Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale

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Abstract

This long-term comprehensive study of the cement systems and field operations applied in the Marcellus Shale play targets elimination of zonal isolation concerns and associated cost, safety, and environmental issues. The approach used in this study was to develop an integrated process to optimize zonal isolation, reduce operational issues, minimize remedial cementing, and optimize rig time spent waiting on cement.

In this study, a systematic and holistic approach was taken to analyze and potentially improve cementing operations on all casing strings. Initially, a method of observation and analysis was developed using laboratory testing, field observation and engineering analysis. This method allowed for identification of areas of improvement or local best practices. From the issues identified, recommendations were made and, implemented. As the project progressed, a constant feedback loop was continuously running with new ideas to improve cementing technology and operations. By focusing on cementing operations and design an overall increase in the quality of cementing processes was accomplished.

Considering the current emphasis on U.S. shale drilling and evidence of improvement from previous research cementing improvement delivers potential for reduced cost and increased safety. Improved cement performance produces better zonal isolation which can result in lower cost to drill, more effective fracturing operations, and higher ultimate productivity of the well. This project was specifically selected by RPSEA to identify issues in shale and identify best practices that will alleviate issues with zonal isolation, safety and the environment in shale reservoirs. This report is submitted in fulfilment of Task 14 of the Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale project.

Signature and Date Stamp

X Jeff Watters 11/13/14

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Acknowledgement Statement

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1 Executive Summary

This report is submitted in fulfillment of Task 14 of the project "Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact thorough Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale". This project combines field observation, laboratory testing, and engineering analysis to identify areas of improvement in the zonal isolation process as well as determine recommendations for the area either from existing designs and practices or new ones. An undertaking of this nature is important in furthering the shale gas movement in the United States. Current data from the EIA show the Marcellus region exceeded 15 billion cubic feet per day of natural gas production in July 2014 (Jozef Lieskovsky). Pennsylvania has also seen major growth in recent years in its natural gas production, from 2011-2012 it grew by 72% (Kopalek). These statistics, combined with the current focus on US shale make it necessary to optimize zonal isolation of these wells being drilled to mitigate environmental impact and improve production performance.

Data collection is the first step in this project, which included both historical data collection and real time field data collection to assess field operations. After that, laboratory testing is conducted to assess the cement designs used in the field. All of this data is collected and analyzed to identify areas where recommendations could improve zonal isolation.

The first areas of improvement identified were in operations. Working closely with the operator and service providers allowed for the collection of data before, during, and after cementing operations. That data was then relayed to engineers for analysis. Areas identified for increased attention were equipment maintenance and the experience levels of personnel. Improvements were seen by the end of the project in both of these areas as a result of increased experience on the job and access to proper training either on the job or elsewhere.

Cement design was the next area of improvement. Laboratory tests were conducted on an initial set of cement field blends to determine a benchmark for average on-site performance. These tests were also performed on pilot samples of the blends used in the field to determine a baseline for how the systems were intended to perform as initially designed in the laboratory. Originally, systems were obtained from two different service companies and included surface, intermediate, production lead and production tail blends. Within the first year of this project, the surface and intermediate blends type changed from conventional to thixotropic. These blends were the main focus of the study as the intermediate section was found to be the highest priority for zonal isolation. Gas migration testing for the cement was the primary area of work. Areas of interest were divided into short term and long term gas migration through cement. After short term gas migration properties were established and implemented in the field, long term gas migration properties were the focus. There were significant differences between the two systems implemented in the intermediate section of the wells. These differences were correlated with historical well performance, showing a higher success rate with one system over the

other. After testing mechanical properties and durability of each cement system, it was found that the one with higher durability and better mechanical properties was the most successful in the field. This resulted in field implementation of new slurry design criteria which included durability and mechanical properties.

The improved operations and cement design has resulted in better zonal isolation in the area as reported by the operator. Data collection from the area shows progress in operations as well. Fewer mistakes are made on the job and procedures run more smoothly than at the beginning of the project. Cement design improvements include enhancement of the properties that prevent gas migration through the cement sheath. Establishing these performance properties has also led to optimal testing of a cement system prior to field implementation.

2 Report Details

In the next sections, all work performed during this project is presented. This includes methods of experimentation and implementation, results and discussions, impact to producers, technology transfer efforts, conclusions and recommendations.

3 Experimental Methods

The next sections detail the methods used for data collection and analysis. A three pronged approach was used to tackle the goals of this project using field observations, laboratory testing, and engineering analysis. This is an efficient and effective way to collect data, produce meaningful results, and make useful recommendations. Throughout this process it is necessary to have open communication with the operator to ensure the recommendations were implemented properly. This communication also allowed for a continuous feedback loop to ensure the processes were effective.

3.1 Field Observations

Field advisors were sent to the Marcellus as independent observers of cementing operations. Each field advisor has 20-30 years of cementing field experience. They performed back to back trips from July 2012-December 2012 and August 2013-December 2013. The field advisors collected job data including:

- Pressures
- Rates
- Density variation
- Temperatures
- Returns
- Contingency plans
- Recovery from issues on job
- Rig up technique
- Performance of service company equipment
- Performance of service company personnel

The field advisor collected documentation when available such as lab sheets, load out sheets, casing tally, simulations, and the cementing program. They worked closely with the operator, service companies, and other third parties in the field. They visited bulk facilities and laboratories to analyze equipment, procedures, storage areas, and personnel.

3.2 Laboratory Testing

Standard laboratory testing as described in API RP 10B-2 was performed and included:

- Thickening time
- Compressive strength
    - Ultrasonic Cement Analyzer (UCA)
    - Ultimate Compressive Strength (UCS) Crush test
- Density
    - Pressurized mud balance
    - Pycnometer
- Free fluid
- Fluid loss
- Rheology
- Fluid migration analyzer (See Interim Report Section 4.2 for a detailed description)
- Settling tests
    - Dynamic (See Appendix 4 – Placement Methods and Slurry Stability section)
    - Static settling - The primary method used is the sedimentation test, detailed in API RP 10B-2, A second method to indicate settling uses the sample from a UCA, measuring the density of a section from each the top, middle and bottom of the cell. The desired variance in density is less than 10%
- Static Gel Strength Analyzer (SGSA)

3.2.1 Annular Seal Durability Testing

Zonal isolation can be compromised in many ways. One of the major causes is physical deterioration of the cement sheath via stress cycling. This can occur due to post cementing operations such as drilling and hydraulic fracturing, or thermal stresses. The testing method used a 3" PVC pipe to simulate an outer barrier and a straightened length of 1" coiled tubing to simulate casing (Figure 3-1: Annular seal durability testing). Cement was cured in the annulus between these two barriers for 48 hours at bottomhole static temperature (BHST) and at ambient pressure. To run the test, a differential pressure of 10 psi was put across the cement sample. The inner pipe was cyclically pressured between either 0 psi to 5,000 or 10,000 psi until the cement sheath failed. Failure was indicated by gas breakthrough at the surface of the sample due to the failure of the cement seal at either the outer boundary or the inner pipe boundary.

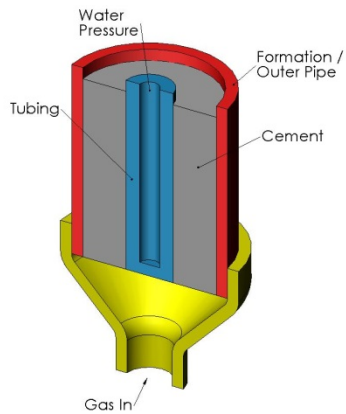

Figure 3-1: Annular seal durability testing

3.2.2 Small Scale Impact Testing

After cementing surface and intermediate casings, drilling typically continues within 12-24 hours. This drilling activity could have an effect on the integrity of the cement sheath due to vibrations or possible impacts from either the drillpipe or the bottom hole assembly during bit trips. Since both of the cement intermediate systems have similar compressive strengths, it was decided an impact test should be run to determine overall durability as well as identify any differences between the cements. There were two types of impact tests developed for this project. The first was a "small impact test". This used a 6" long 1"x1" cement bar that was placed in a fixture and a 66 gram ball was dropped from a height 9.25" above the cement sample. These tests were performed after curing the cement for 24 hours. The number of drops that a cement sample was able to withstand without breaking was recorded. Figure 3-2: Small scale impact testing shows a failed specimen.

Figure 3-2: Small scale impact testing

3.2.3 Large Scale Impact Testing

Large scale impact testing was performed to scale up from the small impact test. These tests were performed using large rectangular pipes and an apparatus to provide an impact force on the layer of cement between the steel walls of the pipe. The idea was that the cement would be contained within two metal walls in the field, the test was performed similarly. Instead of a concentric pipe in pipe

annulus, this test evaluated the cement sheath represented as an unwrapped annulus. This test used a 4' pipe with a 2"x12" cross sectional area (see Figure 3-3: Large Scale impact testing sample mold)

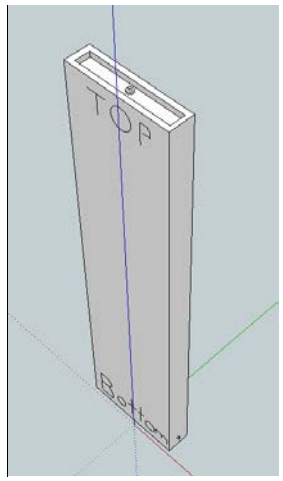

Figure 3-3: Large Scale impact testing sample mold

The rectangular pipe was filled with cement and cured for 48 hours at 100psi. This cement filled pipe was then placed in an apparatus designed to hold it in place while another weighted pipe was dropped on it to simulate impact in the field (see Figure 3-4: Large scale impact testing). To indicate communication, a pressure gauge was hooked to one end of the pipe, while air was flowed into the other end, so when a pathway occurred, pressure would be shown on the gauge.

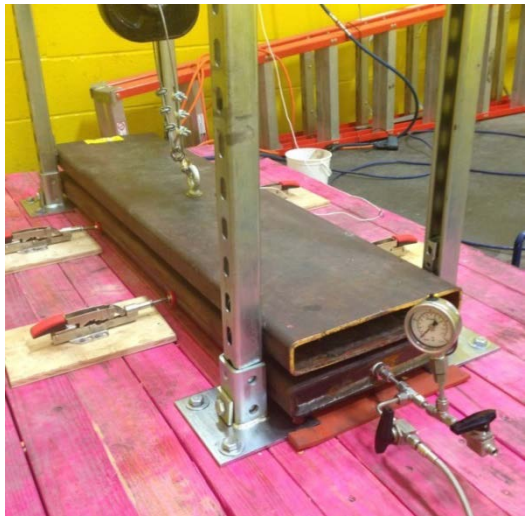

Figure 3-4: Large scale impact testing

3.2.4 Permeability Testing

Small scale gas permeability testing was performed using a permeameter. This process uses 1 inch set cement cores for testing. The cores are cured for up to 5 days and loaded into the cell for testing where air is flowed through one end of the core at different pressures and permeability is determined from the resulting pressure at the other end.

Large scale permeability testing was performed in 2" Schedule-80 pipes. These were cured under pressure for 48 hours before testing began. Testing was performed by holding pressure at the bottom of the cell for up to 20 days. This test was performed to see if permeability will change in the cement system over time. Figure 3-5 shows the setup of the cell and pressure system:

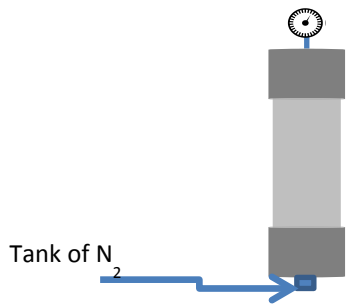

Figure 3-5: Permeability test cell set up

3.2.5 Durability Testing

Durability testing included mechanical properties: Young's modulus, Poisson's ratio, tensile testing, anelastic strain, and flexural strength. Procedures for the first three tests can be found in the interim report.

Anelastic strain testing was also performed on the mechanical load frame. After determining the ultimate compressive strength of a cement system, a new sample of the same system was loaded for cyclic loading. In this test, the sample was loaded from 5% of ultimate compressive strength (UCS) to 50% of UCS and back 25 times. To determine strain during this process the sample was fitted with Linear Variable Differential Transformers (LVDT) that were able to measure axial strain during loading. After loading, the strain was plotted on a graph versus time and the slope of the strain curve was measured to determine anelastic strain. This test was performed to determine how much deformation occurred during a cyclic event. Systems with higher potential for anelastic strain show more total deformation during the cyclic event than the ones with a lower potential for anelastic strain.

Flexural strength measures how a cement sample will be affected by a bending force on the cement. A ¾" rod of cement is created by using a metal round mold. This cement sample is cured 24 hours at temperature and pressure, and then removed and placed on the testing apparatus. A string is placed along the middle of the sample. The string is connected to a torque transducer, and an LVDT is placed to measure the amount of deformation experienced by the cement sample during bending. The test is

started when the motor begins to turn, reeling in the string and bending the sample until failure. The maximum flexural strength is measured upon failure of the cement rod.

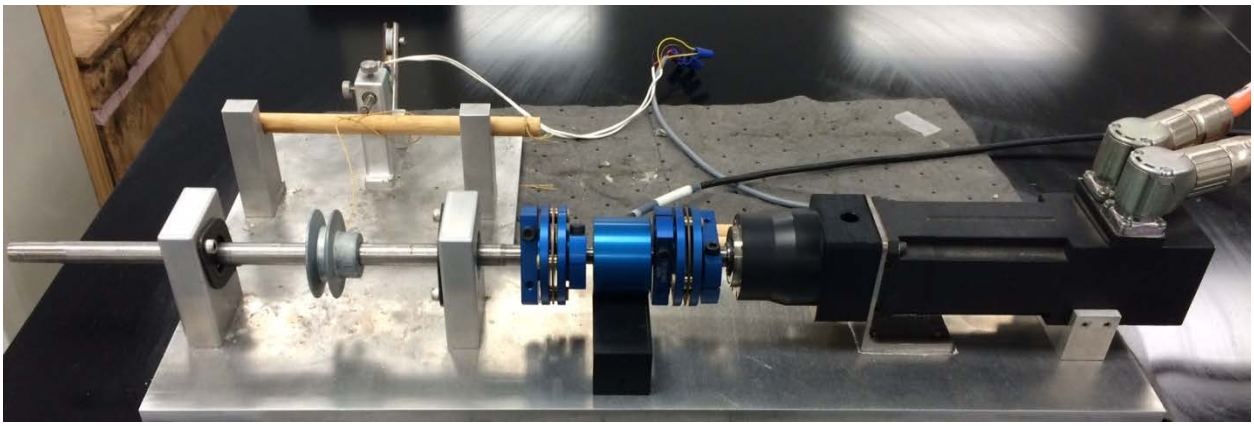

Figure 3-6 shows the flexural testing device. In this set up, a wooden dowel represents the ¾" cement rod used for testing.

3.2.6 Hydration Volume Reduction (HVR) Testing

Volume losses occurring during the time the cement is setting can happen either through fluid loss or hydration volume reduction. Hydration volume reduction in Portland cement is what causes the formation of porosity and volumetric shrinkage and is the result of the hydration reaction between cement and water. This test was run by pouring cement slurry conditioned at BHCT into a UCA cell, applying pressure and temperature, and recording the volume change as the cement sets.

3.3 Engineering Analysis

At the University of Houston, statistics and mathematical modeling was used to analyze the data presented. Two studies were performed. The first study titled "Lowering Drilling Cost, Improving Operational Safety and Reducing Environmental Impact through Zonal isolation Improvements for Horizontal wells Drilled in the Marcellus Shale" details the statistical study performed on the wells where this investigation took place. The second study titled "Study of Rotation Drill Pipe Impacts on Casing Wall" was performed to analyze the potential damage to cement caused by drill pipe impact. To see a report on each of these studies in full, refer to the attached reports from the University of Houston in Appendix 5.

The goal of the first study was to build a model that could be used to analyze the effects of various physical factors on zonal isolation. The ultimate aim of this model is to predict if zonal isolation would be obtained on a well. Sustained casing pressure (SCP), or lack thereof, was used as a measure of success. Partial least squares discriminant analysis (PLS-DA) was used to build these models. The method of leave one out cross-validation (LOOCV) was used to judge the predictive ability of the classification models. Variable importance projection (VIP) variable selection was used to find the

important dimensionless variables. These models were applied to both the intermediate casing cement and the production casing cement. The model used for the intermediate casing cement used the PLS-DA technique on dimensionless input variables. The output was a binary, SCP or no SCP. Using cross-validation, results show that the model is able to classify 73% of wells in this data set correctly. The same PLS-DA Technique was implemented on a different set of dimensionless input variables for the production casing section. This model was able to classify 71% of the wells in the data set correctly. Both models show great promise for determining important variables on wells and predicting success rates of cement jobs in other fields as well. For example, in the intermediate casing model, lower water temperature was linked to higher occurrence of SCP. This could be due to difficulty mixing when the water gets cold. Other variables linked to SCP are cement pump rate, displacement rate, and certain parts of the wellbore geometry. A the full evaluation of each variable and its effect on SCP is included in the report in Appendix 4.

The model in the second study allowed for the study of the drill pipe's interaction with the casing wall and subsequent effect on cement sheath. This area of study was selected to further analyze any potential effects of drill bit or string vibration on the previous casing and the surrounding cement sheath. Lateral vibrations of rotating drill pipe were studied and a mathematical model was created using the effects of linear and non-linear forces such as rock-bit interaction force, viscous force by drilling mudflow, casing wall-drill pipe contact force, centrifugal force, pipe weight, and elastic forces. The drill pipe-casing contact force was modeled using Hertzian contact theory. The contact force between drill pipe and the casing wall was modeled as force acting between a spherical body and a flat surface. The analysis of the drill pipe motion in the horizontal section used a different set of governing equations than drilling the vertical section, all equations are shown in Appendix 5. The results from this study showed the energy input to the casing wall. Results from this study showed an estimate for the amount of energy input to a cement sheath during the drilling process. This aids in determining the mechanical properties needed of the cement.

3.4 Implementation

Suggestions were provided to the operator on a regular basis over the course of this project. This regular communication with the operator allowed for real time adjustments in operations and design. These occurred by email, teleconference, phone conversations, and face to face meetings. These communications occurred on a week by week basis.

The cement designs currently being used in the field were evaluated through laboratory tests described in Section 3.2. When the discovery was made that one cement system had a very high success rate in the field, and the other one had a low success rate, the cement system with the higher success rate was exclusively used on the wells in the area. As reported by the operator, they had continued levels of success with the better cement system.

New cement designs from current service companies were tested as a part of a continuous improvement process in this area. In addition, new cement systems were tested from other service companies for potential use in the area. Improved laboratory testing procedures were used as well. This included testing for cement durability on both surface and intermediate strings so that any future systems would have the same success rate as the operator was experiencing with the previous successful blend at a minimum. Resulting benefits were improved operational practices with training. An online training class was developed for this project. It is a general cementing refresher type course with a focus on specific practices that are beneficial to the Marcellus shale. This course has five sections with accompanying tests covering cementing overview, engineering and design, laboratory testing, bulk plant, and field operations.

Each section discusses some general cementing topics with useful information that applies specifically to cementing design and operations in the Marcellus Shale. This course can be found at: https://csitechnologiesllc.digitalchalk.com. This fully supported course currently costs $100 and is available to the public.

After training materials were provided to the operator, a field advisor from CSI Technologies was sent to Pennsylvania to provide onsite advice when needed. This trip was also to assess any improvements in operations from the beginning of the project. The assessment occurred from May 29th-June 12th 2014. During this time, the field advisor was present on nine cement jobs. Four intermediate, one surface and four production jobs.

4 Results and Discussions

For the first phase of this project, historical data, laboratory data, and field data were collected and are included in the Interim Report. Cement durability and mechanical properties testing was performed on several field blends during the second phase. Table 4-1 summarizes the results and reports the average values for the intermediate string.

Table 4-1 : Average intermediate mechanical properties, for the system being used during the second phase field work.

UCS	Young's Modulus	Poisson's Ratio	Tensile Strength	Anelastic Strain
2239 psi	1.135E6 psi	.31	300 psi	2.49E-5 %/sec

4.1 Field Data

Field work has shown great improvement in efficiency and execution. Improvements have been observed for all strings. Of the total jobs in Phase I, nearly 45% saw issues with equipment on location.

Nearly 28% of the total jobs had issues due to human error. That means around 72% of all the jobs observed had some kind of issue. During the phase 2 observations, these numbers decreased dramatically. Equipment issues were around 12% of the total number of jobs, and human error issues occurred in around 13% of observed jobs. This is a total of 25% of jobs with noted issues in the second phase(Table 4-2 : Field work data).

Table 4-2 : Field work data

	Phase 1 Field Work		Phase 2 Field Work	
Total jobs	69		52	
Total On-Job Issues	50	72.46%	13	25.00%
Equipment	31	44.93%	6	11.54%
Human Error	19	27.54%	7	13.46%

See Appendix 1 for full details.

4.1.1 Standard Cement Testing

Continued field testing to gather this data has been important to assess any changes in the cement system's composition and properties. Changes in these basic properties can indicate a design change or differences in blending and loading. Bulk plant blending and delivery of cement can result in variations. These variations can be due to differences in cement load, chemical additive lot numbers, and poor blending practices. By conducting laboratory tests on each cement blend any variations in the cement properties that may be causing issues in the field can be identified. Fluid loss control is a good example of a property that showed a lot of variation from blend to blend. Fluid loss control is highly dependent on adequate cement blending practices, accurate weight measurements of cement and chemicals, and controlled mixing practices when pumping downhole.

Table 4-3: Average cement testing results

Averages	Surface	Intermediate	Production lead	Production Tail
Thickening time (hr:min)	5:26	4:16	4:56	5:06
Compressive strength, 24h, (psi)	950	1560	1510	1680
Free Fluid %	0.1	0.02	1.0*	1.3*
Fluid Loss (mL/30min)	461	427	417	143
Rheology				
Surface PV	49	39	101	125
Surface YP	44	42	9	22
Conditioned PV	100	92	109	111
Conditioned YP	68	78	15	26
Density variance, %	0.13	1.46	4.28	2.54

*Free Fluid test performed at a 45°angle

Fluid loss control : Adequate fluid loss control reduces the amount of fluid from a cement slurry being lost to the formation. By retaining the fluid in the slurry, the column of cement will continue to provide enough hydrostatic pressure to the formation to prevent gas flow while the cement sets. The only slurry with mostly consistent fluid loss control results is the production tail system. The other systems (surface, intermediate, production lead) all have quite a bit more variance in fluid loss control. In the surface, intermediate and production lead slurry systems, the fluid loss control could be tighter, with lower overall fluid loss. The lower fluid loss helps to create a more competent cement downhole.

Free fluid control: Consistently less than 2% for all strings. This indicates acceptable cement stability, which is very important in the horizontal section for uniform cement coverage. This is also a critical parameter in the vertical section to achieve good top of cement and slurry stability.

Thickening time: Thickening time varies from job to job on each string. This could be due to blending procedures or how the sample was collected on location.

Compressive strength: Compressive strength for each string falls in an acceptable range at the 24hour mark.

Rheology: Rheological properties were acceptable on all field blends received. All were pumpable at both surface and downhole conditions.

Density variance: The density variance on average is low. Commonly accepted variance for this test is less than 10%. All of these are less than 5%. This is especially key in the horizontal section for consistent

pipe coverage. In the vertical section, it is important so the upper portions of the cement sheath have the same properties as the cement was designed to have.

The full data report for the laboratory testing is in the Appendix 2. See the Interim Report for a full description of tests and data from phase 1. Laboratory investigation is in Section 4, starting on page 14. See Appendix 2 in the Interim Report for data regarding the standard cement testing from the first phase.

Complete and competent zonal isolation is the major goal of cementing a well. Without good cement coverage and complete zonal isolation, gas from the formation may leak through to surface resulting in sustained casing pressure. Gas migration can be split into two major time periods, short term and long term. Short term gas migration occurs before the cement has set. Long term gas migration occurs after the cement has hardened. The sections below discuss the data and results found when testing for the specific properties related to each of the gas migration categories.

4.2 Short Term Gas Migration Prevention Results and Discussion

Short term gas migration prevention depends on maintaining enough hydrostatic pressure on the formation to prevent an influx of gas during the time it takes for the cement to set. The properties held responsible for that in a cement system are listed below.

Static gel strength development: The transition time is the time it takes for the cement to develop gel strength from 100 lbs/100ft^2 to 500lbs/100ft^2. This is the time when cement begins to self-support, reducing the amount of hydrostatic pressure it can exert on the formation, which allows gas to enter the cement matrix and migrate toward surface. If this transition period is too long, it can result in the gas creating pathways to surface allowing gas to migrate indefinitely if the hydrostatic pressure exerted by the surly drops below the surrounding formation pressure. Shorter transition times reduce the chance of those pathways forming all the way to surface. Typical industry best practice recommendations are that this time is 40-45 minutes or less. This reduces the critical time that the gas can migrate through the slurry.

Hydration Volume Reduction test: A hydration volume reduction test was run on each of the cement systems used in the intermediate string in the field. This test measures how much volume is lost in a cement slurry during the initial reaction phase. This volume reduction is due to the chemical reaction of cement particles with water. Both systems had only a minor reduction in volume as shown below. Reports from the operator indicate no signs of short term gas migration.

- System 1: 2.6%
- System 2: 2.73%

The earliest systems used in this project had a high potential for gas migration (see Interim Report section 4.1 page 15). A reformulation resulted in the implementation of thixotropic cement systems (results shown in this report and the Interim Report section 4) with much lower potential for short term gas migration and slight bulk expansion. These systems had short static gel transition times and acceptable fluid loss control. When run in a fluid migration analyzer, the potential for gas migration was very low. From that data, it was determined that well integrity failures in this area was most likely due to long term gas migration.

See the Interim Report for more information, including cement system composition and data. Refer to page 17 for gel strength transition times, and Appendix 2 for field design results.

4.3 Long Term Gas Migration Prevention Results and Discussion

Long term gas migration can be due to physical damage to the cement sheath, poor mud removal, channels caused by poor mud displacement, bulk shrinkage of the cement sheath and increased permeability. After finding that there was a very small potential for short term gas migration with the cement systems tested, properties related to long term gas migration were investigated through a series of tests.

