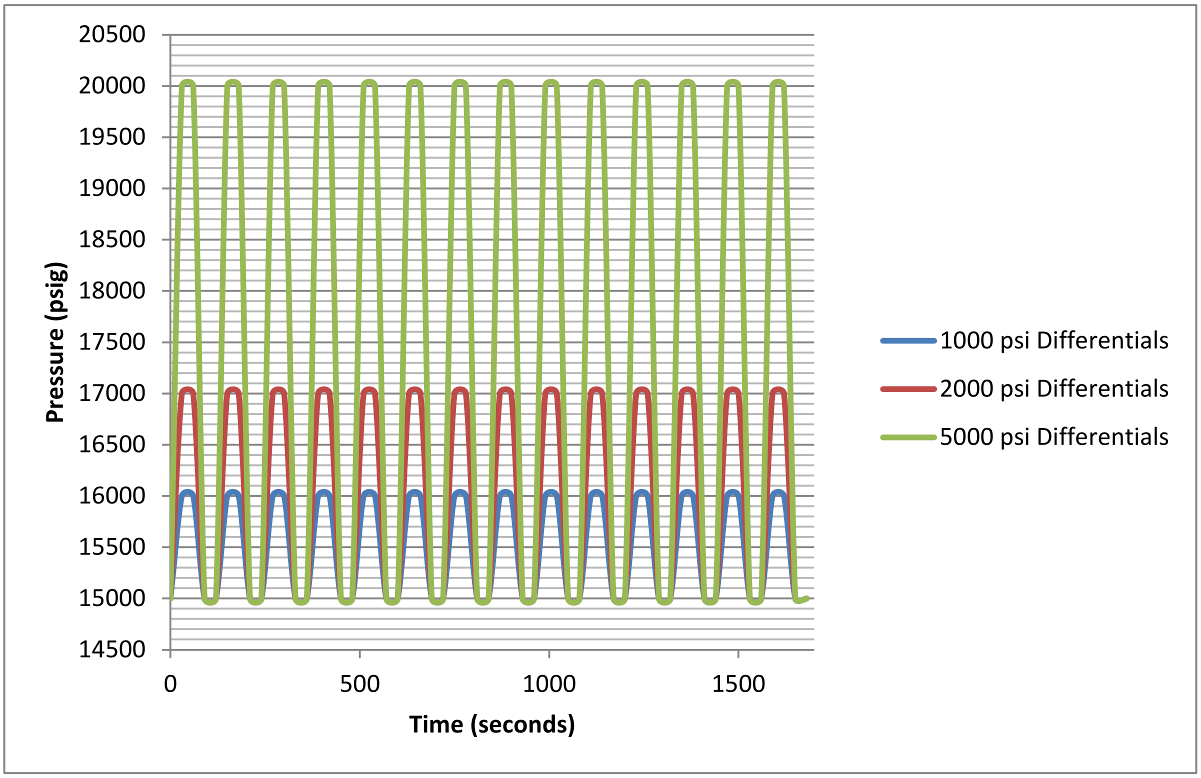


Figure 16: Cyclic Loading of Cell

Figure 16 above shows the ideal cyclic test at various differential pressures. Each period consisted of four stages, each thirty seconds in duration. The cell was gradually raised to the differential pressure over 30 seconds, held constant at the desired pressure for 30 seconds, lowered to the initial pressure over 30 seconds, and held at the initial pressure for 30 seconds. The confining pressure was held constant at 15,000 psi throughout the duration of cyclic testing. The anticipated result was the degradation of the cement integrity due to internal stresses caused by the continuous deformation of the casing cell.

Set A Results

The first sample (Figure 17) was tested under the conditions defined in Set A found in Table 2. The pressure and temperature were defined in RHEO, however no real time data was recorded due to operator error. It was discovered that after 14 cycles of 1,000 psi differentials, the cement sheath was not fractured. The second sample (Figure 18) was tested and pressure and temperature data was gathered. The data is shown in Figure 19. A third sample shown in Figure 20 was conducted and data was gathered to verify the results (Figure 21). It was revealed that there was an offset error in the sample temperature set point, as the sample temperature was above the desired temperature. Even though the schedule was programed to maintain a sample temperature of 330°F, the heater would overcompensate and heat the sample to approximately 370°F.

Figure 17: Sample I-A, No Cracks

Throughout several experiments the set point was varied until the sample was at the desired temperature. It was found that the programming the sample temperature to 291°F would actually yield the desired sample temperature of 330°F. The disparity in temperature set point and actual sample temperature could be the result of sensor error

