A METHOD FOR CEMENT INTEGRITY EVALUATION IN UNCONVENTIONAL WELLS

A Thesis

by

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ABSTRACT

Chances of cement sheath failure increase considerably when the application involves deep, high pressure/ high temperature (HPHT) wells. Such failures occur as a result of temperature and pressure-induced stresses created by well events such as hydraulic fracturing, well testing, enhanced oil recovery, completion, production, and work over, or other remedial treatments. These would impose huge operational costs and in some circumstances lead to loss of production. Analytical and FEA modeling research has been done in the past but fewer experimental studies focused on finding the fatigue endurance cycles of oil well cements under HPHT conditions.

Abundant unconventional resources, producing from deeper horizons, numerous frac jobs in the US, and safety significance were the prime motivations for creating a new testing procedure for evaluating cement integrity under HPHT conditions. A novel HPHT cell was manufactured and mounted on a Chandler 7600, an extreme HPHT Rheometer. Cylindrical cement samples were cured and tested at constant confining pressure while the casing pressure varied cyclically. These samples failed after a certain number of cycles when reaching their fatigue endurance limit or if they had inconsistent chemistry to withstand the HPHT conditions.

This research explains a method for cement integrity evaluation and identifies the fatigue failure cycles for 1,000 psi, 2,000 psi and 5,000 psi pressure differentials between the confining pressure and maximum casing pressure. Class H cement and class H plus 35% silica were used in these experiments and cement failures such as radial cracking, debonding and disking were observed.

DEDICATION

To God who never left me alone,

To my loving parents,

To my only brother,

To all my teachers who patiently taught me,

To my good-hearted friends,

To all whom I lost and missed,

And finally to the Society of Petroleum Engineers.

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

The U.S. shale gas production has grown rapidly in recent years; in 2010 production was at 10 bcf/day and in 2012, it raised to around 25 bcf/day. This combined with a need for more domestic energy has brought more focus on U.S. shale gas drilling. Production of natural gas from these shale regions is dependent on wellbore integrity and the durability of the cement sheath throughout the life of the well. Shale wells are often drilled vertically through the upper formations, and then progress horizontally through the target reservoir.

In the vertical section, zonal isolation and prevention of gas migration are top priority while in the horizontal section, cement slurry stability, set cement durability, and ability to withstand post cementing operations such as hydraulic fracturing and production through the life of the well are important concerns. Laboratory studies focused on shale plays can examine the effects of post cementing operations and cyclic stresses on a cement sheath.

The applications performed after cementing any string can have a significant effect on the cement sheath integrity. The cyclic stresses due to continued drilling, fracturing and production can lead to bond failure at the cement interface with the casing or formation. This can lead to impaired zonal isolation, and sustained casing pressure, resulting in possible remedial work and down time.

Gas Migration

Gas migration is defined as gas entry into a cemented annulus creating channels with the potential to provide a flow path of formation fluids, including hydrocarbons, into the wellbore. Previous laboratory research has determined that a static gel strength (SGS) of 500 lbf/100 ft^2 or more is required to prevent short term gas migration.

Short Term Gas Migration

The most common problem occurring during primary cementing is the invasion of gas into the cement during the setting process. As cement gels, it loses the ability to transmit hydrostatic pressure. During this period, fluids (water and/or gas) can invade the cement and form channels. This flow of formation fluids can be from the pay zone to the surface or can be cross-flow between zones of differing pressure. This type of short term fluid migration problem often leads to long term zonal isolation problems and SCP.

Long Term Gas Migration

Changes in pressure and temperature which occur in expansion and contraction of the casing and cement sheath can cause cement to debond from the cement. Portland cement is a brittle material and susceptible to cracking when exposed to thermally induced or pressure induced tensile loads, (Bourgoyne and et al. 1991). Long-term gas migration occurs due to cracks in the cement sheath, microannuli, or channels in the set cement. Numerous factors during drilling operation such as poor mud removal, poor casing centralization, excessive free water and cement sheath shrinkage directly affect the long term well integrity. After drilling and reaching the total depth, events such as hydraulic fracturing, well testing, enhanced oil recovery, depletion, and work over, or other remedial treatments considerably affect the integrity of cement sheath. In addition, high pressure high temperature conditions impose a huge risk on effective zonal isolation if the cement slurry is not properly designed. Cement sheath failures occur as a result of temperature and pressure-induced stresses.

Flexible and expanding cements with enhanced mechanical properties have been introduced. Such flexible cements provide controlled expansion and have high tensile strength and young modulus. Resistance to corrosive gases such as CO_2 is very important in order to reduce long term gas migration. Self-healing cement (SHC) provides long-term zonal isolation with a sealing material that has an intrinsic self-healing property. Hydrocarbons activate the self-healing material whenever the integrity of the cement sheath is compromised (e.g., cracks and microannuli) and would then efficiently seal the leak path by swelling when in contact with hydrocarbons (Cavanagh et al. 2007). Engineering analysis must be utilized in order to assess stresses on the cement sheath during various well operations. Such a study keeps the cement sheath below its endurance limit and improves cement sheath integrity during the well life (Ravi et al. 2007). With the current momentum of tapping the new resources, cement integrity analysis is a key to operate securely offshore and onshore.

Throughout the life of a well, operators and service companies implement several techniques such as hydraulic fracturing, EOR methods and gas lift, to produce more efficiently. Cement hydration, well testing, changeover from displacement fluid to completion fluid and depletion also inevitably affect cement integrity due to the stress change. There have been many studies on cement integrity (Griffith et al. 2004; Ravi et al. 2003; Ravi et al. 2008) but less attention has been given to the experimental side especially due to the lack of a HPHT equipment for cement integrity evaluation. The new HPHT cell that was patented, manufactured and mounted on the Chandler 7600, provides the possibility of testing cement integrity under the HPHT conditions.

Once the cement is repeatedly stressed, the number of cycles that it can withstand depends on the stress magnitude and the mechanical properties. In various industries, ‘endurance limit’ is the term coined for the stress below which the material can withstand a large number of stress cycles. Cement mechanical properties, such as Young’s modulus, tensile strength, and compressive strength, by themselves are not sufficient to determine integrity of the cement sheath.

A detailed engineering analysis should to be conducted to determine how such operations change the stresses in the cement sheath and if the sheath can withstand these changes, (Ravi et al. 2004). Cement sheath failure cycle under cyclical loading could be determined from lab experiments. The objective of this research is to evaluate the integrity of class H plus 35% silica under cyclical loading at HPHT conditions. **Figure 1** shows different types of four cement failure that might occur during the life of a well. This study, between the five mechanical damages that can be induced to a cement sheath, focuses mainly on radial cracking, disking and inner debonding.
Long-term cement integrity under downhole HPHT conditions and an approach for determining the integrity of cements under elevated pressure and temperature conditions have been investigated (Bois et al. 2012), however, this study offers new sets of data on cement failure under cyclical loadings at higher pressures and temperatures.

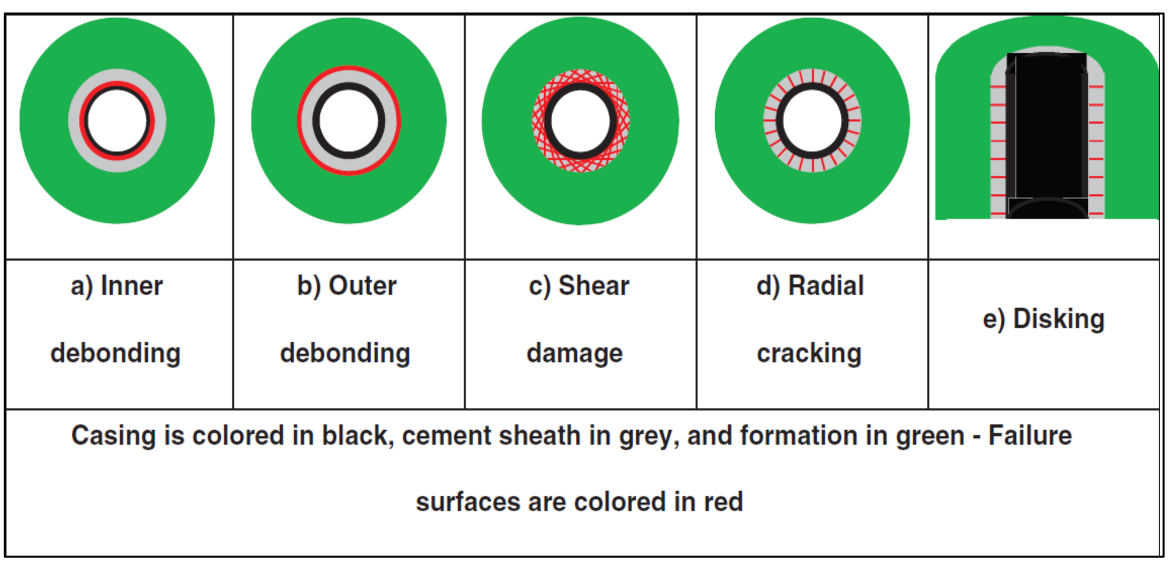

Figure 1. Types of cement sheath damage.

Hydraulic Fracturing

Hydraulic fracturing has been evolving since the 1940s to boost production from reservoirs with declining productivity. In addition, this technology along with horizontal drilling has enabled upstream industry to initiate production from unconventional oil and gas formations. Hydraulic fracturing is defined as injecting large volumes of water, sand or other proppant, and chemicals into production wells with enough pressure to create a crack in low-permeability geologic formations. The sand or other proppant holds the new fractures open and facilitates the oil or gas to flow out of the formation and into a production well. Water and the fracturing fluid remaining in the fracture zone can inhibit oil and gas production and must be pumped back to the surface, (Murrill 2013). **Figure 2** shows the global assessed shale plays.

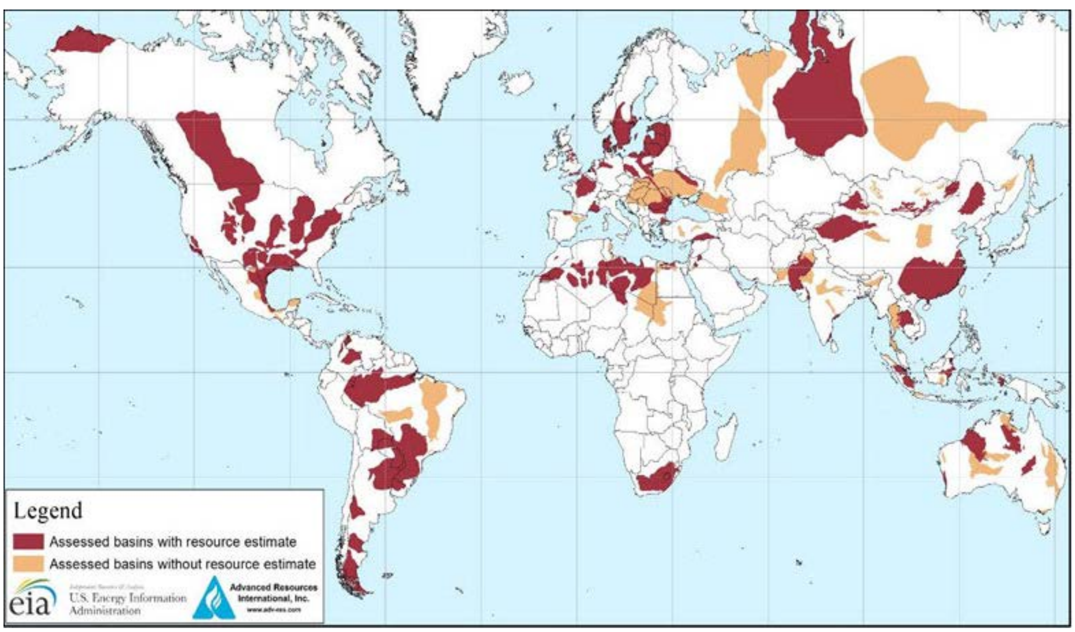

Figure 2. Global assessed shale plays.

In-situ Stresses

Underground formations are confined and under stress. The local stress state at depth for an element of formation can be divided into 3 principal stresses: σ_1 is the vertical stress, σ_2 is the maximum horizontal stress and σ_3 is the minimum horizontal stress, where $\sigma_1>\sigma_2>\sigma_3$. Depending on geologic conditions, the vertical stress could also be the intermediate (σ_2) or minimum stress (σ_3). These stresses are often compressive and are distinguished in magnitude particularly in the vertical direction. The direction and magnitude of principal stresses are significant since they control the pressure needed to initiate and propagate a fracture, the shape and vertical extent of the fracture, the direction of the fracture. A proper understanding on stress state distribution is a key to have a successful horizontal drilling and consistent production after hydraulic fracturing operation. **Figure 3** demonstrates hydraulic fracturing in a horizontal well versus a vertical well, (American Petroleum Institute 2009).

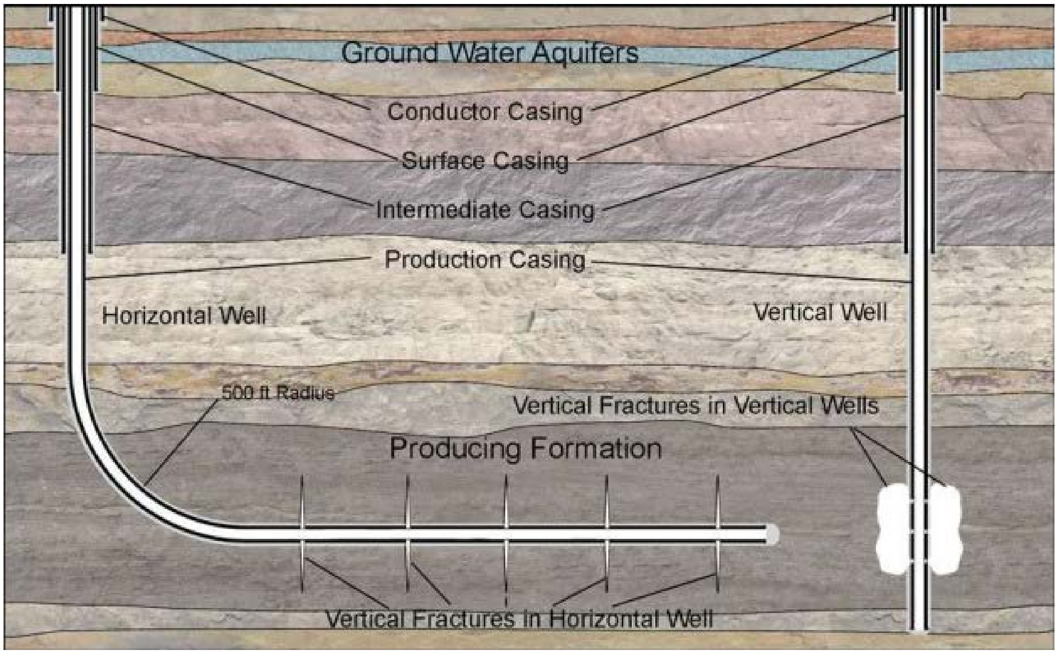

Figure 3. Hydraulic fracturing in a vertical well vs. a horizontal well.

