GES23-162

Combination of Methods to Assess the Success of a Cement Sheath Placement While Rotating: A Case Study

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ABSTRACT

Scope:

Cementing operations, especially in modern-day wells that push the technological envelope, present challenges related to slurry design, job design and execution, and measurement or validation upon completion of the job. Multiple methods and tools are used to predict and evaluate how well a cement sheath has been placed. This paper is a case study combining proven industry equations, an established cementing software model, and cement logs to evaluate a cement sheath placed around a liner using Rotation.

Methods, Procedures, and Process:

This paper presents pre-job calculations, fluid design, and the job design in conjunction with pre-job predictive software modeling results. The well data is also presented, including top drive torque, fluid volumes and rates, pump pressures, fluid densities, and actual vs. synthetic logs sets. These are then compared to assess and validate the success of the cement sheath after the slurry has been pumped.

Unfortunately, a software model is limited by necessary assumptions with input data, methods used to generate synthetic logs are naturally limited, and field data collected for comparison is often challenging to interpret. Experienced field personnel using engineering best practices can use current tools in combination to overcome the limitations commonly inhibiting accurate design during the planning stages. Combining these available tools with field data allows operators and service companies to alter their approach for the next well in that field, increasing the likelihood of success.

Results, Observations, and Conclusions:

Data measured in the field and lab data, combined with field measurements, were evaluated to gain confidence in the inputs used for the software models. Synthetic and actual logs were used to validate and gain confidence in conclusions. The software models were then compared to rig data. As these all matched reasonably, confidence was gained in the conclusions drawn from all data sources. The quality of the cement job was compared to two offset wells, and accurate recommendations were reached for application in the next well.

Novel/Additive Information:

The authors aim to disseminate technical information on the methodology and practice of combining available resources and modeling wells post-job to validate the accuracy of post-job evaluations and equip engineers in the industry to recommend changes for future offset wells better.

INTRODUCTION

Definitions of a Successful Job/Goals of Cementing:

A successful primary cement job results in the placement of a mechanical barrier bonded to casing and formation, which prevents fluid migration between permeable zones and across the surface of the casing. This is of great importance to ensure well integrity, which includes preservation of the casing, preventing contamination of aquifers, zonal isolation, and the protection of and ability to produce from the hydrocarbon zone.

Common Measurements/Field Data Used to Verify Successful Jobs:

Pump pressure is one of the most common field data verification methods because it occurs at the surface and is easily measurable. Plug bumps at the expected volume pumped indicate that the cement has been fully displaced. Expected pressures at the end of the job can indicate mud displacement (absence of channeling).

Bond logs are a common downhole measurement that indicates cement coverage. These are used to verify that gas zones have been covered by cement, the top of cement (TOC) is at the desired depth, and whether or not channeling has occurred. Log interpretation can be challenging and has been likened to 'half art and half science.' Temperature logs immediately after the cement is placed can indicate the cement's mechanical integrity.

Description of Challenges Related to Measurement/Validation of Successful Cement Jobs:

The actual physical events of concern often happen thousands of feet below the surface in a very narrow annular space at high temperatures and temperatures. Actual data is difficult to get and often does not directly measure the desired property. A combination of techniques and job facts is therefore needed.

Logs are the highest standard of measurement as related to cement. As logs are an indirect image of cement presence resulting from the interaction of sonic and ultrasonic waves, there is significant room for interpretation of the displayed response of the log and the presence of defects. Unfortunately, this means logs cannot stand alone but must be combined with other verification methods and measurements.

One of the most powerful tools available to cementing engineers is cementing software. Job simulation software is excellent for pre-job assessments and determining the potential types, locations, and severity of downhole problems that are unknown before the job. A significant downside is that 'garbage in equals garbage out.' Even well-built models by competent engineers are still limited to the formation details known and the assumptions made beforehand.

Determining the causes of failures is done after the job is over. This does not help prevent failures but is helpful. Post-job analysis helps with the development of best practices and the avoidance of similar failures during future similar jobs.

CASE STUDY

Cementing Job Objectives:

The primary objective of the well assessed in this paper was to produce from a gas reservoir. Cementing a gas-producing well can be challenging as gas can migrate through smaller pore spaces than liquids. The primary objective of the cement job was to prevent gas migration across the gas zones in the cemented interval and from the production zone in the next section.

The cement for this section required the maximum compressive strength achievable on all slurries. This was dependent on the densities. It was critical to reduce the initial setting time to begin compressive strength development in the slurries more rapidly. Also important was to maximize the compressive strength rate of development.

Well/Job Description:

The case study looks at the cementing of the 7" production liner to a TD of 1,465.24 m MD at 89 degrees deviation. A 1,000 m 6 ½" open hole section was planned following the installation of the production liner. The production hanger was set at 566 m MD inside a 9 5/8" casing run to 675 m MD, with an 8 ½" open hole section to 1,498.39 m MD. The liner was run on, and cement was pumped through a 5" drill pipe to the surface. A well schematic and the final fluid positions for the 7" liner cement job are shown below (left and right, respectively).