Figure 18: Sample II-A, No Cracks

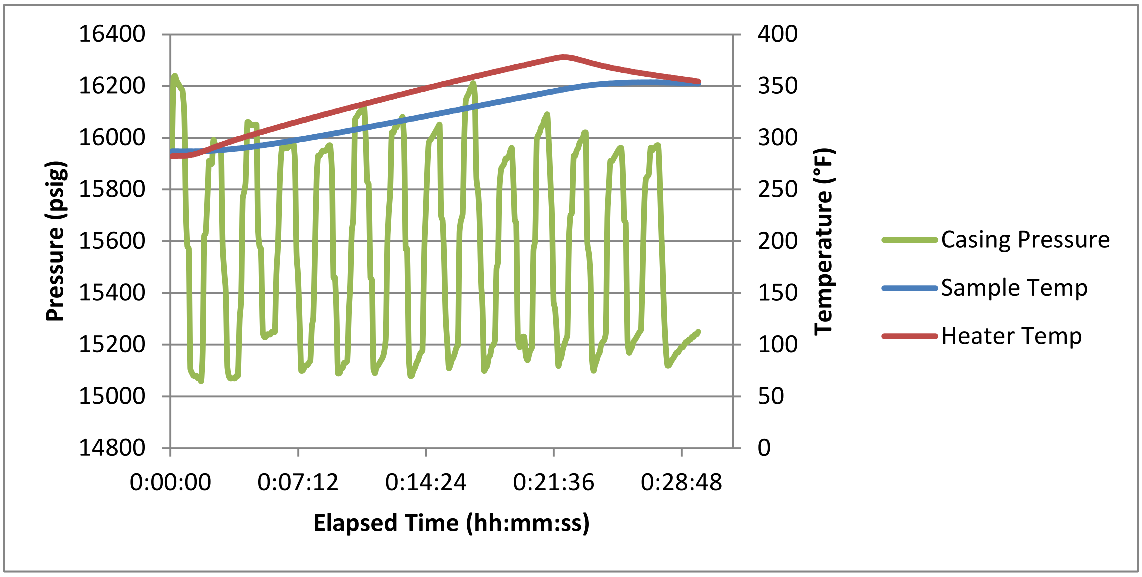


Figure 19: Real Time Data from Test II Set A

Figure 20: Sample III-A, No Cracks

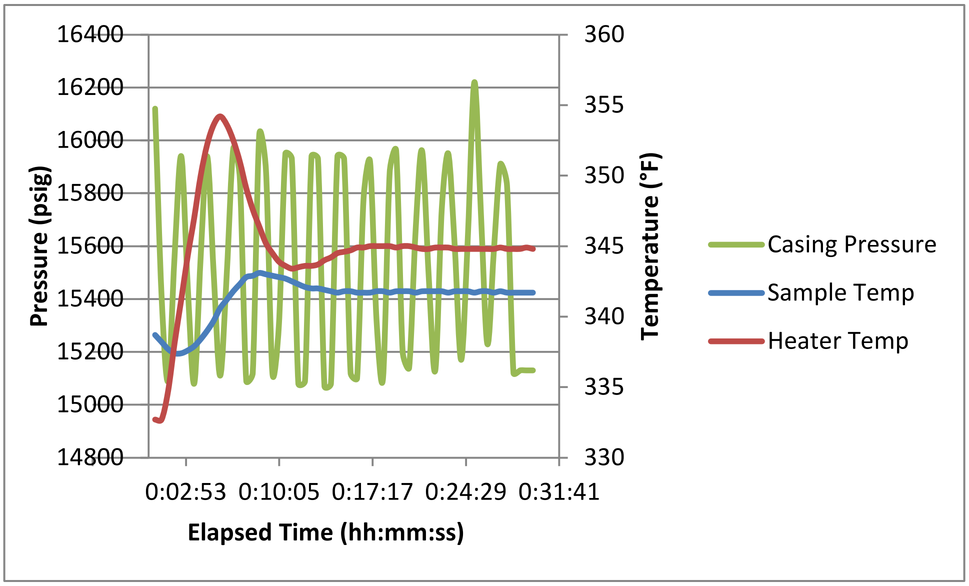


Figure 21: Real Time Data Plot from Test III Set A

and marks the need for calibration of the Chandler 7600 by a certified technician. Both tests II-A and III-A revealed identical results to test I-A, that is, there were no cracks in the cement sheath after 14 cycles of 1,000 psi differentials. As mentioned previously, the sample temperature exceeded the desired set point for the first three tests of Set A. To help find the set point value that would achieve the desired sample temperature a calibration curve was plotted. As seen in Figure 22, a temperature set point of 291°F was estimated to yield the desired sample temperature. In order to determine the fatigue endurance limit, the number of cycles which the sample first begins to fail must be found. The samples did not fail after 14 cycles, so the cycle number was raised to 15 cycles for the next few samples of Set A.