Knowledge about fatigue is extremely valuable both from an economic point of view and from the aspect of safety of the structures. New cement chemistries have become resistant to harsh downhole conditions. In other words, they can withstand higher concentrations of stresses and a higher percentage of varying loads. The Haynesville Shale, which is located in northwestern Louisiana, is a recent play with massive potential, estimated by some to hold four times the reserves of the Barnett. The Haynesville is not only becoming one of the hottest plays with respect to activity, but also in regards to one of the hottest downhole temperatures. Indeed, some of this play's wells are reaching 380°F in bottomhole temperatures. Hydraulic fracturing creates artificial fractures inside the low permeability formations which allow more hydrocarbons to be produced. This procedure, however, will cause an inevitable series of fatigue cycles in downhole structures. The fatigue cycles may vary according to the well events and number of stages in hydraulic fracturing. Doubtlessly higher pressures and temperatures add complexity to daily well operations and hydraulic fracturing has to be properly utilized in a sense that not only it unleashes undeveloped unconventional resources but also responsibly stays compatible with environmental constraints.

Fatigue

The American Society for Testing and Materials (ASTM) defines fatigue life, N_f, as the "number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs", (Wikipedia). Fatigue is defined as the initiation of micro cracks and their propagation due to repeated applications of stress. A structural member that may not fail under a single application of static load may easily fail under the same load if it is applied repeatedly. Failure under cyclic (repeated) loads is called fatigue failure, (Petrowiki). Damage due to fatigue may be divided into different categories dependent of the loading conditions. Different types of fatigue are as follows:

- *High-cycle fatigue*: When the material requires more than 10^3 cycles to fail, the material undergoes the high-cyclic fatigue. The deterioration process is related to load frequencies.
- *Low-cycle fatigue*: This type of fatigue is defined by a number to failure which is less than 10^3. The low-cycle fatigue is often connected to high loading amplitudes which results in loss of material stiffness.
- *Thermal fatigue*: Result of temperature gradient that varies with time in such a manner as to produce cyclic stresses in a material specimen. This type of fatigue exists when rapid cycles of alternate heating and cooling occur. Due to expansions and extensions, crack propagation will start and the fatigue process will be accelerated significantly by increasing of temperature variation.

Oil and gas wells usually go through low cycle and thermal fatigue during the life of a well. Occurrence of fatigue failure in the drill string is one of the most common and expensive type of failures in drilling operations. Cyclic stresses along with corrosion can considerably shorten the life of a drill pipe. **Figure 4** shows a long term pressure transient test to understand the reservoir limits and define the reservoir potential. Such a test occurs with several pressure and temperature changes and it can cause low-cycle and thermal fatigue in the cement.

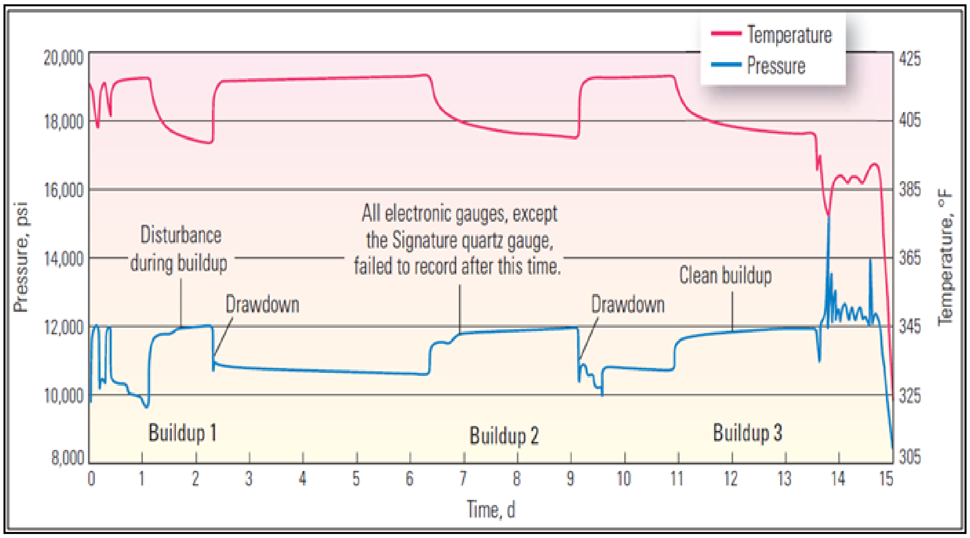

Figure 4. Extended well test results in pressure and temperature cycles.

Characteristics of Fatigue

There are five important fatigue characteristics:

I. The greater the applied stress range, the shorter the life.

II. Fatigue life scatter tends to increase for longer fatigue lives.

III. Fatigue is a stochastic process, often showing considerable scatter even in controlled environments.

IV. Damage is cumulative. Materials do not recover when rested.

V. Fatigue life is influenced by temperature, surface finish, microstructure, presence of oxidizing or inert chemicals, residual stresses, etc. Cements with higher Poisson’s ratio and lower Young’s Modulus show better.

At temperatures below 300 ° F, the temperature has negligible effects on the cement low cycle fatigue. The elastic strain and plastic strain developed by thermal stress in cement are very small compared to the strain developed by the bottomhole pressure under low cycle fatigue range, (Yuan and et al., 2013a, 2012b). As the confining pressure increases, the cement shows more plasticity and can take more pressure cycles.

In high pressure wells, the cement fatigue failure probability increases as the reservoir pore-pressure decreases. Cements with higher Poisson's ratio and lower Young's Modulus show better low cycle fatigue behavior. Within the requirement of compressive strength, the cement with higher plasticity is preferred for HPHT wells and steam injection wells.

More investigations need to be carried out to verify cement fatigue behavior at the confining pressure above 10,000 psi and temperature above 300 ° F. Beyond 300 ° F, the temperature may have effect on cement low cycle fatigue however below 300 ° F, the temperature may have effect on the high cycle cement fatigue (Yuan et al. 2012b). Cyclic stress state, geometry, cement porosity, loading direction, environment and crack closure affect fatigue-life of a cement sheath.

The basis of the analytical model for determination of stresses in wellbores was presented by Ugwu (2008). It takes the mechanical properties of casing, cement and the formation into account and the casing and cement are treated as multi-cylinder-setup as assumptions. The stress distributions are expected in the cement sheath depending on the loading situation. **Figure 5** illustrates the radial and tangential stress. These stresses might create microannuli or cause a tensile or compressional failure. The ideal cement with high durability must have excellent tensile strength.

Most of the commercial software have not yet been validated by experimental data and they purely are derived of FEA analysis. In addition, the initial stress in the cement sheath is another key unknown which the industry has been trying to understand. Extreme conditions and how different cements would react to downhole environments is still being researched.

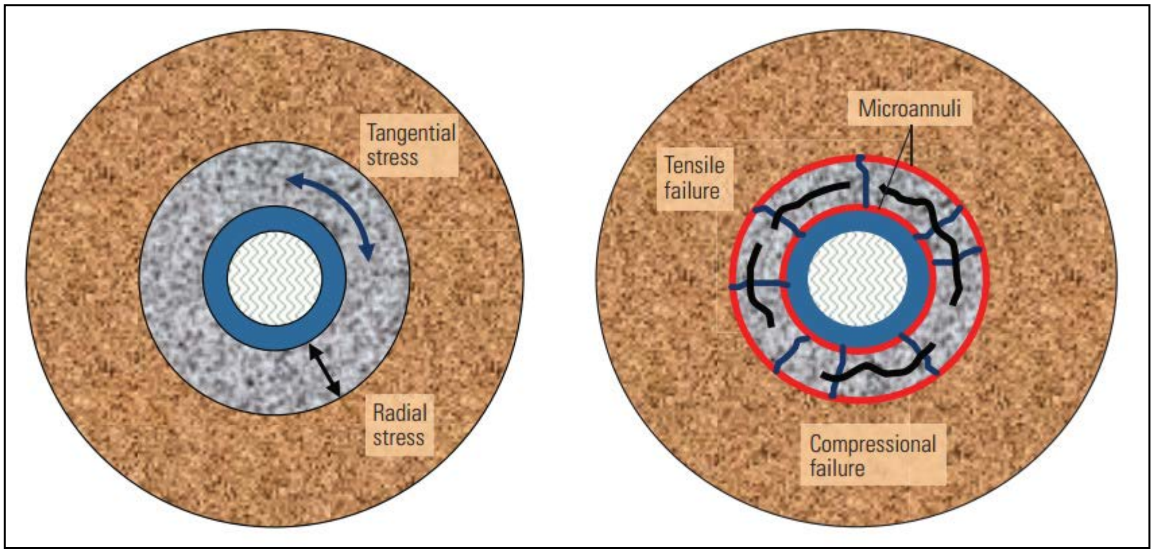

Figure 5. Stress distributions in the cement sheath.

Sustained Casing Pressure

Sustained Casing Pressure (SCP) is a major concern of wellbore integrity. If the casing string is cemented properly, gauges on the casing annulus should read zero psi. A small amount of pressure can be created by thermal expansion of fluids, but once that pressure has been bled off, the pressure on the casing annulus should remain at zero psi. If the pressure returns after the well has been bled down, then the well is said to exhibit SCP. This could be the result of the cement slurry not having been placed in the entire annulus and/or the inability of the cement sheath to withstand stresses from well operations (Ravi and Darbe 2010). Bourgoyne et al. (1991) identified 11,000 casing strings in 8,000 wells in the Gulf of Mexico that indicated sustained casing pressure. According to an MMS report in 2004, about 6,650 wells had SCP and 33% of them were linked to leaking cement. The cost of removal was estimated as $650 MM. In 2006 the Petroleum Safety Authority of Norway (PSA) determined that about 18 % of wells on the Norwegian Continental shelf (NCS) may suffer from well integrity issues. According to Watson and

Bachu (2007, 2009), in onshore Alberta, about 142,000 wells surveyed, exhibited surface casing gas migration, **Figure 6**, (Feather 2011). Sustained casing pressure buildup over time may be analyzed to determine cement permeability, location of leak and the nature of the leakage process. SCP can be caused by tubing or casing leaks, poor cementing, or damage to the cement sheath resulting from thermal and pressure loading.

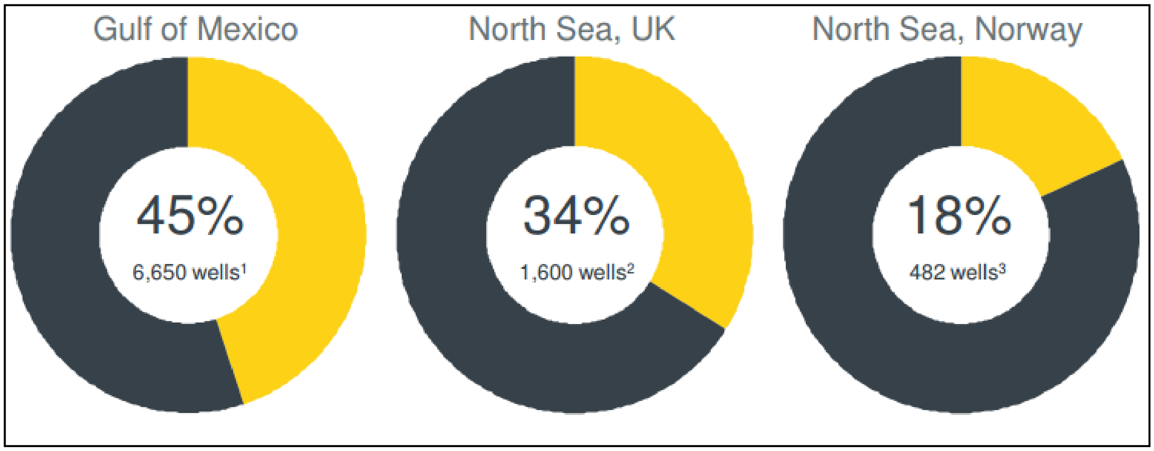

Figure 6. A global percentage of wells with integrity issues.

There are two main solutions for SCP. First, cement slurry should be designed with optimal elasticity and tensile strength which allows cement sheath to withstand cyclic loads and reduces the likelihood of fatigue failure. The second solution would be using self- healing cement which repairs itself automatically when is exposed to formation fluids such as crude oil or gas. **Figure 7** shows Crystal Geyser, where CO_2 is leaking out from an abandoned well, Photo courtesy of Gouveia2.

Figure 8 displays the Deep Horizon blowout which occurred in 2010 in Gulf of Mexico, (U.S Coast Guard via Getty image). Experimental results indicated that the thermal and stress induced fatigue affect the integrity of cement sheath. Changing the pressure of a casing string was researched by Jackson and Murphey (1993) while Goodwin and Crook (1990) investigated both pressure and temperature effects. Casing pressure tests are routinely conducted to verify the competency of each string. Pressure tests are also performed prior to perforating, fracturing and after setting packers or bridge plugs.

Figure 7. Crystal Geyser, CO_2 from abandoned well**.**

High pressures are also experienced during acidizing, fracturing, and cementing operations, (Bourgoyne and et al. 1991). Goodwin and Cook (1992) showed that at the time that the pressure inside the casing is reduced, the cement may not have full elastic recovery. This can result in damage to the casing/cement bond by making small micro annulus. Casing expansions induced by excessive internal casing pressures can cause radial stress cracks in the set cement as well.

Figure 8. Deep Horizon blowout, 2010.

Cement sheath stress cracking as a result of excessive temperature changes, generally occurs in the upper one-third to one half of the well. Typical causes of such cracks include pressure testing the casing after the cement has attained high compressive strength. Low-compressive-strength (500 to 1,000 psi) cements are more ductile than other cements and can withstand the stress cycling (Goodwin and Crook 1992). Also, cement with ultrahigh compressive strength (> 12,000 psi) will withstand stress cycling without cracking. One suggestion for circumventing the cracking problem is to use low density cement slurry to for the entire well (deleting the high-strength tail slurry); where pumping low-density, low-compressive strength cements was possible, the cracking problem practically was eliminated (Goodwin and Crook 1992). Chevron researchers (Jackson and Murphey 1993) examined the effect of increasing internal casing pressure.

The cement was cured with the internal casing pressure of 1,000 psi and then pressurized and depressurized cyclically to investigate the effect of increasing internal casing pressure as observed during pressure testing. A microannulus was made which resulted in flowing gas after a cycle to 8,000 psi followed by a depressurization to 1,000 psi. This micro annulus stayed active whenever internal casing pressure was below 3,000 psi, (Bourgoyne and et al. 1991). **Table 1** shows the consequences of poor well integrity before and at the time of production, (Sminchak et al. 2013).

Table 1: Wellbore integrity: what can go wrong?