Permeability: Permeability was tested two ways for this project. The first used the permeameter with 1" diameter cores, and the second used 2" diameter schedule 80 pipe, 12" long. Both tests showed no measurable permeability of the cement samples. For the large scale testing, observation occurred for up to 21 days to check for leakage of any kind. No leakage occurred during the entire test. Flow was measured using a flowmeter. Small scale testing showed up to 200psi and no flow at the two day and 5 day tests. See Appendix 3 for full results.

Expansion/shrinkage: Ring mold tests were reported in the Interim Report, page 18, Chart 3. This test showed that overall, the systems showed at least a slight expansion. For a full discussion, please refer to the Interim Report.

Durability: These tests were conducted to assess how a set cement system will react to various stresses downhole. Set cement performs best in compression, however, downhole, it will be exposed to various other stresses like tensile stress. The source of these stresses is the post cementing operations such as thermal fluctuations, drilling, casing pressure tests, and hydraulic fracturing. Long term exposure to these stresses can result in damage to the cement sheath. For example, drilling the production string takes 1-2 weeks after setting the intermediate casing. During drilling operations, bit trips will take place, possible impact force from the drill pipe may occur, and then about 13,000' of production casing is run through the intermediate casing. This sort of cyclic stressing on the cement sheath may cause damage to the cement sheath that could open pathways for gas migration through the cement.

Field data shows the intermediate casing had the highest occurrence of casing pressure when compared to the surface and production casings. For an extended discussion regarding this result see the Interim Report section 3.4 page 12. The main result from this investigation showed that one cement system fared better than the other cement system. Lab testing confirmed the more successful cement system higher durability than the other, less successful cement system (Section 4.4.3 and 4.4.4 in the Interim Report).

To investigate further, a series of tests were conducted to assess the possibility of predicting cement failure versus energy applied to the cement sheath. This was based on a model developed previously by CSI Technologies to assess cement design and long term gas migration potential. The original model was not adequate for the cement designs and stresses predicted for the Marcellus area, so a new model was developed as detailed in SPE1913405 and SPE168650.

The systems chosen for the laboratory investigation were selected based on the cement systems used in the field. Variations in gypsum content, fluid loss control agent, and cement class were made to create 10 cement systems to create a trendline indicating average failure rate. This is fully discussed in SPE1913405. The main findings from this investigation were that no single cement property can adequately predict failure of a cement system. By combining the properties in a dimensionless number, it is possible to scale up this failure prediction to accurately represent field scenarios.

The following shows the properties tested and their results. The results from the field samples tested are in the Interim Report, Table 7 for Young's Modulus, Poisson's ratio and Ultimate Compressive Strength. Impact testing is shown in chart 4, and tensile strength is shown in Chart 5.

The testing run was:

- Young's Modulus
- Poisson's Ratio
- Tensile strength
- Anelastic strain
- Impact strength
- Annular seal durability
- Flexural strength

4.4 Field System Results

These results are from testing the systems that were being used in the field. System 1 is from Service Company A, System 2 is from Service Company B, System 3 is a proposed re-design. See Interim Report table 4 for designs

Table 4-4 : Field system results

	System 1	System 2	System 3
Young's Modulus (PSI)	1.24E+06	6.51E+05	9.21E+05
Poisson's Ratio	0.23	0.16	0.25
Compressive Strength (PSI)	1885	1685	1760
Tensile Strength (PSI)	161	114	143
Anelastic Strain (% deformation/seconds)	1.10E-05	8.49E-05	2.71E-05
Impact Strength in-lb/in^2)	4.20	1.96	4.77
Annular Seal Durability (in-lb)	649,097	319,916	Not Tested

4.5 Energy Study Results

These results are from the systems designed to develop the average failure line to help predict failure of a cement sheath. Ten cement systems were selected to be tested along-side the systems seen in the field.

Table 4-5 : Cement system compositions

Cement System	1	2	3	4	5	6	7	8	9	10
Cement Type	Class H	Class A	Class H	Class H	Class A	Class A	Class H	Class H	Class A	Class A
Gypsum %bwoc	-	-	3	5	3	5	-	-	-	-
CaCl %bwoc	2	2	2	2	2	2	2	2	2	2
Fluid Loss %bwoc	-	-	-	-	-	-	0.3	0.3	0.3	0.3

4.5.1 Energy Study Results

Table 6 shows the results from the energy study. These results were used to create the dimesionless variables used in the correlation in section 4.5.2. These results were obtained by the testing detailed in section 4.3.

Table 6: Results from testing for the energy study. Samples 1-10 are listed in table 4-5. Field 1 and Field 2 are the two systems that have been pumped in the field

Sample	Density	Ultimate Compressive Strength (psi)	Young's Modulus (psi)	Poisson's Ratio	Tensile Strength (psi)	Anelastic Strain Potential	Annular Seal Durability (in-lb)	Water/ cement ratio	Impact Strength (in-lb/in2)	Flexural Strength (lbf/sqin)
1	15.6	1520	879000	0.32	99	2.33E-05	12726	0.46	3.41	-
2	15.6	2922	1125781	0.28	206	2.14E-05	370570	0.47	4.77	1.74
3	15.6	2829	1180369	0.29	143	2.60E-05	205166	0.48	4.77	1.64
4	15.6	1692	756547.4	0.19	199	3.56E-05	357847	0.48	6.13	1.34
5	15.6	1732	759324.7	0.23	62	1.51E-05	335581	0.48	3.41	1.41
6	15.6	2058	845597	0.25	148	1.39E-05	434188	0.49	3.41	1.64
7	15.6	2545	1342695	0.29	327	1.31E-05	834977	0.46	4.77	1.65
8	15.6	2080	1635662	0.26	253	1.90E-05	675933	0.46	5.45	0.37
9	15.6	2008	953995.7	0.32	229	1.46E-05	612316	0.47	3.41	1.80
10	15.6	1555.5	1630563	0.26	191	1.40E-05	319677	0.47	2.73	1.57
Field 1	15.6	1885	1240000	0.23	161	1.10E-05	649097	0.48	4.20	1.49
Field 2	15.8	1685	651000	0.16	114.6	8.49E-05	319916	0.84	1.96	0.24

4.5.2 Energy Study Discussion

When comparing the results of each test, CSI found trends indicating improved performance associated with specific cement properties. However, these trends only showed weak correlations between individual cement properties and performance on energy tests. These weak single variable correlations suggest the problem is more complicated. Looking back at work previously done for MMS showed the cement properties can be correlated into dimensionless variables, as stated earlier, to determine failure. The two variables created were Energy Applied and Energy Resistance.

Equation 4-1: Energy applied

$$Ea = \frac{Energy\ from\ Stressor * Pipe\ ID}{Pipe\ Cross\ Sectional\ Area * Formation\ Young's\ Modulus * Annular\ Area}$$

Table 4-7 : Variable descriptions for EA equation

Variable	Definition	Units	Lab Data	Field Data
Energy from stressor	Energy calculated from annular seal durability test or from well operations	in-Lb	From data set results	From data set
Pipe ID	Casing ID	Inches	0.75	8.835
Pipe Cross sectional area	Cross sectional area of casing	In^2	0.34	11.45
Formation Young's Modulus	Young's modulus of the surrounding formation	psi	500,000	10,000,000
Annular Area	Cross-sectional area of where cemented annulus	in^2	6.28	180

The first variable discussed is energy applied. In this relationship, the applied energy can be from the annular seal durability test or the well operations in the field. The other factors in this ratio are how the applied energy affects the cement sheath.

- Energy from stressor: energy imparted on the cement sheath from either the annular seal durability test or estimated field stress
- Pipe ID: a larger diameter on the pipe will decrease the amount of force applied to the cement, therefore decreasing the amount of energy applied to the cement sheath.
- Pipe cross sectional area: a thicker casing will expand less when pressure is applied, therefore applying less force to the cement sheath, decreasing the amount of energy applied to the cement sheath.
- Formation Young's modulus: A higher formation Young's modulus will provide a better confining force on the cement, decreasing the effects of the force on the cement, by preventing excess deformation of the cement.
- Annular area: A larger annular area allows for a thicker cement sheath, which can help reduce the effects of a cyclic stress event on the cement sheath.
- Energy Resistance (Re) – Determined using set cement properties that relate to mechanical durability

Equation 4-2 : Energy resistance

$$Re = \frac{Poisson's\ Ratio * Tensile\ Strength * Impact\ Strength}{Pipe\ OR * W{:}C\ Ratio * Cement\ Young's\ Modulus * Anelastic\ Strain * Compressive\ Strength}$$

Table 4-8: Variable descriptions for Re equation

Poisson's Ratio	Poisson's ratio of the cement	unitless
Tensile Strength	Tensile strength of the cement	psi
Impact Strength	Impact strength of the cement	in-lb/in^2
Pipe OR	Outer radius of the inner pipe	Inches
W:C ratio	Water to cement ratio of the cement slurry	Unit less
Cement Young's Modulus	Young's modulus of the cement	psi
Anelastic Strain	Anelastic strain of the cement	unitless
Compressive Strength	Compressive strength of the cement as determined by destructive crush testing	psi

The dimensionless ratio for Energy Resistance was determined by observing the effect a mechanical property has on the cement system when tested to failure. Each mechanical property has an effect on the cement during a cyclic stress event.

- Young's Modulus: A high Young's modulus is associated with increased stiffness and brittleness. However, if the value is too low, the cement may not be strong enough. This property must be optimized in a cement system, and for the relationship in this study, it is negatively correlated with energy resistance.
- Poisson's Ratio: An increase in Poisson's ratio is associated with an increase in a cement system's durability during a cyclic stress event.
- Anelastic strain potential: This is a measure of how much a set cement sample deforms plastically over time when exposed to a cyclic load. The more the cement sample deforms, the higher the anelastic strain value is. So the lower the anelastic strain value, the more durable the cement.
- Ultimate compressive strength: This is another property that must be optimized. Very high compressive strengths correspond to more brittle materials. With cement, it is easy to get very high compressive strengths.
- Impact strength: the more impact strength a cement system has, the better it will perform when exposed to a cyclic stressing event. This property is positively correlated with energy resistance
- Tensile strength: Generally, cement has a very low tensile strength, so a high tensile strength would improve cement's durability. This is positively correlated with energy resistance.

By plotting the revised Energy Applied (Ea) variable on the X axis, against the revised Energy Resistance (Re) variable on the Y axis, a more meaningful correlation was found and is seen in the below chart. The trendline in this case represents where each of these samples should fail on average. With a predicted

energy applied on the specimen, if the Ea/Re point falls below the line, failure of the annular seal is predicted. If the point falls above the line, that particular specimen should survive the energy applied. With the variables being dimensionless, this relationship is scalable to field applications.

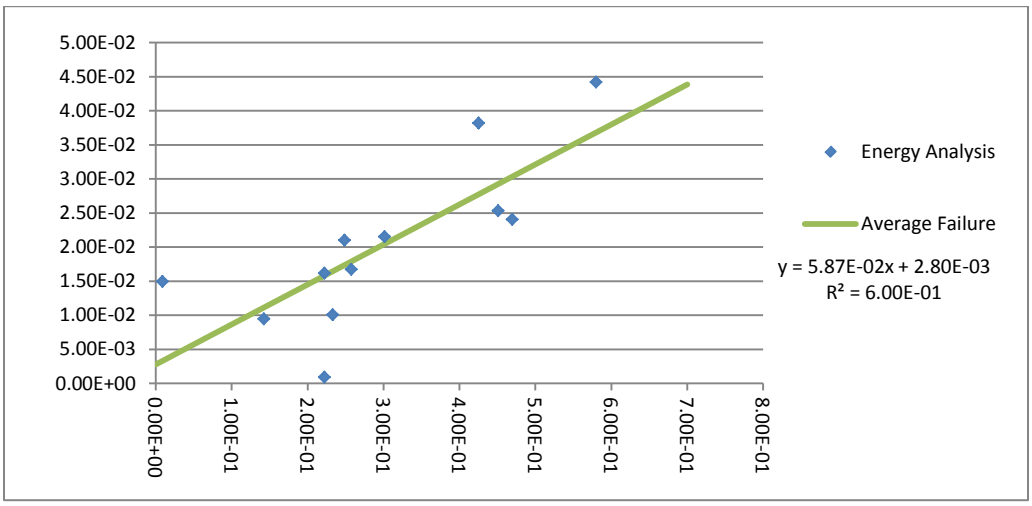

Figure 4-1: Energy applied versus Energy resistance

Inserting the field data gathered from System 1 and System 2 testing as well as field energy estimations was used to test the validity of this relationship. The two systems showed a significant difference when applied in the field. System one's success rate was nearly 90%, System Two's success rate was less than 50%. When using estimated field energy, Ea was calculated for predicted forces.

Equation 4-3: Energy applied variable

$$Ea = \frac{Estimated\ Field\ Energy * Pipe\ ID}{Pipe\ Cross\ Sectional\ Area * Formation\ Young's\ Modulus * Annular\ Area}$$

Table 4-9: Data comparison between field samples

Sample	Ultimate Compressive Strength (psi)	Young's Modulus (psi)	Poisson's Ratio	Tensile Strength (psi)	Anelastic Strain	Predicted Field Energy	Impact Strength (in-lb/in^2)	Density	Water to Cement Ratio	Success Rate
Field 1	1885.00	1.24E+06	0.23	161.00	1.10E-05	2.00E+06	4.20	15.6	0.48	89%
Field 2	1685.00	6.51E+05	0.16	114.60	8.49E-05	2.00E+06	1.96	15.8	0.84	43%

The field data fit this relationship well. The system labeled Field 1 had nearly a 90% success rate in preventing SCP when applied in the field. This point falls on the Average Failure line, indicating it would survive the predicted energy applied. System Field 2 had around a 40% success rate. As can be seen here, that system falls far below the Average Failure line indicating the mechanical properties of this cement system are not adequate for the estimated applied energy.

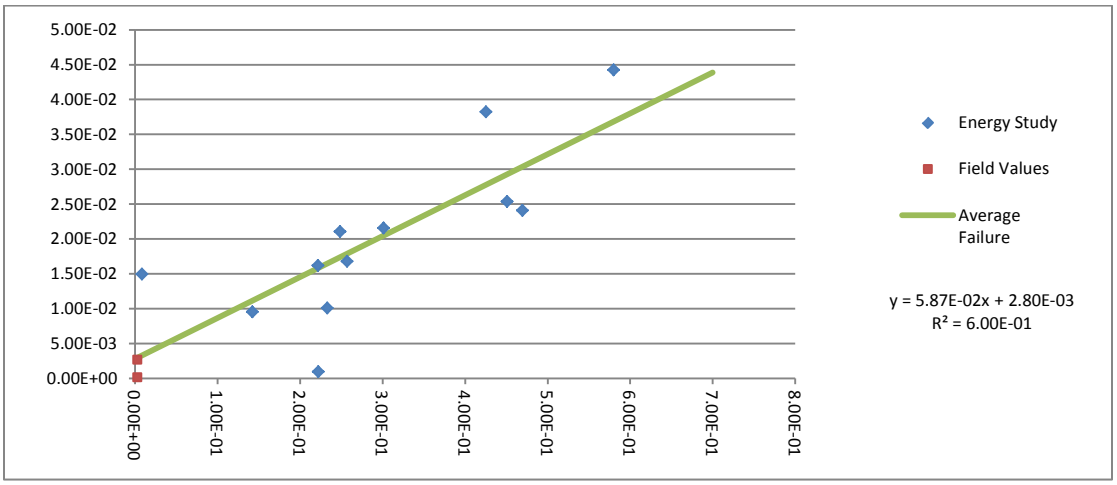

Figure 4-2: Average failure comparison between field and energy study

4.6 Impact to Producers

4.6.1 Gas Migration

A concern in many shale gas areas is zonal isolation and gas migration, and the lab testing done prior to the start of this project addressed that concern. Gas migration can occur either short-term or long-term. Short-term gas migration occurs between the end of cementing operations and before the cement is completely set. Long-term gas migration occurs after the cement has set; this can begin weeks or months after a well is cemented. The causes and solutions to each of these types of gas migration differ greatly.

Short-term gas migration occurs due to a loss in hydrostatic pressure, and can be due to reasons such as cement gel strength development or fluid loss[4]. When this occurs, gas from the formation my enter the annulus and migrate through the cement slurry creating permanent pathways through the cement matrix. As a cement slurry begins to set and develops gel strength, the hydrostatic pressure applied to the formation is reduced as the cement begins to support itself. This allows gas to migrate into and up through the cement slurry. Fluid loss is the second concern for short-term gas migration and occurs in the following ways:

When fluid is lost to the formation the overall volume of the slurry is reduced, reducing the hydrostatic pressure exerted on the formation.

When the hydrostatic pressure of the cement column equals the formation pressure, the additional volume losses caused by fluid loss will determine how much gas will enter the cement to maintain equilibrium.

If the slurry is dehydrated against a zone and bridging occurs, hydrostatic pressure transmitted below that zone is restricted.

Long-term gas migration occurs due to cracking the cement sheath, micro annuli, or channels in the set cement. Cracking can be due to any stress applied to the cement sheath such as fluctuation in pressures and temperatures due to weather or fracturing operations, continued drilling operations, or tectonic stresses from the formation. Channels and micro annuli are the result of poorly bonded cement. This can be due to poor mud removal, poor centralization, and excessive free water or cement sheath shrinkage.

The figure below demonstrates the possible causes for gas migration.

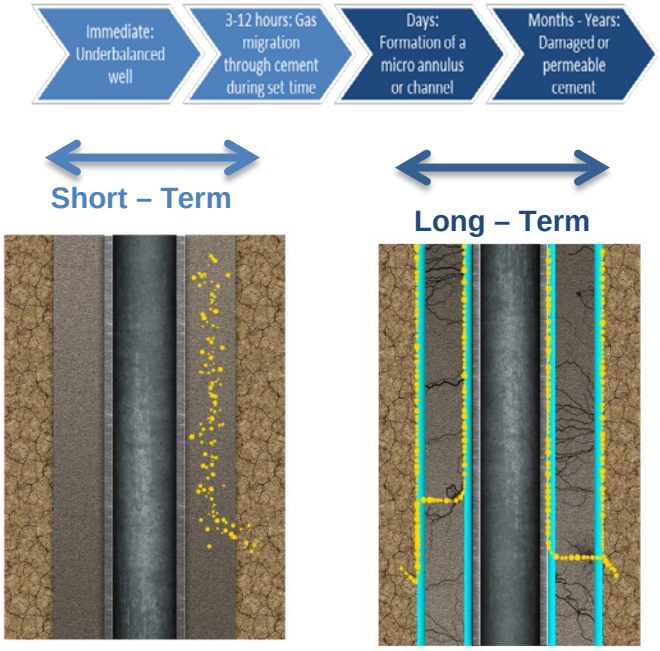

Figure 4-3: Gas migration illustration showing short term on the left, and long term on the right

4.6.2 Improvements

Operationally, there have been several improvements throughout this course of this project. The main improvement is the reduction in occurrence of sustained casing pressure. There are fewer intermediate sections experiencing sustained casing pressure in this area. Wells that have used System 1 cement are experiencing a success rate of around 90% (as reported by operators). However, there are many other areas where changes have occurred, not just in cement design.

In the field, there are improvements operationally as reported in section 4.1. This has allowed the cementing process to proceed more efficiently. This has likely been a result of the increase in experience level in the field. To aid in this, as part of this project a training program has been designed and is available online for use. The website is listed in section 3.4.

Another area where change has occurred is the casing pressure test. When using a thixotropic cement system, running a casing pressure test right after cement placement can result in a microannulus due to the quick gelation of the cement. This can lead to gas migration. Instead, a casing pressure test is run after the cement has had a chance to harden and resist the force from a pressurized casing.

4.6.3 Predictive Models

The techniques used to develop the predictive models described in section 3.3 can be applied in any field provided there is adequate data available for analysis. The model using PLS-DA developed by the University Of Houston can work with data readily available from each well's cement jobs. As long as there is a specific marker for success, such as lack of sustained casing pressure or good bond integrity, historical well data can be used to predict future well performance and highlight any specific practices or designs that may be more successful than others. This model is shown in detail in Appendix 5.

The energy model developed at CSI Technologies described in section 4.5.2 requires additional laboratory testing to determine the cement's mechanical properties and durability. The testing required is minimal and provides valuable information on the cement's durability. The next piece of information, vital to making the CSI energy model valid is a reliable prediction of field energy. This can be performed using measurements, estimations or computer simulations such as the drill pipe impact model developed at the University of Houston seen in Appendix 5.

4.6.4 Cement Design

Cement design recommendations can be found in the training materials. Design recommendations were developed based on the performance seen in the field and laboratory. These design recommendation are only valid as long as other drilling, completion and production practices remain as they were during this study. Any change in the amount of energy placed on the cement due to differences in drilling, completion and production practices may lead to early failure of the cement. For short term gas migration prevention, cement systems should have good fluid loss control and short gel transition times. For long term durability of a system and prevention of long term gas migration, the cement system should show acceptable results for the following properties:

- No shrinkage

    - Slight expansion preferred
- Acceptable mechanical properties including:
    - Young's modulus
    - Poisson's ratio
    - Tensile strength
    - Anelastic strain
- Acceptable annular seal durability

Specialized testing for these properties is required to determine if gas migration may be a concern. Currently, these tests are being requested for all new cement systems prior to implementation. This testing can help to determine if a cement sheath may show short or long term gas migration. These tests should be requested prior to implementing a cement design in the field, and the periodically after that.

For more standard tests, that need to be requested on every cement job, and every field blend prior to pumping the tests required are:

- Thickening time
- Compressive strength
- Free fluid, rheology
- Fluid loss if a fluid loss additive is being used.

By requesting these tests on every cement job the operator will see

    - Increased job success
    - Verified compressive strength, fluid loss control and thickening time.

4.7 Technology Transfer Efforts

The following set of technology transfer efforts covers the presentations given. Each of these presentations was given to various groups to discuss the Marcellus project and answer any questions people had. Each presentation was about 20 minutes long.

2013 RPSEA Onshore Production Conference, 10/17/2013 - Technological Keys to Enhance Production Operations – Long Beach – Small Producer Program: "Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact Through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale"

This presentation gave an overview of the project from the beginning to October 2013. This showed project process and the goals as well as the major findings to date. First, the presentation covered tasks completed, including lab testing to date, cement jobs observed and analyzed from both historical data mined at the operator's office and field data collected real time. The analysis of this information showed areas of improvement for the area in operations and cement design. Some practices identified

as being important were density and mixing, equipment maintenance, job execution skills and gas flow prevention in the cement design.

Major cement design changes early in the project went from a conventional system to a thixotropic system with good fluid loss control. This system had a short static gel transition time, so once it was in place it quickly developed enough strength to prevent any short term gas migration. Recommended improvements were listed in this presentation and included operational improvements and design recommendations regarding cement stability and gas migration prevention. This also touched a little on cement durability. Another part of this presentation talked about how to identify potential for problems using a statistical analysis tool developed by the group at University of Houston. This model developed used the information gathered from each well and combined them to end up with a tool that was able to predict failure correctly 80% of the time.

2014 RPSEA Onshore Production Conference, 6/17/2014 - Technological Keys to Enhance Production Operations – Houston – Small Producer Program: "Improving Zonal Isolation in the Marcellus Shale Formation"

Presentation and question and answer panel– The presentation for this meeting did a short project summary discussing the major issues encountered, solutions proposed, and project status. The main focus was on gas migration and cement durability. It went into more specific details regarding the differences in cement system design and how that could lead to more cement damage and more gas migration. Cement durability properties were discussed and the specialized testing required to assess those properties. Young's Modulus, Poisson's Ratio, tensile strength, anelastic strain, impact strength and annular seal durability were discussed and their relation to cement durability and gas migration was highlighted. Results from this project were briefly mentioned including the attention to detail and expanded suite of testing needed for each cement system. This all led to an improvement in zonal isolation as reported by the operator.

Poster – The poster for this meeting summarized SPE 1913405. This was discussed with the group after all of the presentations.

Drilling Engineer's Association, 11/13/2013 – Houston, TX: "Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact Through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale": This presentation was requested to give drilling engineers a better idea of how to apply and design cement properly in the Marcellus shale and other shale plays. A general project overview was given first to review the background and major issues for those unfamiliar with the project. At this point, the project had only really addressed short term gas migration, and the appropriate way to approach a project like this through field observation, laboratory testing, and engineering analysis. This approach can work in any field to identify issues and develop solutions and recommendations to improve cementing operations and design.

Environmentally Friendly Drilling Systems Wellbore Integrity Workshop, 9/4/2013 – Canonsburg PA: "Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact Through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale"

Presentation and question and answer panel– This workshop was designed to bring people in industry together with governmental and regulatory groups to discuss the importance of well integrity and how it can be improved in the Marcellus shale play. Similar to the presentation for the DEA, this did a brief overview to acquaint the group with the project before diving into the findings and results. Major findings discussed were the effects of cement design on gas migration in the short term, with some talk of long term gas migration. Recommendations mentioned were with regards to cementing operations such as communication, density control and mix water temperature. The presentation then covered the path forward for adequate implementation of the recommendations.

Each of the following SPE papers has a presentation also associated with it. Presentations were 20 minutes long followed by a short Q&A session.

North American Wellbore Integrity Workshop, 8/12/2014 - Hosted by the University of Pittsburgh – "Improving Zonal Isolation in the Marcellus Shale":This workshop was held to bring together experts in various fields concerning wellbore integrity. The presentation for this project covered cement design regarding the prevention of gas migration thru cement. This included techniques to prevent short term gas migration as well as long term gas migration.

Appalachian Basin: Wellbore Integrity throughout its Life Cycle (Drilling, Stimulation, Production), 10/1/2014 –hosted by PTTC and EFD, Morgantown, WV – "Improving Zonal Isolation in the Marcellus Shale" This presentation will be given following the workshop session. The presentation will cover the approach and findings for improving zonal isolation in the Marcellus shale play. This presentation will run about 30 minutes.

Multiagency Hydraulic Fracturing Group Webinar – DOE's Cement R&D Portfolio, 10/21/14 –hosted by the EPA with involvement from NETL and DOE. – Cement Sheath Durability: Increasing Cement Sheath Integrity to Reduce Gas Migration in the Marcellus Shale Play. This webinar is focused on cement and casing issues with the intent of re-starting researcher-to-researcher dialogue on R&D projects related to hydraulic fracturing among the multi-agencies. The presentation itself will review this project with a focus on cement durability issues.

Unconventional Resources Technology Conference: Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale, SPE 1582346

This is the first paper published for this project. It is an overview of the project and the actual process used, and how it has been used in past projects to yield good results by making cementing operations and designs more effective and cost efficient. The approach uses laboratory testing, engineering analysis and field observation to identify problem areas and create recommendations for improvement.