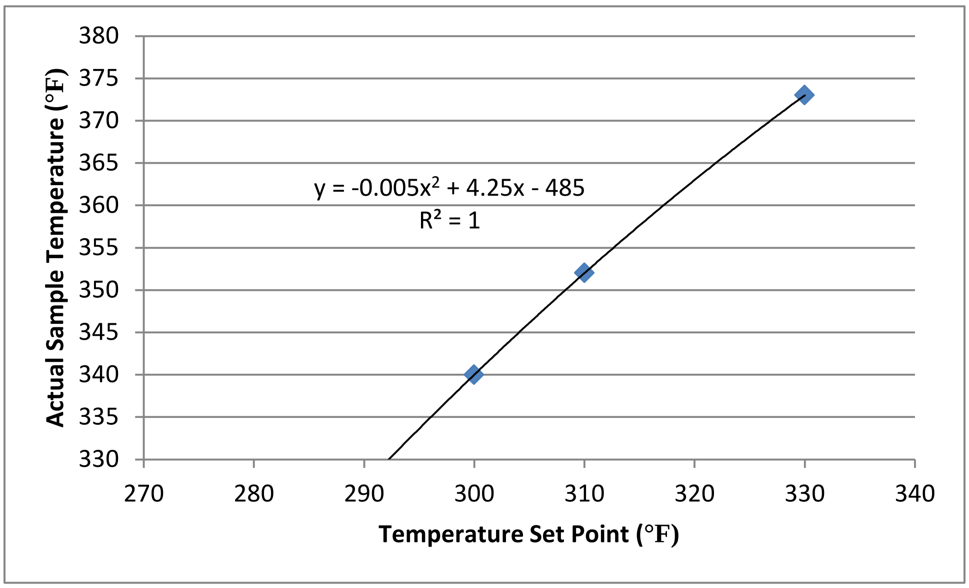


Figure 22: Temperature Calibration Curve

The second set of tests were conducted at the same conditions outlined in Set A, however the cycle number was increased to 15. Sample IV-A was removed from the HPHT cell and it was immediately clear that failure had occurred. The cement sheath had a single radial crack that extended from the top of the cell to the bottom. In addition to real time pressure and temperature data capture via excel, the test was monitored with the data plotting system in RHEO. Both the data and plot revealed that the test was conducted at the desired pressure and temperature conditions.