Pre-Production	Formation damage during drilling (caving)	
	Casing decentralization (incomplete cementing)	
	Inadequate drilling mud removal	
	Incomplete cement placement	
	Inadequate formation-cement/cement-casing bond	
	Cement shrinkage	
	Contamination of cement by mud or formation fluids	
Production	Mechanical Stress/Strain	Micro-annulus at casing-cement interface
		Disruption of formation cement bond
		Fracture formation within cement

High Pressure High Temperature Wells

Drilling into some shale plays such as Haynesville or deep formations and producing oil and gas at HPHT condition, have been crucially challenging. Therefore, companies are compelled to meet or exceed a vast array of environmental, health and safety standards. Projections of continued growth in hydrocarbon demand are driving the oil and gas industry to explore new or under-explored areas. As the search for petroleum becomes more extreme in terms of depths, pressures, and temperatures, companies are leading the way with innovative technologies and products for HPHT drilling. A number of innovations are in the pipeline to help companies access hydrocarbon that were once deemed too difficult to exploit.

HPHT Cementing Challenges

HPHT conditions add many complexities to well cementing operations. Such harsh conditions can raise the risk of short term gas migration during the placement of the cement slurry and eventually create cracks in the set cement during the life of the well (Wray and Bedford 2009) . Cement sheath integrity is extremely critical in the salt during the production phase and narrow margin formations in which the fracture pressure and pore pressure are very close. Primary cementing is a critically important operation in construction of a well. Apart from providing structural integrity to the well, the chief purpose of the operation is to provide a continuous impermeable hydraulic seal in the annulus, preventing uncontrolled flow of reservoir fluids behind the casing(Yetunde and Ogbonna 2011). It is however speculative to believe that cementing is the only consideration for effective zonal isolation.

CHAPTER II

HPHT CEMENT EXPERIMENTAL SET UP

The Model 7600 Ultra HPHT Viscometer is the highest pressure viscometer available to the oil and gas industry. It is designed specifically for the most severe conditions, it handles any temperature or pressure encountered during drilling and completion operations. The device also has proper safety features that ensure proper protection along with a removable sample vessel assembly with vessel elevator mechanism to facilitate set-up and cleaning.

HPHT Cell

This chapter presents the components of the high-pressure/high-temperature (HPHT) cell that were designed at Clausthal University of Technology, in Clausthal, Germany. The new setup which allows testing cement samples under wellbore conditions and geometry uses the Chandler 7600's controlling software to reduce the cost of the experiment. Therefore, a cell-in-cell system was designed consisting of a large cell which is used to apply a confining pressure on a cement sample and a small cell which simulates the casing.

Every sample is a cement sheath around the small cell located in the outer cell. After a confining pressure is applied to the outer cell, the pressure in the small cell can be cycled and thus the failure cycle of cement would be investigated. To reduce the expenses necessary to setup the experiment, a HPHT cell was built as an extension packet for the Ultra HPHT Chandler 7600 Rheometer. Also, the Chandler 7600's controlling software, which is originally designed for measuring the rheological properties of drilling fluids, could be used for cement integrity evaluation experiments. This chapter also provides a better understanding about the equipment and how it operates. The top cell and the cell body are made of 42Cr4Mo-steel. This material is also commonly used in manufacturing drill collars. The cell top has two high pressure connections to pressurize the cell itself with the first one and an inner cell with the second one. This inner cell can be surrounded by a cement sheath, which can be tested on the strength against tensile failure under cyclic loading. The setup allows the recreation of the situation as it appears in the borehole during production operations. **Figure 9** shows the top cell which screws to the cell body (Teodoriu et al. 2013 and Kosinowski, C. 2012). **Figure 10** demonstrates different part of an small cell which basically simulates a casing's role in these experiments. **Figure 11** compares the small cell under no pressure versus when it expands due to increasing internal pressure.

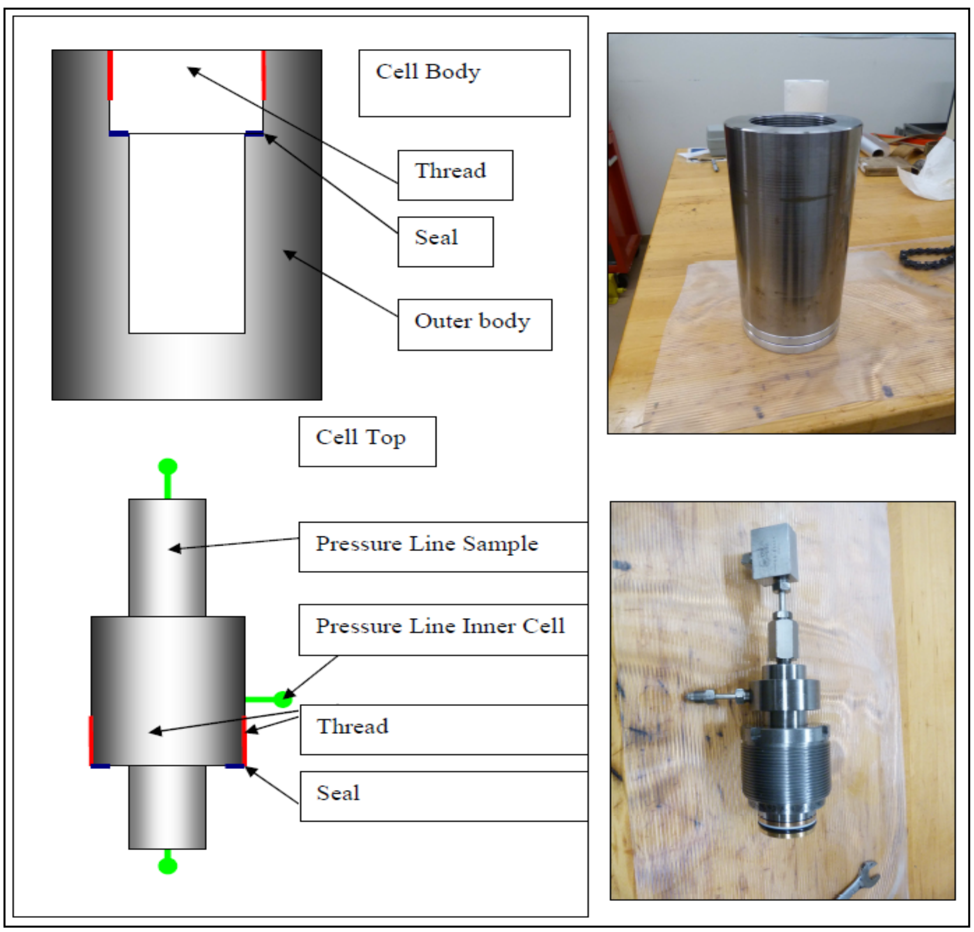

Figure 9. HPHT cell body and cell top.

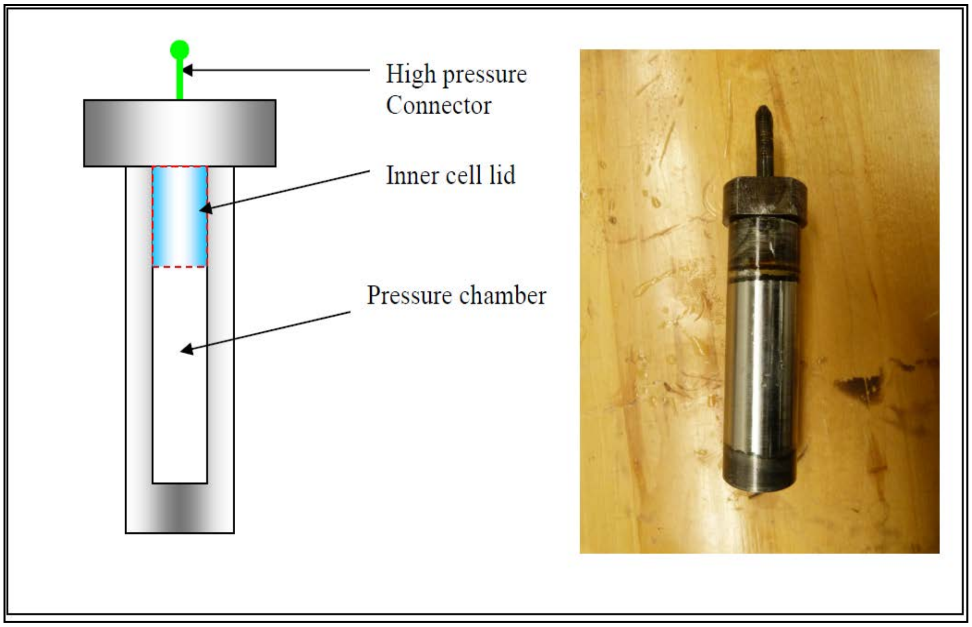

Figure 10. Inner small cell.

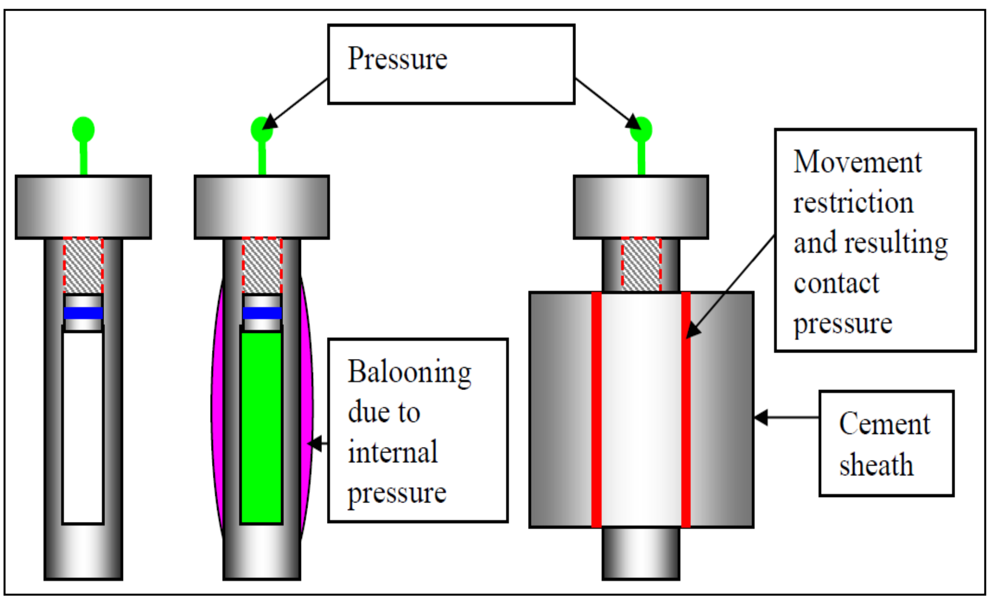

Figure 11. Casing and cement sheath expansion.

Sample Preparation

The preparation of the samples is one of the most important steps in the testing procedure and special attention should be given to this part of the experiment. The inner cell has to be molded with cement sheath which will be tested in the cell. The small cells should be kept clean at all times and in case they get rusted, they should be instantly cleaned. Chipboard should be prepared where the molds can be glued on; it should be around ½ inch thick. Circles of 4 inch indicate the position of the Plexiglas mold for the cement sheath and 1 inch holes are drilled into it to center the cement on the inner cell. Second chipboard is attached to the bottom of the first one to prevent the cement slurry from flowing out to the bottom, **Figure 12**.

Figure 12. Chipboard, PVC pipes and smalls cells.

In order to clean the inner cells, a solvent like acetone could be used. It is important that no oil is on the surface before cementing the samples in order to achieve a good cement-cell bond. A few drops of silicone may be put into the drilled holes in the chipboard, the cell gets inserted while being rotated. Some of the silicone will be squeezed out of the holes and should be removed to avoid impurities in the cement. Silicone will be also used to glue the PVC pipes on the chipboard. The tube should have an axial cut which is patched off with tape. This makes it far easier to remove the PVC pipe after the cement has cured for a sufficient amount of time. After the cells and the PVC pipe has been glued, the silicone sealant should dry for at an hour to avoid cement leaking from the mold.

The next step would be mixing the cement according to API recommended practices 10B, using the constant speed mixer. The molds should be filled a little bit over the top with slurry due to cement volume shrinkage during the curing process. Initial curing must take place under water to receive optimum hydration of the cement. Curing under air might either cause cracks in the cement which significantly reduce its strength or create in situ stresses which affect the sample failure behavior. After curing, sample should be removed from the chipboard and PVC mold from cement sheath. To remove the samples from the chipboard we can either try to lift them by using a large screwdriver or unscrew the second chipboard and push them through the bore.

The PVC pipe should be easy to remove if you widen the cut in it by inserting a screwdriver. After atmospheric curing, the sample would be placed in the HPHT cell and get cured under pressure and temperature. Curing under HPHT conditions is a straight process. It must be ensured that the small cell is fully centralized unless fitting it in the cell might be problematic due to insufficient clearance in the cell. **Figure 13** displays a schematic of the experiment while **Figure 14** demonstrates a correct cement assembly to the top cell.

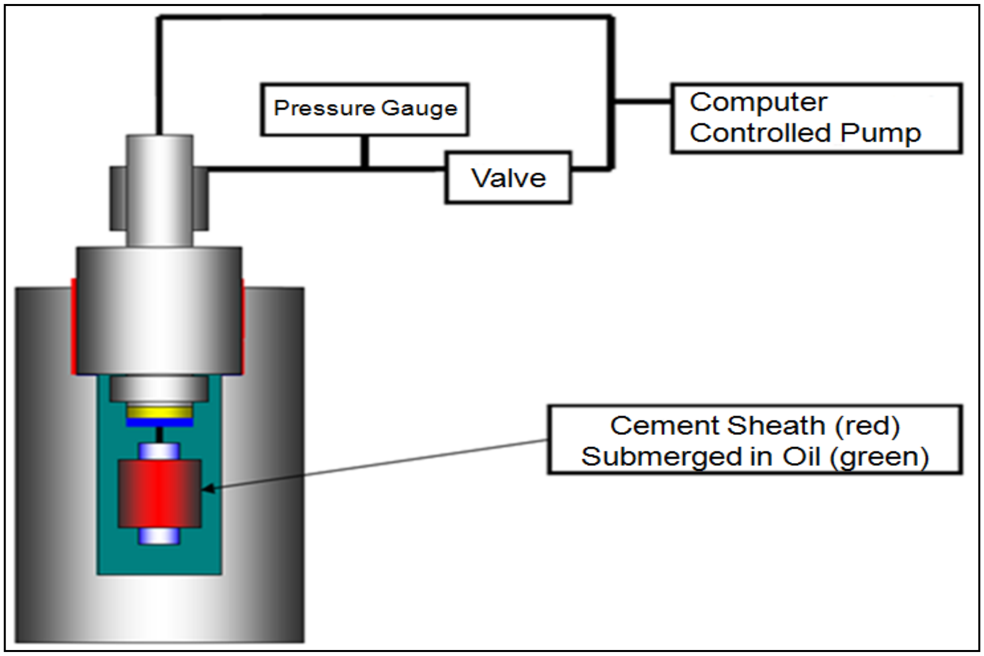

Figure 13. Experimental set up schematic.

Figure 14. Cement sample.

CHAPTER III

CEMENT INTEGRITY EVAULATION TESTING PROCEDURE

The primary step in the slurry design is to quantify the stresses the cement sheath will be exposed to. This step enables the cement engineer to choose the right mechanical properties for the set cement. For this purpose, computer-aided stress analysis software is the key to understanding stresses in the cement sheath, (Taoutaou et al. 2007). According to the API procedure, in order to make 600 mL of slurry of 16.4ppg class H cement, 328 grams of water and 851 grams of cement is required. They should be weighed up separately and the water gets poured into a waring blender. The blender is set to shear at 4000 rpm for 15 seconds and all of the cement is added to the water during this period. After 15 seconds, the blender is set to high shear (12000 rpm) for 35 seconds.