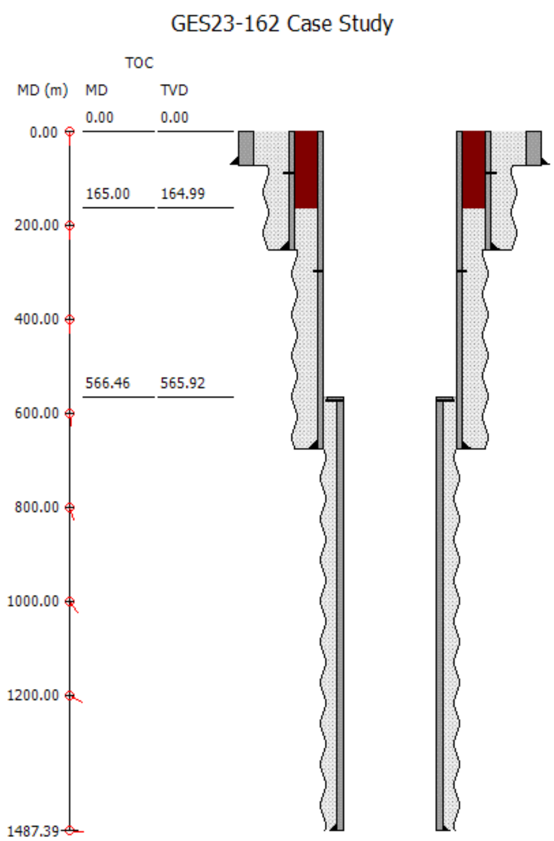

Figure 1: Well Casing Schematic

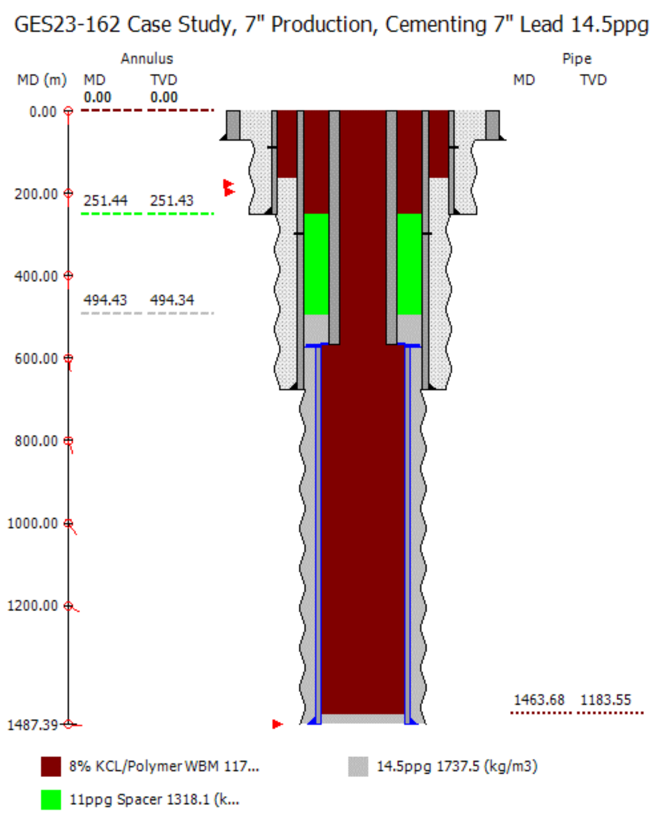

Figure 2: Final Fluid Position Schematic

The temperature gradient of the well was 2.02 deg C/100m with a BHST of 53 deg C at 1,186.89 m TVD. Multiple spacers and slurries were considered for cementing the production liner, with the primary options shown below. The 11 ppg spacer and a single slurry using the 14.5 ppg cement were selected for the final design.

	Description	Type	Density (ppg)	Model
1	8% KCL/Polymer WBM	Drilling Fluid	9,80	Power Law
2	10.5ppg Spacer	Spacer	10,50	Bingham
3	14.5ppg	Cement	14,50	HB
4	Tail 15.8ppg	Cement	15,80	Bingham
5	Lead 12.5ppg	Cement	12,50	Bingham
6	11ppg Spacer	Spacer	11,00	HB
7	16ppg Tail	Cement	16,00	Bingham

Table 1: Fluid Properties Considered

The pump program used 40 bbl of the spacer and 84 bbl of cement slurry. 130.432 bbl of the drilling mud in the hole was used as the displacement fluid. The pumping schedule is shown below.

	Stage	Input	Vol. (bbl)	Front (m)		Len. (m)	
				Ann.	Pipe	Ann.	Pipe
1	8% KCL/Polymer WBM	Front - Ann.	0,000	0,00		251,44	0,00
2	11ppg Spacer	Vol.	40,000	251,44		242,99	0,00
3	Bottom Plug						
4	14.5ppg	Vol.	84,000	494,43		992,96	23,71
5	Top Plug						
6	8% KCL/Polymer WBM	Front - Pipe	130,432		1463,68	0,00	1463,68

Table 2: Pump Schedule

The rig rotates during the cement job to help ensure a uniform quality cement sheath at an essentially horizontal deviation. A rotation speed of 25 rpm was maintained while pumping the cement and displacement fluids. Expected mud displacement efficiency is shown below with and without rotation.