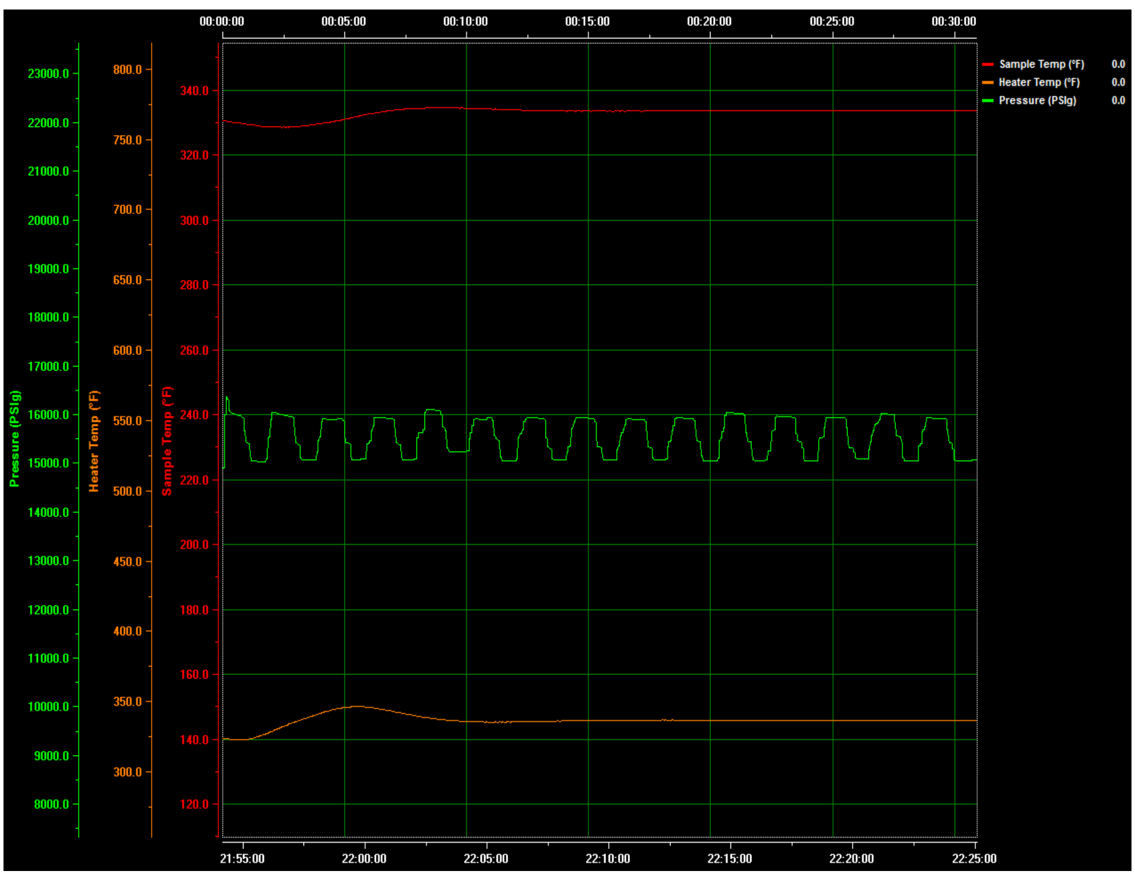


Figure 23: Test IV-A, Shows 15 Cycles

Figure 24: Sample IV-A, Single Radial Crack

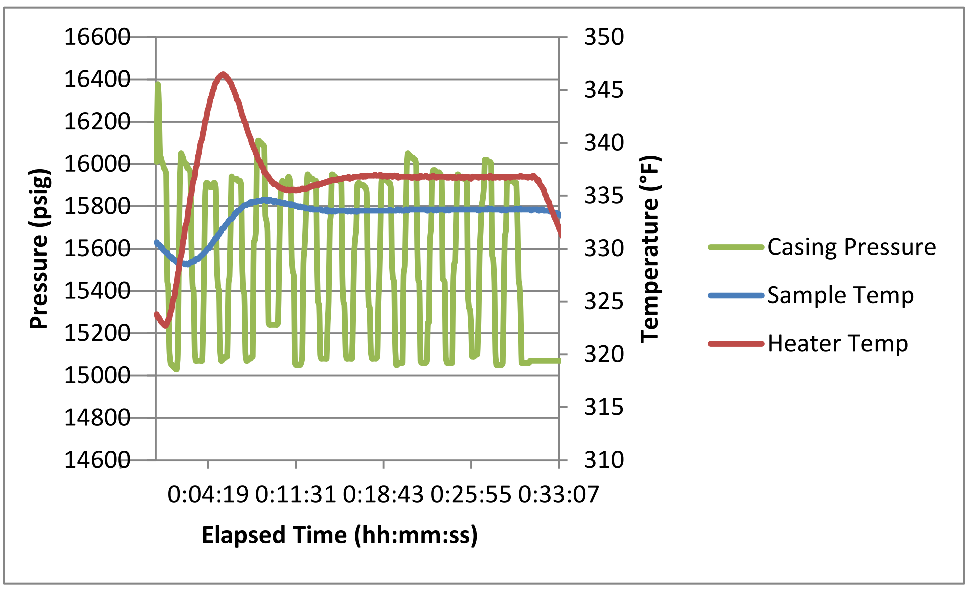


Figure 25: Real Time Data Plot from Test IV Set A

Additional tests were conducted at Set A conditions at 15 cycles to verify the experimental results. The physical results can be found in Figures 23-29. Both V-A and VI-A displayed signs of failure. V-A had a radial crack extending from the top to the bottom of the sheath, whereas VI-A had a more subtle crack that appeared to be propagating from the top of the sheath to the bottom. It is clear that the fatigue endurance limit of Class H cement at 1,000 psi pressure differentials is 15 cycles. This is a significant result, as Class H Cement without fiber failed one cycle sooner than cement with the added nylon fiber (Table 3).

Set A	Class H No Fiber	Class H 0.5% Nylon Fiber
Confining Pressures, psi	15,000	15,000
Casing Pressures, psi	15,000 - 16,000	15,000 - 16,000
Sample Temperature, °F	330	330
Failure Cycle #	14	15
Failure Type	Radial Crack	Radial Crack