Then working with the drilling team, identify the best recommendations and implement them in the field.

Hydraulic Fracturing Technology Conference: Cement Sheath Durability, 2/6/2014: Increasing Cement Sheath Integrity to Reduce Gas Migration in the Marcellus Shale Play, SPE 168650

This was the second SPE paper published for this project. It begins to shed some light on the link between mechanical properties of a cement sheath and the effect those have on long term durability of a cement sheath in a well. This was noticed when the comparison of two cement systems showed there was a very high success rate in one system and a very low success rate in another. Application of the cement and standard cement properties were similar between the two cement systems. Upon testing for mechanical durability, major differences were seen, with lower durability seen in the less successful cement when compared to the more successful cement. This paper is what led to the SPE1913405.

Unconventional Resources Technology Conference: Zonal isolation Assurance, 8/26/2014: Relating Cement Mechanical Properties to Mechanical Durability, SPE 1913405

This is the third SPE paper published for this project. It uses several mechanical properties of the set cement in the variable "energy resistance, or Re. That shows how much energy a set cement sample can withstand before failure. This paper also details Ea or "energy applied". This takes into account the well's geometry, and the energy actually applied to the cement through post cementing operations, such as drilling and fracturing. These values were generated in the laboratory. By plotting those two variables against each other, an average failure line was formed. This was validated with field data. The cement used in the field that had the most success, fell on the average failure line, while the cement with the least success fell below line, indicating that the lesser cement would not withstand the amount of stress seen in the field. This equation needs more refinement. The plan forward is to include flexural data when computing energy resistance.

The next series of technology transfer efforts are magazine articles published to help spread the information learned during this project.

Horizontal Learning Curve, February 2013, Oilfield Technology Magazine

This magazine article was published to highlight some of the major challenges when drilling horizontal wells. With complete zonal isolation so important on every well, it is critical to get a good cement job. Such challenges include mud removal, settling of solids in the cement or mud, among others. This article also emphasizes the importance of a quality cement job as that is extremely important on every job especially those in horizontal sections.

Zonal Isolation Critical in Developing Unconventional Resources, August 2013, American Oil & Gas Reporter

This article was published to cover the importance of full zonal isolation when developing unconventional resources. There is already a lot of attention being paid to unconventional resources.

Adequate zonal isolation is vital to preventing gas migration and optimizing production as much as possible. This article covered 2 different cement systems that were being used in the area and showed the improvement in gas tightness and reducing short term gas migration.

Cement Sheath Must Endure Long Term, April 2014 PIOGA/EOGCTS, American Oil & Gas Reporter

This article focused on long term gas migration in the damaging forces seen in post cementing operations such as drilling and hydraulic fracturing. Cement is designed to isolate zones in the formation from one another to prevent communication to aquifers and to the surface. This the cement sheath however, may become damaged after some force is applied. This article discusses these forces and the properties to look for in a cement system to reduce the amount of damage that occurs to the cement sheath.

The following are a series of abstracts submitted for consideration in the conferences listed above them.

HFTC

This abstract was also published. A short description can be found in the previous section in the description of SPE168650. Title is as stated earlier.

ATCE

"Complex Well Structure: Identifying the Issues and Developing Best Practices": For this conference, an abstract was submitted titled "Complex Well Structure: Identifying the Issues and Developing Best Practices". This was going to use data and findings from two projects, this Marcellus project, and one CSI is participating in with BSEE. This abstract was going to tackle the idea that both horizontal wells in shale areas and deepwater wells have complex structures and many challenges. These challenges may be overcome by sharing knowledge of overlapping concerns. Specialized laboratory testing, current state of the art and best practices were all discussed.

HSE Conference

"Cementing Best Practices for Major US Shale Plays": This abstract was titled "Cementing Best Practices for Major US Shale Plays". The main focus of this was to share the experience from several CSI projects including this Marcellus zonal isolation project, to show some common themes and ways to identify issues and develop recommendations. While all shale areas are different, this abstract aimed to show some commonality in the way issues can be identified and resolved.

This last section covers the miscellaneous technology transfer efforts by CSI for this project.

Training

Online training offered. See section on training and implementation located at https://csitechnologiesllc.digitalchalk.com

CSI Open House

An open house was held for around 20 clients of CSI technologies, which includes RPSEA. This openhouse included a tour of the facilities and short 5-10 minute talks about major projects, including this project in the Marcellus. There was a lot of interest and questions during the talk. The preparation involved drafting some notes to speak from and doing a dry run for management prior to the actual open house. This also included a poster created from the project fact sheet to have material for visitors to read for further information.

5 Conclusions

Preventing gas migration and promoting zonal isolation has been the main focus of this project. This requires optimized cement design, solid engineering practices, and proper job execution.

5.1 Design

The first cement design parameter discussed was short term gas migration. It was found early in the project that the systems used in the surface and intermediate strings were not suited to preventing gas migration while the cement was in the process of setting. This was remedied through changes in design to a specialized thixotropic system that worked well for the Marcellus field it was applied in. For this project the cement designs with the highest success in the field had very short static gel strength transition time and good fluid loss control. The designed target for fluid loss control was 150 mL/30 minutes API and the static gel strength transition time was 20 minutes.

After reviewing data from the field after the implementation of these cement systems, it was discovered that there were still some failed cement sheaths. The data from this showed one of the two systems had a very low success rate, around 40%; the other system was higher at almost 90%. This indicated there was still an issue with the design. Removing the system with the lower success rate resulted in a nearly 90% success rate in the field overall. Testing indicated the differences in the systems were mechanical properties and long term cement durability. The slurry with the lower success rate could have been negatively affected by stresses from drilling and running casing in the production section of the well. This indicates that cement systems used in the Marcellus need to show enhanced properties for durability to provide protection against long term gas migration and sustained casing pressure. This is further detailed in the recommendations section.

Predicting long term durability may be possible, given adequate testing and information from the field is provided. This includes all of the testing mentioned in the section below as well as information from the field regarding the amount of energy input to the cement sheath. This is important to know for the design and implementation of future cementing processes. The rules of thumb here are valid for the Marcellus area and current practices. Key testing indicators include

- Young's Modulus
- Poisson's Ratio

- Anelastic Strain potential
- Tensile Strength
- Impact Strength
- Annular seal durability

Other long term gas migration properties to be considered include bulk shrinkage and long term permeability. Both of these properties must be controlled in a cement system used in the Marcellus shale. The last concern with cement design is stability. This is especially important in the horizontal section. Good cement stability will ensure a competent cement sheath surrounds the pipe and will help provide adequate isolation for the production zone from the upper zones. The systems tested in this project had acceptable stability, with very low free fluid and low density variance shown in both the dynamic and static settling tests. Adequate stability and therefore isolation is important for completion work, optimized production, and prevention of sustained casing pressure.

5.2 Operations

For operations, the best designed cement can do nothing for zonal isolation if it is not placed correctly to and fill the annular space. There are several areas to focus on when placing the cement to prevent gas migration. These include

- Mud removal
- Cement density
- Equipment
- Experience

For mud removal, prior to cementing, ensuring the mud is properly conditioned such that it can be effectively removed by the pre-flush and spacer and then allow the cement to effectively bond to the pipe and formation is vital for good isolation. This is achieved through adequate mud design, effective spacer design and volume and proper mud conditioning. This is an area in which the operator and service company excelled during the project. Satisfactory mud removal prevents channels and the potential for micro annuli.

Maintaining the correct slurry density during a cement job is important. Pumping cement outside of the recommended window of $\pm$0.2ppg can result in excess free fluid, poor cement bonding, excessive settling, and weak points in the cement sheath. Results from the PLS-DA modelling indicate that as mixing rate increased, likelihood of sustained casing pressure also increased. When mix rate is high, it can be difficult to get adequate bulk delivery to the mix tub, resulting in poor density control. This further encourages the idea that if the rate of mixing is too high, the cement integrity can suffer due to density control issues.

Adequate equipment maintenance is important for adequate performance while on the job. It can be seen in the results section that equipment performance improved over the course of this project. This resulted in more efficient cement job execution and more consistent cement density throughout the

jobs. Improvements were made in pump maintenance, bulk equipment and bulk delivery, and maintenance of measurement devices.

Over the duration of the project, one of the most improved areas was in experience. As the project progressed, the crews became more knowledgeable and efficient at their jobs. This led to improvements in communication and job execution. Proper training is necessary for these improvements to occur. Effective and easy to access training is not always available in every new play especially in areas of high activity. Training programs seen during this project varied from on-the-job training to internet research. Near the beginning of the project, the experience levels varied from a few weeks to several years, with many crews having several new members.

Providing complete documentation on a wellsite will help to avoid confusion on material available, cement job procedures and prevention of recurring issues. On the cement side, this includes laboratory sheets, bulk plant load sheets, a simulation of the job, a job procedure, and equipment maintenance records. Having laboratory sheets available during the job can show valuable information such as the length of time cement will remain pumpable, and the lot numbers from the materials tested.

Paperwork arriving with the bulk materials serves to identify the material as well as provide safety information. The load out sheets should provide the amount of dry cement and spacer material on location as well as the lot numbers the cement and additives were loaded from. These lot numbers should match the laboratory results sheet to ensure the test results are valid. Proper maintenance of equipment has been identified as a possible cause leading to issues mixing and pumping in the field. The high job volume leads to very little yard time to work on the equipment, resulting in some issues with equipment disrepair. The equipment performance can be monitored more closely if maintenance paperwork is continually updated and available with the equipment. Performing a cement job simulation prior to all cement jobs will help to indicate issues prior to the job. They can also assist in determining rates needed and pressures seen prior to running the job. A job program will help to keep all those involved in the job aware of the task being performed and what task is occurring and when.

5.3 Analysis

Two systems were developed over the course of this project to identify causes of failure for a cement job. For this project, failure was defined as sustained casing pressure as reported by the operator. The sustained casing pressure observed on most wells was low and not considered an issue by any regulatory bodies, but the goal of this project was to analyze even the smallest amount of pressure build up. The first system developed used a statistical analysis approach that considered all available data. This is detailed in the report by the University of Houston in Appendix 5. This system was shown to be accurate in predicting failure 73% of the time for the intermediate string in the available data set. This system identified the following areas of interest when predicting failure for the intermediate string:

- Water to cement ratio
- Mix water temperature
- BHST and BHCT

- Displacement volume
- Sacks of cement
- Displacement volume
- Gel strength development
- Cement mixing rate

This system was also used for the production string cement. The ability to accurately classify a string as successful or not was 71% in this data set. The following areas were identified as important in predicting failure with this tool:

- Mix water temperature
- BHST and BHCT
- Fluid loss control in cement.

The second system, developed at CSI Technologies, was an energy analysis. This system analyzes a combination of set cement properties and energy applied to the cement system to predict how much energy can be put into a cement sheath before failure. Initially, as detailed in the results and discussion section, it was noted that failure in the field was more common with "system 2". Cement durability comparison showed system 2 to be less durable than system 1. The dimensionless variables developed from this study show a correlation that can be used to predict the cement properties necessary to reduce the likelihood of failure. This correlation is only valid on:

- Wells in this area
- The same average amount of stress applied to these wells as was applied to the wells in this study

The performance criteria developed from this is currently in use with the operator as necessary for the cement systems used in the area. This system was developed analyzing intermediate casing cements. The properties identified as indicators of long term durability are:

- Young's Modulus
- Poisson's Ratio
- Anelastic strain potential
- Impact strength
- Compressive strength
- Energy applied
- Well characteristics

The cement properties are the easiest to manipulate when designing a well to withstand a specific amount of energy applied are part of an existing well program. That program and wellbore structure may be difficult to alter due to location of pay zone, and other constraints.

To use these failure correlations in other fields, a similar approach will work. However, well and cementing data will need to be collected and put into the correlations. The cement performance criteria that worked for the energy study in this field may not be applicable for other fields with different stresses applied to the cement sheath. The statistical tool developed would need data from wells to identify variables of interest.

6 Recommendations

Based on the results and observations from this project, the following testing and operational changes are recommended for work in the Marcellus shale under similar conditions as were presented in this project.

6.1 Design

In the Marcellus shale it is important to consider what affects gas migration in the well from the time drilling begins until the well is abandoned. There are several ways to properly cement a well help prevent either short term or long term gas migration.

Short term gas migration: In the short term, during and right after cementing, there are several properties to consider. These include:

1. Short static gel strength transition time: The systems that performed successfully in the field had a very short transition time. These transition times were 20 minutes or less. Short transition times prevent gas from migrating through the cement matrix, and prevent the formation of a channel due to the stream of gas.
2. Fluid loss control: As stated earlier, controlling the cement slurry's fluid loss rate is important to controlling gas migration by reducing the amount of fluid lost to the formation. This helps to maintain the volume of fluid in the annulus, and prevents cement dehydration. The successful cement used in this region had a designed fluid loss of around 150mL or less. This is recommended for the area and other areas where gas migration is a concern.
3. Hydration volume reduction: The results from this test indicate that a volume reduction should be low, less than 3%.

Long term gas migration: Long term gas migration through cement can be altered through cement design and performance properties such as cement durability, shrinkage, stability and permeability. There are several parameters associated with cement durability and they include:

- Young's modulus
- Poisson's ratio
- Anelastic strain potential
- Tensile strength
- Impact strength
- Annular seal durability

Current recommendations are to conduct a full energy study on the well and drilling procedures to determine the amount of energy input to the cement sheath. For systems used in this study, the following tables detail the recommended ranges for cement performance.

Performance criteria for cements used in the Marcellus shale

1. Surface string cementing criteria

Property	Optimum Range
Thickening Time	Dependent on placement time
Fluid Loss (static)	<150 mL/30 minutes API
Free Fluid	0%
12 hr compressive strength	400 psi or higher
24 hr compressive strength	1000 psi or higher
Young's Modulus	500,000 psi or higher
Poisson's Ratio	0.2 or higher
Anelastic Strain	$3*10^{-5}$ or less
Static gel strength development transition time	40 minutes or less
Tensile Strength	150 psi or more

Short gel transition time and good fluid loss control are important for short term gas migration prevention, while good mechanical properties are vital to having a competent cement sheath for the life of the well.

2. Intermediate string cementing criteria

Property	Optimum Range
Thickening Time	Dependent on placement time
Fluid Loss (static)	<150 mL/30 minutes API
Free Fluid	0%
12 hr compressive strength	400 psi or higher
24 hr compressive strength	1000 psi or higher
Young's Modulus	800,000-1,300,000 psi
Poisson's Ratio	0.2 or higher
Anelastic Strain	$2*10^{-5}$ or less
Static gel strength development transition time	40 minutes or less
Tensile Strength	150 psi or more

Short gel transition time and good fluid loss control are important for short term gas migration prevention, while good mechanical properties are vital to having a competent cement sheath for the life of the well.

3. Production Lead

Property	Optimum Range
Thickening Time	Dependent on placement time
Fluid Loss (static)	<150mL/30 mins API
Free Fluid	0%
12 hr compressive strength	1000 psi or more
24 hr compressive strength	2000 psi or more
Settling % Variance	<10% dynamic settling, <5% static settling

4. Production Tail

Property	Optimum Range
Thickening Time	Dependent on placement time
Fluid Loss (static)	<50mL/30 mins
Free Fluid	0%
12 hr compressive strength	1000 psi or more
24 hr compressive strength	2000 psi or more
Settling % Variance	<10% dynamic settling, <5% static settling

The testing program suggested for this area is designed to provide the optimal amount of quality control for cement blends. This will help prevent issues with cementing related to gas migration, pump time, wait on cement time and top of cement. Testing required should be performed on every pilot blend as well as field blends. This will aid in the assurance that all cement will perform as needed on location.

Requiring each of these tests on every field blend will help provide cement that performs as intended on every job. If the cement blend has similar results as the pilot test, then it is acceptable for use. If the results vary greatly, it may indicate issues with blending, sample collection or the actual additives. The recommended tests include Thickening time, 24hr compressive strength (UCA), Rheology, Fluid loss (static cell), and Free water (Vertical for surface and intermediate cement systems and 45° angle for production lead and tail blends).

When designing a new blend to be implemented in the field, or when a new service company will be employed, the following tests are recommended:

- Mechanical properties
  - Young's Modulus
  - Poisson's Ratio
  - Anelastic strain potential
  - Tensile strength
- Expansion/shrinkage testing
- Static gel strength analysis

    - Preferred method is with a mechanical analyzer such as the CTE or MACS II
- Settling test
    - Dynamic
    - Static

6.2 Operations

Operationally, there were a few areas in job preparation and execution that should be examined further when working to improve zonal isolation in a well.

Providing a cementing operations simulation using specially designed software for cement jobs is important. Cementing operations simulations take the well and casing data as and the cement system properties and simulate the cement job prior to actually going to the field. These simulations provide valuable information on every part of the cement job from pressures expected, rates necessary, fluid volumes needed and any possible issues. This simulation will also aid in developing the job procedure needed on location.

The following recommendations have been developed to provide the optimum cementing work for the area.

When working on this project, crew size ranged from 3-4 people to over 15. In any crew, however, there were numerous "green hats" or employees with limited experience with the company. To help improve experience levels within the crews there are a few recommendations:

1. Provide and document a training program for all new employees (See online training provided for this project).
2. Ensure no more than 1 new employee per crew of 5. This will allow the crew to perform effectively and the new employee to learn procedures and operations.
3. Implement a mentorship program for new employees, pairing them with more experienced employees.

While loading cement at a bulk plant, there are several recommended procedures to follow to ensure adequate cement blending. Properly blended cement will be easier to mix and maintain good density throughout the job.

Bulk equipment should be well maintained as this aids in good blending and allows easier mixing of cement during the job. All silos and bulk tanks should be properly cleaned prior to using them on a job. Good documentation of maintenance is necessary to ensure it is done on a regular basis.

For the bulk mixing and delivery equipment, blow down and ensure the tank is completely empty by comparing to tare weight or visual inspection prior to re-loading it with material. This ensures material from a previous job will not be accidentally mixed with the new material. Ensure all equipment used for measurements is calibrated on a regular basis or monthly if needed.

Adequate blending of cement is necessary to maintain constant density. This was an issue seen on several jobs and the following recommendations are given:

1. When preparing additives and cement for loading, check the laboratory sheet to ensure additives and cement are being taken from the proper lot numbers for the job.
2. Use the sandwich method when initially loading the cement to blend it: 1/3 cement – ½ additives - 1/3 cement – ½ additives - 1/3cement
3. After using the sandwich method, transfer the cement 5 times, with the last transfer being to the bulk transport unit. On this last transfer, collect the cement sample to test in the lab prior to pumping. Catch 25lbs cement for testing and Use 1 gal of location water for testing.
4. When loading the cement at location into the silo or field storage bin, use as few bins as necessary for each cement system, and ensure they are properly identified. This streamlines the process during the job.

While on location there are steps that can be taken to help optimize the cementing application.

Pre-Job preparations:

1. Job calculations should be performed by both the service company and the company representative on location to ensure enough volume of each material is available to complete the job successfully.
2. Mud conditioning: The practices currently implemented by the operator observed for this study are excellent in ensuring optimal mud removal.
    a. Prior to every cement job, the mud is conditioned at least one hole volume to help ensure the mud will perform as designed. The rheology and density hierarchy will be met. Excess solids are removed from the hole
3. Pipe movement: During mud conditioning and during the cement job, pipe movement is utilized to help move gelled mud and excess solids out of the hole. Both reciprocation and rotation are recommended when operationally feasible.
4. Spacer: A spacer and/or wash are used prior to every job to help ensure mud will be completely displaced and mud film will be removed from the pipe surface and the surface of the formation. This can be further optimized by providing a mud removal simulation.
5. Centralization: On every job, centralizers have been run to aid in the complete displacement of mud and full cement coverage.

Materials:

1. Volume: Ensure excess volume is available for all materials (water, spacer, displacement fluid) except cement, where the designed excess should be available.
2. Temperature: During analysis of the data supplied, it was found that water temperature may be affecting cement jobs. It is important that the water available for mixing cement is

at a temperature tested for use with the cement blend. This is typically 70-80°F. As temperatures dip below this ideal range, cement becomes more difficult to mix effectively.

During the cementing operations:

1. Cement slurry: The cement slurry must be at the proper density to perform as designed. As the cement is being mixed, it is vital to measure the first tub of slurry with a calibrated pressurized mud balance to ensure density is adequate and the densitometer is functioning correctly. During the cementing process, cement density must be maintained over cement rate. The largest deviation in density must be no more than 0.2 pounds per gallon higher or lower than designed density. This means when needed, pump rate should be slowed to mix cement adequately.
2. Samples: Collecting cement samples during a cement job helps in the event of any problems after the cement job to determine if the cement could have been involved in any issue, if one occurs during operations.
    a. 25 lbs of cement for each lead and tail
    b. 1 gallon of mix water for each lead and tail.
3. During the entire cement job, monitor pressure, density and returns to ensure they are adequate, and watch all lines for leakage.

Effective communication is vital to executing a cement job well. Good communication needs to start during well planning, to establish expectations for the cement needed.

1. Operator – Service Company: Communication between the operator and the service company must begin during the well planning stage. This will include relaying information regarding the cement properties required for optimal well performance. This also includes the service company's needs and expectations while on location regarding site preparation. Information needed to design cement should be provided early in the planning phase and includes: Well data (Depth, Size, Lithology, Temperature, Pressure, Cement needs), Issues from previous jobs (any problems that had occurred previously needs to be addressed, with a plan for correcting the problem. This includes bringing the necessary back up equipment as a contingency plan, equipment maintenance, adjusting cement properties, and ensuring material delivery to location is adequate. Documentation is an easy way to relay important information about the cement and equipment performance. These documents should be provided on location at every job (Lab testing sheets, Job program, Simulation of Job, Load out sheets, Equipment maintenance and capabilities)
2. Drilling and production groups: The next area of communication is within the operating company. With little communication between the drilling and production groups, field issues can go unnoticed. By holding regular meetings where field data regarding production performance and well performance is exchanged, the groups can work together to identify the cause of the issues and work to resolve them. Some examples

would be: Information on production performance, any issues seen after drilling such as SCP, and changes in well performance over time.

Reports after the cement job is placed are important in identifying ways to improve the current processes and include:

1. Monitoring the well after cementing is important to see if the cement is providing the zonal isolation needed, and how completion and production work affects the cement sheath by monitoring pressure on the casing. This should be done on a periodic basis, information recorded and analyzed to continuously improve the processes. (Good production, No gas migration shown – no SCP)
2. Cement bond logs can be run on cemented casing strings to determine if cement is bonded to the casing/formation. These bond logs can be helpful when properly interpreted.
3. A cementing post job report can be very useful when documenting issues or best practices for cementing. A post job report should be sent from the service company to the operator after every cement job. These reports will compare expected results to what actually happened on the job. They will also document any issues or good practices that occur.

6.3 Analysis of Data

As shown in this project, a predictive method can be developed to help with analysis of cementing operations and design data. This can be done in many different ways, and this project focuses on two different models. The first used partial least squares discriminant analysis (PLS-DA) to develop a predictive model. To use this model in a field, accurate data needs to be collected regarding the cementing operations, design and the performance of the cement sheath after placement. This model requires data collection on 25 to 50 wells for model development, and then another set of wells need to be analyzed to ensure the model will provide accurate predictions.

The second model developed for failure prediction used laboratory testing and field data in the energy study. To use this type of model in a field, laboratory testing should be run to determine cement sheath durability as detailed in the above sections. Additionally, estimation or other calculation of field energy needs to be developed. This can include actually measuring the energy put on the cement sheath, or estimating the energy put on the cement sheath for the life of the well based on predicted activities. Again, to work well, this model needs data from several wells including cement design and properties along with placement operations and post cementing operations.

Developing a predictive model to aid in data analysis requires several wells worth of accurate data regarding cement sheath performance and cement design properties. The models developed here focused on the intermediate and production string cementing data. Data collected ranged from the historical data early in the project, to real time data collected by CSI in the field and in the laboratory. The PLS-DA method required the widest range of data to provide accurate predictions, while the energy

analysis model required only cement properties and cement sheath performance data. Both models require more data to be refined and reliable, but results indicate these types of models can be used in the field with success.