Once the 35 seconds is up, the slurry can be used for any standard testing. Weights of cement and water may change slightly based on the actual specific gravity of the cement sample. Different classes of cement have different water requirements. It is based on reactivity and grain size, highly reactive cements use more water so that they do not react too quickly, also cements with smaller grain size use more water because they tend to react more quickly.

Set Cement Properties

Standard 16.4 ppg neat Class H slurry will build 4,000 to 5,000 psi overtime at any temperature below 230°F. Depending on the temperature, this can take hours or weeks. The higher the temperature, the quicker the strength will build. Above 230°F, standard 16.4 ppg Class H slurry, builds strength and then begin to degrade. Due to the temperature, the crystalline structure formed becomes unstable and the cement loses compressive strength and becomes more permeable over time. In order to mitigate the instability, 35% by weight of cement silica can be added to the slurry. By adding silica, the molar ratios of calcium and silica are shifted from that of normal cement and the crystalline structure that is created (xonolite) is stable at temperatures above 230°F. Final compressive strengths will be in about the same range as neat cements.

Set A: Class H Cement

Previously a cement integrity evaluation test was not performed under HPHT conditions thus set A was prepared to evaluate the class H cement durability at elevated pressures and temperatures under cyclical loadings. 16.4 ppg neat class H slurry was prepared for three identical samples according to the API standard procedure. Shortly after the slurry set, samples were placed under water at 110 °F and curing phase started, **Figure 15**. After a day of curing at 110°F and 15 psi, one of the three samples was tested under HPHT conditions while the other two were still curing under water.

This sample was exposed to the constant confining pressure of 8,000 psi and casing pressures between the minimum of 8,000 psi and maximum of 19,000 psi, **Figure 16**. In real field operations 11,000 psi pressure difference might be rare however for the first set, high pressure differentials was chosen to ensure that the system operates properly and smoothly under HPHT conditions.

In this experiment, as 8,000 psi was reached at the very first stage of the test, 5th second, T valve was closed while the sample's temperature was 130˚F. The temperature of the confining fluid, mineral oil, kept increasing until it reached 300˚F. Since the volume was constant, the confining pressure started increasing while it was supposed to stay at 8,000 psi. Inconsistent confining pressure caused the sample to catastrophically fail. **Figure 17**, shows sample I-A before and after the test. Therefore, it was decided to keep the T valve open until the final temperature is reached.

Figure 15. Set A, Class H cement.

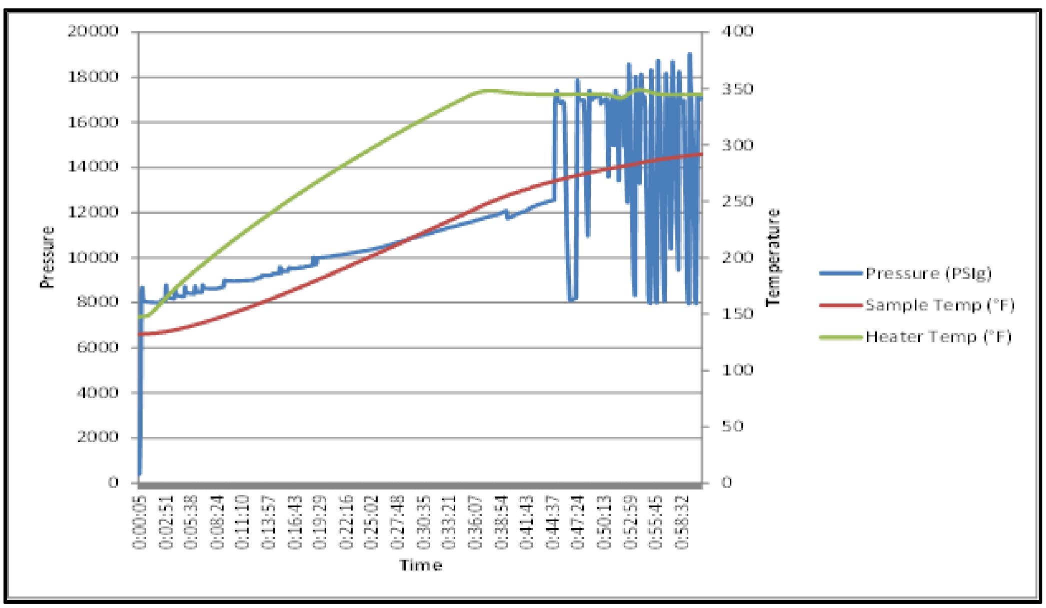

Figure 16. Plot of pressure and temperature versus time, sample I-A.

Figure 17. Inconsistent confining pressure caused severe cement sheath destruction.

Sample II-A which was cured for two days under water was tested at HPHT conditions in a cyclical mode with different time intervals. For this test, the T valve remained open until the temperature of 300° F was achieved and the confining pressure remained constant while the casing pressure was changing from 8,000 to 17,000 psi, **Figure 18**. **Figure 19**, shows the sample II-A before (left) and after (middle and right). Cyclical loading at HPHT condition caused a radial crack.

Sample III-A, which was cured for three days under water, got tested under HPHT conditions with the confining pressure of 8,000 psi and 35 casing pressure cycles between 8,000 psi and 17,000 psi, **Figure 20**. The purpose of this test was to evaluate the equipment capability for higher cycles at HPHT conditions. One radial crack was observed after the test. **Figure 21** displays One radial crack in sample III-A after the test.

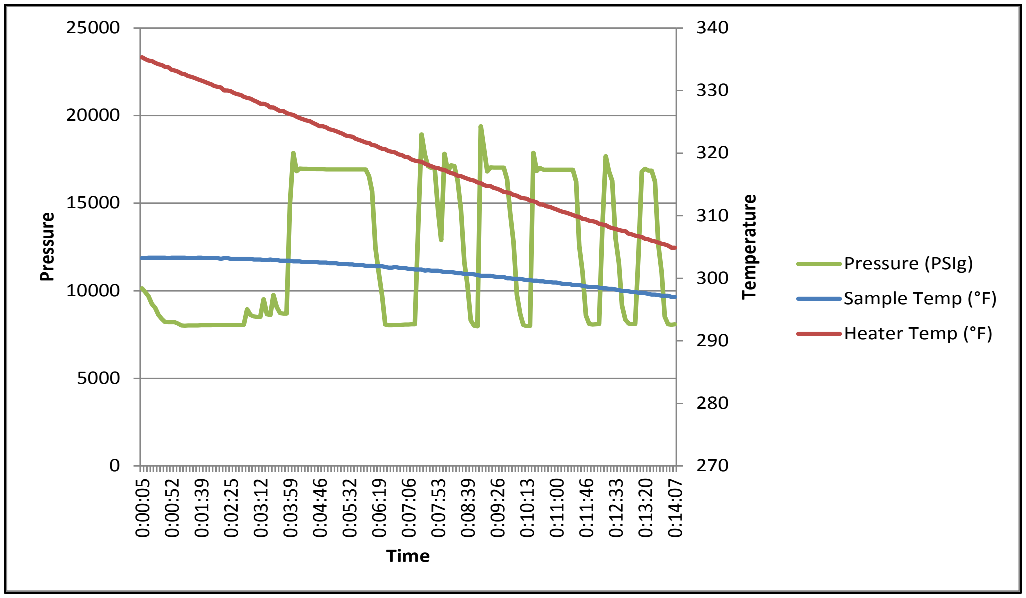

Figure 18. Pressure and temperature versus time, sample II-A.

Figure 19. Cyclical loading caused a radial crack in sample II-A.

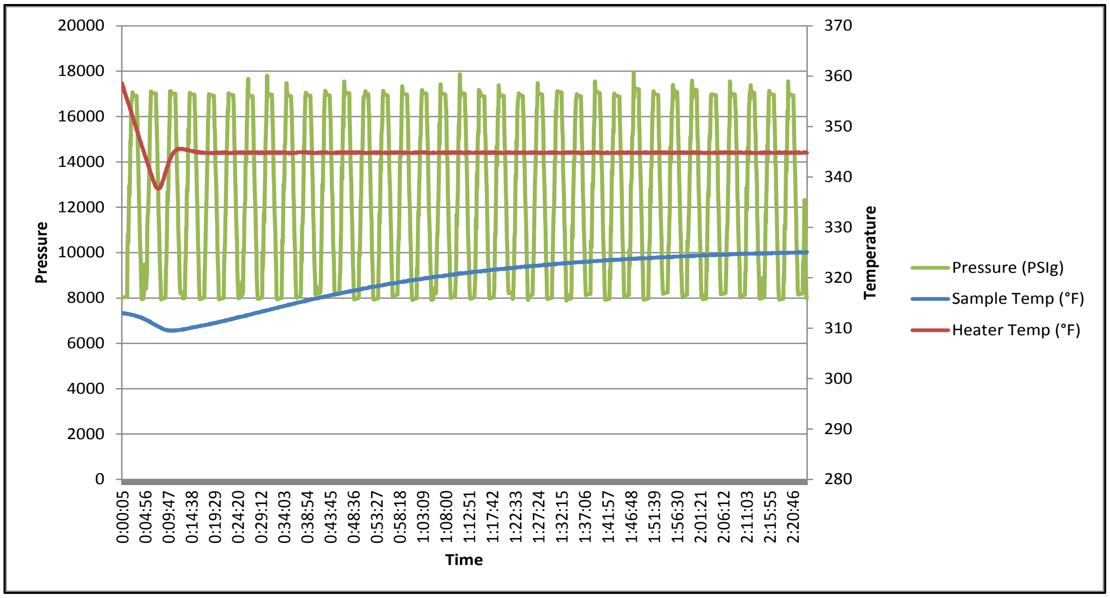

Figure 20. Sample III-A, pressure and temperature vs. time.

Figure 21. One radial crack in sample III-A after the test.

Analysis on Set A, Class H Cement

Test on sample I-A showed that in order to simulate the formation pressure in this experimental set-up, the confining pressure during the test must remain constant. Any test with inconsistent confining pressure is not valid and should be repeated. The second test performed on sample II-A showed the capability of this set-up to run cycles with different time intervals. The amount of time during which each cycle is performed, can be critical to simulate the time intervals in a well-test operation or a multi-stage frac job. The third test represents a higher cycle experiment at the similar HPHT conditions.

Table 2: Analysis test matrix for three samples, Set A

Sample #		I	II	III
Curing	Time, hours	24	48	72
	Pressure, psi	15	15	15
	Temperature, ˚F	110	110	110
Testing	Confining Pressure, psi	Variable	8,000	8,000
	Casing Pressures, psi	8,000 - 17,000	8,000 - 17,000	8,000 - 17,000
	Sample Temperature, ˚F	300	300	300
	Cycle #	10	6	35
Failure Type		Totally Destructed	One Radial Crack	One Radial Crack

Sample III-A and II-A end up both with a radial crack failure. It appears that curing one extra day for sample III-A made it more resistant towards higher cycles while sample IIA had the same failure by only 6 cycles due to one day less curing time, **Table 2** and **Figure 22**.

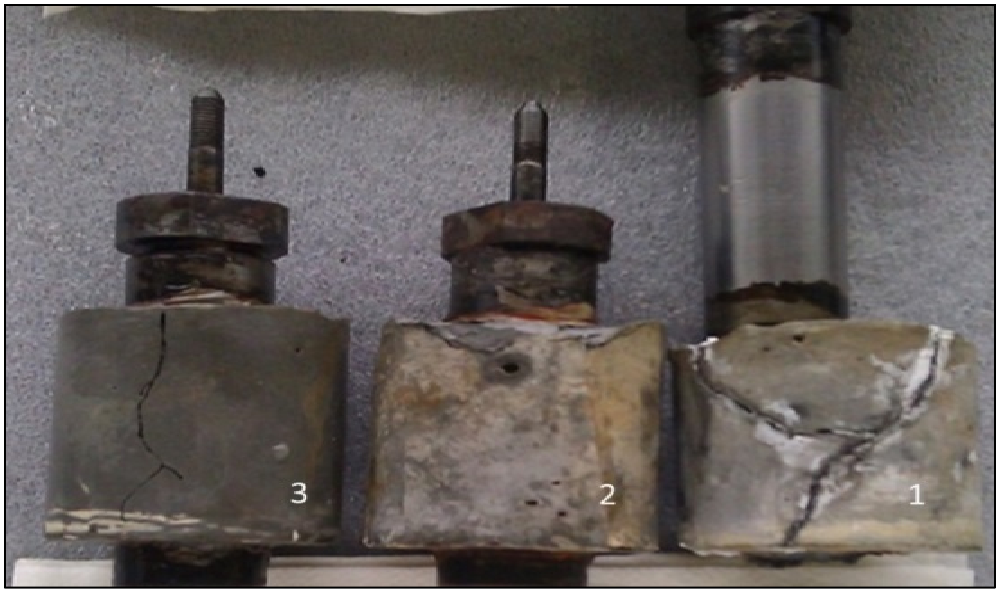

Figure 22. Set A, cement failures after at HPHT conditions.

Set B: Failure Cycle Investigation

After successfully evaluating the HPHT cement integrity set up, it was intended to find out when the failure happens for class H cement samples, therefore set B was prepared. Sample I-B was cured for one day at atmospheric pressure and 170 ˚F. This sample then went through 106 cycles between 8,000 psi and 17,000 psi while the confining pressure remained constant at 8,000 psi, **Figure 23**. **Figure 24** shows three types of cement failures after 106 cycles, one radial cracking and two disking failures. Also after the test and when the sample cooled down, a slight twist caused the cement sheath to debond from the casing. The second sample was cured for two days under the same conditions.

During the second test unfortunately while the temperature was stable and the T valve was closed, the delta pressure could not be achieved thus the test was stopped. This could be due to a mechanical leak in the small cell. The damaged cell was removed from the set to prevent future use. **Figure 25** and **Figure 26** show the test results on sample III-B. Two radial cracks were created after 28 cycles.