Table 3: Set A Cyclic Test Results

Figure 26: Sample V-A, Single Radial Crack

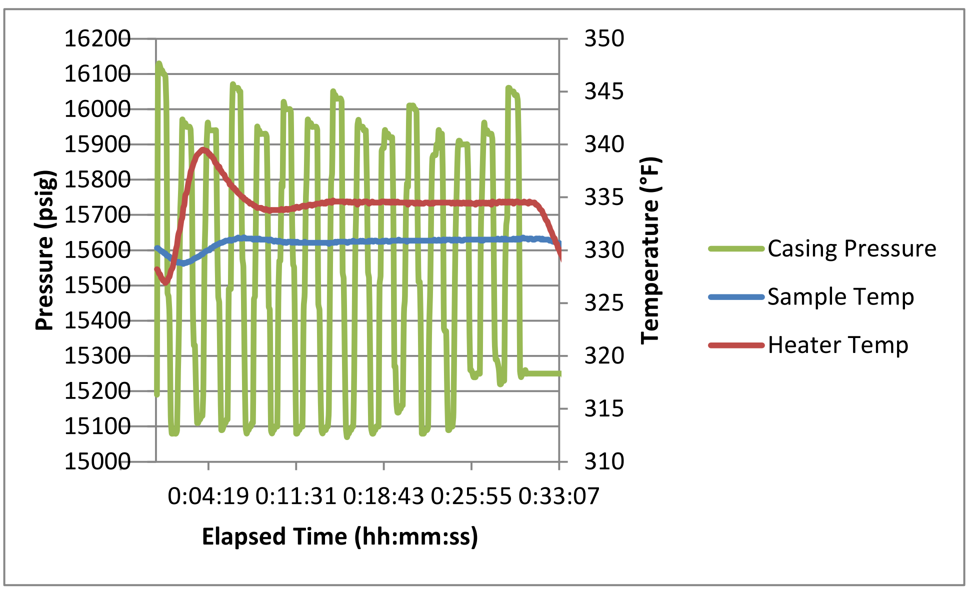


Figure 27: Real Time Data from Test V Set A

Figure 28: Sample VI-A, Propagating Radial Crack

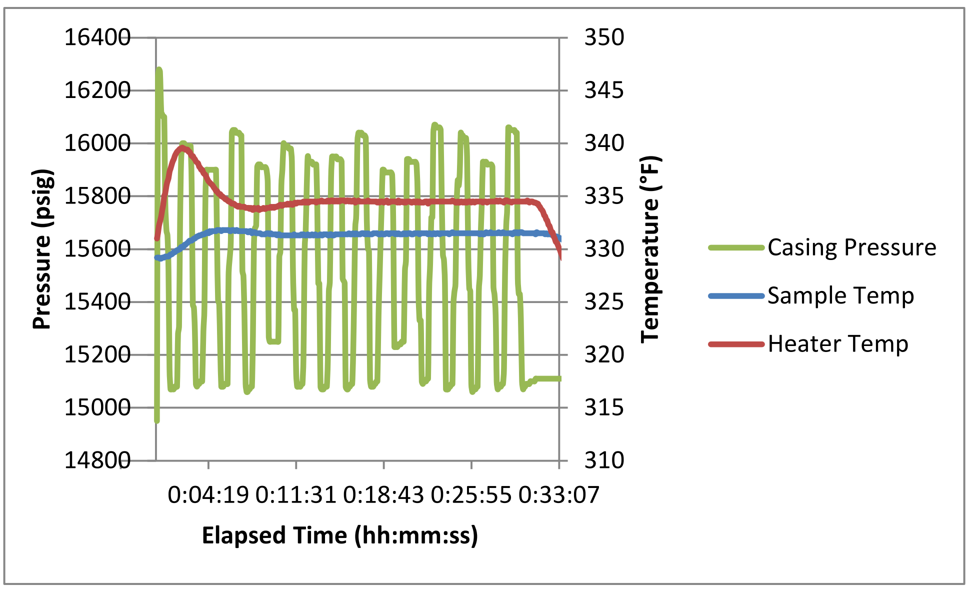


Figure 29: Real Time Data from Test VI Set A

Set B Results

Set B trials were conducted at the conditions outline in Table 2. The physical results can be found in Figures 30, 32, 33. Cyclic testing was started at 13 cycles which was the fatigue endurance limit of Class H cement with no fiber for 2,000 psi differentials. Test I-B was conducted in the same manner as the tests in Set A. According the real time data in Figure 31, I-B had various pressure spikes, where the pressure exceeded the desirable maximum pressure of 17,000 psi. The Chandler 7600 appeared to be operating normally, and it was unknown why this occurred. Despite this setback, the test was ended after 13 cycles, and the sample did not show signs of failure.

Test II-B was tested at 2,000 psi differentials for 14 cycles. This test went smoothly with no large pressure spikes, however it was noted that the confining pressure started to vary at the end of the test. This phenomenon could have occurred due to the fatigue of the casing cell. It is probable that the metal seal between the casing cell and HPHT cell failed due to continuous use. It was discovered that the cement sheath fractured with severe radial cracking and some disking. Additional testing was unable to be conducted to verify the test results of Set B because differential pressure between the casing pressure and confining pressure was unable to be established. In addition, mechanical failure in the pump exhaust and fatigue in several key components halted the experiment. The experimental apparatus had been use rigorously for three independent experiments without recalibration or maintenance by a certified technician. It therefore became a safety concern and the project was ended.