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Nomenclature:

bbl: Barrel

BHCT: Bottom Hole Circulating Temperature

BHP: Bottom Hole Pressure

BHST: Bottom Hole Static Temperature

bpm: Barrels per minute

HVR: Hydration Volume Reduction

ID: Inner Diameter

LOOCV: Leave Out One Cross Validation

LVDT: Linear Variable Differential Transformer

MD: Measured Depth

OD: Outer Diameter

PLS-DA: Partial Least Squares Discriminant Analysis

ppg: Pounds per gallon

PV: Plastic Viscosity

SCP: Sustained Casing Pressure

SGSA: Static Gel Strength Analyzer

TOC: Top of Cement

TOL: Top of Liner

UCA: Ultrasonic Cement Analyzer

UCS: Ultimate Compressive Strength

VIP: Variable Importance Projection

WOC: Wait on Cement

YP: Yield Point

Appendix

Appendix 1 : Collected Field Data

Well number	Job Date	Well name	String	Stage	Average Density (ppg)	Average Rate (bbls/min)	Average Pressure (psi)	Volume (bbls)	Note
1	5/30/2014	Champdale 2H	Intermediate	Gel Sweep	8.4	6	250	100	
			Intermediate	Intermediate	15.6	6	453 psi	195	Job went successfully as planned
				Displacement	8.4	5.3	655 psi	140	
	6/11/2014		Production	Gel Spacer	14	3.5	720 psi	50	
				Production Lead	15.3	8	2000 psi	165	Job went successfully as planned
				Production Tail	15.3	8	1470 psi	350	Job went successfully as planned
				Displacement	8.4	8	2460 psi	311	
2	6/4/2014	Yost BRA 6H	Surface	Gel & Water Spacer	8.4	6	190	120	
				Surface	15.6	5.5	450 psi	133	Job went successfully as planned
				Displacement	8.4	5.5	250 psi	80	
	6/7/2014		Intermediate	Gel & Water Spacer	8.4	6	200	120	
				Intermediate	15.6	7	680 psi	199	Job went successfully as planned with little variation in density (+0.1 ppg for the last 40 bbls of cement slurry)
				Displacement	8.4	5.5	520 psi	147	
3	6/3/2014	Redmond N Wyo 4H	Production	Gel Spacer	14	4.1	860 psi	48	
				Production Lead	15.2	7.7	1450 psi	195	Lead density dropped -0.5 ppg at the last 45 bbls

				Production Tail	15.5	7.8	1300 psi	333	
				Displacement	8.4	7.2	2251	303	Equipment problem
4	6/6/2014	Rosalie N Wyo 1H	Production	Gel Spacer	14	4	680 psi	50	
				Production Lead	15.2	5.7	890 psi	178	Lead density fluctuates -0.4 ppg for 50 bbls.
				Production Tail	15.4	7.5	1100 psi	369	Tail density was +0.3 ppg at the last 100 bbls
				Displacement	8.4	8	2200 psi	330	
5	6/1/2014	Franclaire W Wyo 9H	Production	Gel Spacer	14	4	702	50	
				Production Lead	15.4	5.9	1430	185	Lead density was +0.2 ppg at the first 50 bbls of lead
				Production Tail	15.4	7.2	1930	455	Tail density was +0.1 ppg and +0.2 ppg for the whole tail 335 bbls
				Displacement	8.4	7.7	2950	356	
6		Porter Wyo 1H	Intermediate	Gel & Fresh water spacer	8.4	8	240	130	
				Intermediate Cement	15.7	7	680	195	55 bbls of 16 ppg cement slurry was pumped at the end of the job. +0.4 ppg was off design desity.
				Displacement	8.4	5	360	147	
7		Smurkoski S Wyo 1H	Intermediate	Intermdiate Cement	15.6	5.4	430	203	Job went successfully as planned
				Displacement	8.4	5.3	345	123	Job went successfully as planned

8	12/18/2013	Odowd SUS 4H	Intermediate	Gel & Fresh water spacer	8.3	6.8	568	43	
				Intermediate Cement	15.6	7	500	180	Job went successfully as planned
				Displacement	8.3	5.5	800	120	Job went successfully as planned
9	11/20/2013	Tinna WYO 2H	Intermediate	Gel & Fresh water spacer	8.3	7	500	50	
				Intermediate Cement	15.6	7	750	180	No packers used on this sting of pipe. Job went successfully as planned
				Displacement	8.3	5	1100	140	
10	1/2/2014	Rosiemar SUS 2H	Intermediate	Gel & Fresh water spacer	8.3	5	150	45	
				Intermediate Cement	15.6	6	600	150	Density off by +0.2 ppg at first 50 bbl
				Displacement	8.3	5.5	1200	145	
11	12/10/2013	Hooker SUS 3H	Intermediate	Gel & Fresh water spacer	8.4	5.3	440	13	Top plug was dropped on the fly. Good density control throughout job
				Intermediate Cement	15.6	6.3	650	180	
				Displacement	8.3	3	1300	130	
12	11/29/2013	Odowd SUS 2H	Intermediate	Gel & Fresh water spacer	8.4	6.5	600	17	
				Intermediate Cement	15.6	7	700	170	Job went successfully as planned
				Displacement	8.3	4.9	950	145	
13	11/16/2013	Hooker SUS 1H	Intermediate	Gel & Fresh water spacer	8.3	4	220	50	
			Intermediate	Intermediate	15.6	6.3	500	150	Job went successfully as planned
				Displacement	8.3	5.8	920	142	Inflatable

									packer set at 918'
	11/13/2013		Surface	Gel & Fresh water spacer	8.3	5	260	50	
				Surface	15.6	5	350	150	Densometer plugged up initially and gave false readings. Fixed later
				Displacement	8.3	3	460	105	Job went successfully as planned
	12/2/2013		Production	Super Surf Spacer	14.5	4.2	650	40	
				Production Lead	15.5	5	850	180	Job went successfully as planned
				Production Tail	15.5	7.5	1000	350	Job went successfully as planned
				Displacement	8.33	7	2500	312	
14	10/23/2013	Tinna WYO 1H	Intermediate	Gel & Fresh water spacer	8.4	3.5	100	20	No job simulation for pumping rates to optimize displacement efficiency. Consistometer test was provided in lieu of lab test
			Intermediate	Intermediate	15.6	6	500	150	
				Displacement	8.3	5	1300	141	
	10/21/2013		Surface	Gel & Fresh water spacer	8.4	2	125	3	
				Surface	15.6	4	300	130	
				Displacement	8.33	5	633	93	Job went successfully as planned
	11/15/2013		Production	Weighted Spacer	15.1	3	1200	45	
				Production Lead	15.3	7	1250	150	Job went successfully as

									planned
				Production Tail	15.3	8	1280	365	Job went successfully as planned
				Displacement	8.3	3	3900	320	
15	10/21/2013	Sharp WYO 5H	Intermediate	Gel & Fresh water spacer	8.4	7	350	50	Cementer had difficult time with bulk equipment and mixing was difficult
				Intermediate Cement	15.6	7.1	750	175	
				Displacement	8.3	8.3	1550	146	
16	10/11/2013	Visneski WYO 3H	Intermediate	Gel & Fresh water spacer	8.4	4	50	20	Inflatable packer set at 892'
			Intermediate	Intermediate	15.6	6.5	550	175	Job went successfully as planned
				Displacement	8.3	5	1300	139	
	10/8/2013		Surface	Gel & Fresh water spacer	8.4	5.2	330	20	
				Surface	15.6	6	410	150	
				Displacement	8.33	3	900	99	Job went successfully as planned
	10/28/2013		Production	Gel Spacer	14.8	4	910	50	
				Production Lead	15.3	7.3	1800	175	Job went successfully as planned
				Production Tail	15.3	7.3	2200	225	Job went successfully as planned
				Displacement	8.3	8.4	3500	300	
17	11/19/2013	Penecale WYO 3H	Intermediate	Gel & Fresh water spacer	8.3	7	445	50	No inflatable packer used
			Intermediate	Intermediate	15.6	6.5	1200	130	Job went successfully as planned
				Displacement	8.3	7	1100	146	
	11/16/2013		Surface	Gel & Fresh water spacer	8.3	4	300	50	

				Surface	15.6	5	430	155	
				Displacement	8.33	3	1240	101	Inflatable packer set at 142.44'
18	10/28/2013	Penecale WYO 1H	Intermediate	Gel & Fresh water spacer	8.4	6	260	20	Large density spikes, -0.5 for 40 bbls
				Intermediate Cement	15.6	6.6	375	174	
				Displacement	8.3	6.1	1460	144	
19	12/20/2013	Tinna WYO 3H	Intermediate	Gel & Fresh water spacer	8.3	5	200	20	One shut down while mixing cement due to cement tub gel up
				Intermediate Cement	15.6	7	700	70	
				Displacement	8.3	5.3	1000	142	
20	10/24/2013	McEnaney BRA 2H	Intermediate	Gel & Fresh water spacer	8.4	4.2	170	5	Density was erratic through entire job
			Intermediate	Intermediate	15.6	6.2	540	200	
				Displacement	8.3	4.2	1500	140	
	10/21/2013		Surface	Gel & Fresh water spacer	8.4	0.2	50	5	
				Surface	15.6	5.8	365	135	Bulk pod carrier did not unload properly
				Displacement	8.33	3	820	134	
	11/6/2013		Production	Gel Spacer	14.5	3.5	900	50	
				Production Lead	15.5	5.8	1020	100	Switched to standby truck with 71 bbls displacement due to pump cavitation
				Production Tail	15.5	6	2070	155	
				Displacement	8.3	5	2900	281	

21	9/18/2013	Visneski WYO 1H	Intermediate	Weighted Spacer	8.3	4	195	50	Job went successfully as planned
			Intermediate	Intermediate	15.6	5	700	120	
				Displacement	8.3	3	1000	145	
	9/15/2013		Surface	Weighted Spacer	8.3	5	400	50	Inflatable packer at 125'
				Surface	15.6	5	450	167	Job went successfully as planned
				Displacement	8.33	3	1600	99	
	10/6/2013		Production	Barite weighted spacer	14	5	975	25	
				Production Lead	15.3	7.9	1560	150	Swell packer at 5680'
				Production Tail	15.3	8	2220	180	
				Displacement	8.3	8	3250	250	
22	10/3/2013	Jes BRA 2H	Intermediate	Gel & Fresh water spacer	8.4	5	340	20	Job went successfully as planned
			Intermediate	Intermediate	15.6	4.6	900	100	
				Displacement	8.3	6	1450	129	
	10/1/2013		Surface	Gel & Fresh water spacer	8.3	8.4	140	30	Inflatable packer at 117'
				Surface	15.6	5.5	527	160	Job went successfully as planned
				Displacement	8.33	3	1100	111	
	9/28/2013		Production	Weighted Spacer	14.5	4	820	50	
				Production Lead	15.3	8	1460	150	Job went successfully as planned
				Production Tail	15.3	6.5	1900	200	
				Displacement	8.3	3	3330	340	
23	9/20/2013	McEnaney BRA 3H	Intermediate	Weighted Spacer	8.3	4	560	75	Job went successfully as planned
				Intermediate	15.6	5	1056	110	

			Intermediate						
				Displacement	8.3	3	1575	145	
	9/16/2013		Surface	Weighted Spacer	8.3	5	420	50	Inflatable packer at 127'
				Surface	15.6	5	350	100	Job went successfully as planned
				Displacement	8.33	3	1100	68	
24	10/6/2013	McEnaney BRA 4H	Intermediate	Gel & Fresh water spacer	8.4	6	220	30	Inflatable packer at 674'
			Intermediate	Intermediate	15.6	5.4	880	160	
				Displacement	8.3	3.5	1180	142	
	10/4/2013		Surface	Gel & Fresh water spacer	8.3	5.7	160	30	Inflatable packer at 117'
				Surface	15.6	6	245	143	Job went successfully as planned
				Displacement	8.33	2.5	1500	72	
	10/18/2013		Production	Gel & Fresh water spacer	14.5	3	250	5	
				Production Lead	15.3	5.5	950	100	Bulk delivery was erratic causing the rate to fluctuate for virtually the entire lead.
				Production Tail	15.3	6.1	1900	175	
				Displacement	8.3	3.1	2400	250	
25	9/4/2013	Finan BRA 5H	Intermediate	Weighted Spacer	8.5	8	425	20	Inflatable packer at 1,111'
			Intermediate	Intermediate	15.6	7	520	160	
				Displacement	8.3	6.5	1300	142	
	9/20/2013		Production	Weighted Spacer	14.5	4	1225	50	
				Production Lead	15.5	5.6	1500	100	
				Production Tail	15.5	5.5	3400	232	Job went successfully as planned

				Displacement	8.3	3	4200	355	
26	8/20/2013	Champlin NE SUL 3H	Intermediate	Gel Water	8.5	4	401	50	Job went successfully as planned
			Intermediate	Intermediate	15.6	6.5	710	219	
				Displacement	8.3	3	1600	165	
	9/10/2013		Production	Weighted Spacer	14	3	925	45	
				Production Lead	15.3	7	1900	150	
				Production Tail	15.3	8	3450	243	Job went successfully as planned
				Displacement	8.3	5	4050	340	
27	11/15/2013	James Barrett 3H	Intermediate	Gel & Fresh water spacer	8.3	5.8	250	50	Inflatable packer at 1336'
			Intermediate	Intermediate	15.6	5.5	480	150	Displacement was off by 12bbls
				Displacement	8.3	2.5	1800	130	
	11/12/2013		Surface	Gel & Fresh water spacer	8.3	5	300	50	Inflatable packer at 481'
				Surface	15.6	5	335	130	Job went successfully as planned
				Displacement	8.33	3	700	74	
	11/29/2013		Production	Super surf spacer	14.5	4.4	180	21	
				Production Lead	15.5	5.5	725	211	Pump went down during displacement
				Production Tail	15.5	6.2	1007	315	
				Displacement	8.3	3.5	2258	308	
28	8/24/2013	Lopatofsky WYO 3H	Production	Weighted Spacer	14	4.2	875	25	
				Production Lead	15.3	5.5	958	150	Job went successfully as planned
				Production Tail	15.3	6	1554	250	
				Displacement	8.3	4.5	3100	301	

29	10/19/2013	Evelyn WYO 1H	Production	Gel & Fresh water spacer	14.3	4.4	750	25	Casing was stuck 1324' from bottom.
				Production Lead	15.3	6.8	1550	125	Casing was stuck 1324' from bottom.
				Production Tail	15.3	7.8	1875	225	Cemented in place
				Displacement	8.3	3	3250	250	Job went successfully as planned
30	11/14/2013	Penecale WYO 2H	Production	Weighted Spacer	15.1	3	1300	45	
				Production Lead	15.3	7.7	1900	150	
				Production Tail	15.3	7	2830	200	
				Displacement	8.3	3	3550	310	Job went successfully as planned

Appendix 2 : Full Standard Testing Results

Surface

Well Number	20	14	27	13	18	32	17	16	24	21	23	22
BHST	60	60	60	60	60	60	60	60	60	60	60	60
BHCT	67	67	67	67	67	67	67	67	67	67	67	67
BHP	500	500	500	500	500	500	500	500	500	500	500	500
Density	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Yield	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Thickening time (hr:mn)	3:56	4:41	4:50	05:11	4:57	N/a	4:33	4:56	3:50	6:49	10:12	6:00
Thickening time (min)	236	281	290	311	297		273	296	230	409	612	360
UCA												
50psi	2:59	6:12	6:13	10:50	4:16	3:58	-	-	1:33	4:06	9:49	-
350psi	7:16	13:39	13:35	15:58	8:56	7:37	-	-	14:17	9:39	-	-
500 psi	9:23	17:10	17:00	20:22	11:02	9:18	-	-	-	12:22	-	-
12h	686	281	282	194	567	737	-	-	313	480	89	-
24h	1396	803	835	649	1410	1658	-	-	468	1054	291	-
PMB(ppg)	15.6	15.5	15.6	15.6	15.5	16.2	-		15.6	15.6	15.7	15.6
Free Fluid (ml)	0	0	0	0	1	1	1	-	0	1	0	0
Free Fluid (%)	0	0	0	0	0	0	0	-	0	0	0	0
Static fluid loss (ml/30min)	52	519	560	530	544	620	38	-	515	361	604	728
Rheology												
Surface PV	50	42	45	41	53	43	-	34	35	40	117	44
Surface YP	58	43	38	30	55	33	-	32	33	32	93	38
Conditioned PV	78	103	94	93	79	103	-	120	78	109	142	110
Conditioned YP	62	74	60	63	68	65	-	66	79	69	62	86
TMB												
T (ppg)	15.5	14.7	15.8	15.2	15.4	15.7	15.3	14.2	15.3	15.9	15.2	15.6
M (ppg)	15.3	14.8	15.4	15.0	14.8	15.9	15.4	14.7	15.3	16.1	15.9	15.5
B (ppg)	15.2	14.5	15.5	15.0	15.0	16.0	15.4	14.4	15.0	16.1	16.0	15.5
Variance (%)	-2%	-1%	-2%	-1%	-2%	2%	1%	2%	-2%	1%	5%	-1%

Intermediate

Well Number	8	9	10	11	12	13	14	15	16	17	18	19	20
BHST	80	80	80	80	80	80	80	80	80	80	80	80	80
BHCT	70	70	70	70	70	70	70	70	70	70	70	70	70
BHP	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
Density	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6
Yield	1.22	1.22	1.22	1.22	1.24	1.23	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Thickening time	-	-	-	-	3:36	7:31	4:55	4:41	4:57	4:32	5:10	4:06	5:33
Thickening time(min)	-	-	-	-	216	451	295	281	297	272	310	246	333
UCA													
50psi	3:05	3:55	3:09	3:31	2:27	03:32	1:13	2:43	2:13	2:40	3:20	5:47	-
350psi	6:05	9:03	6:30	7:04	5:05	07:07	3:05	5:50	4:47	5:27	6:32	10:37	-
500 psi	7:32	11:18	7:34	8:42	6:38	08:40	6:30	7:28	6:13	7:03	8:08	12:52	-
12h	963	548	1003	824	1048	847	739	884	1006	854	865	442	-
24h	1779	1315	2066	1772	1830	1943	1611	1576	1623	1266	1762	1226	-
PMB(ppg)	15.40	-	15.40	15.60	15.70	15.60	15.60		15.70	15.50	15.60		-
Free Fluid (ml)	-	-	-	-	0	0	0	0	0	0	0	0	0
Free Fluid (%)	-	-	-	-	0	0	0	0	0	0	0	0	0
Static fluid loss (ml/30min)	-	-	-	-	493	696	211	506	42	56	482	471	-
Rheology	-	-	-	-									
Surface PV	-	-	-	-	39	49	34	41	38	26	41	33	40
Surface YP	-	-	-	-	46	59	32	42	37	25	34	35	46
Conditioned PV	-	-	-	-	66	75	112	94	110	61	97	72	80
Conditioned YP	-	-	-	-	64	77	73	71	72	61	75	59	74
TMB													
T (ppg)	15.9	15.5	15.7	15.6	15.5	16.1	15.1	15.8	15.5	15.5	15.8	15.7	15.2
M (ppg)	15.8	15.8	15.9	15.8	15.6	16.2	14.7	15.8	15.2	15.9	16.0	16.0	15.6
B (ppg)	16.0	16.0	15.8	15.7	15.7	16.8	14.1	15.5	15.4	16.1	16.2	16.2	15.3
Variance (%)	1%	3%	1%	1%	1%	4%	-7%	-1%	-1%	4%	2%	3%	0%

Intermediate cont.

Well Number	31	21	22	23	24	25	26
BHST	80	80	80	80	80	80	80
BHCT	70	70	70	70	70	70	70
BHP	1200	1200	1330	1330	1330	1330	1330
Density	15.6	15.6	15.6	15.6	15.5	15.6	15.6
Yield	1.22	1.22	1.22	1.22	1.22	1.22	1.22
Thickening time	NA	4:38	4:52	1:29	-	3:47	4:20
Thickening time(min)	0	278	292	89		227	260
UCA							
50psi	5:04	4:19	4:04	4:06	2:42	2:47	4:24
350psi	9:25	10:04	10:34	7:42	5:43	6:06	
500 psi	11:15	12:48	14:17	9:25	7:18	7:45	10:40
12h	562	457	109	736	964	881	615
24h	1538	1011	804	1696	1836	1602	1526
PMB(ppg)	15.6	15.6	15.5	15.5	15.5	15.5	15.6
Free Fluid (ml)	0.5	0	0	0.2	0	0	0
Free Fluid (%)	0.2	0	0	0.08	0	0	0
Static fluid loss (ml/30min)	698	439	518	26	775	465	529
Rheology							
Surface PV	39	61	38	50	35	39	35
Surface YP	36	52	36	76	23	54	51
Conditioned PV	88	128	106	110	127	73	87
Conditioned YP	73	78	109	92	98	87	90
TMB							
T (ppg)	15.0	15.6	15.2	16.0	15.9	15.6	15.8
M (ppg)	15.5	15.9	15.7	16.1	16.2	15.7	15.9
B (ppg)	15.5	16.0	15.8	16.2	16.4	16.2	16.1
Variance (%)	3%	3%	4%	1%	3%	4%	2%

Production Lead

Well Number	27	14	13	24	16	32	20	18	29	30	28	21	22	31	26	25
BHST	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
BHCT	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130	130
BHP	5930	6670	5930	6910	6260	6530	5990	6460	6580	6080	5420	5880	6150	5800	6250	6430
Density	15.5	15.3	15.5	15.3	15.3	15.3	15.5	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.5
Yield	1.22	1.35	1.22	1.35	1.35	1.35	1.22	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.21
Thickening time	8:15	3:37	9:45	05:02	2:53	3:55	7:17	4:28	-	3:58	3:20	2:19	5:21	3:54	2:18	7:51
Thickening time (min)	495	217	585	302	173	235	437	268	-	238	200	139	321	234	138	471
UCA																
50psi	25:31	4:48	16:53	14:46	-	-	-	4:34	-	4:37	4:35	3:19	5:42	5:25	2:28	9:06
350psi	27:09	7:16	19:35	17:06	-	-	-	6:03	-	6:42	6:20	4:31	7:42	6:27	4:18	19:21
500 psi	27:46	8:41	20:27	18:08	-	-	-	6:41	-	7:41	7:11	5:05	8:38	6:58	5:10	20:03
12h	2	759	18	29	-	-	-	1353	-	1002	1129	1599	950	1506	1187	64
24h	0	1101	1222	1679	-	-	-	1897	-	1529	1688	2057	1532	2088	1638	1659
PMB(ppg)	15.50		15.70	15.50	15.30	15.70	15.50	15.20		15.20	15.40	15.40	15.10	15.30	15.40	15.40
Free Fluid (ml)	0	0	0	1	4	4	0	1	2	8	4	0	2	0	14	N/A
Free Fluid (%)	0	0	0	0	2	2	0	0	1	3	2	0	1	0	6	N/A
Static fluid loss (ml/30min)	24	557	26	86	900	657	28	569	790	853	50	356	614	84	666	N/A
Rheology																
Surface PV	126	35	266	107	37	74	-	56	-	82	30	175	82	207	42	N/A
Surface YP	14	5	25	10	5	10	-	5	-	4	6	14	4	22	4	N/A
Conditioned PV	193	55	148	212	69	61	-	45	-	55	83	119	101	180	99	N/A
Conditioned YP	24	10	15	26	20	21	-	7	-	7	12	8	13	21	16	N/A
TMB																
T (ppg)	13.87	15.18	15.3	15.56	15.55	15.691	15.6	14.43	15.4	14.5	15.31	15.44	14.69	15.4	14.8	15
M (ppg)	14.55	15.34	15.15	15.75	15.02	15.62	15.9	15.21	15.399	15	13.11	15.78	15.37	15.6	15.6	14.99
B (ppg)	14.93	15.34	15.21	16.1	16.68	15.595	16.2	15.24	15.421	15.5	18.73	15.88	15.75	15.8	15.6	15.05
Variance (%)	7%	1%	-1%	3%	7%	-1%	4%	5%	0%	6%	18%	3%	7%	3%	5%	0%

Production Tail

Well Number	13	29	14	24	32	18	31	22	26	28	21	30	25
BHST	130	130	130	130	130	130	130	130	130	130	130	130	130
BHCT	130	130	130	130	130	130	130	130	130	130	130	130	130
BHP	5810	6500	6670	5910	6530	6460	5800	6150	6250	5420	5880	6080	6430
Density	15.5	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3	15.3
Yield	1.21	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Thickening time	8:31	3:23	3:43	11:57	4:11	4:56	4:49	N/A	3:32	5:52	3:46	4:17	3:34
Thickening time (min)	511	203	223	717	251	296	289		212	352	226	257	214
UCA													
50psi	15:06	3:42	3:14	-	-	3:29	5:33	5:38	3:34	9:52	5:39	6:46	12:17
350psi	16:34	4:40	4:13	-	-	4:19	7:46	6:41	4:48	11:06	6:48	11:25	13:58
500 psi	17:03	5:07	4:44	-	-	4:42	8:44	7:13	5:27	11:40	7:23	20:49	14:48
12h	7	1708	1539	-	-	1850	904	1451	1350	578	1396	380	22
24h	1793	2099	1858	-	-	2225	1470	1982	1662	1783	2007	516	1639
PMB(ppg)	15.60	15.40	15.40	15.40		15.30	15.20	15.50	15.20	15.30	15.30	15.25	15.40
Free Fluid (ml)	2	2	0	0	2	1	10	6	0	8	2	0	20
Free Fluid (%)	1	1	0	0	1	0	4	2	0	3	1	0	8
Static fluid loss (ml/30min)	156	137	68	88	78	60	504	70	74	90	64	70	240
Rheologies													
Surface PV	63	113	226	51	216	208	57	176	228	144	191	178	54
Surface YP	12	6	32	3	29	35	7	24	26	12	28	26	10
Conditioned PV	160	66	131	92		152	45	116	150	107	130	130	135
Conditioned YP	26	6	15	10		26	7	13	14	12	18	16	31
TMB													
T (ppg)	15.83	14.56	14.91	15.32	14.69	14.41	11.56	15.01	15.04	15.66	15.6	15.3	15.59
M (ppg)	16.26	15.55	15.04	15.43	14.72	14.56	12.64	15.4	15.79	15.67	15.7	16.7	15.71
B (ppg)	16.45	15	15.16	15.33	14.88	14.72	13.04	14.6	15.8	15.62	16.1	17	15.76
Variance (%)	4%	3%	2%	0%	1%	2%	11%	-3%	5%	0%	3%	10%	1%

Appendix 3 : Permeability Testing

Large Scale – Cured for 48hrs prior to testing.

	System 1 Flow Rate (ml/min)		System 2 Flowrate (ml/min)	
Day	1	2	1	2
1	1-2	-	-	-
2	0-1	0-1	0-1	-
3	0-1	0-1	0	-
4	0-1	0-1	0-1	0-1
5	2	1	1	1
6	0/1	0/1	0/1	0/1
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	No Reading - Weekend			
12	No Reading - Weekend			
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	No Reading - Weekend			
19	No Reading - Weekend			
20	0	0	0	0

Small Scale

System 2	Sample	10ml/min	20ml/min	30ml/min	40ml/min	50ml/min	60ml/min
2-day	3-1	200+					
	3-2	200+					
	3-3	160	165	170	175	180	200+
	3-4	200+					
	Sample	10ml/min	20ml/min	30ml/min	40ml/min	50ml/min	60ml/min
5-day	3-1	175	200				
	3-2	141	161	167	173	195	200+
	3-3	145	189	200+			
	3-4	175	200+				
System 1	Sample	10ml/min	20ml/min	30ml/min	40ml/min	50ml/min	60ml/min
2-day	4-1	200+					
	4-2	200+					
	4-3	200+					
	4-4	200+					
	Sample	10ml/min	20ml/min	30ml/min	40ml/min	50ml/min	60ml/min
5-day	4-1	200+					
	4-2	200+					
	4-3	200+					
	4-4	200+					

Conduct Laboratory Investigation

Cement Composition Design

The first step in the laboratory study was to determine the current composition and how it performed under normal test procedures. This testing included

- Thickening time
- Compressive strength development
- Free water
- Fluid loss
- Rheology (surface and downhole)
- Measured density
- Settling tests

All cement samples gathered in the field were tested in the laboratory and a summary of the results were recorded, average results are in Appendix 2A and 2B. These results were used to analyze and compare the results to the expected results. Certain parameters, such as fluid loss, can be greatly affected by the quality of the blend, as well as small adjustments in the fluid loss additive as a result of an inconsistent blend or lack of chemical.