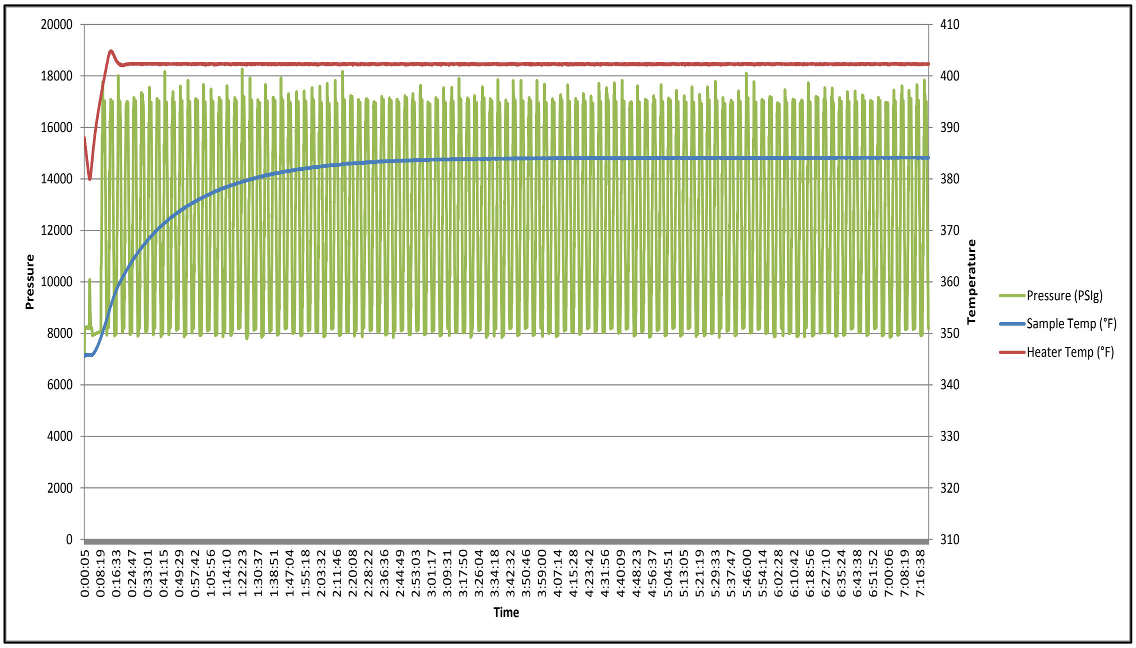

Figure 23. Sample I-B, pressure and temperature vs. time, 106 cycles.

Figure 24. Sample I-B, radial cracking and disking, cement failures after 106 cycles.

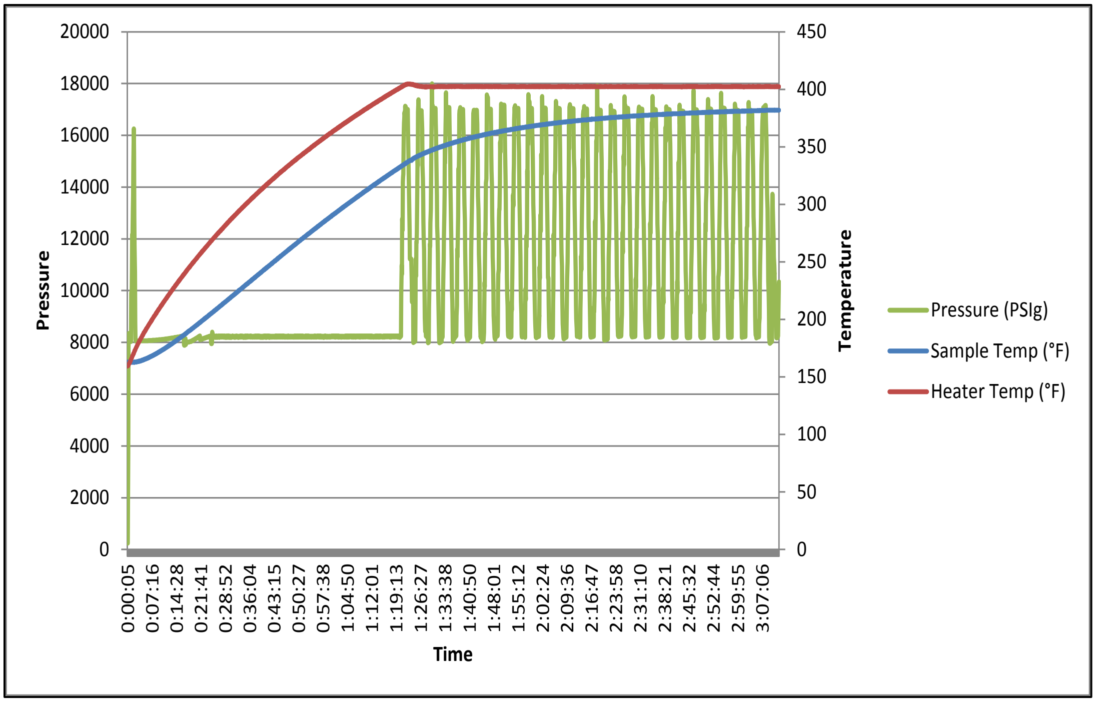

Figure 25. A cycle was attempted at the beginning of the test, Sample III-B

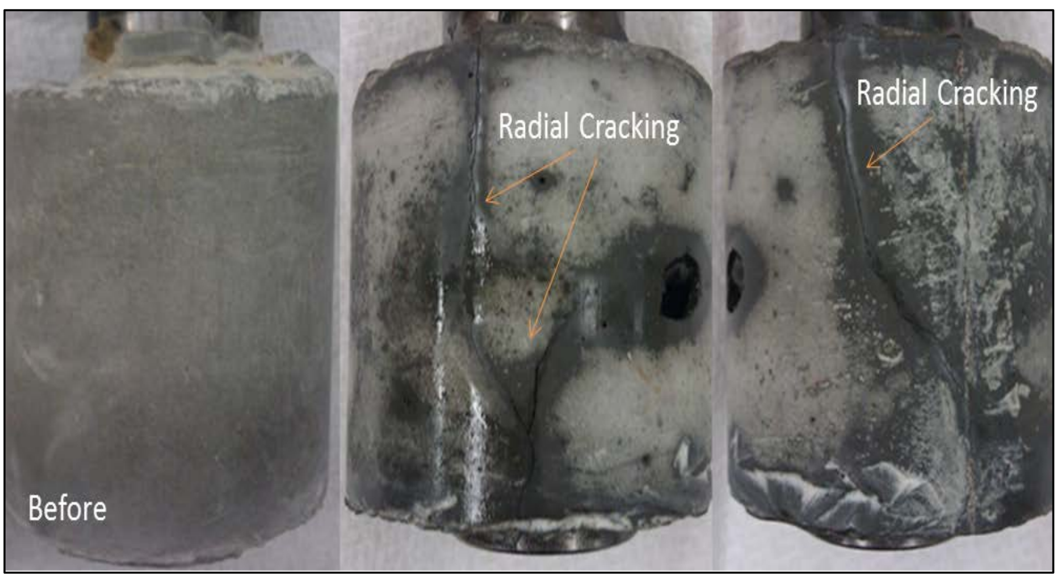

Figure 26. Two radial cracks, cement failures after 28 cycles, Sample III-B.

Analysis on Set B, Class H Cement

Sample I-B faced inner debonding, radial cracking and disking failures after 106 cycles with one day of curing time however sample III-B was cycled 28 times and with more curing period (three days). Less repetition of cycles with 9,000 psi magnitude and higher curing time (more compressive strength) caused fewer fatigue effects in sample III-B, **Table 3**. **Figure 27** shows the failure in three samples after being cycled at HPHT conditions. In the field, production casings are usually more susceptible to higher pressure and temperature cycles rather than intermediate casings. The cement systems designed for different casings might vary. It is prudent to schedule a fatigue endurance list experiment for each specific formulation with the realistic curing time, load and frequency of occurrence (cycles).

Table 3: Analysis test matrix for three samples, Set B

Sample #		I	III
Curing	Time, hours	24	72
	Pressure, psi	15	15
	Temperature, ˚F	170	170
Testing	Confining Pressure, psi	8,000	8,000
	Casing Pressures, psi	8,000 - 17,000	8,000 - 17,000
	Sample Temperature, ˚F	350	350
	Cycle #	106	28
Failure Type/s		Two Radial, One Disking and Inner Debonding	Two Radial

Figure 27. Set B, neat class H failures after the HPHT test

Set C: HPHT Curing

Another two samples of neat class H cement were mixed to evaluate how curing at HPHT conditions and cyclical loadings might affect the subsequent cement failure. A new confining pressure and casing pressures were selected. For this set, the confining pressure was held constant at 10,000 psi and the casing pressure cycles changed between 10,000 psi to 15,000 psi. The differential pressure between the confining and casing was reduced to 5,000 psi while for Set B it was 9,000 psi. Moreover the one minute time span could have caused a hammering effect defined as applying excessive loads in insufficient amount time for the cement sheath to recover. Therefore more time was given for the delta to hold at the higher pressure cycle (15,000 psi).

Sample I-C was cured for 3 hours at 15 psi and 170˚F. Then it was placed immediately in 7600 and cured for another 22 hours at 12,500 psi and 380 ˚F. 12,500 psi was chosen as a middle value between 10,000 psi and 15,000 psi. After the curing process and one cycle, the pressure differential between the confining pressure and casing pressure could not be held anymore and the test was stopped and the sample was taken out, **Figure 28**.

The second sample, which was cured under water for two days, went through 18 hours of curing. Since the pressure differential could not be achieved for sample one, HPHT curing was done for a shorter time. Sample II-C went through four cycles and had two radial failures after the test. **Table 4** summarizes the experiments in set C.

Table 4: Analysis test matrix for two samples, Set C

<table>
<tr><td colspan="2">Sample #</td><td colspan="2">I</td><td colspan="2">II</td></tr>
<tr><td rowspan="3">Curing</td><td>Time, hours</td><td>3</td><td>22</td><td>48</td><td>18</td></tr>
<tr><td>Pressure, psi</td><td>15</td><td>12,500</td><td>15</td><td>12,500</td></tr>
<tr><td>Temperature, ˚F</td><td>170</td><td>380</td><td>170</td><td>380</td></tr>
<tr><td rowspan="5">Testing</td><td>Confining Pressure, psi</td><td colspan="2">10,000</td><td colspan="2">12,500</td></tr>
<tr><td>Casing Pressures, psi</td><td colspan="2">10,000 - 15,000</td><td colspan="2">12,500 - 15,000</td></tr>
<tr><td>Sample Temperature, ˚F</td><td colspan="2">380</td><td colspan="2">390</td></tr>
<tr><td>Cycle #</td><td colspan="2">1</td><td colspan="2">4</td></tr>
<tr><td>Cycle Intervals, min</td><td colspan="2">10</td><td colspan="2">10</td></tr>
<tr><td colspan="2">Failure Type/s</td><td colspan="2">One Radial and One Slicing</td><td colspan="2">Two Radial</td></tr>
</table>

Analysis on Set C, Class H Cement

Experiments performed in this section were intended to assure a successful HPHT curing process and subsequently perform cyclical loadings. Two samples were cured at 10,000 psi and 12,500 at least for 18 hours and the system stayed reliable. These tests showed samples can be cured at HPHT conditions prior to cyclical loadings.

Figure 28: Sample I-C, slicing and radial failures for neat class H

Set D: Cement Integrity at Ultra High Pressure High Temperature

Three samples of class H were prepared and tested under Ultra HPHT conditions. Table 5 shows that sample I-D had one radial and two disking failures at the first cycle. More cycles yielded more catastrophic failures however three failures after one cycle seemed not enough to create such failures based on previous experience. Ultra high temperature of 400 F was recognized as the dominant reason behind creating three failures after only one cycle. Then sample II-D was tested under 25 cycles and consequently 5 failures were observed. Sample III-D was cured for 10 hours under 25,000 psi and 500 F. Severe failures and shattered sheath was observed after the test due to extreme conditions. Results clearly showed that a better chemistry could be utilized for HPHT conditions and 25,000 psi and 450 F as the limit for cement integrity evaluation test.

Table 5: Analysis test matrix for three Samples, Set D

Sample #		I	II	III
Curing	Time, hours	18	18	10
	Pressure, psi	12,500	12,500	25,000
	Temperature, ˚F	400	400	500
Testing	Confining Pressure, psi	10,000	10,000	20,000
	Casing Pressures, psi	10,000- 15,000	10,000- 15,000	20,000- 25,000
	Sample Temperature, ˚F	400	400	500
	Cycle #	1	25	7

CHAPTER IV

CEMENT FATIGUE ENDURANCE LIMIT MATRIX

Previously, the capability of the HPHT cement integrity evaluation set up was measured. The purpose of the experiments in this chapter is to provide comparable data for cement failure under cyclical loadings. Three sets of class H cement plus 35% Silica were prepared. All samples were cured for 15 hours at 15,000 psi and 330 ˚ F. They were tested under various pressure differentials between the maximum casing pressure and confining pressure.

Set E was tested under 1,000 psi differential pressure, set F was tested under 2,000 psi differential pressure and set G was tested under 5,000 psi differential pressure. The purpose was to find out the fatigue endurance cycle for class H cement plus 35% silica under these pressure differentials, examine how different pressure magnitude affects the cement failure and generate comparable data.

Set E: 1,000 psi Differential Pressure

Set E was tested with 1,000 psi pressure differentials. Confining pressure was kept constant at 15,000 psi and casing pressure varied from 15,000 psi to 16,000 psi. After one, three and five cycle test no crack was observed. In other words it was found that cumulative of 9 cycles is not the fatigue endurance limit for 1,000 psi differentials however after performing another 11 cycles (total of 20 cycles), a radial failure was observed, **Figure 29**. Cracking at 20 cycles implied that the failure cycle number is either equal to or less than 20 cycles and surely more than 9 cycles. As a result another sample (II-E) was prepared and tested with 11 cycles but it ultimately did not crack. After cycling this sample 5 more times, a radial crack was observed, **Figure 30**. At this point, it was clear that the fatigue endurance limit is either 16 or less than 16 and for sure more than 11 cycles.

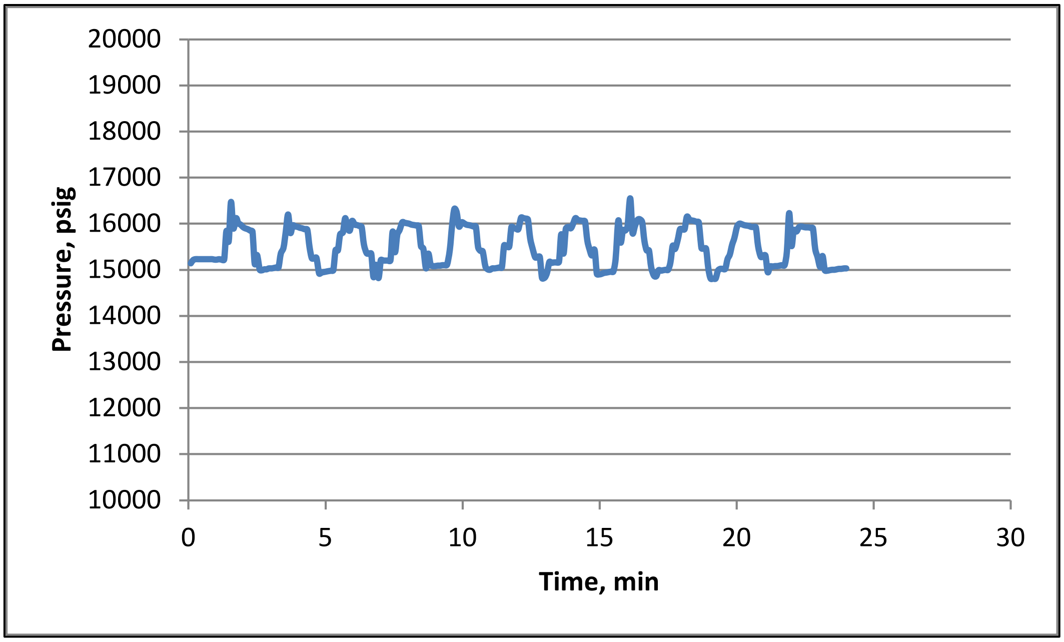

Figure 29. Sample I-E, 11 more cycles with 1,000 psig differential, total of 20 cycles.