Figure 30: Sample I-B, No Cracks

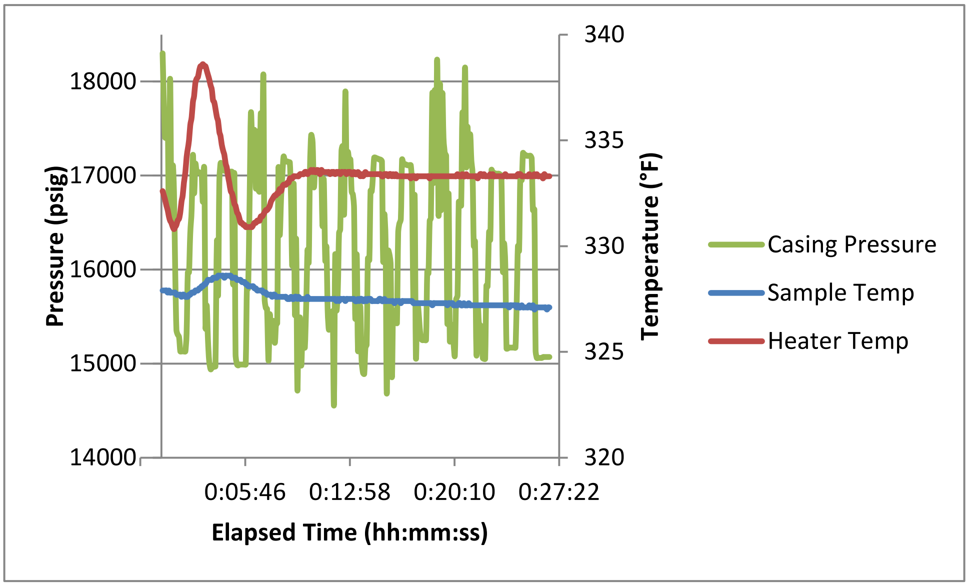


Figure 31: Real Time Data from Test I Set B

Figure 32: Sample II-B, Single Radial Crack and Disking

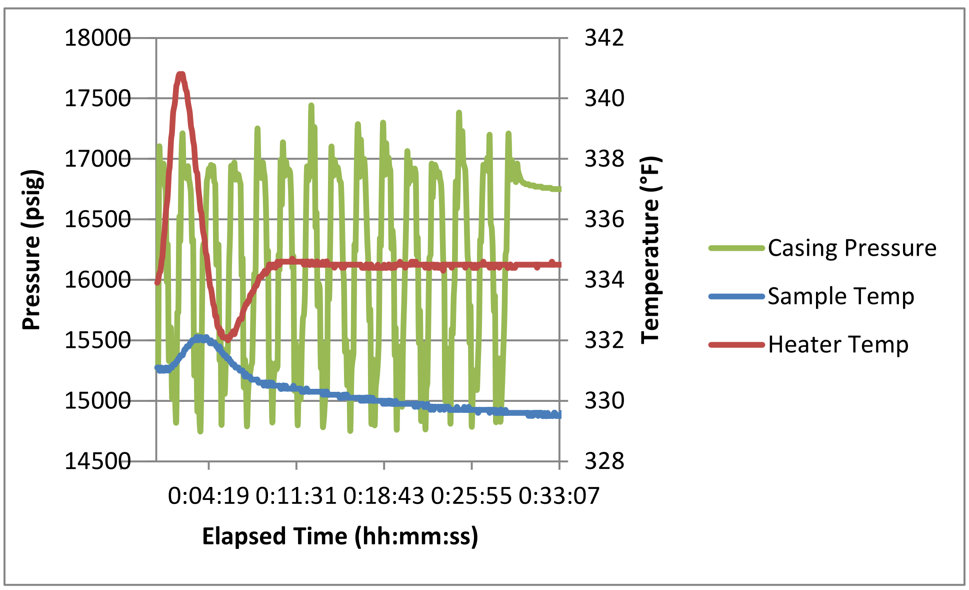


Figure 33: Real Time Data from Test II Set B

The results of Set B are displayed in Table 4. Once again, the Class H cement with added fiber fared better under cyclic conditions. The failure type of radial cracking and disking was the prominent indicator that the cement integrity was compromised. Tests at 5,000 psi differentials (Set C) with Class H cement with 0.5% fiber were unable to be conducted due to mechanical failure of the Chandler 7600 and the loss of a pressure seal between the casing cell and HPHT cell.

In comparison with Set A, Set B failed at fewer cycles and had more prominent radial cracking and disking was present. Figure 34 displays the results of the Class H cement experiments and it is clear that the added fiber increased the durability of the cement under cyclic loading.

Set B	Class H No Fiber	Class H 0.5% Nylon Fiber
Confining Pressures, psi	15,000	15,000
Casing Pressures, psi	15,000 - 17,000	15,000 - 17,000
Sample Temperature, °F	330	330
Failure Cycle #	13	14
Failure Type	Radial cracking and disking	Radial cracking and disking