During this project, two main service companies are being used. The cement systems used by them are as seen in Tables 3 and 4. These tables show API cement class and concentrations in percent by weight of cement (%bwoc) of various additives.

Table 10: Composition of surface and intermediate systems

Service Company	A		B		
Cement System	**Surface/ Intermediate 1**	**Surface/ Intermediate 2**	**Surface/ Intermediate 1**	**Surface/ Intermediate 2**	**Re-Designed Surface/ Intermediate 3**
Cement Type	Class H	Class H	Class A	Class A	Class H
Gypsum %bwoc	-	3	-	100	5
CaCl %bwoc	2	2	1.25	-	3
NaCl%bwow	-	-	-	12	-
Retarder %bwoc	-	-	-	0.3	-
Fluid Loss %bwoc	0.2	-	0.5	0.85	0.4
Suspension aid %bwoc	0.5	0.2	-	-	-
Stablizer %bwoc	-	0.5	-	-	-
Antifoam %bwoc	0.4	0.4	-	-	-
Dispersant %bwoc	-	-	0.75	0.5	-
Defoamer %bwoc	-	-	0.1	0.3	0.3
De-static %bwoc	-	-	-	0.02	-

Table 11: Composition of production cement systems

Service Company	A		B	
Cement System	**Production Lead**	**Production Tail**	**Production Lead**	**Production Tail**
Cement Type	Class H	Class H	Class A	Class A
Gypsum %bwoc	5	-	-	-
Pozzalon %bwoc	5	-	-	-
KCL %bwow	-	5	-	-
Retarder %bwoc	0.1	-	0.325	0.35
Fluid Loss %bwoc	0.8	0.6	0.1	0.5
Suspension aid %bwoc	-	0.1	-	-
Stablizer %bwoc	-	-	-	0.2
Antifoam %bwoc	0.4	0.4	-	-
Dispersant %bwoc	0.2	0.1	0.75	0.5
Defoamer %bwoc	-	-	0.3	0.3
De-static %bwoc	-	-	0.15	0.15
Gas Producing %bwoc	-	-	1.2	-

The major difference in Service Company A versus Service Company B is the composition of the cement slurry. The ratio of gypsum to cement as well as the class of cement used is where they differ the most.

Service Company A is using class H cement with 3% gypsum. Service Company B is using Class A cement and 100% gypsum. This means that the cement to gypsum ratio is 1:1 for Service Company B. The major difference between the surface/intermediate 1 and surface/intermediate 2 for both service companies is system 2 is thixotropic. These systems were put into use in September of 2012, these results may also be seen in Appendix 2B. The re-designed surface/intermediate system used by company B was made in response to reported well performance data (Chart 1). Results from the new system are still being finalized, initial results are also in Appendix 2B

Gas Flow

The first of the specialized tests performed was gas flow. This was performed on a fluid migration analyzer. A fluid migration analyzer has the ability to test potential for gas flow in a cement system in a scaled down manner. There are two parts to this test, the fluid loss portion and the gas migration portion. The two parts simulate what is occurring in the well both before the slurry begins to develop gel strength, and during the development of gel strength.

The static gel strength development of a slurry must be tested prior to testing for gas flow. This requires a static gel strength test to be performed. There are currently three options available for this test.

- Chandler SGSA: The SGSA is run similarly to the standard ultrasonic cement analyzer. The static gel strength is determined by measuring the change in ultrasonic signal that is transmitted through the cement sample as it cures. This has been proven empirically, through many tests. This test is one of the easiest to operate as it is run typically while a compressive strength test is running on an SGSA/UCA combination machine. The downside is it does not offer a way to condition the sample prior to testing gel strength. Any conditioning needs to be done on pressurized consistometer before loading the sample.
- Rotating Paddle Consistometer/Static Gel Strength Analyzer: This machine has a slurry cup with a rotating paddle inside. This can be programmed to condition the slurry to simulate placement before measuring gel strength without switching machines. After the conditioning cycle, machine switches to gel strength measurement. To measure gel strength, the paddle moves slowly through the slurry as it is developing gel strength. The torque applied to the paddle is measured and converted to a gel strength measurement.
- Multiple Analysis Cement System II (MACS II): This machine performs static gel strength test on cement slurry samples. The cement is first conditioned to simulate cement placement in downhole conditions. Then the instrument begins collecting gel strength data. Unlike the previous 2 systems, the MACS II directly measures gel strength instead of inferring the gel strength from another reading.

The fluid loss portion of the testing begins by mixing the slurry according to API specifications. Then, the slurry conditioned on an atmospheric consistometer for a predetermined time to simulate the slurry placement in the well. After conditioning, the slurry is poured into the gas migration cell which is pre-heated to bottom hole circulating temperature and a backpressure is applied to the bottom of the slurry. Pressure is applied to the top as slurry at an initial pressure which is determined by the well and

cement job conditions. The differential between the two pressures is equal to the scaled down differential pressure of actual well conditions. (SPE 19522) This differential pressure squeezes the cement, simulating the fluid loss experienced in a well. During this stage, pressure is decreased at time specified by a correlation with the amount of gel strength the cement is developing. When this approaches a zero pressure differential, the gas migration portion of the test is started. If there is little fluid loss control in the cement system, the result may be too much dehydration of the cement column resulting in gas migration in the second portion of the test.

During the gas migration portion of the test, nitrogen gas is used to simulate gas bubbling through the slurry. The rate and volume of gas entering and exiting the slurry are recorded and from those, coupled with the gas permeability calculation, it can be determined if the slurry has sufficient gas migration control or not. In addition, if the permeability of the set cement is below 0.2 mD, the slurry is considered a good cement to prevent gas migration. This is desirable in the areas with high potential for gas migration.

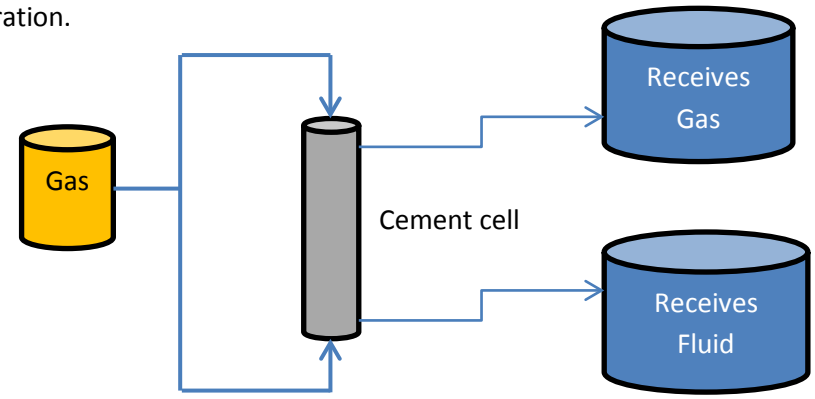

Figure 10: Testing procedure for gas migration potential

Table 12: Cement system transition times and gas migration potential at surface and intermediate conditions

Service Company	A2		B2		B3	
String	Surface	Intermediate	Surface	Intermediate	Surface	Intermediate
100 lb/100sqft (hr:mn)	1:23	1:37	2:11	1:51	1:09	1:34
500 lb/100sqft (hr:mn)	1:42	1:50	12:56	3:44	1:22	1:44
Total time (hr:mn)	**0:19**	**0:13**	**10:45**	**1:53**	**0:13**	**0:10**
Gas Migration Potential	**Passed**	**Passed**	**Passed**	**Passed**	**Not Tested**	**Not Tested**

The thixotropic systems tested showed good transition times for service company A and service company B's third system. Slurries with short transition times are considered to be resistant to gas migration, reducing the amount of time gas can enter a cement matrix and migrate to surface. These systems were tested with a MACSII machine.

Placement Methods and Slurry Stability

Slurry stability in a dynamic and static state was studied using various methods. The first method to determine the static stability of a slurry is to measure the density of the top, middle and bottom of cement cured under bottomhole temperature and pressure. If the variance between the top and bottom is significant, that can translate to poor cement coverage in a well. If the section is vertical, the top portion will have very poor compressive strength and low density. In a horizontal section, the upper portion may have a large amount of free water, potentially resulting in a channel and cement with low compressive strength. This can impact fracturing operations and final production.

To measure dynamic stability, two methods were used. The first method is used to indicate whether there may be an issue or not. This is to measure the top, middle and bottom densities of a sample from a thickening time test. Differences greater than 5-7% can indicate need for more testing. A more stringent test is a dynamic settling test. This test uses the same equipment as a thickening time, but a different schedule. After ramping to temperature and pressure, the cement is conditioned for another 20 minutes. After initial conditioning, the motor is turned off for 10 minutes, to simulate a shut down during a cement job. The motor is turned on again for another 10 minutes, then off again. At the end of the last on-off cycle, the motor is turned and the spike in consistency is recorded. The motor is turned off again, and machine is cooled to remove the cement sample as quickly as possible and measure the top, middle and bottom densities. This test helps to indicate the potential for failure during a cement job. If the settling is severe during this test, it can translate to catastrophic failure in the field.

Additional Specialized Testing

Through this project, CSI and Chesapeake were able to identify ideas and potential issues that had not been previously included in the scope of work. Once these were identified, the processes for testing them were developed and the systems were tested. Analyzing the results helped to identify trends and decide if any of the potential issues identified could be actually affecting zonal isolation in these wells. Testing was performed to identify any shrinkage or expansion of the cement, gel strength transition time, mechanical properties of the cement, impact resistance, tensile strength, and permeability of set cement.

Shrinkage and Expansion Rings

A cement system must remain bonded to the casing and the formation in order to maintain zonal isolation. Shrinkage of the cement sheath can occur in as little as a few days and begin to allow gas to flow. All systems were tested for shrinkage and expansion. This test set up requires a ring mold and a curing chamber. This ring mold is filled with cement and allowed to cure for several days. Each day, the mold is removed from the chamber and measured. Measurements are recorded and compared to the original measurement to determine percentage expansion or shrinkage.

As can be seen in Chart 3, all systems tested showed expansion during the 14 day test. This expansion indicates the cement sheath continued to expand slightly upon placement and did not shrink. The likelihood that the cement remained bonded to the casing and formation is very good. Char three also shows some cement systems that have a slight shrinkage near the beginning of the test. This is likely an

issue with the measurement device or the testing apparatus rather than actual shrinkage. Overall, this system shows at least slight expansion indicating that there is no overall shrinkage over time.

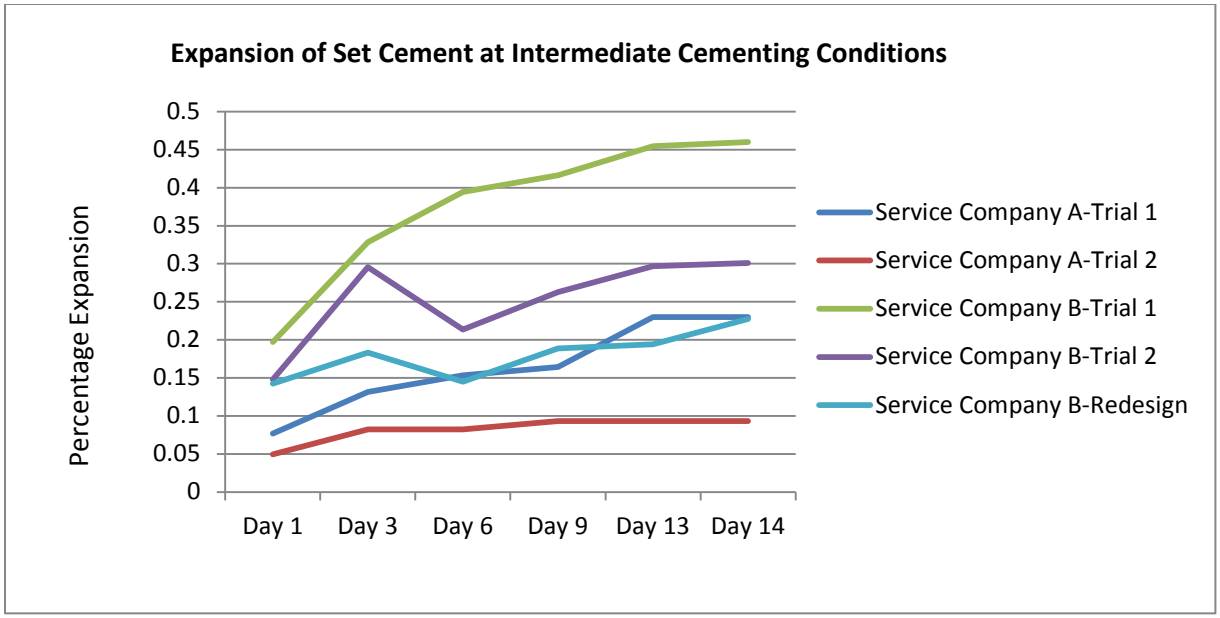

Chart 1: Expansion of set cement at intermediate cementing conditions

Impact testing

Midway through this project, Chesapeake and CSI discussed the possible culprits resulting in compromised zonal isolation, specifically in the intermediate casing. One area of interest was post cementing operations. After cementing surface and intermediate casings, drilling continues within 12-24 hours. The question was if this affects the integrity of the cement sheath. Since both of the cement systems have similar compressive strengths, it was decided a type of impact test should be run to determine any differences. There were two types of impact tests developed for this project. The first was a small impact test. This used a 6" long 1"x1" cement bar that was placed on holder and a 66 gram ball was dropped from a height 9.25" above the cement sample. The number of drops this cement sample was able to withstand without breaking was recorded. These tests were performed after curing the cement for 24 hours. These results were compared between cement systems and the average results are shown in Chart 4. As can be seen in the chart, the system with less gypsum performed better than the system with 100% gypsum.

Figure 11: Showing an impact test being performed as well as the fractured sample post test.

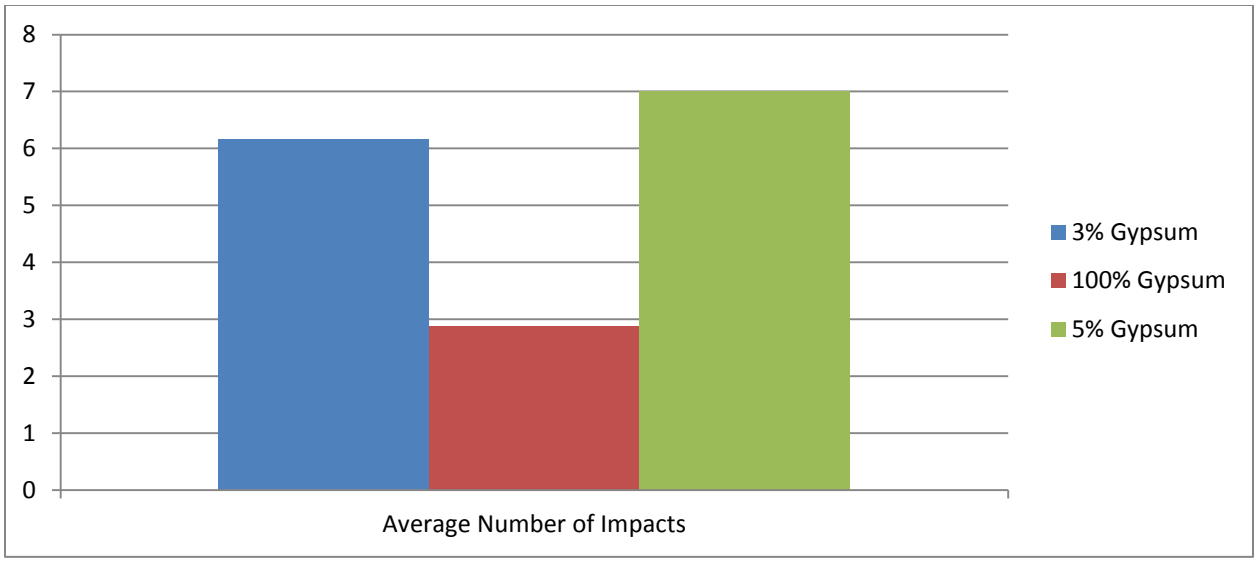

Chart 2: Average number of impacts required to fracture a bar sample after 24 hours of cure time

Mechanical properties testing

Mechanical properties of cement can vary from one system to the next. In this project, the mechanical properties were correlated to the performance of the cement system in the laboratory setting as well as to the performance of the actual well these cement systems were being used on. These systems were tested for ultimate compressive strength, Possion's ratio, and Young's Modulus. Each of these results was compared for the different systems. As seen in Table 6, Service Company A's intermediate system performed better than Service Company B's system. This is likely due to the amount of gypsum in the system. A third system was presented for testing. This system is a re-designed one from Company B. It contains just 5% gypsum, and uses class H cement. Refer to Table 7 results show this system has a Young's Modulus and Possion's ratio much closer to that of Company A.

Table 13: Mechanical properties results

Service Company	A - Design	B-Original	B-Redesign
Young's Modulus (psi)	1.24E+06	6.51*10^5	9.21E+05
Possion's Ratio	2.30E-01	0.16	2.50E-01
Ultimate Compressive Strength (PSI)	1886 psi	1685 psi	1760 psi

Tensile Testing

Tensile testing was performed using a splitting tensile strength method. This method is similar to ASTM C496-90 (standard test method for splitting tensile strength of cylindrical concrete specimens). For this test, the slurry is cured in a 1.5x5-in mold to make three specimens. After curing, each specimen was prepared by cutting ¼" section from each end. Those pieces were discarded, and the specimen was split into three 1 inch segments specified as top, middle or bottom. Density is then calculated for each

segment using Archimedes principle. Each sample is then crushed in the testing apparatus as shown in Figure 6. The maximum reading is noted and used to calculate the tensile strength as per the equation below.

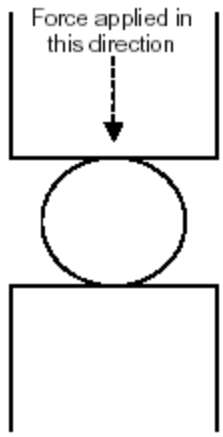

Figure 6: Diagram of tensile test

Tensile strength is calculated by the following equation:

Equation 4: Tensile strength equation

T(psi) = (2*F) / (Pi*L*D)

Where:
T = Tensile Strength (psi)
F = Maximum Force Recorded (lbf)
Pi = 3.14
L = Sample Length (in.)
D = Sample diameter (in.)

Tensile test results show a large difference in tensile strength between the three cement systems tested.

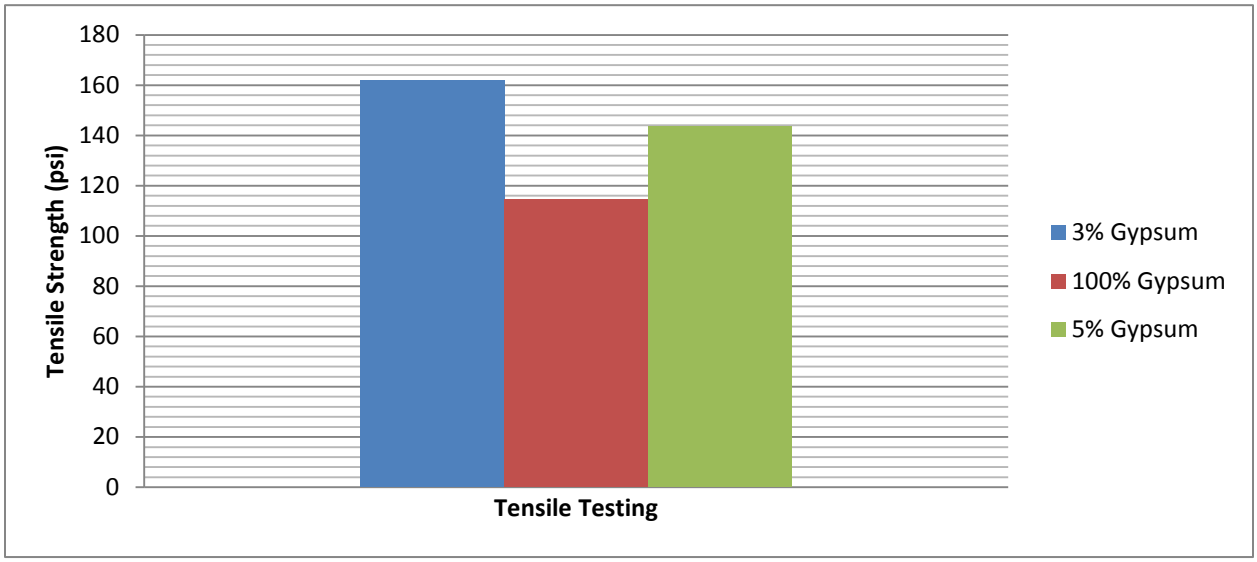

Chart 3: Tensile strength results

Appendix 5: University of Houston reports

Report on "Lowering Drilling Cost, Improving Operational Safety, and Reducing Environmental Impact through Zonal Isolation Improvements for Horizontal Wells Drilled in the Marcellus Shale"

By Shyam Panjwani and Michael Nikolaou

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Introduction

Lowering drilling cost, enhancing operational safety and reducing adverse environmental effects of shale gas exploration are the major aims of this project. These goals can be achieved by improving zonal isolation of shale gas wells. The primary task of this project is to study the quality of well cementing and suggest improvements in cementing design and protocols to ensure effective zonal isolation.

Cement Quality Evaluation

Quality of well cementing can be defined in terms of annular sustained casing pressure (SCP). Micro-annulus and poor cement bonding with casing or formation are main causes of annular SCP. Sustained casing pressure can occur on any annulus for a variety of reasons.

Statistical Analysis

It is well known that a large number of factors affect the cement bond quality and SCP. Using data (provided by CSI Technologies) from various wells, two categories were formed. The first category had wells with detectable SCP and the remaining wells were classified as the second category. The type of

data available needed a statistical classification analysis to assess how these physical factors affect SCP.

Partial Least Square Discriminant Analysis (PLS-DA) (1) is an effective way to study these kinds of systems. It is a statistical method for finding the relationship between predictor variables (X) (i.e. cement system data, additives, rheological properties etc.) and binary response variables(Y) (i.e. sustained casing pressure for different casings). Based on the discriminant functional analysis, wells with unknown sustained casing pressure can be classified in either category. PLS-Toolbox Eigenvector research was used for programming purposes (http://www.eigenvector.com/software/pls_toolbox.htm).

X and Y matrices were formed using the cementing data provided by CSI Technologies. PLS-DA analysis was done on intermediate by surface casing and production by intermediate casing SCP data(Y) and dimensionless parameters(X) obtained from original predictor variables. As each annulus uses different cementing designs, it required separate analysis for each.

PLS-DA was repeated multiple times on different sets of parameters. Variable selection methods based on the VIP (Variable Importance for Projection) statistic and selectivity ratio (SR) (2) were used for variable selection in each modeling step. The VIP variable selection method was found to be better than the selectivity ratio method (See appendix). After each step, parameters with a VIP (3) value less than 0.7 were removed from the model and an analysis was performed with the rest of the parameters. Model-1 and model-2 (for both casings) were obtained as result of two and three such iterations respectively.

Results

Based on number of dimensionless parameters used, two models (i.e. Model-1 and Model-2) were established for each region. Model -1 uses more number of dimensionless parameters than model-2 but there is a trade-off between the number of factors taken and classification ability of the model. Results for both the regions are summarized below:

Intermediate Casing

Model-1

Model-1 for the intermediate by surface annular space uses 16 dimensionless parameters. Figure 1 shows the weighting of each latent variable obtained from PLS-DA analysis. Correlations of dimensionless parameters with SCP are summarized in Table 1. Based on the VIP statistic, the relative importance of all parameters is given in Figure 2 .

Table 1: Dimensionless Parameters and their correlation with SCP for Model-1 (Intermediate Casing)

S.No.	Dimensionless Parameters	Correlation with SCP
1	Gel Strength(10 min)/(Mud weight*Casing Internal Diameter)	Negative
2	Gel Strength(10 sec)/(Mud weight* Casing Internal Diameter)	Negative
3	BHCT/(Water Temperature)	Positive
4	BHST/(Water Temperature)	Positive
5	Spacer volume (bbls)/Annulus volume	Negative
6	Displacement rate/Cement Pump rate	Positive
7	Water to mix (bbls)/ Annulus volume	Positive
8	Depth/ Casing Internal Diameter	Positive
9	Sacks/Annulus volume	Negative
10	Casing Weight/casing Length/(Mud Weight* Casing Internal Diameter^2)	Negative
11	Anti foam	Negative
12	Extender	Negative
13	Retarder	Positive
14	Sulfates	Negative
15	pH	Negative
16	Centralizers	Positive

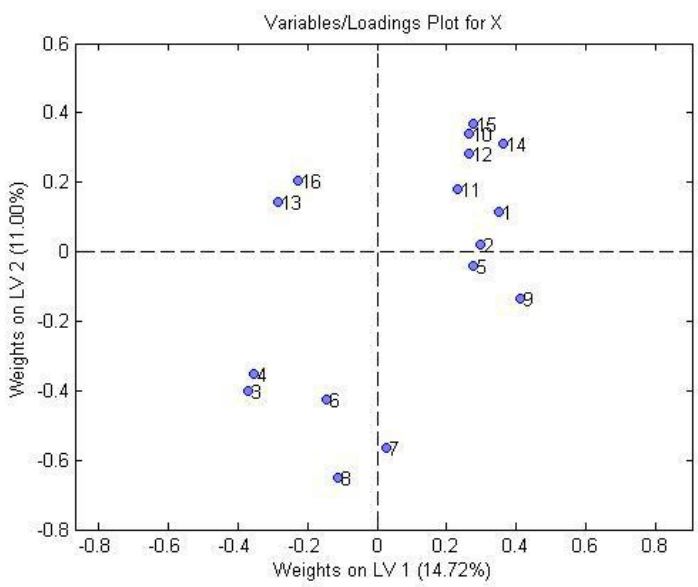

Figure 1: Latent variable weights for Model-1 (Intermediate Casing)

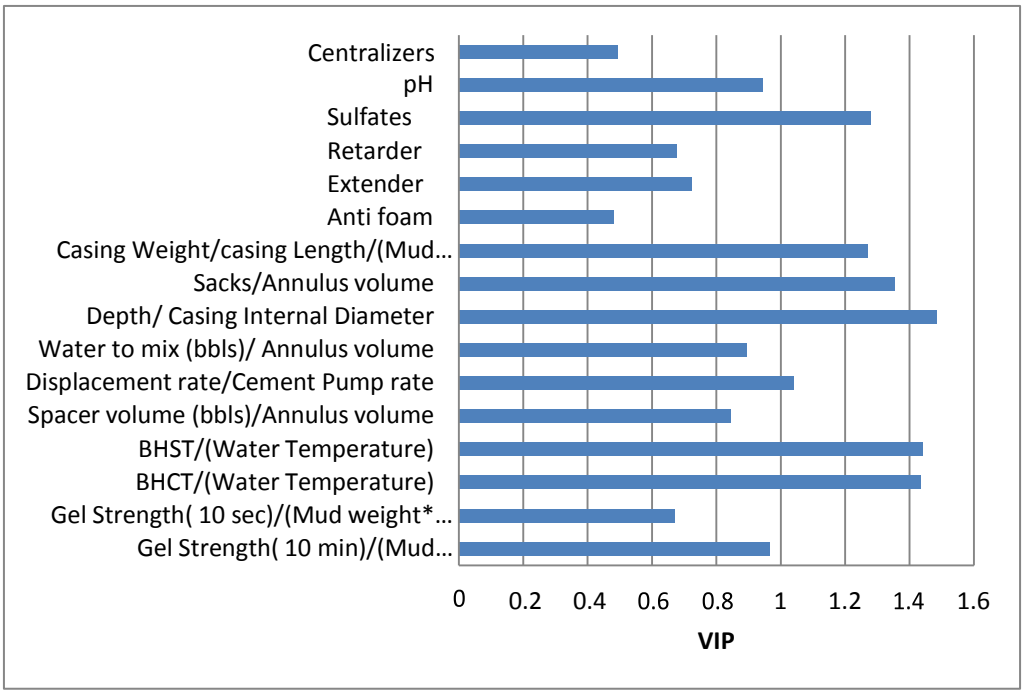

Figure 2: VIP (Variable Importance Projection) values of dimensionless parameters for Model-1(Intermediate Casing)

Model-2

Model-2 for the intermediate casing uses 12 dimensionless parameters. Figure 3 shows weights associated with the latent variables obtained from PLS-DA analysis. Based on the VIP statistic, the relative importance of all parameters is given in Figure 4. The correlations of dimensionless parameters with SCP are summarized in Table 2. Table 3 shows the model fit and the cross validation results for both models.