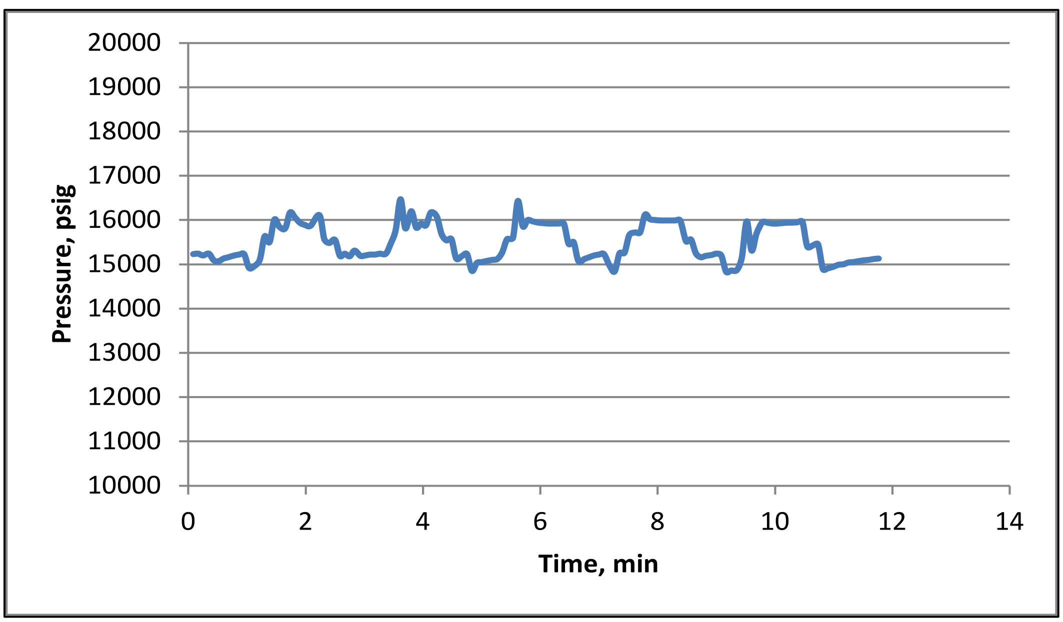

Figure 30. Sample II-E, one radial crack was observed after cumulative of 16 cycles with 1,000 psi pressure differentials (11 cycles plus 5 cycles).

Finally third test was performed on sample III-E with 12 cycles but it did not crack, **Figure 31** and **Figure 32**, therefore another 2 cycles were performed and ultimately a radial crack was observed, **Figure 33**. This test was repeated and another sample similarly cracked at cycle no. 14.

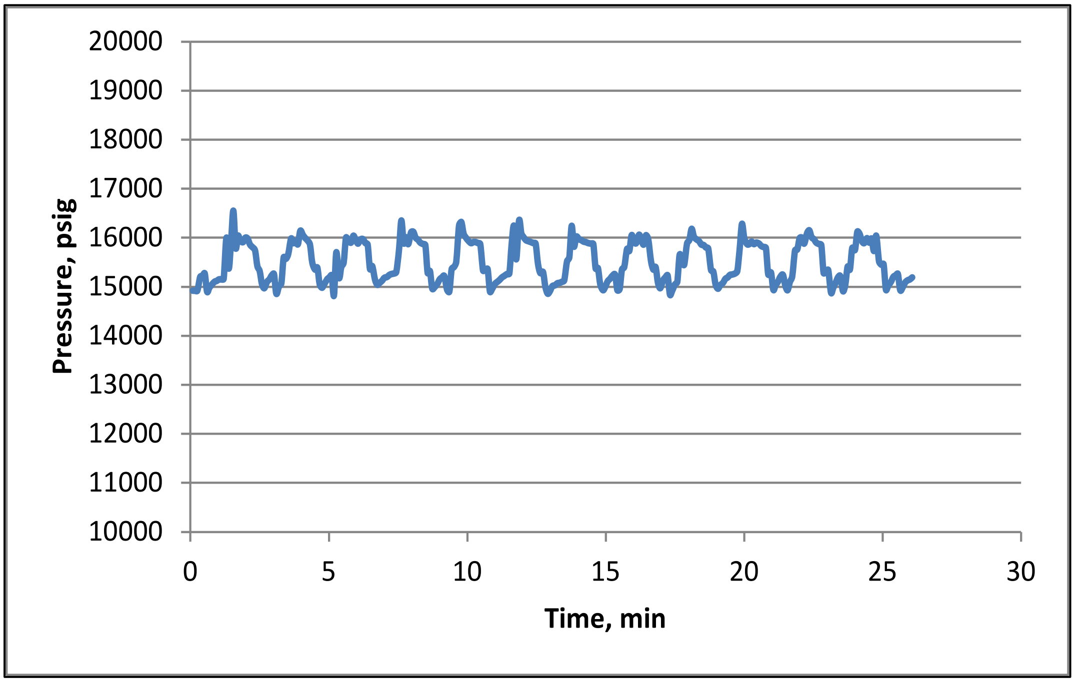

Figure 31. Sample III-E, 12 initial cycles with 1,000 psig differentials, and no crack.

The fifth sample was cycled 13 times however no failure was observed. The 16.4 ppg class H cement with 35% Silica failed and radially cracked after the cumulative of 14 cycles of 1,000 psi differentials between the confining pressure and the maximum casing pressure. Cycle no. 14 is the fatigue endurance limit for 1,000 psi differential at 15,000 psi confining pressure. However this number might be different for various chemistries. It is clear that adding silica significantly added to the strength of cement. **Figure 34** summarizes all the experiments done on set E. Every color represents one sample which was tested.

Figure 32. Sample III-E, 12 initial cycles, no crack.

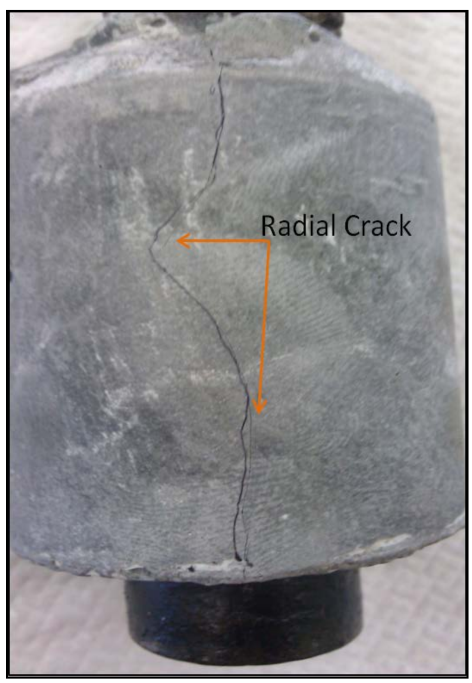

Figure 33. 1,000 psig differentials caused a radial crack.

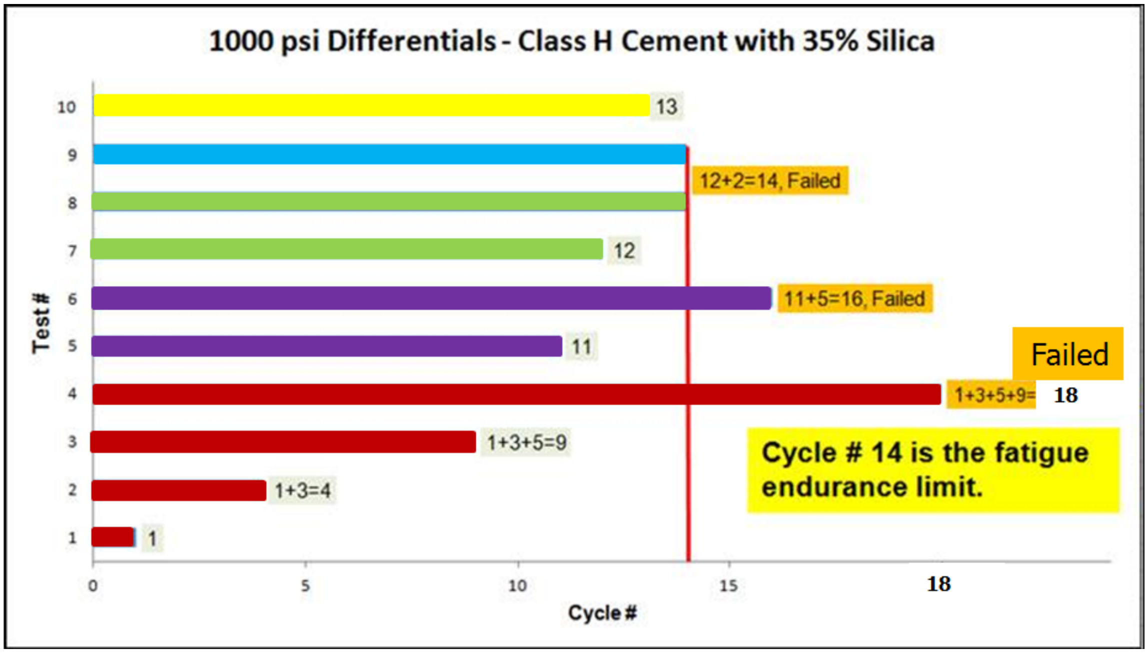

Figure 34. Failure cycle for 1,000 psi differential.

Set F: 2,000 psi Differential Pressure

Set F was tested with 2,000 psi differentials. Confining pressure was kept constant at 15,000 psi and casing pressure varied from 15,000 psi to 17,000 psi, Sample I-F was cycled 7 times and after the test a micro crack was observed at the top of the sample, **Figure 35** and **Figure 36**. To investigate whether or not cycle no.7 is the fatigue endurance limit, sample II-F was prepared, cured at HPHT conditions. Then it was cycled five times however no crack was detected therefore it went through another 3 cycles.

After a cumulative of 8 cycles no failure was observed so it was cycled for 5 more cycles till finally it cracked. In fact at this time it was evident that 2,000 psi differential pressure after 13 cycles caused a crack in sample II-F. As a result the failure cycle should be more than 8 cycles and less than or equal to 13 cycles, **Figure 37** and **Figure 38** .

Figure 35. Sample I-F, a micro crack.

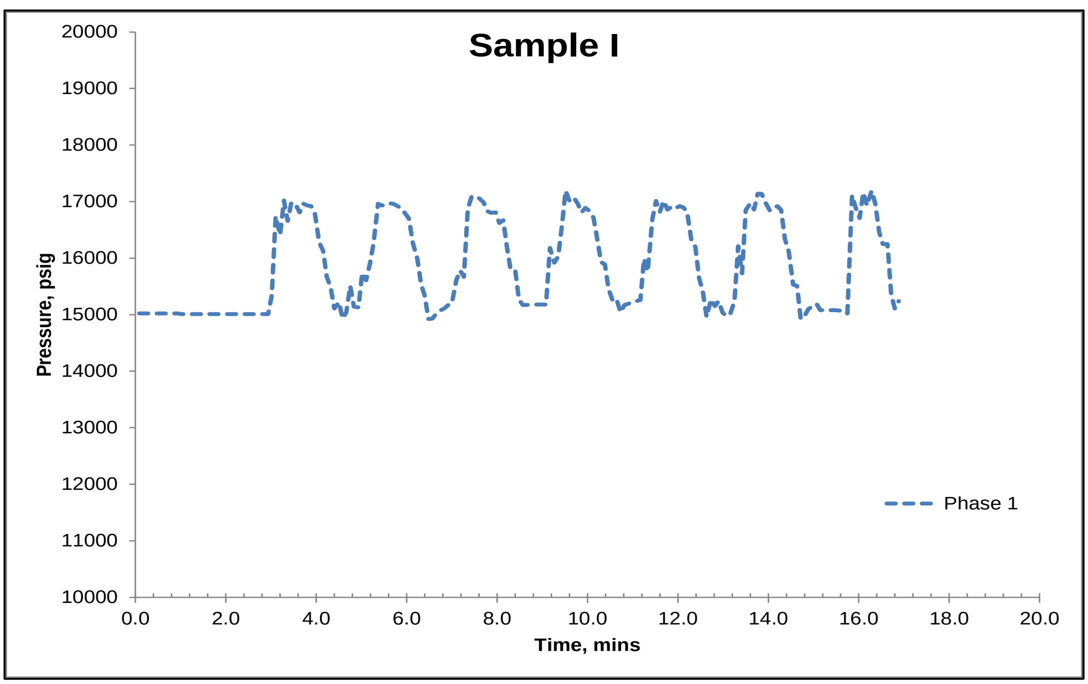

Figure 36. 7 cycles in sample I-F, micro crack.

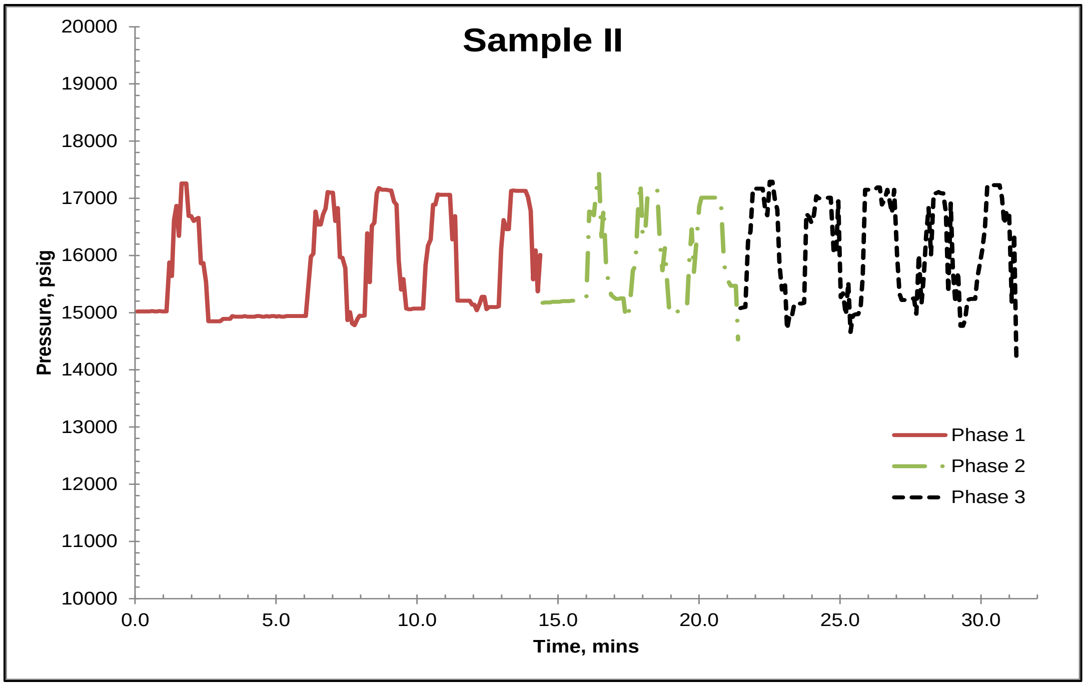

Figure 37. Sample II-F, cracked after three phases of cycling.