Table 4: Set B Cyclic Test Results

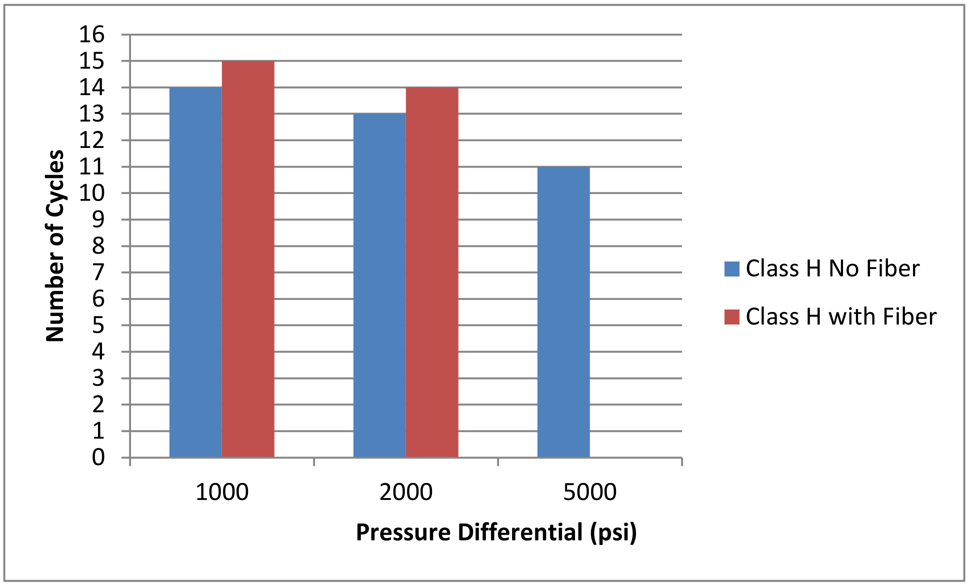


Figure 34: Comparison between Class H Cement Experiments

CHAPTER V

MAINTENANCE AND REPAIR

The Chandler 7600 with the HPHT Cell setup has been used for several research experiments including Shadraven (2013), Teodoriu et al. (2013), and Kosinowski et al. (2012). This particular apparatus was a prototype and the first produced by Chandler Engineering and Clausthal University of Technology. After intensive cyclic tests, several key components of the apparatus failed and developed pressure leaks. Before the author could conduct research, extensive repair was required to eliminate pressure leaks in the system. In order to pinpoint the location of the pressure leaks, the author added a UV oil based tracer to the oil supply tank. The pump was then cycled for several cycles at low pressure until oil spillage was present. Visible in Figure 35 and Figure 36, the oil was fluorescent green when exposed to UV light. It was discovered that several leaks existed along the high pressure supply line, and that the automatic air operated valve was malfunctioning and leaking oil. The lines that were leaking were disassembled and hardware such as the collars and glands were replaced. The automatic air operated valve was removed and it was found that the diaphragm within the valve had failed. A new air operated valve was installed and the high pressure lines were tightened to the manufacturer’s specification. After additional pressure testing, the high pressure hydraulic system of the Chandler 7600 was free of leaks (Figure 37). Unfortunately, shortly after the leaks were repaired on the Chandler 7600, the HPHT cell began to have issues with isolation of the confining pressure from the casing pressure.