Table 2: Dimensionless Parameters and their correlation with SCP for Model-2(Intermediate Casing)

S.No.	Dimensionless Parameters	Correlation with SCP
1	Gel Strength(10 min)/(Mud weight*Casing Internal Diameter)	Negative
2	BHCT/(Water Temperature)	Positive
3	BHST/(Water Temperature)	Positive
4	Spacer volume (bbls)/Annulus volume	Negative
5	Displacement rate/Cement Pump rate	Positive
6	Water to mix (bbls)/ Annulus volume	Positive
7	Depth/ Casing Internal Diameter	Positive
8	Sacks/Annulus volume	Negative
9	Casing Weight/casing Length/(Mud Weight*Casing Internal Diameter^2)	Negative
10	Extender	Negative
11	Sulfates	Negative
12	pH	Negative

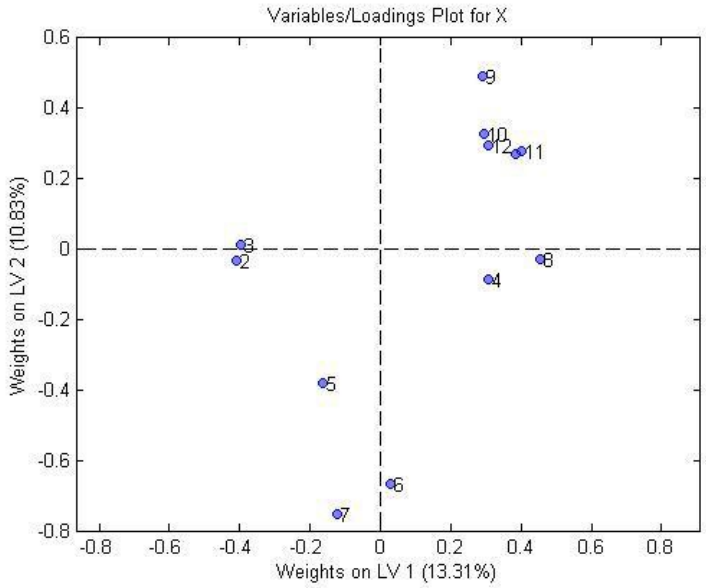

Figure 3: Latent variable weights for Model-2(Intermediate Casing)

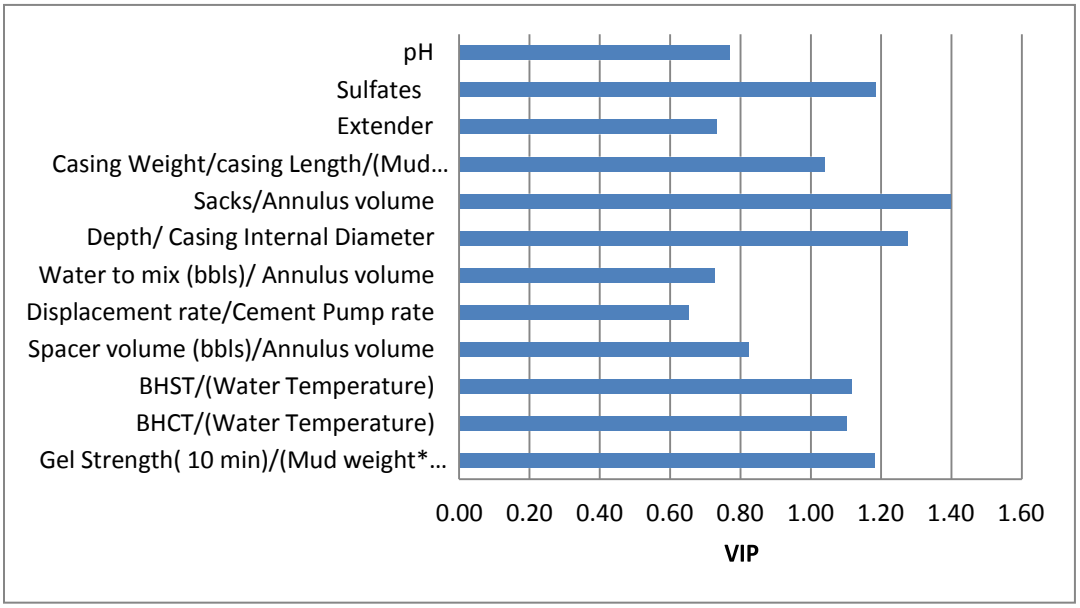

Figure 4: VIP (Variable Importance Projection) values of dimensionless parameters for Model-2(Intermediate Casing)

Table 3: Model fit and Cross validation results for Model-1 and Model-2 (Intermediate Casing)

	Model Fit (Match success (%))		Cross Validation (Match success (%))	
	Category-1	**Category-2**	**Category-1**	**Category-2**
Model-1(16 Dimensionless Parameters)	89.47	84.61	68.42	76.92
	Total Match Success(%) : 86.67		**Total Match Success (%) :** 73.33	
Model-2(12 Dimensionless Parameters)	84.21	84.61	78.95	80.77
	Total Match Success (%): 84.44		**Total Match Success(%) :**80.00	

Production Casing

Model-1

Model-1 for the production by intermediate casing annulus uses 20 dimensionless parameters. Figure 5 shows weights associated with latent variables obtained from PLS-DA analysis. Based on the VIP statistic, the relative importance of all parameters is given in Figure 6. Correlations of dimensionless parameters with SCP are summarized in Table 4.

Table 4: Dimensionless Parameters and their correlation with SCP data for Model-1 (Production Casing)

S.No.	Dimensionless Parameter	Correlation with SCP
1	Yield Stress(Lead)*Casing Internal Diameter^4/(Cement Pump Rate^2*Mud Weight)	Negative
2	Plastic viscosity(Tail)* Casing Internal Diameter/(Cement Pump Rate*Mud Weight)	Negative
3	Gel Strength(10 min-Lead)/(Mud Weight * Casing Internal Diameter)	Negative
4	Gel Strength(10 sec-Lead)/(Mud Weight * Casing Internal Diameter)	Negative
5	BHCT(Tail)/BHST(Lead)	Positive
6	BHCT(Lead)/Water Temperature	Positive
7	BHST(Tail)/ Water Temperature	Positive
8	BHST(Lead)/ Water Temperature	Positive
9	Spacer Volume/Annulus Vol.	Positive
10	Casing Weight/casing Length/(Mud Weight* Casing Internal Diameter ^{2})	Positive
11	Depth/ Casing Internal Diameter	Negative
12	Displacement Volume/ Annulus volume	Positive
13	Anti foam(Lead)	Positive
14	Anti foam(Tail)	Positive
15	Gas migration(Lead)	Positive
16	Anti gel(Lead)	Positive
17	Anti gel(Tail)	Positive
18	Extender(Lead)	Negative
19	Dispersant(Lead)	Negative
20	pH	Negative

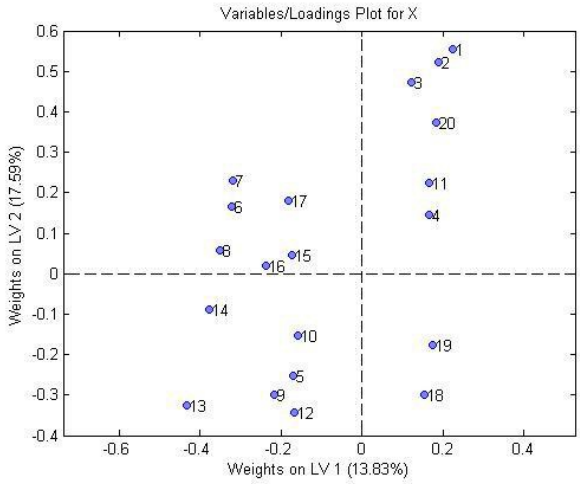

Figure 5: Latent Variable Weights for Model-1 (Production Casing)

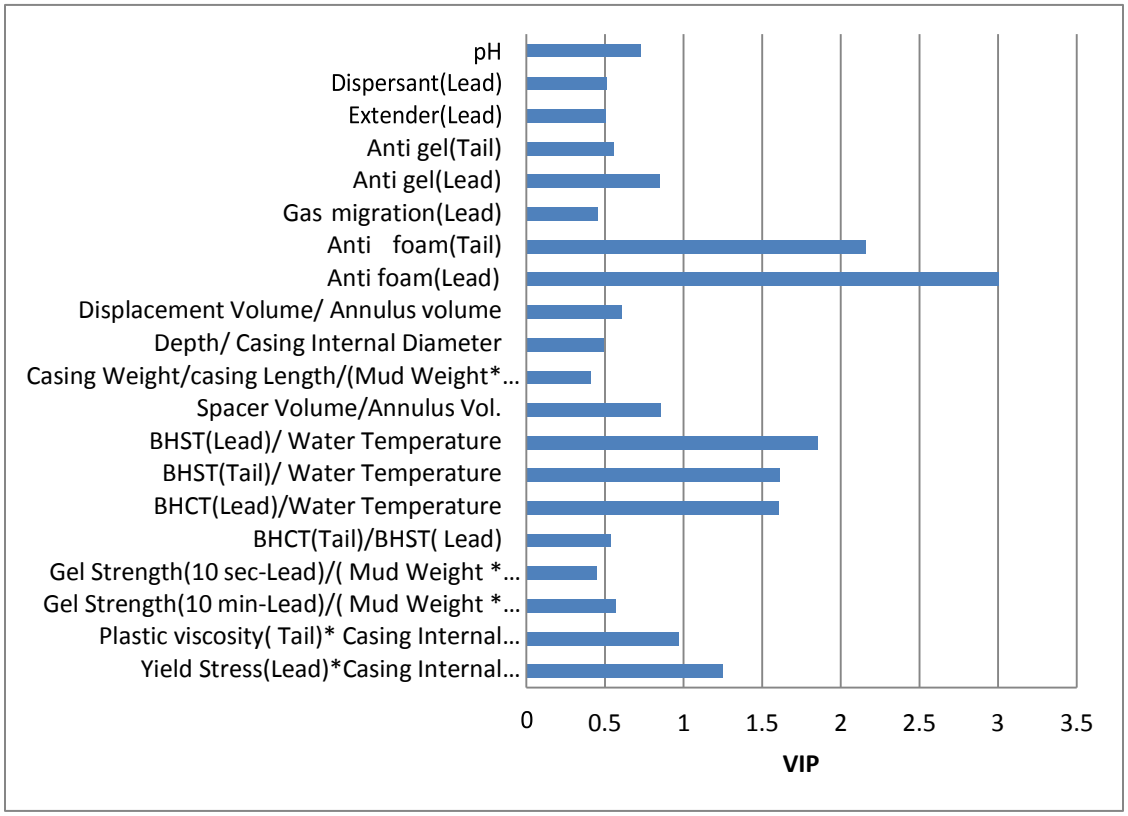

Figure 6: VIP (Variable Importance Projection) values of dimensionless parameters for Model-1 (Production Casing)

Model-2

Model-1 for the production by intermediate casing annulus uses 10 dimensionless parameters. Figure 7 shows the weighting associated with each latent variable obtained from PLS-DA analysis. Based on the VIP statistic, the relative importance of all parameters is given in Figure 8. Correlations of dimensionless parameters with SCP are summarized in Table 5. Table 6 presents a comparative study of model-1 and model-2 for the production by intermediate casing annulus.

Table 5: Dimensionless Parameters and their correlation with annular gas-leakage data for Model-2 (Production Casing)

S.No.	Dimensionless Parameter	Correlation with SCP
1	Yield Stress(Lead)*Casing Internal Diameter^4/(Cement Pump Rate^2*Mud Weight)	Negative
2	Plastic viscosity(Tail)* Casing Internal Diameter/(Cement Pump Rate*Mud Weight)	Negative
3	BHCT(Lead)/Water Temperature	Positive
4	BHST(Tail)/ Water Temperature	Positive
5	BHST(Lead)/ Water Temperature	Positive
6	Spacer Volume/Annulus Vol.	Positive
7	Anti foam(Lead)	Positive
8	Anti foam(Tail)	Positive
9	Anti gel(Lead)	Positive
10	pH	Negative

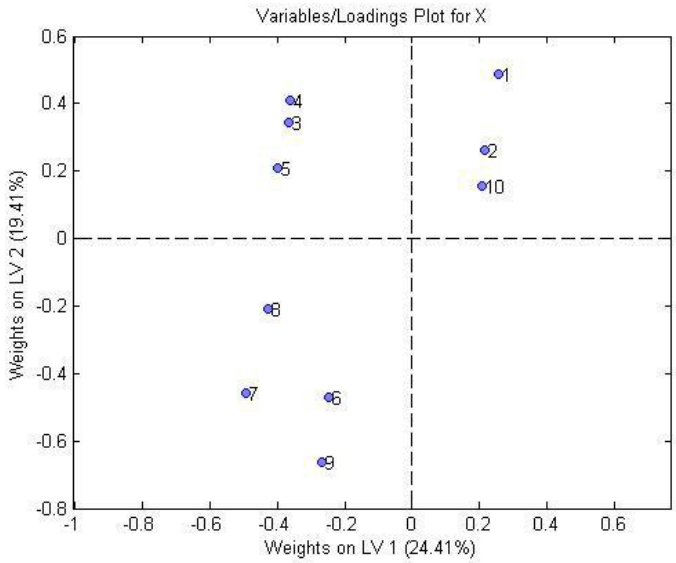

Figure 7: Latent Variable Weights for Model-2 (Production Casing)

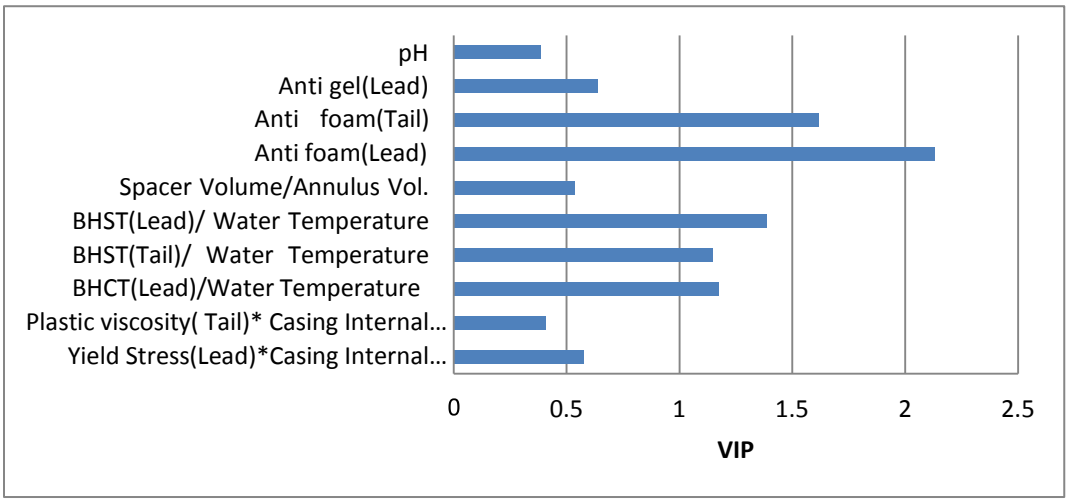

Figure 8: VIP (Variable Importance Projection) values of dimensionless parameters for Model-2 (Production Casing)

Table 6: Model fit and Cross-validation results for Model-1 and Model-2 (Production Casing)

	Model Fit (Match success (%))		Cross Validation (Match success (%))	
	Category-1	**Category-2**	**Category-1**	**Category-2**
Model-1 (20 Dimensionless Parameters)	66.67	91.67	61.11	70.83
	Total Match Success(%) : 80.95		**Total Match Success (%) :** 66.67	
Model-2(10 Dimensionless Parameters)	61.11	87.5	55.56	87.5
	Total Match Success (%):76.19		**Total Match Success(%) :**73.80	

Discussion

As it is evident from Table 3 and Table 6 that a decrease in number of dimensionless parameters results in an increase in the ability for classification, but exclusion of too many parameters might give

erroneous results. A cross validation classification match for category-2 was found to be better than the category-1 classification match, because of the higher number of wells under category-1 than category-2. Correlations obtained from discriminatory analysis can be further tested under laboratory settings.

Conclusion

Since there was little data available for analysis, drawing final conclusions with this analysis might be erroneous. Including more data would certainly enhance the predictability of both the models and it would provide a more realistic picture of responsible factors for sustained casing pressure.

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1. M. Barker, W. Rayens, *J Chemometr* **17**, 166 (Mar, 2003).
2. K. Fujiwara, H. Sawada, M. Kano, *Chemometr Intell Lab* **118**, 109 (Aug 15, 2012).
3. T. Mehmood, H. Martens, S. Sæbø, J. Warringer, L. Snipen, *Algorithms for Molecular Biology* **6**, (2011).

Appendix

VIP Variable Selection Method

VIP value of independent variable expresses its contribution in model. Generally variable with VIP values less than 1 are not considered as important variables. In case of small number of total independent variables, taking VIP value above 1 as selection criteria will leave very few variables after variable selection, which might affect the physical relevance of model. Different values for VIP statistic can be tried as variable selection criteria. Table 7 & Table 8 describe model results with various such VIP values for intermediate casing and production casing respectively.

Table 7: Model fit and Cross-validation results for PLS-DA with variable selection for different VIP values on Intermediate casing data

VIP	No. of selected variables	Model Fit (Match success (%))	Cross Validation (Match success (%))
0.6	14	84.4	75.5
0.7	**12**	**84.4**	**80**
0.8	9	80	73.3
0.9	8	75.5	68.8
1	15	84.4	68.8

Table 8: Model fit and Cross-validation results for PLS-DA with variable selection for different VIP values on Production casing data

VIP	No. of selected variables	Model Fit (Match success (%))	Cross Validation (Match success (%))
0.6	11	78.5	73.8
0.7	**10**	**76.1**	**73.8**
0.8	8	76.1	71.4
0.9	5	71.4	71.4
1	5	71.4	71.4

Selectivity Ratio variable selection method

For independent variable, selectivity ratio (SR) is defined as ratio of variance explained by latent variables to the variance of the errors. In this variable selection method, variables are selected in descending order of their SR values until following constraint remains satisfied:

$$\frac{\sum SR_{selected}}{\sum SR} \leq \mu$$

$$0 < \mu \leq 1$$

Intermediate and production casing data were modeled for various μ values. Results obtained are presented in Table 9 &Table 10 respectively.

Table 9: Model fit and Cross-validation results for PLS-DA with variable selection for different μ values on Intermediate casing data

μ	No. of selected variables	Model Fit (Match success (%))	Cross Validation (Match success (%))
0.6	6	73.3	68.8
0.7	8	71.1	66.6
0.8	6	73.3	68.8
0.9	14	80	71.1

Table 10: Model fit and Cross-validation results for PLS-DA with variable selection for different μ values on Production casing data

μ	No. of selected variables	Model Fit (Match success (%))	Cross Validation (Match success (%))
0.6	6	70.4	65.9
0.7	8	73.8	69
0.8	12	71.4	64.2
0.9	5	71.4	71.4

Study of Rotating Drill Pipe Impacting the Casing Wall

By Shyam Panjwani & Michael Nikolaou

4th August 2014

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Introduction

Lateral vibrations of rotating drill pipe were studied here to yield a better understanding of stresses induced in the casing wall by the drill pipe motion. Drill pipe motion is governed by many linear and non-linear forces such as rock-bit interaction force, viscous force by drilling mudflow, casing wall-drill pipe contact force, centrifugal force, pipe weight, elastic forces etc. (Figure 1). Many of these forces vary with time and hence a time dependent mathematical model was necessary to understand this phenomenon.

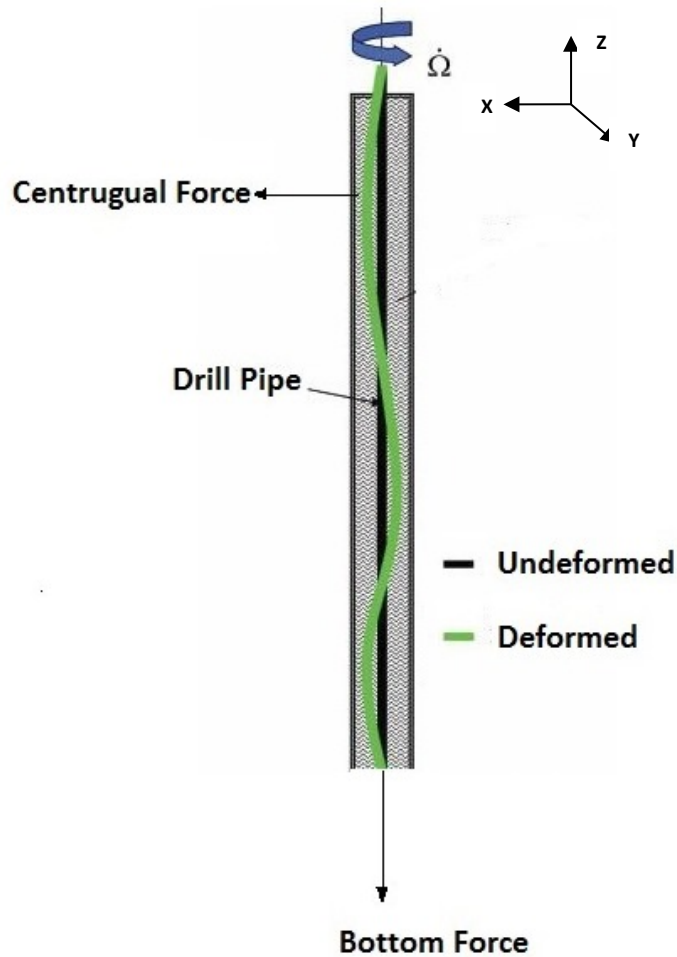

Figure 1: Schematic of drill pipe

Mathematical Model

Equations (1) and (2) describe the motion of the vertical drill pipe, which includes the effects of the above mentioned forces (Dareing 2012). The non-dimensional form of the drill pipe motion equations (equations (4) - (5)) were derived using the given definitions (equation (3)). Contact force starts acting between drill pipe and casing wall when the radial vibrational displacement of the pipe exceeds the gap between casing inner diameter and drill pipe outer diameter. Drill pipe-casing contact force was modelled using the Hertzian contact theory (Yigit and Christoforou 1994).

$$EI\frac{\partial^4 x}{\partial z^4} - T\frac{\partial^3 y}{\partial z^3} - \frac{\partial}{\partial z}\left([F + w(L-z)]\frac{\partial x}{\partial z}\right) + m\left(\frac{\partial^2 x}{\partial t^2} - 2\omega\frac{\partial y}{\partial t} - \omega^2 x\right) = 0 \quad (1)$$

$$EI\frac{\partial^4 y}{\partial z^4} + T\frac{\partial^3 x}{\partial z^3} - \frac{\partial}{\partial z}\left([F + w(L-z)]\frac{\partial y}{\partial z}\right) + m\left(\frac{\partial^2 y}{\partial t^2} + 2\omega\frac{\partial x}{\partial t} - \omega^2 y\right) = 0 \quad (2)$$

$$v = \frac{x}{\delta}, u = \frac{y}{\delta}, \xi = \frac{z}{L}, \tau = \frac{t}{t_c} \quad (3)$$

Non-dimensional equations of drill pipe motion

$$\frac{\partial^4 v}{\partial \xi^4} - N_1 \frac{\partial^3 u}{\partial \xi^3} - \left(N_2 + N_3\left(1-\xi\right)\right)\frac{\partial^2 v}{\partial \xi^2} + N_3 \frac{\partial v}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} - 2N_4 \frac{\partial u}{\partial \tau} - N_4{}^2 v = 0 \quad (4)$$

$$\frac{\partial^4 u}{\partial \xi^4} + N_1 \frac{\partial^3 v}{\partial \xi^3} - \left(N_2 + N_3\left(1-\xi\right)\right)\frac{\partial^2 u}{\partial \xi^2} + N_3 \frac{\partial u}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} + 2N_4 \frac{\partial v}{\partial \tau} - N_4{}^2 u = 0 \quad (5)$$

where

$$N_1 = \frac{TL}{EI}, \mathrm{N}_2 = \frac{FL^2}{EI}, \mathrm{N}_3 = \frac{wL^3}{EI}, N_4 = \omega t_c, t_c = \sqrt{\frac{mL^4}{EI}} \quad (6)$$