Figure 38. Sample II-F, cracked after 13 cycles.

Sample III-F which had been cured at 15,000 psi and 330 ˚F for 15 hours, was tested with the confining pressure of 15,000 psi and varying casing pressures between 15,000 psi to 17,000 psi. During this test periodically the casing pressures slightly went under 15,000 psi (confining pressure) but its effect was negligible since neither any debonding nor other cement sheath failures was observed after 12 cycles, **Figure 39**.

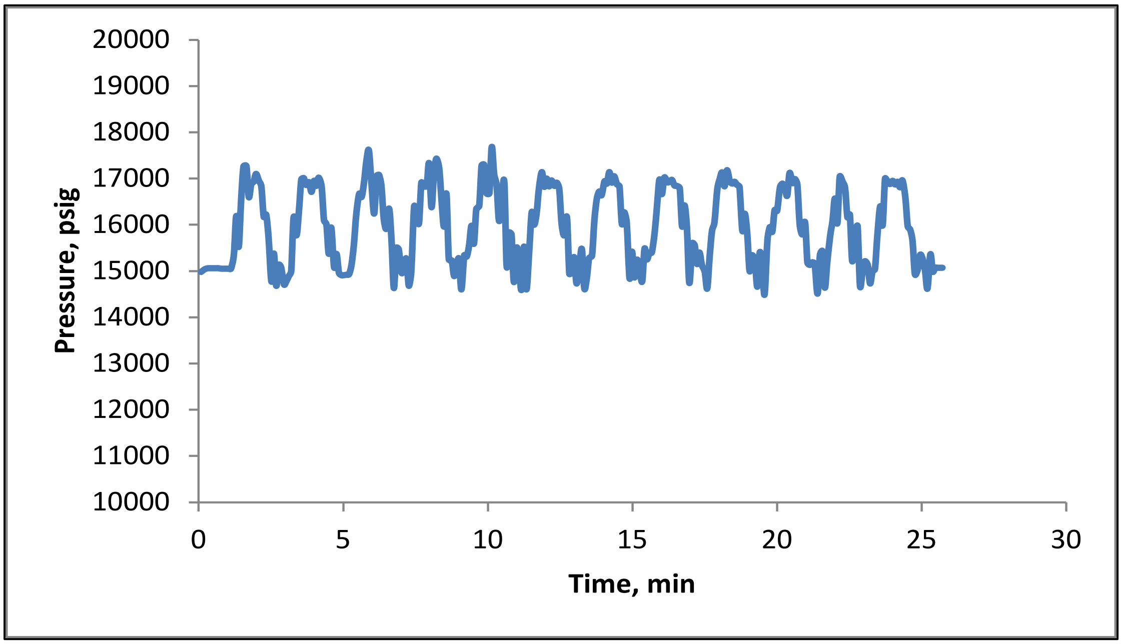

Figure 39. Sample III-F, did not crack after 12 cycles.

A fourth sample, IV-F, was tested with 8 cycles followed by another 4 cycles and no crack was observed after a cumulative of 12 cycles, **Figure 40** and **Figure 41**. However when one more cycle is added, a failure happened. **Figure 42** summarizes the test on set E and shows cycle no. 13 as the failure cycle, fatigue endurance limit, for 2,000 psi differentials at the 15,000 psi confining pressure for class H cement plus 35% silica.

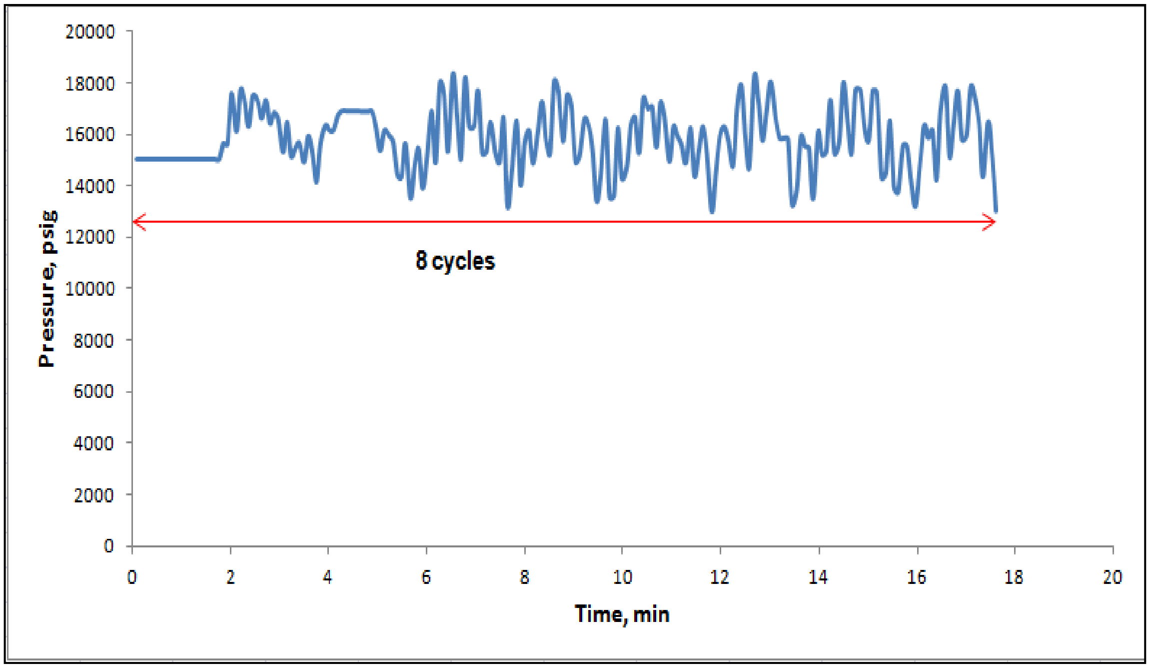

Figure 40. Sample IV-E, did not crack after 8 cycles, repeatability test.

Figure 41. Sample IV-E, No crack after 8 cycles, repeatability test.

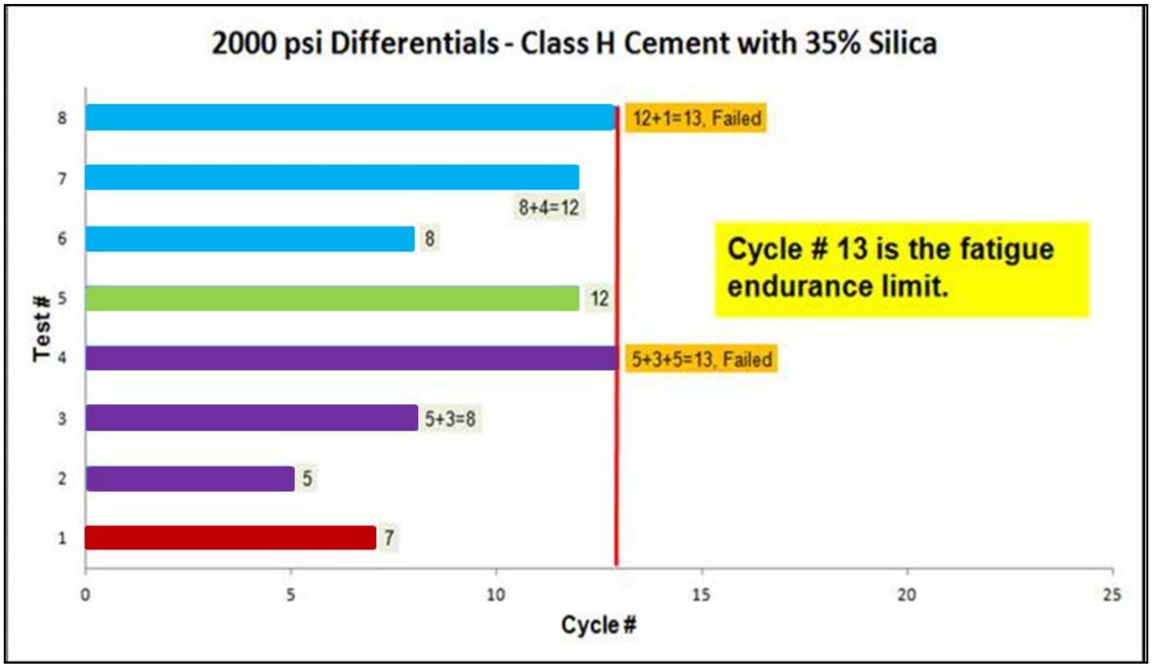

Figure 42. Failure cycle for 2,000 psi differential

Set G: 5,000 psi Differential Pressure

Set G was tested with 5,000 psi differentials. Confining pressure was kept constant at 15,000 psi and casing pressures varied from 15,000 psi to 20,000 psi. Sample I-G was cycled 10 times however it did not crack therefore it went through another 3 cycles. After the cumulative of 13 cycles, this sample cracked, **Figure 43**. Sample II-G was prepared and cured at the same conditions, **Figure 44** and **Figure 45**. It was then cycled for 11 straight cycles and hence it cracked. For repeatability, another sample (III-G) was cured at the same conditions of 15,000 psi and 330 ˚F. After cycling this sample for 10 times it was observed that it did not crack so another cycle was performed and sample III-G ultimately cracked. As a result cycle no. 11 is recognized the fatigue endurance limit for class H cement plus 35% silica with confining pressure of 15,000 psi and 5,000 psi differentials, **Figure 46**.

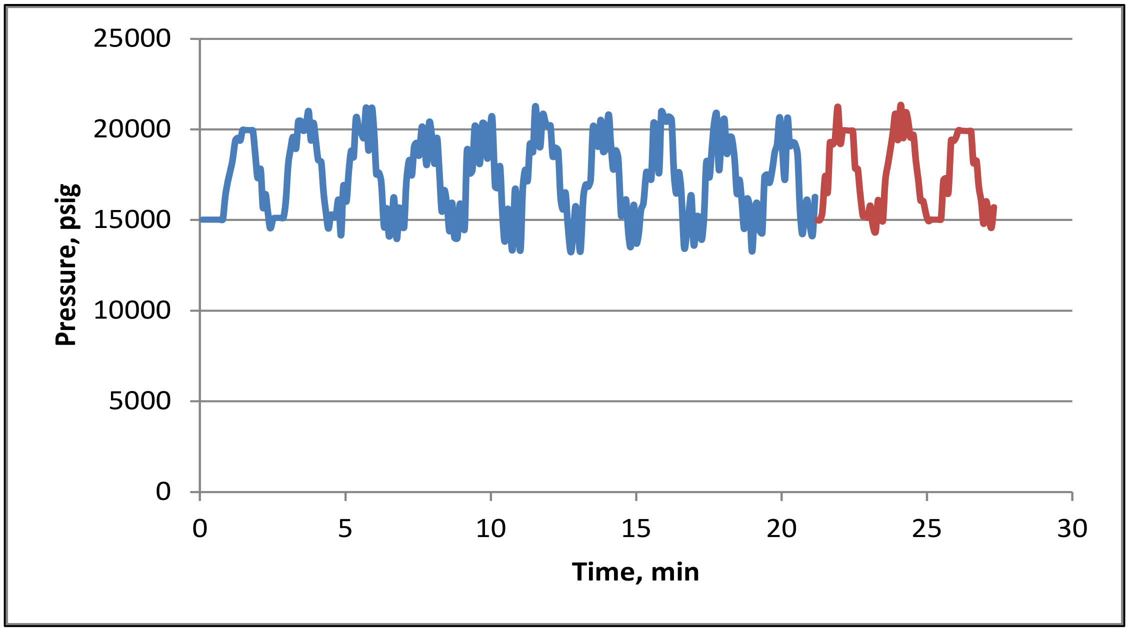

Figure 43. Sample I-G did not crack at 10 cycles but cracked after 13 cycles.

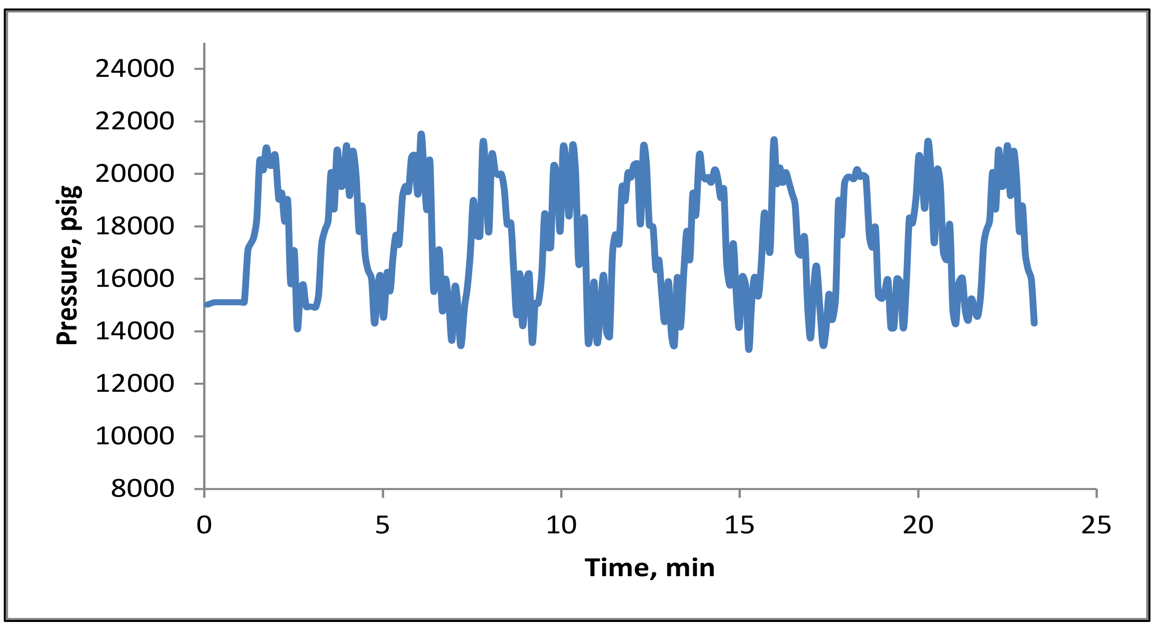

Figure 44. Sample II-G, cracked after 11 cycles.