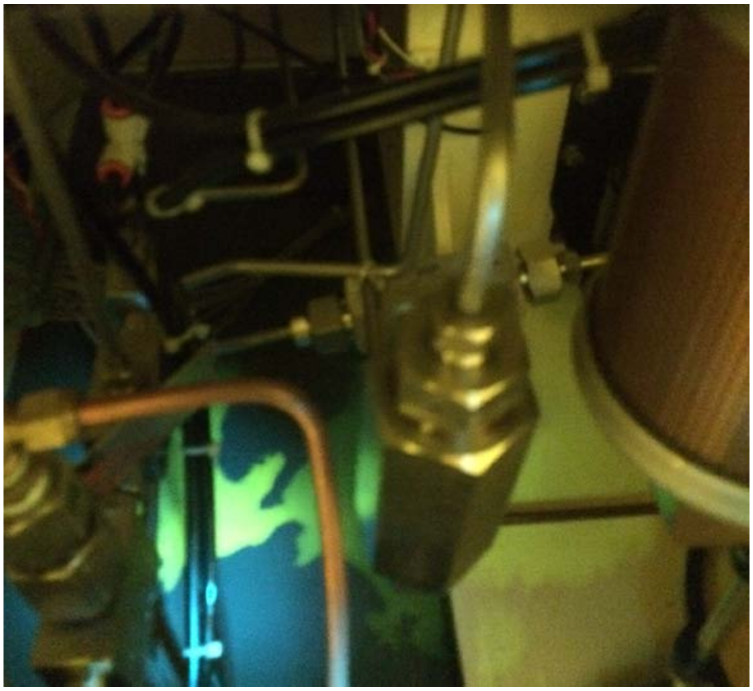


Figure 35: Leak in High Pressure Line

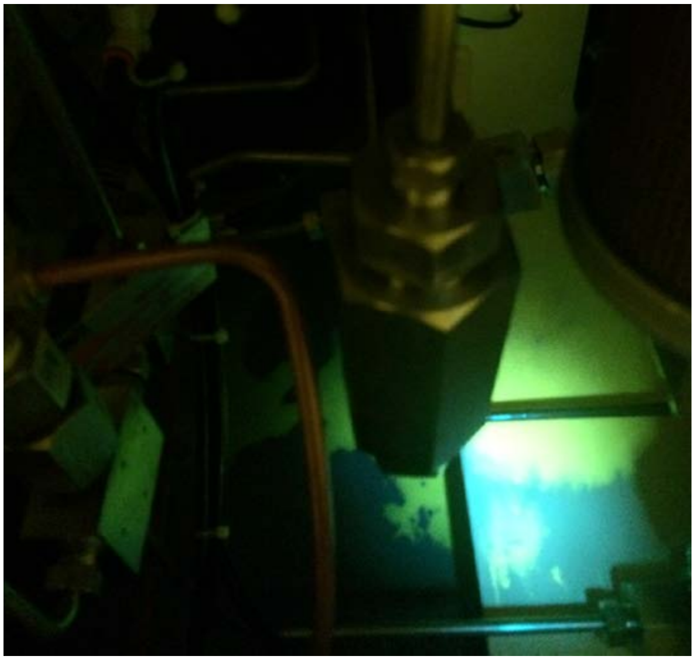


Figure 36: Leaking from Air Operated Valve

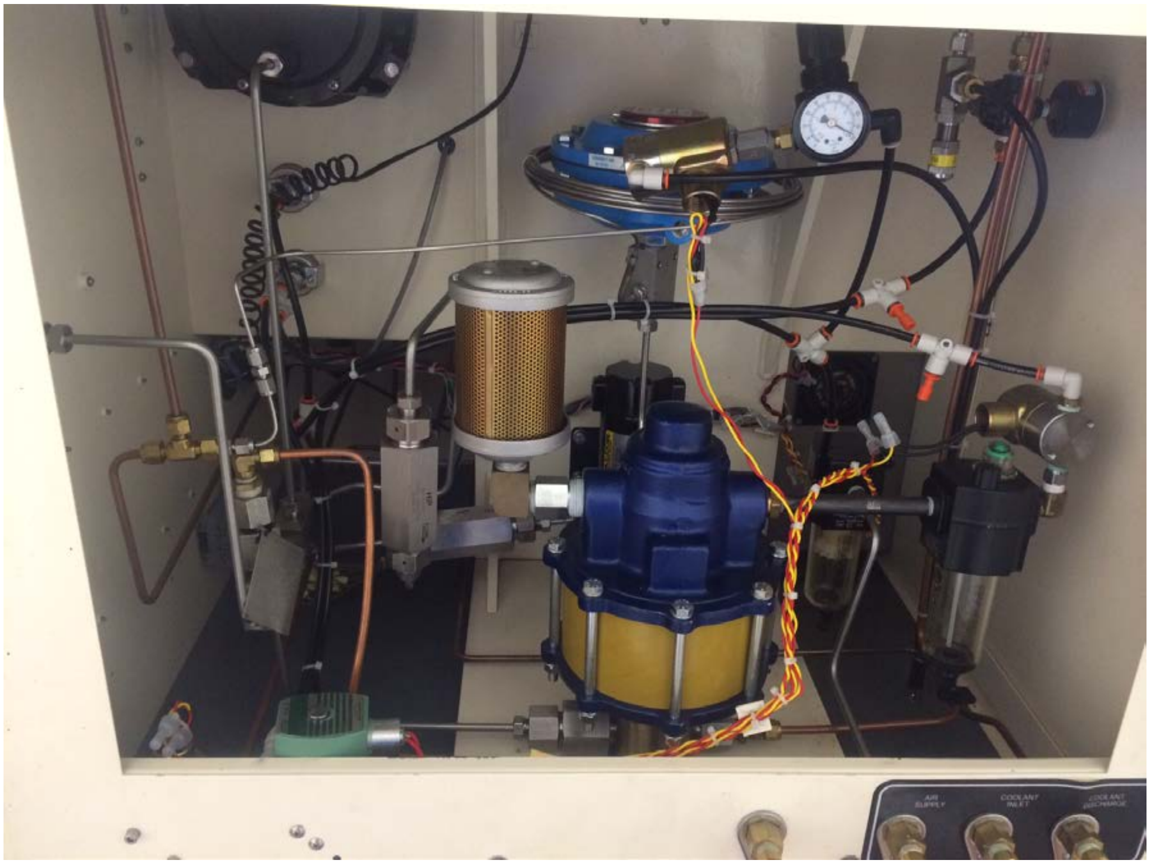


Figure 37: Repaired Chandler 7600, No Leaks

The isolation valve was removed and it was found that the valve needle and seat were severely deformed. The isolation valve was replaced with a new one and the HPHT cell was able to isolate the confining pressure from the casing pressure. After several experimental trials, it became apparent that some areas were prone to leaking, and extra care was given to these areas when reassembling the HPHT cell. Figure 38 shows leak-prone areas with blue arrows. In most cases additional tightening would remediate the problem, however the threaded connection between the HPHT cell and the casing pressure supply line required complete disassembly, reapplication of Teflon tape and torqueing to 56 in-lbs.

Figure 38: Common Leak Points in HPHT Cell Setup

After the completion of two experiments at 2,000 psi differentials, the HPHT cell was unable to isolate the confining pressure from the casing pressure. As mentioned earlier, this could have been a result of fatigue in the small casing cells, or the failure of the new isolation valve. Additional investigation and repair was not carried out because there were safety concerns about the integrity of the HPHT cell setup.

CHAPTER VI

CONCLUSION

The experiment was setup to mimic well bore conditions of high pressure, high temperature wells, and the research objective was to investigate the reaction of Class H cement with 35% silica and 0.5% nylon fiber to cyclic loading. The fatigue endurance limit was found for 1,000 psi and 2,000 psi cyclic pressure differentials for the Class H with added fiber and the results were compared with that of Class H cement without fiber. At 1,000 psi pressure differentials, the cement with fiber remained intact until 15 cycles, whereas the cement without fiber failed at 14 cycles. At 2,000 psi pressure differentials the cement with nylon failed at 14 cycles, whereas the cement without nylon fiber failed at 13 cycles. These results clearly show that the cement with 0.5% nylon maintained integrity for one cycle longer for both 1,000 and 2,000 psi differentials tests when compared to the same cement without nylon fiber. The cement with added nylon therefore exhibits an increased tolerance to cyclic loading.

There are several improvements to be made to the HPHT Cell and Chandler 7600 assembly. The first is to acquire a new HPHT cell and small cells in order to be able to conduct the experiments accurately and safely. Another is to have the Chandler 7600 recalibrated and repaired by a licensed Ametek technician. Once these improvements are made, future experiments can be conducted. It would be beneficial to conduct cyclic tests at 5,000 psi differentials with Class H Cement with 35% silica and 0.5% nylon fibers, as well as test the repeatability of the results for 1,000 and 2,000 psi differentials. This would allow a correlation to be built that would show the relationship between the fatigue endurance limit and the added nylon fiber. Concentrations of nylon could also be varied to build further correlations and help determine the optimum amount of nylon fiber needed in a cement slurry to resist the damage created by cyclic loading.

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