Initial conditions

$$v(\xi,0) = \varepsilon_v \sin\left(n\pi\xi\right)$$
$$\mathrm{u}(\xi,0) = \varepsilon_u \sin\left(n\pi\xi\right)$$
$$\frac{\partial v(\xi,0)}{\partial \tau} = 0 \quad (7)$$
$$\frac{\partial u(\xi,0)}{\partial \tau} = 0$$

Boundary conditions

$$v(0,\tau) = 0$$
$$\mathrm{v}(1,\tau) = 0$$
$$\frac{\partial^2 v}{\partial \xi^2}(0,\tau) = N_1 \frac{\partial u}{\partial \xi}(0,\tau) \quad (8)$$
$$\frac{\partial^2 v}{\partial \xi^2}(1,\tau) = N_1 \frac{\partial u}{\partial \xi}(1,\tau)$$
$$\mathrm{u}(0,\tau) = 0$$
$$\mathrm{u}(1,\tau) = 0$$
$$\frac{\partial^2 u}{\partial \xi^2}(0,\tau) = -N_1 \frac{\partial v}{\partial \xi}(0,\tau) \quad (9)$$
$$\frac{\partial^2 u}{\partial \xi^2}(1,\tau) = -N_1 \frac{\partial v}{\partial \xi}(1,\tau)$$

Using classical Hertzian contact theory, contact force F_c between drill pipe and casing wall was modeled as force acting between a spherical body and a flat surface (equation (10)). Hertzian stiffness K_h depends on the material properties and contact geometry (equation (11)).

$$F_c = K_h(\sqrt{x^2 + y^2} - \delta)^{1.5} \quad (10)$$

where

$$K_h = \frac{4}{3}\sqrt{R}E^*$$

$$R = \frac{\Delta L_{\text{drill-pipe element}}}{2} \tag{11}$$

$$\frac{1}{E^*} = \frac{1-\upsilon_p{}^2}{E_p} + \frac{1-\upsilon_c{}^2}{E_c}$$

In the case of collision between the casing wall and the drill pipe, the dimensionless form of radial contact force F_c was added in the equations (4) - (5) to obtain equations (12)-(13).

$$\frac{\partial^4 v}{\partial \xi^4} - N_1 \frac{\partial^3 u}{\partial \xi^3} - \left(N_2 + N_3\left(1-\xi\right)\right)\frac{\partial^2 v}{\partial \xi^2} + N_3 \frac{\partial v}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} - 2N_4 \frac{\partial u}{\partial \tau} - N_4{}^2 v$$
$$+N_5\left(\frac{u}{\sqrt{u^2+v^2}}\right)\left(\left(v^2+u^2\right)^{0.5} - 1\right)^{1.5} = 0 \tag{12}$$

$$\frac{\partial^4 u}{\partial \xi^4} + N_1 \frac{\partial^3 v}{\partial \xi^3} - \left(N_2 + N_3\left(1-\xi\right)\right)\frac{\partial^2 u}{\partial \xi^2} + N_3 \frac{\partial u}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} + 2N_4 \frac{\partial v}{\partial \tau} - N_4{}^2 u$$
$$+N_5\left(\frac{v}{\sqrt{u^2+v^2}}\right)\left(\left(v^2+u^2\right)^{0.5} - 1\right)^{1.5} = 0 \tag{13}$$

where $N_5 = \dfrac{K_h \delta^{0.5} L^3}{EI}$ (14)

Since the production zone has a large horizontal section, analysis of the drill pipe motion in this part of the well requires a different set of governing equations from the vertical section. As the drill bit assembly drills horizontal part of the well, one part of the drill pipe remains vertical and other part is horizontal. Dimensionless equations, governing motion of the drill pipe are given as follows (equations (15)-(16)):

$$\frac{\partial^4 v}{\partial \xi^4} - N_1 \frac{\partial^3 u}{\partial \xi^3} - \left(N_2\psi + N_3\left(1-\psi\right)\left(1-\xi\right)\right)\frac{\partial^2 v}{\partial \xi^2} + N_3 \frac{\partial v}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} - 2N_4 \frac{\partial u}{\partial \tau} - N_4{}^2 v$$
$$+N_5\left(\frac{u}{\sqrt{u^2+v^2}}\right)\left(\left(v^2+u^2\right)^{0.5} - 1\right)^{1.5} + N_6\psi = 0 \tag{15}$$

$$\frac{\partial^4 u}{\partial \xi^4} + N_1 \frac{\partial^3 v}{\partial \xi^3} - \left(N_2\psi + N_3\left(1-\psi\right)\left(1-\xi\right)\right)\frac{\partial^2 u}{\partial \xi^2} + N_3 \frac{\partial u}{\partial \xi} + \frac{\partial^2 v}{\partial \tau^2} + 2N_4 \frac{\partial v}{\partial \tau} - N_4{}^2 u$$
$$+N_5\left(\frac{v}{\sqrt{u^2+v^2}}\right)\left(\left(v^2+u^2\right)^{0.5} - 1\right)^{1.5} + N_6\psi = 0 \tag{16}$$

where

$$\psi = 0 \text{ for vertical section}$$
$$= 1 \text{ for horizontal section} \quad (17)$$
$$N_6 = \frac{wL^3}{EI\delta}$$

Simulation Results

Coupled partial differential equations were solved using the method of lines. Spatial derivatives were discretized using 2nd order central finite difference schemes and the resulting ODE (in time) was numerically solved in MATLAB. The initial and boundary conditions are given in equation (7) and equations (8) and (9) respectively. Lateral displacement and velocity profiles were obtained using the Hertzian contact force theory. Results for vertical and horizontal drilling are summarized below:

Vertical Drilling

Equations (12) and (13) were solved to obtain drill pipe displacement and velocity profiles during vertical drilling. As the dimensionless numbers (equation (6)) depend on the pipe length L_P, these numbers were calculated for different pipe lengths (see Appendix A) and various simulations were run for different pipe lengths. Figures 2 and 3 show time varying dimensionless radial displacement and dimensionless radial velocity with respect to dimensionless drill pipe length (for L_P=1814 ft). The simulation results for other drill pipe lengths are given in Appendix B.

As the purpose of the study was to evaluate the effect of the drill pipe impact on the intermediate casing, the average drill pipe impact velocity and intensity of such impacts were calculated for different pipe lengths. It was found that the average radial velocity of drill pipe impact with the intermediate casing increases with an increase in drill pipe length or drilled well depth (Figure 4) and the intensity of such impacts decreases with an increase in drill pipe length or drilled well depth (Figure 5).

Horizontal Drilling

For the drill pipe motion in the horizontal section of the well, equations (15) and (16) were solved using given initial and boundary conditions. Average radial drill pipe impact velocity and intensity of the impacts follow a similar trend as vertical drilling (Figure 6 and Figure 7).

As the drill pipe strikes with the casing, there is a transfer of some amount of the drill pipe's kinetic energy to casing elastic energy. The amount of energy absorbed by the casing during drill pipe impact can be calculated using the theory presented by (Hunter 1957) and (Reed 1985). Here the impact of the drill pipe with the casing was modelled as the impact of a spherical body with a semi-infinite solid half plane.

A fraction of the energy transfer from the drill pipe to the cement and casing during a single impact:

$$\chi = 1.04 \times \left(\frac{V_p}{V_b}\right)^{0.6}$$

where V_p = Drill pipe impact velocity

V_b = Wave velocity in solid half plane

It is shown by field data that drilling the vertical and horizontal sections of the well takes approximately 5 and 10 days respectively. Energy transfer E from the drill pipe to the casing during drilling was calculated as

$$E = \int_0^T \frac{1}{2} M_P V_P(t)^2 \times \chi \times \mathrm{N(t)} \times dt$$

where

M_P =Mass of single drill pipe element

$V_P(t)$=Drill pipe impact velocity

$N(t)$=Number of drill pipe impacts with casing per unit second

T = Total drilling time

Using the numerical values of defined above, total energy transfer *E* was found to be 1.45×10^7 in-lb (See Appendix C for sample calculation).

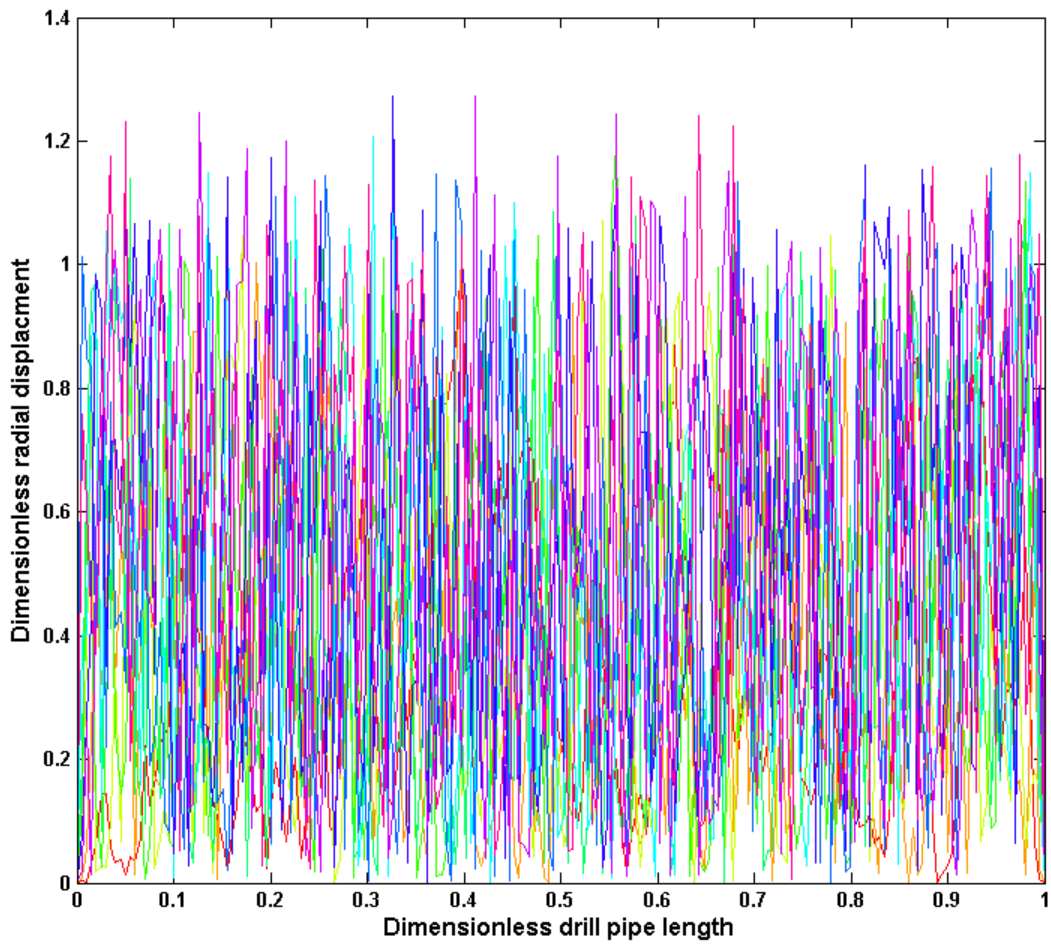

Figure 2: Vertical drilling: Time varying profile of dimensionless radial displacement of drill pipe vs dimensionless drill pipe length (for L=1814 ft)

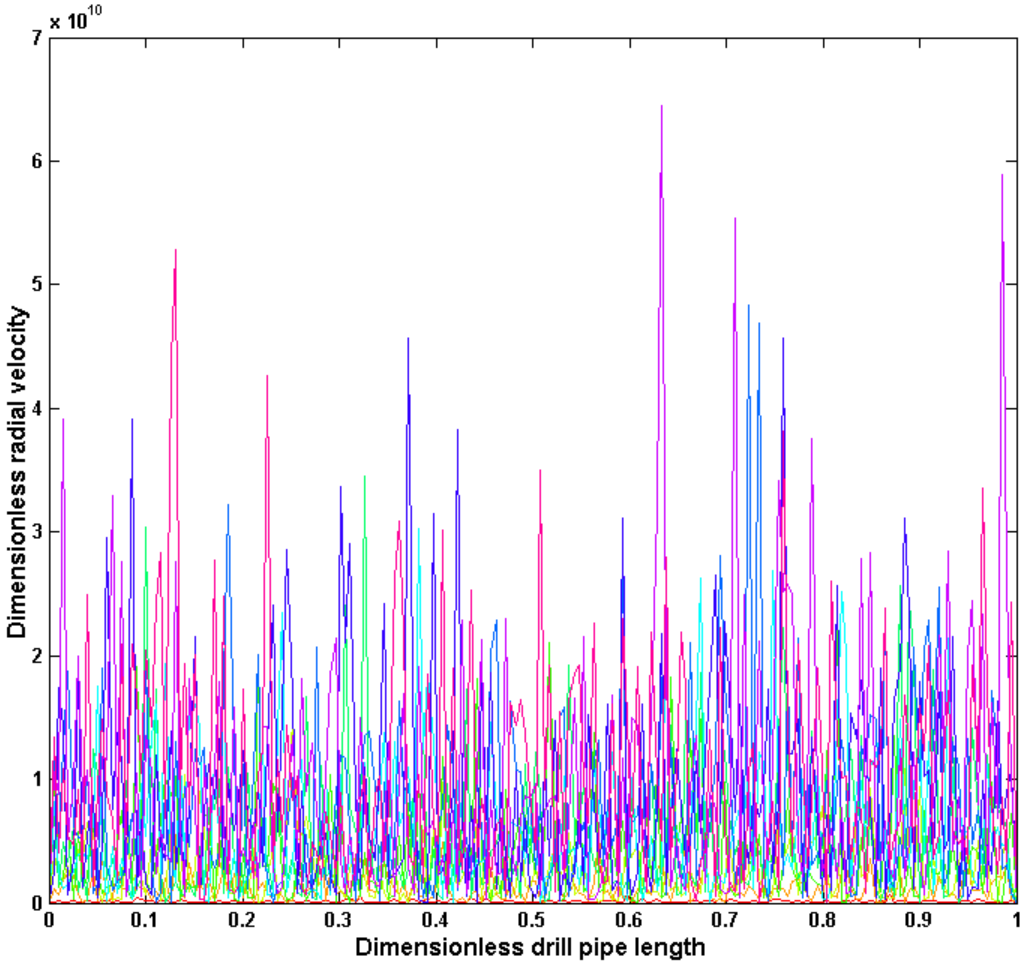

Figure 3: Vertical drilling: Time varying profile of dimensionless radial velocity of drill pipe vs dimensionless drill pipe length (for L=1814 ft)

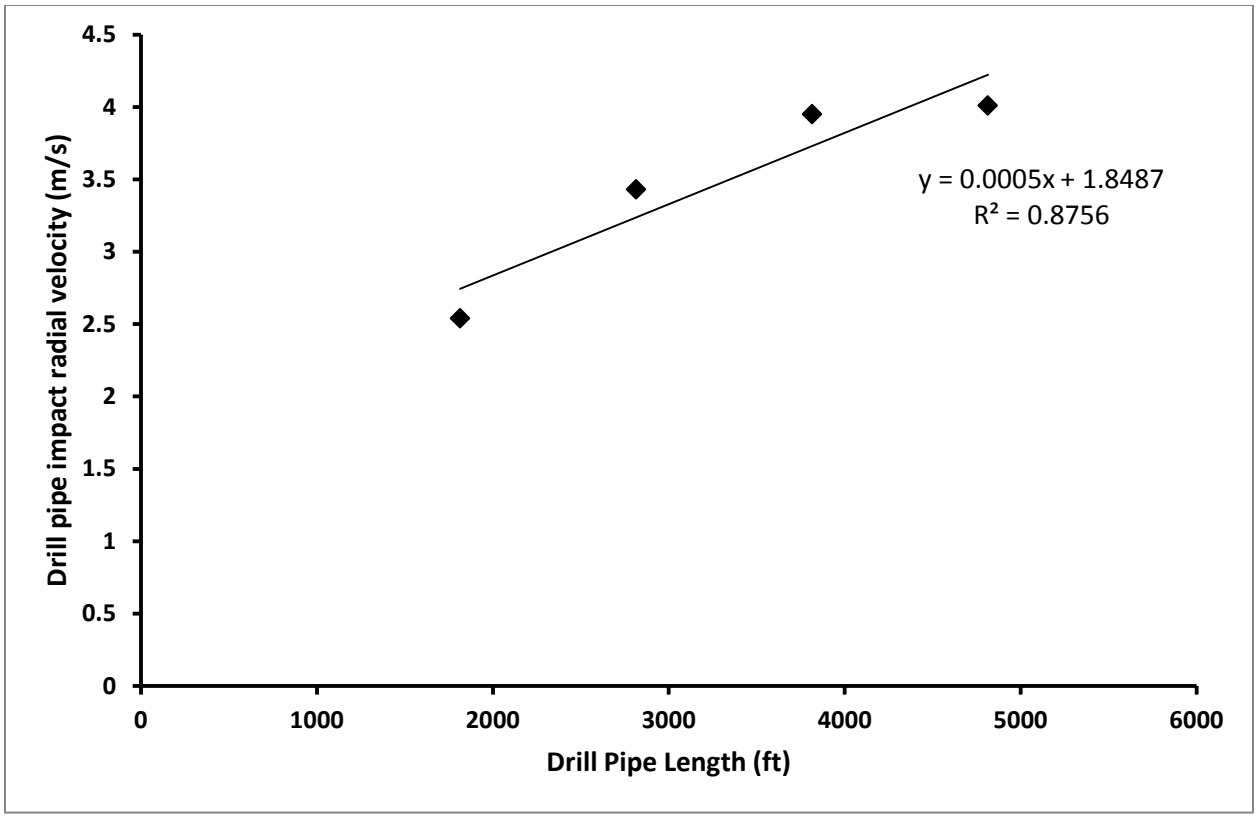

Figure 4: Vertical drilling: Change in drill pipe impact radial velocity with drilled well depth

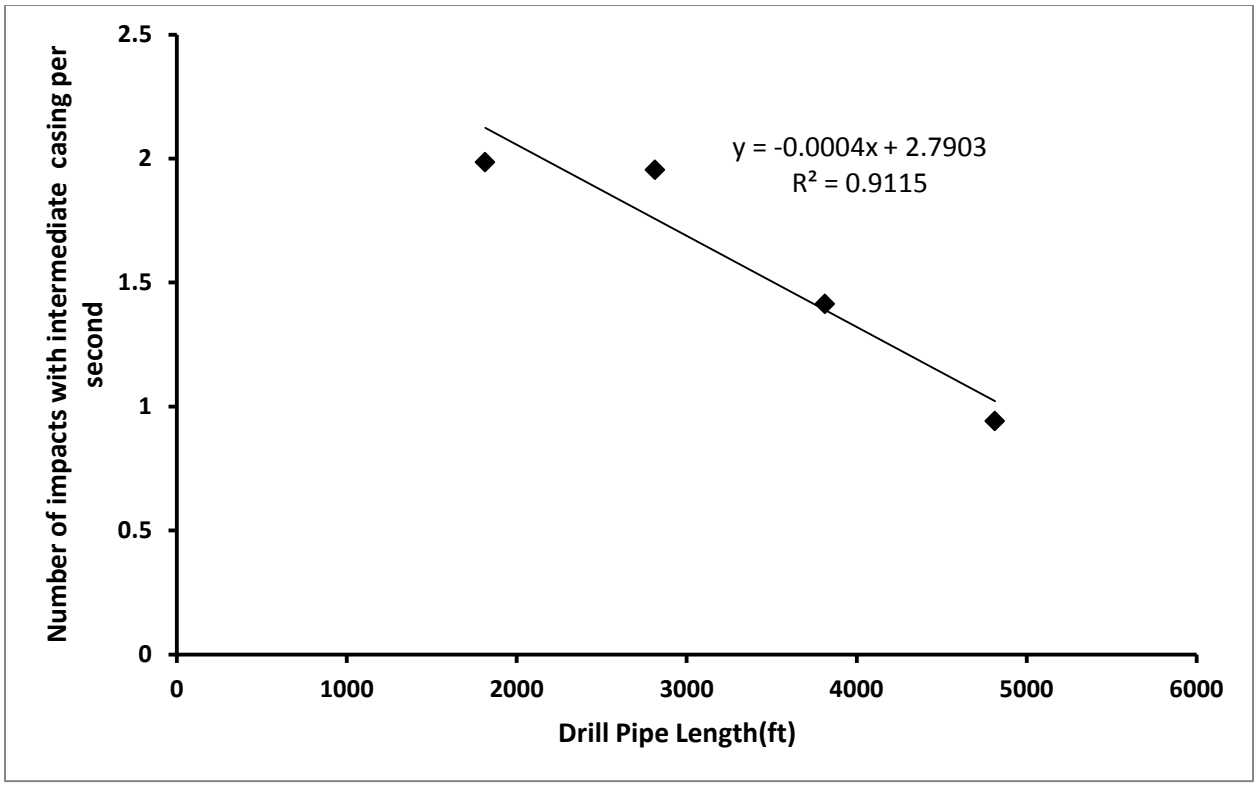

Figure 5: Vertical drilling: Change in number of drill pipe impacts (against intermediate casing) per second with drilled well depth

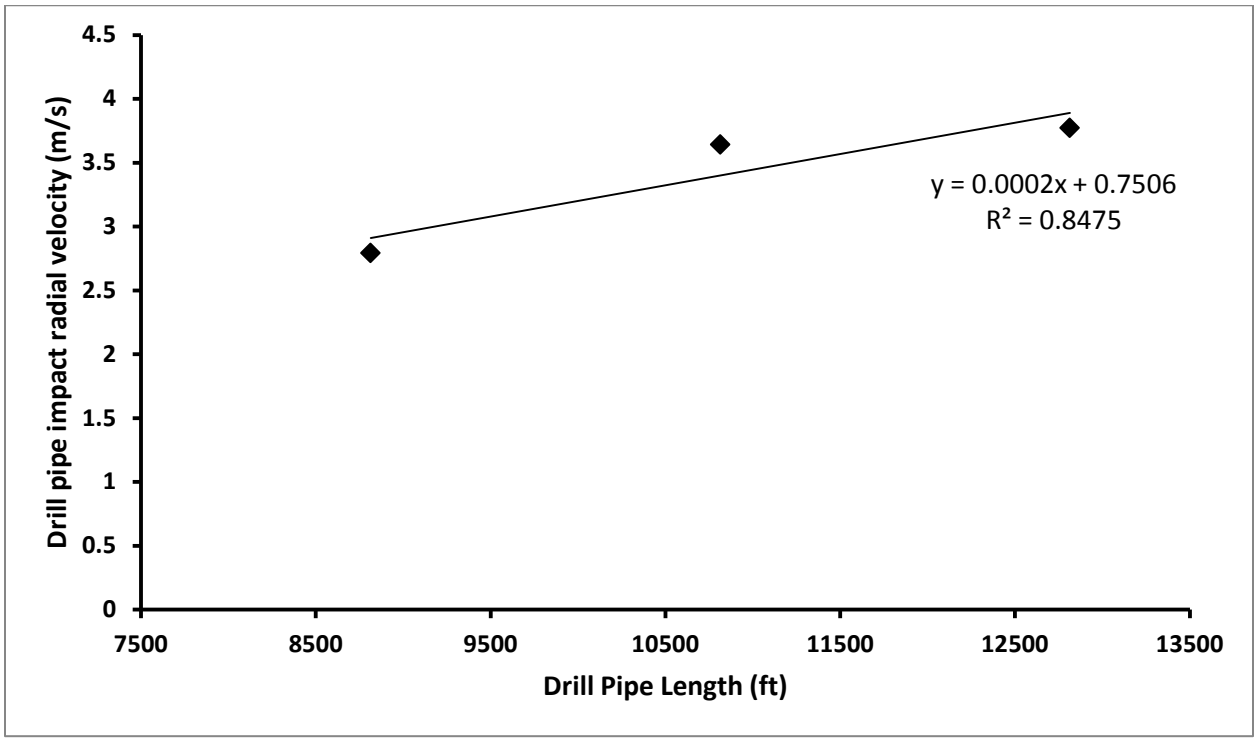

Figure 6: Horizontal drilling: Change in drill pipe impact radial velocity with drilled well depth

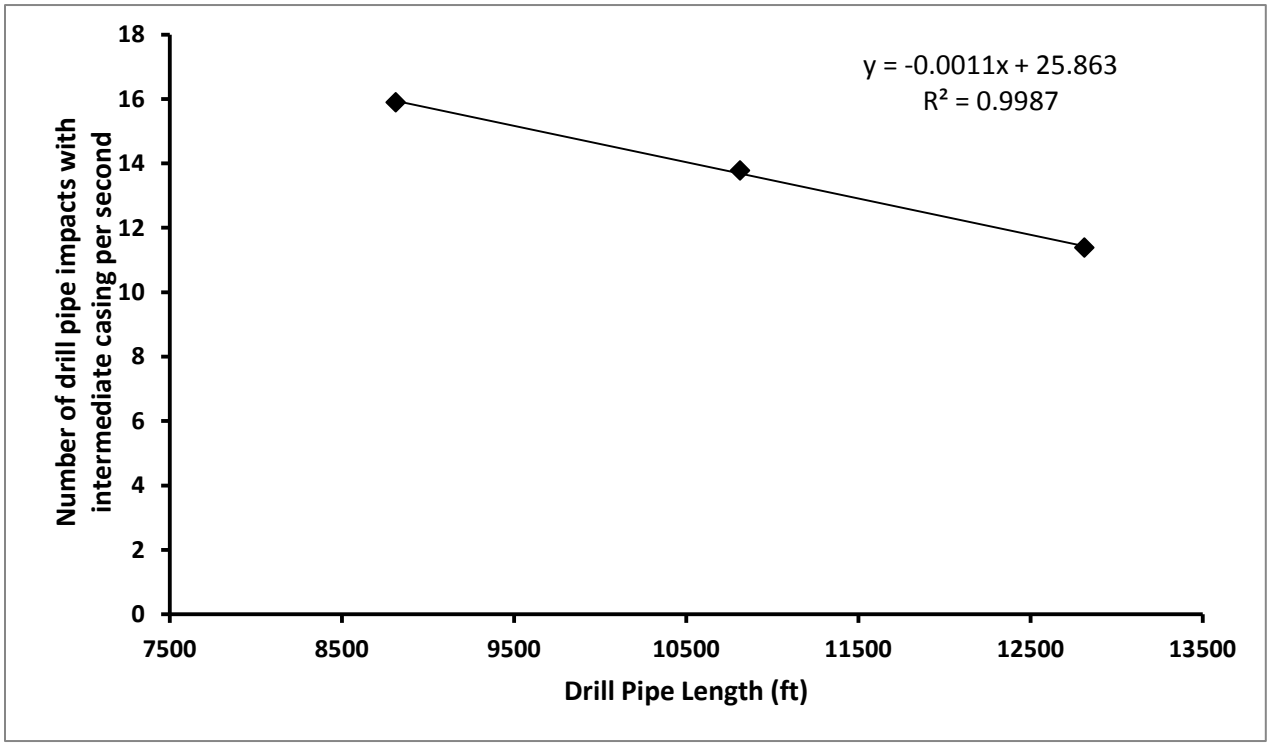

Figure 7: Horizontal drilling: Change in number of drill pipe impacts (against intermediate casing) per second with drilled well depth

Conclusion and Discussion

As per simulation results, total energy input to the intermediate casing during the production zone drilling was 1.45×10^{7} in-lb while energy input reported by field experiments during complete drilling was 2.5×10^{6} in-lb. Although the simulated energy result is a good estimate of reported energy figures, the slight over estimation might be due to a difference in simulation time period and actual drilling duration. The model assumes continuous drilling for 15 days but actual drilling faces many short breaks because of drill bit change. The model presented here analyzed only lateral vibrations. Future work will include axial and torsional vibrations in addition to the lateral vibrations making the model more realistic.