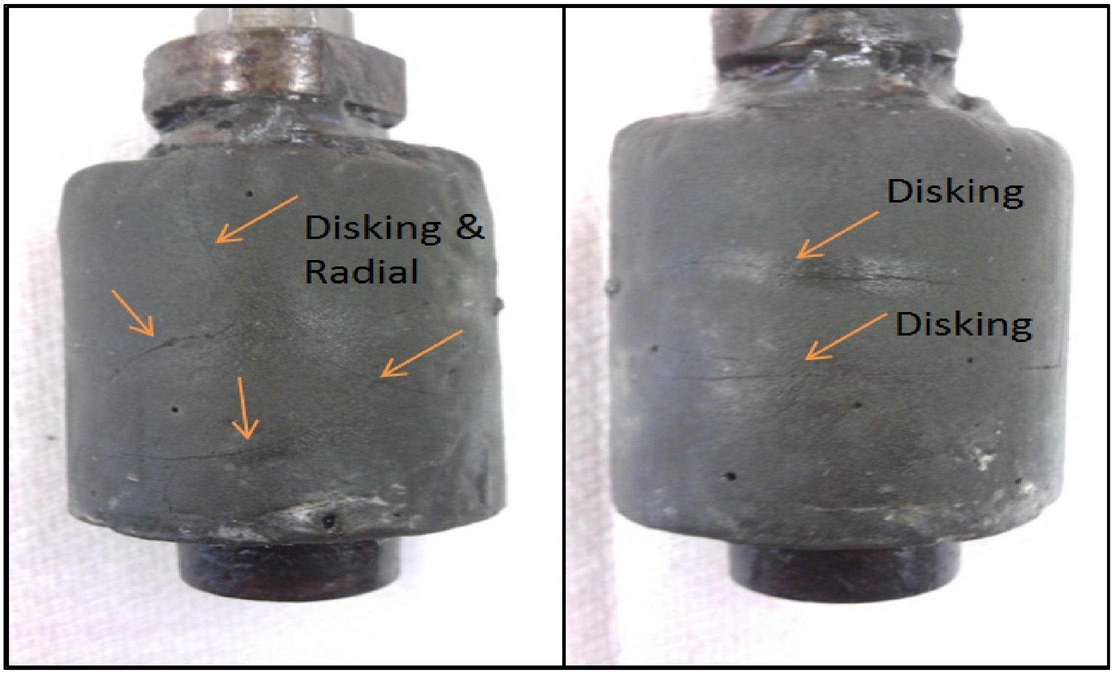

Figure 45. Sample II-G, catastrophic failures.

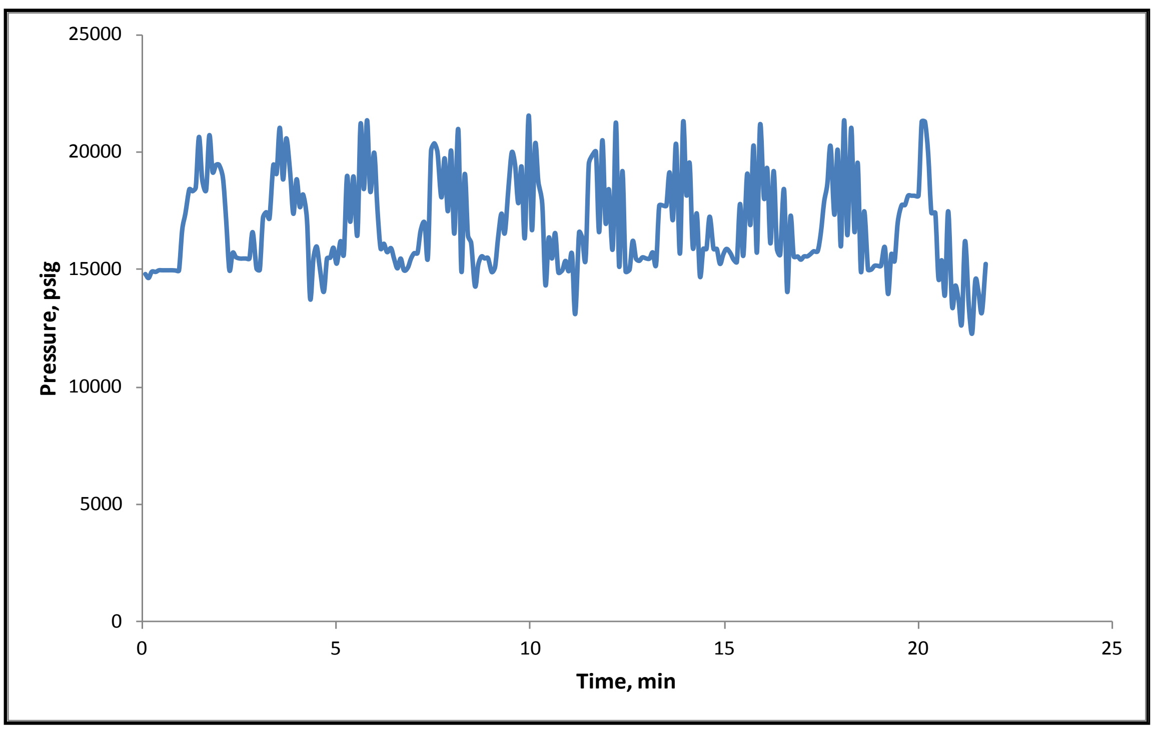

Figure 46. Sample III-G, no failure after 10 cycles- repeatability test.

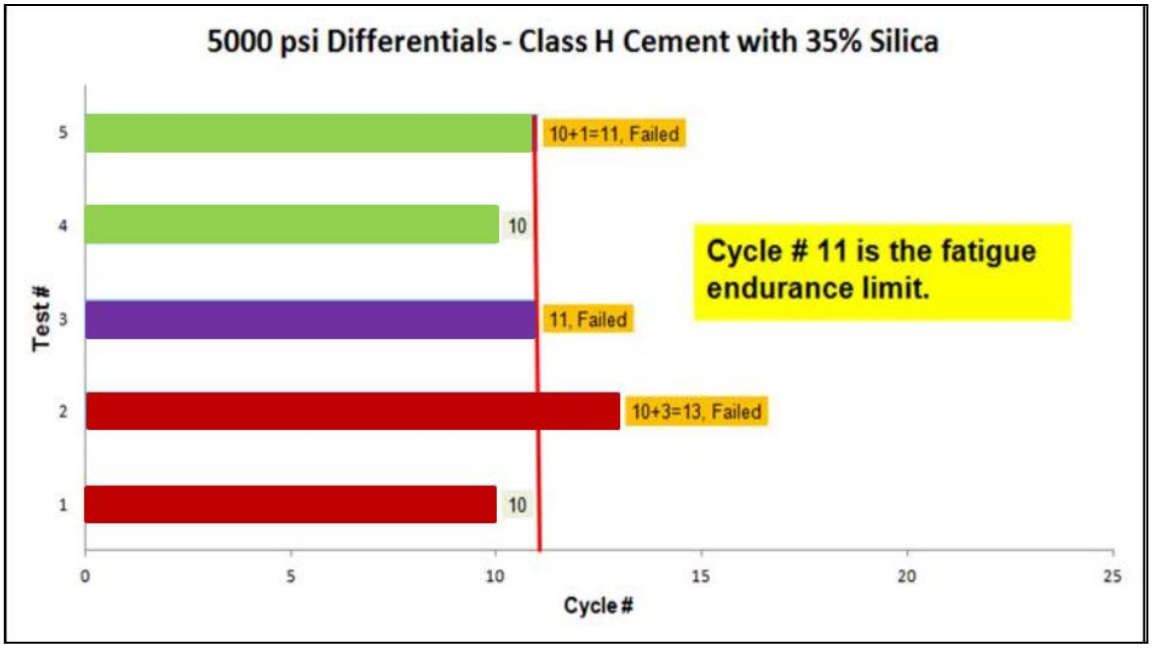

Figure 47. Failure cycle for 5,000 psi differential

Table 6 summarizes the failure cycle number and the type of failures for sets E, F and G. All samples were prepared and cured under the same condition of 15,000 psi and 330 ˚F. Set E was tested for the maximum pressure differentials of 1,000 psi. Running tests with low pressure differentials sometimes is hard and the pump steps should be tuned if low pressure differentials is intended to be achieved. Set F was tested for the maximum pressure differentials of 2,000 psi. Disking failure observed for this set is the only distinguishable criteria with 1,000 psi pressure differentials. Set G which was tested for the maximum pressure differentials of 5,000 psi more catastrophically failed at reaching its fatigue endurance limit.

The failure cycle might vary if the length of the sample increases or it is given more time to for building up higher compressive strength. Mechanical properties of the material placed at the outer boundary of the cement will be another dominating factor. These tests were performed by no outside bond between cement and the formation. The samples were all submerged in oil with the confining pressure of 15,000 psi.

Table 6: Analysis test matrix for set alpha, class H and 35% Silica

Set		E	F	G
Curing	Time, hours	15	15	15
	Pressure, psi	15,000	15,000	15,000
	Temperature, ˚F	330	330	330
Testing	Confining Pressure, 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
	Failure Cycle #	14	13	11
	Failure Type/s	Radial Crack	Radial Crack & Disking	Radial Crack & Disking& Combination of Both

Several mechanical failure tests emanated from civil engineering have been done on cement samples however results represent a more realistic picture of what happens to oil well cement. **Figure 48** shows the behavior of class H cement plus 35% silica which was cured at 15,000 psi and 330˚F for 15 hours. Higher pressure differentials have caused the cement sheath to fail more catastrophically and at the lower cycle number. The failure behavior (failure cycle number) of class H cement plus 35% silica does not have a linear behavior at HPHT conditions.

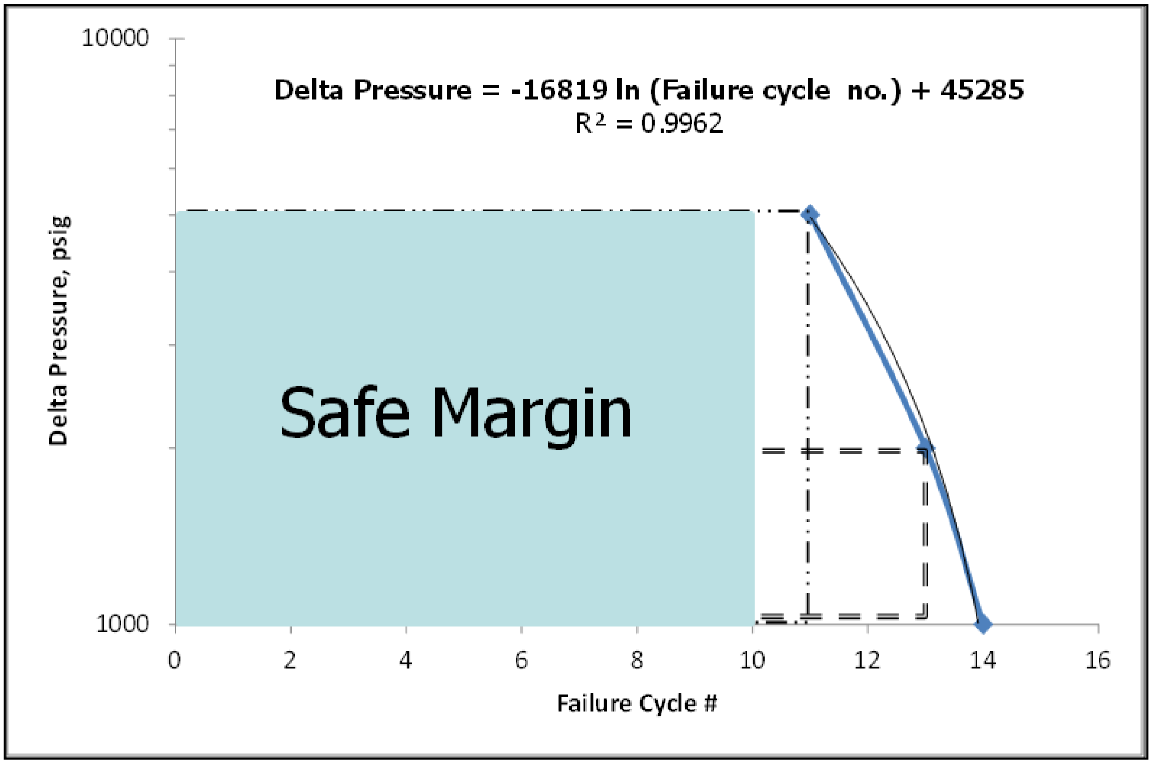

Figure 48. Delta Pressure vs. Failure Cycle #, Class H cement plus 35% silica.

CHAPTER V

CONCLUSION

1) To prevent cement sheath failure a HPHT testing procedure was developed which can help unconventional wells to achieve better zonal isolations by providing a realistic fatigue endurance limit for well cement.

2) Samples of class H cement plus 35% silica were cured under 15,000 psi and 330˚ F for 15 hours. They failed at cycle no. 11 under 5,000 psi, pressure differentials, at cycle no. 13 under 2,000 psi, pressure differentials and at cycle no. 14 under 1,000 psi pressure differentials. Higher pressure differentials will cause a more catastrophic failures when the fatigue endurance limit (cycle) is reached.

3) Cyclical loadings at very low cycles usually cause a radial failure for class H but the failure cycle is higher, e.g. 11 with 5,000 psi differentials, when 35% silica is added to class H. Adding Silica will result in modifying some chemical reactions above 220˚F which ultimately lead to a better integrity of cement sheath.

4) Radial failure (cracking) occurred before or along with other types of cement failures. In the entire experiments with class H and class H plus 35% Silica, radial failure is likely to be the primary failure that takes place under cyclical loadings at HPHT conditions.

5) Disking failure for neat class H cement happened only for pressure differentials more than 5,000 psi and temperatures beyond 350˚ F. Higher pressure differentials are more likely causing disking failure for class H. On the other hand, for class H plus 35% silica disking failure happened for pressure

differentials beyond 2,000. No such a failure was detected for 1,000 pressure differentials.

6) Types of failure can be effective in fluid flow through the cracks and reasonably fewer failures will reduce the chance of gas migration therefore testing the integrity of the cement sheath is critical before applying it in the field.

7) Class H cements is not a good comparison criterion for evaluating cement integrity at HPHT conditions due to the unstable chemistry and cement retrogression phenomenon. Modifying the slurry by adding 35% Silica considerably added to the performance of cement under cyclical loadings at HPHT conditions.

8) Inconsistent confining pressure can have very detrimental effects on the integrity of the cement. This can imply that pressure maintenance methods should not be carried out while hydraulic fracturing is being done in close by wells.

CHAPTER VI

RECOMMENDATIONS AND FUTURE WORK

1) A more accurate pressure gauge could be installed to accurately monitor the possible changes of the confining pressure.

2) The design of the cell could be modified so that the samples that are not perfectly centered can be also tested. The current set up does not have enough room for asymmetrically set samples.

3) Disassembling is quiet easy except for taking out the top cell. Modifications in design or disassembling procedure might be helpful.

4) Other types of slurry could be tested and the effect of various curing time should be practiced for a more comprehensive matrix development of a cement integrity behavior under HPHT conditions.

5) The experimental results should be compared with the commercial cement integrity simulation software and real field data since they are complementary to each other.

6) The set up should be modified with a new design in which the failure cycle could be investigated while the cement is under HPHT conditions. Also flowing a fluid through the sheath under cyclical testing at HPHT conditions would be an ideal and realistic way to ensure the optimum cement integrity evaluation.

7) Fatigue analysis is a complex subject for even homogeneous alloys and more complicated for cement. Curing process and the effect of the percentage of air bubbles trapped in the sheath should be considered and more researched.

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