Appendix A

Table 1: Physical properties of drill pipe system for vertical drilling

Physical Quantity	Value(unit)
Drilling Torque	4000 (lbf)
Elastic modulus(E)	2.9x10^{7} (psi)

Casing ID(r_c)	12.615 (inch)
Drill pipe OD (r_o)	5 (inch)
Drill pipe ID (r_i)	4.276 (inch)
Weight on Bit (WOB)	5000 (lbf)
BHA weight (W_{BHA})	22399 (lbf)
Angular speed (ω)	35 (rpm)
Drill pipe weight per unit length ($W_{\text{drill-pipe}}$)	19.5 (lbf/ft)
Poisson's ratio of steel ν_s	0.265

Table 2: Calculated physical parameters for different drill pipe lengths for vertical drilling

Physical Quantity	**Formula**	$L_P = 1814$ ft	$L_P = 2814$ ft	$L_P = 3814$ ft	$L_P = 4814$ ft
Area moment of inertia(I) ft^4	$\pi \frac{(r_o^4 - r_i^4)}{4}$	6.88×10^{-4}	6.88×10^{-4}	6.88×10^{-4}	6.88×10^{-4}
E^* (psi)	$\frac{1}{E^*} = \frac{1-\upsilon_p^2}{E_p} + \frac{1-\upsilon_p^2}{E_p}$	1.56×10^7	1.56×10^7	1.56×10^7	1.56×10^7
Number of elements used in simulation N_{element}		200	310	420	530
$\Delta L_{\text{drill-pipe element}}$ (ft)	$\frac{L_{\text{drill-pipe}}}{N_{\text{element}}}$	9.1	9.1	9.1	9.1
Hertzian stiffness K_h (lbf/ft$^{1.5}$)	$K_h = \frac{4}{3}\sqrt{R}E^*$	6.40×10^9	6.40×10^9	6.40×10^9	6.40×10^9
Bottom Force F (lbf)	$(W_{BHA} - WOB)$	1.74×10^4	1.74×10^4	1.74×10^4	1.74×10^4
Characteristic time ($t_c(s)$)	$\sqrt{\frac{W_{\text{drill-pipe}}L^4}{EIg}}$	1.51×10^3	3.64×10^3	6.68×10^3	1.06×10^4
N_1	$\frac{TL}{EI}$	2.53	3.92	5.31	6.70
N_2	$\frac{FL^2}{EI}$	1.99×10^4	4.80×10^4	8.81×10^4	1.40×10^5
N_3	$\frac{wL^3}{EI}$	4.05×10^4	1.51×10^5	3.77×10^5	7.57×10^5
N_4	ωt_c	8.82×10^2	2.12×10^3	3.90×10^3	6.21×10^3
N_5	$\frac{K_h \delta^{0.5} L^3}{EI}$	5.32×10^{12}	1.99×10^{13}	4.94×10^{13}	9.94×10^{13}

Appendix B

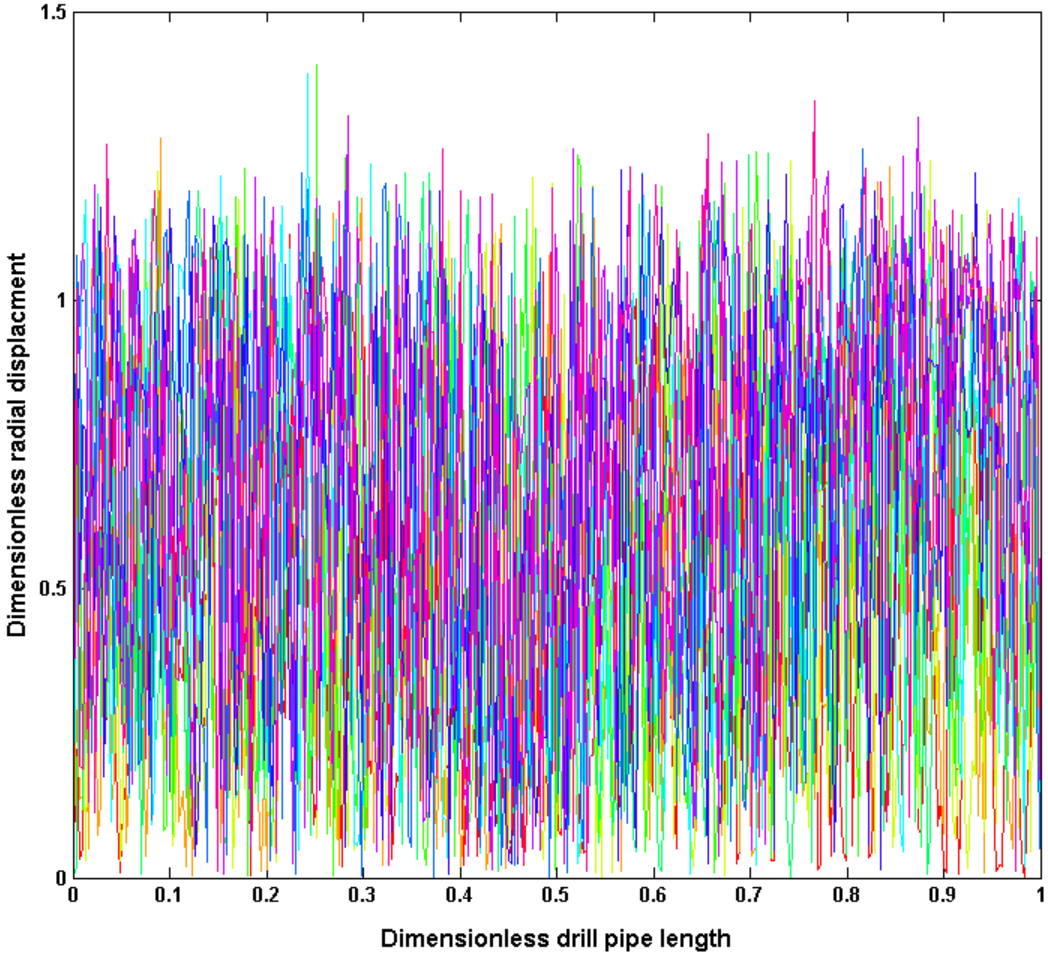

Figure 8: Vertical drilling: Time varying profile of dimensionless radial displacement of drill pipe vs dimensionless drill pipe length (for L=2814 ft)

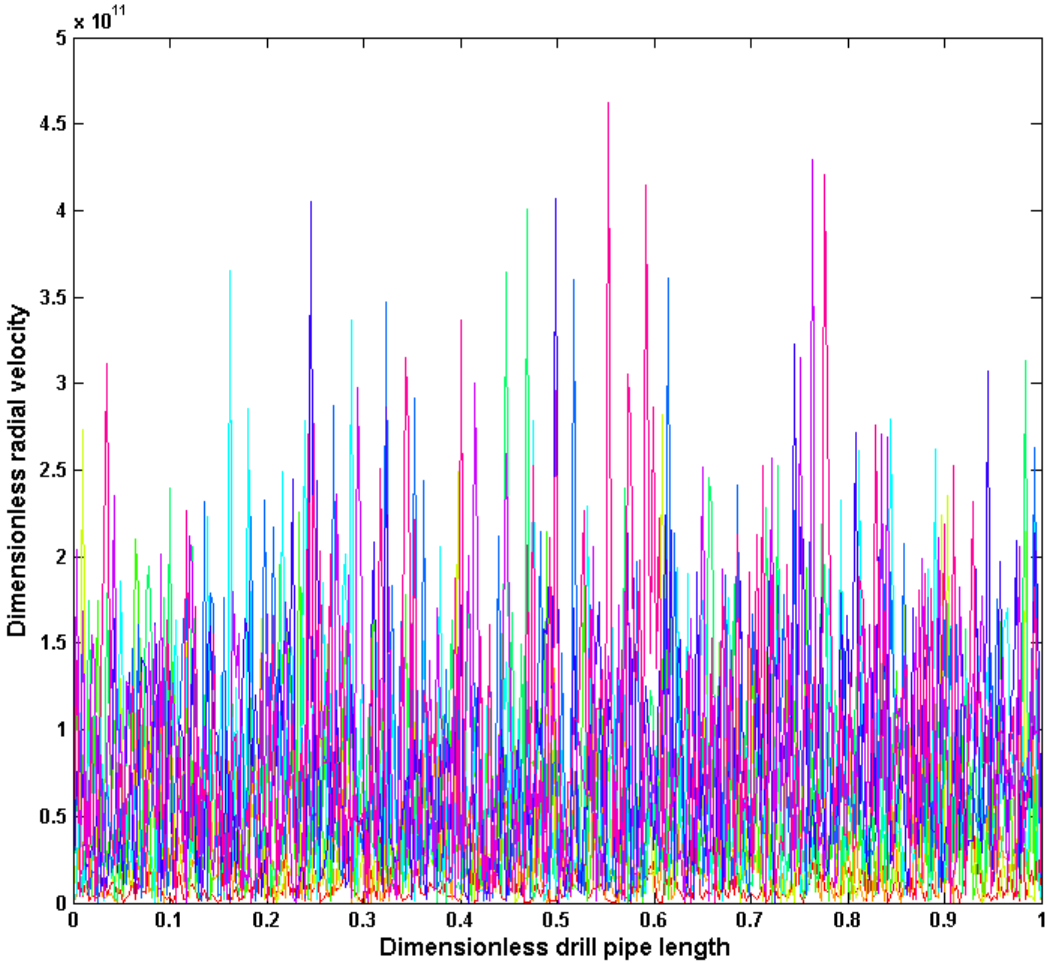

Figure 9: Vertical drilling: Time varying profile of dimensionless radial velocity of drill pipe vs dimensionless drill pipe length (for L=2814 ft)

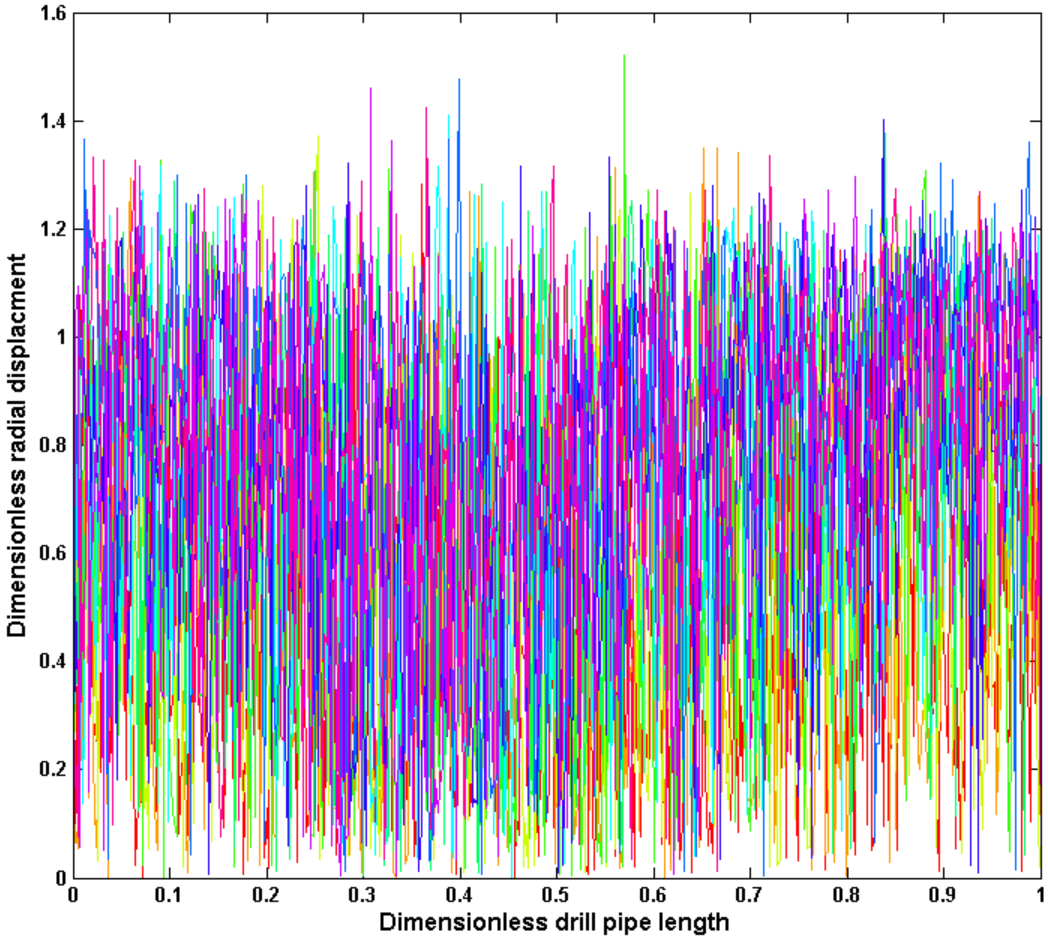

Figure 10: Vertical drilling: Time varying profile of dimensionless radial displacement of drill pipe vs dimensionless drill pipe length (for L=3814 ft)

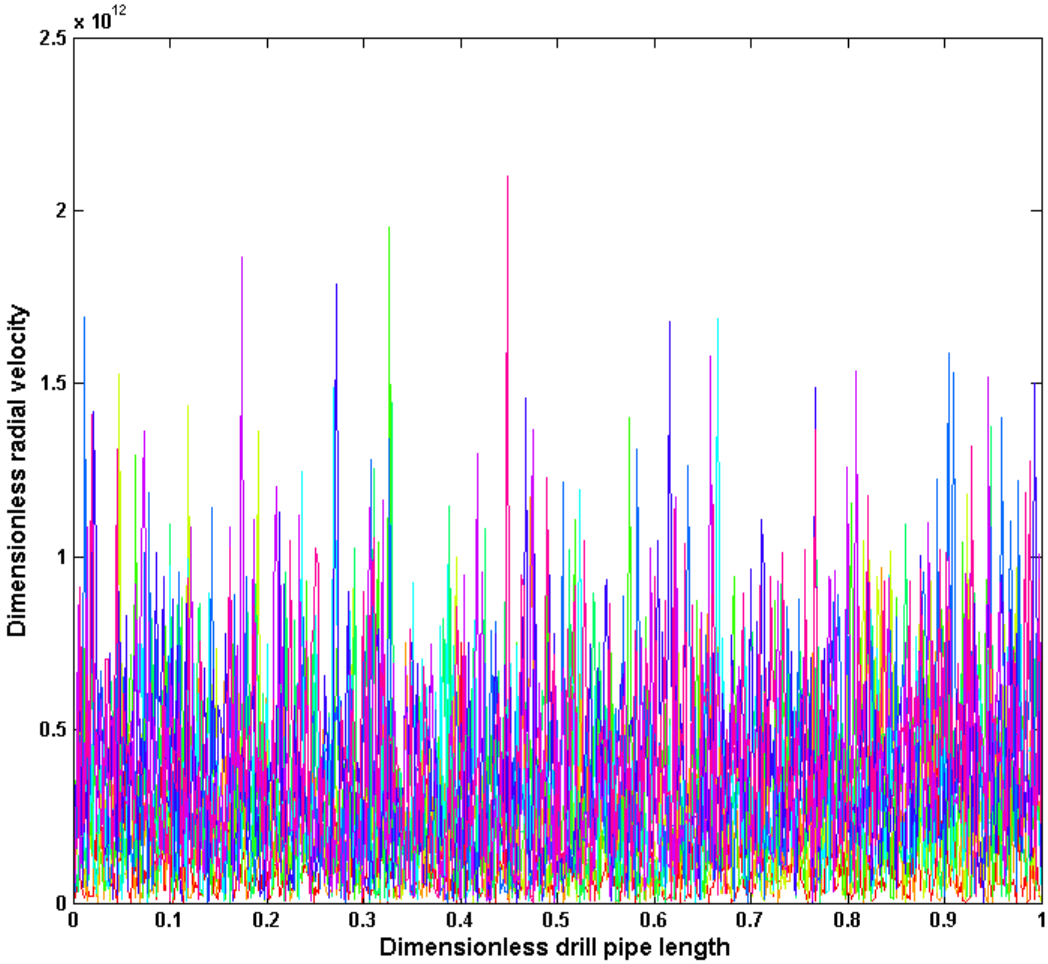

Figure 11: Vertical drilling: Time varying profile of dimensionless radial velocity of drill pipe vs dimensionless drill pipe length (for L=3814 ft)

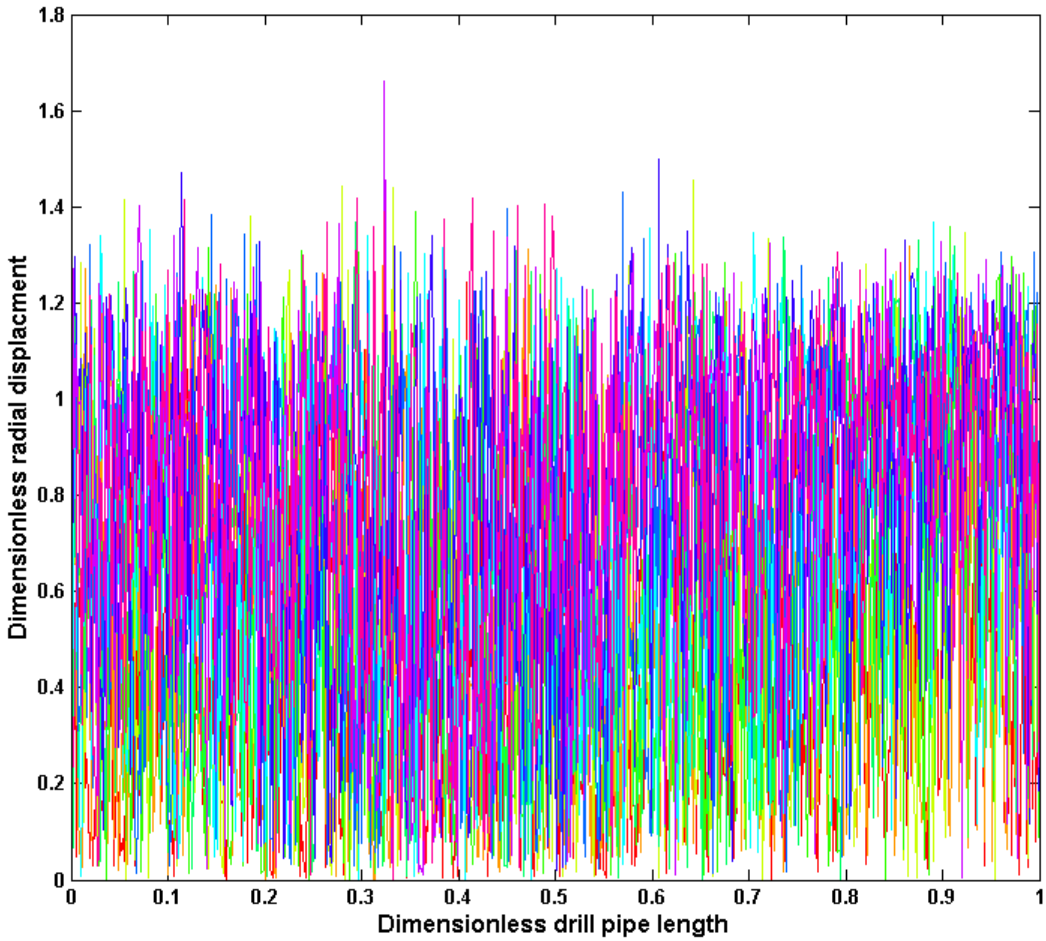

Figure 12: Vertical drilling: Time varying profile of dimensionless radial displacement of drill pipe vs dimensionless drill pipe length (for L=4814 ft)

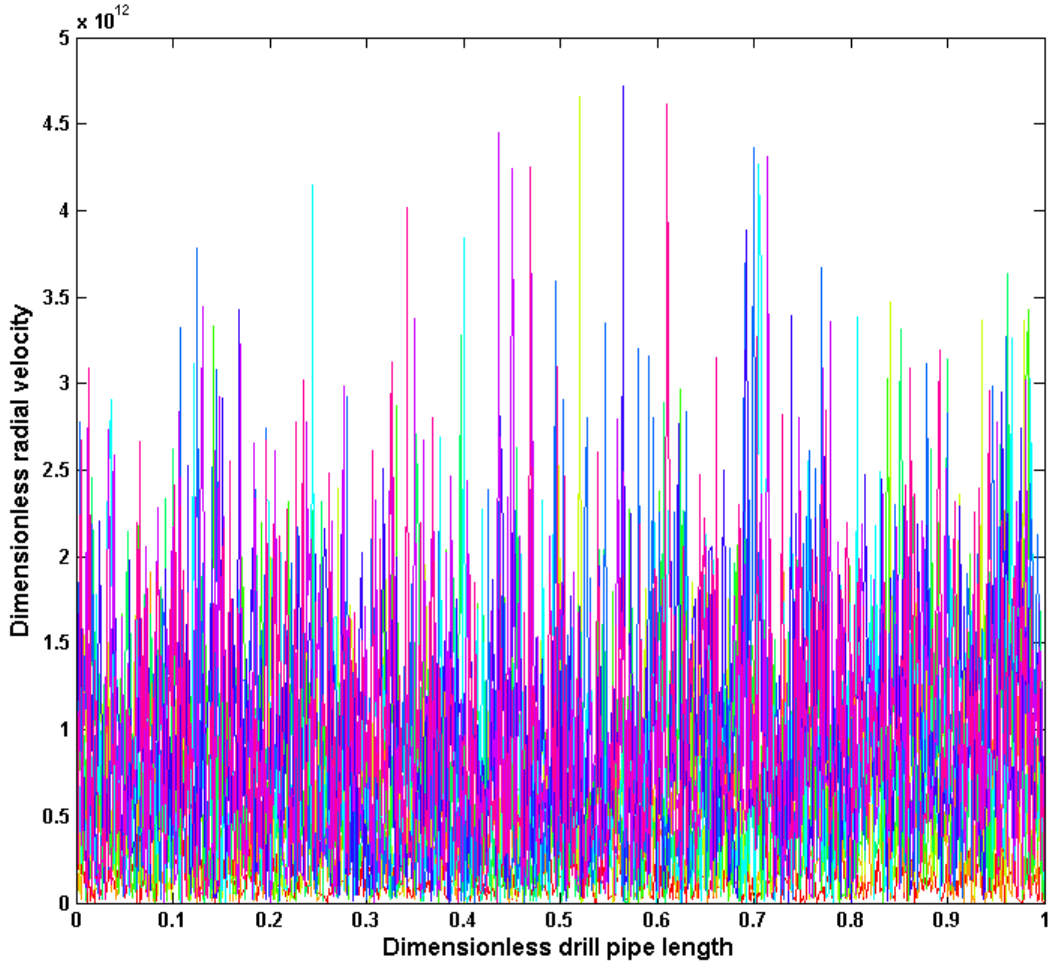

Figure 13: Vertical drilling: Time varying profile of dimensionless radial velocity of drill pipe vs dimensionless drill pipe length (for L=4814 ft)

Appendix C

Sample Calculation for Vertical Drilling

Drilling the vertical section (from L_1=2000 ft to L_2=7422 ft) takes approximately 5 days. Assuming drill pipe goes inside the well with a constant velocity V, the equation describing the axial motion of drill pipe is:

$$L_p(t) = Vt + L_1 \tag{18}$$

where $V = \left(\dfrac{7422 - 2000}{5 \times 24 \times 60 \times 60} \right) \dfrac{\text{ft}}{s}$

$$= 0.0126 \ \frac{\text{ft}}{s}$$

Drill pipe radial impact velocity V_p (Figure 4):

$$V_P(t) = 5\times10^{-4} L_p(t) + 1.8487 \ \frac{\text{m}}{s}$$
$$= 5\times10^{-4}(Vt + L_1) + 1.8487 \ \frac{\text{m}}{s}$$
$$= 6.28\times10^{-6} t + 2.8487 \ \frac{\text{m}}{s} \qquad (19)$$

Number of drill pipe impacts per second N (Figure 5):

$$N(t) = -4\times10^{-4} L_p(t) + 2.7903$$
$$= -4\times10^{-4}(Vt + L_1) + 2.7903 \qquad (20)$$
$$= -5.02\times10^{-6} t + 1.9903$$

Total Energy $E = \int_0^T \frac{1}{2} M_P V_P(t)^2 \times \chi \times \text{N(t)} \times dt$

where

$$M_p = 2.5 \text{ kg}$$
$$V_b = 5000 \ \frac{\text{m}}{s}$$
$$T = 4.32\times10^5 \text{ s} = 5 \text{ days}$$
$$N(t) = -5.02\times10^{-6} t + 1.9903 \qquad \text{for } 0 \le t \le 3.96\times10^5 \text{ s}$$
$$= 0 \qquad \text{for } t \ge 3.96\times10^5 \text{ s}$$
$$V_P(t) = 6.28\times10^{-6} t + 2.8487 \ \frac{\text{m}}{s}$$
$$E = 1.02\times10^5 \text{ J} \approx 9.09\times10^5 \text{ in-lb}$$

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