FIELD MEASUREMENT METHODS AND RESULTS

<u>Measurement methods applied:</u>

Surface torque is readily predicted in a software model (Figure 3). Once rotation starts, shown at 40 bbls, a surface torque of 4,400 ft-lbs was expected. As the heavy fluids travel into the highly deviated lateral, the effective weight of the casing increases, and therefore the torque increases as well. The surface torque was expected to max at 5,200 ft-lbs, then drop as the heavy fluids turned the shoe and entered the annulus. Heavy fluids in the annulus not only vacate the pipe for the lower-density displacement fluid that follows but also provides a greater buoyancy for the liner.

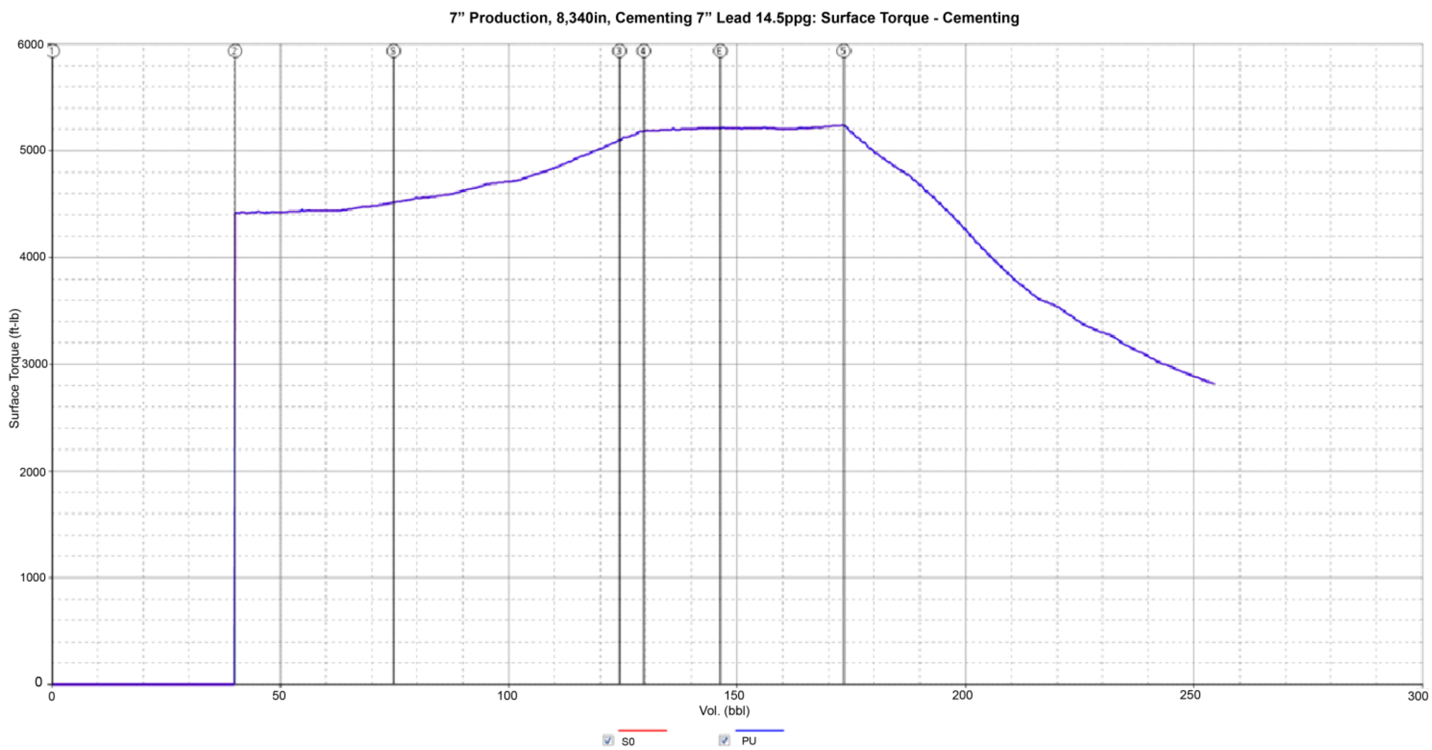

Figure 3: Predicted Surface Torque While Pumping Cement

Pump pressure matching between a software model and the rig is used to verify the hole in the gauge and the absence of slurry contamination. A successful match also validates the software model for calculated ECDs downhole.

A predictive pump pressure graph is shown below (Figure 4). This graph evaluates the pressure test on green cement at the plug bump and pump pressure during the cement job. To ensure an accurate match, fluid densities in the model are also calibrated to those measured at the surface as the fluids are pumped downhole.

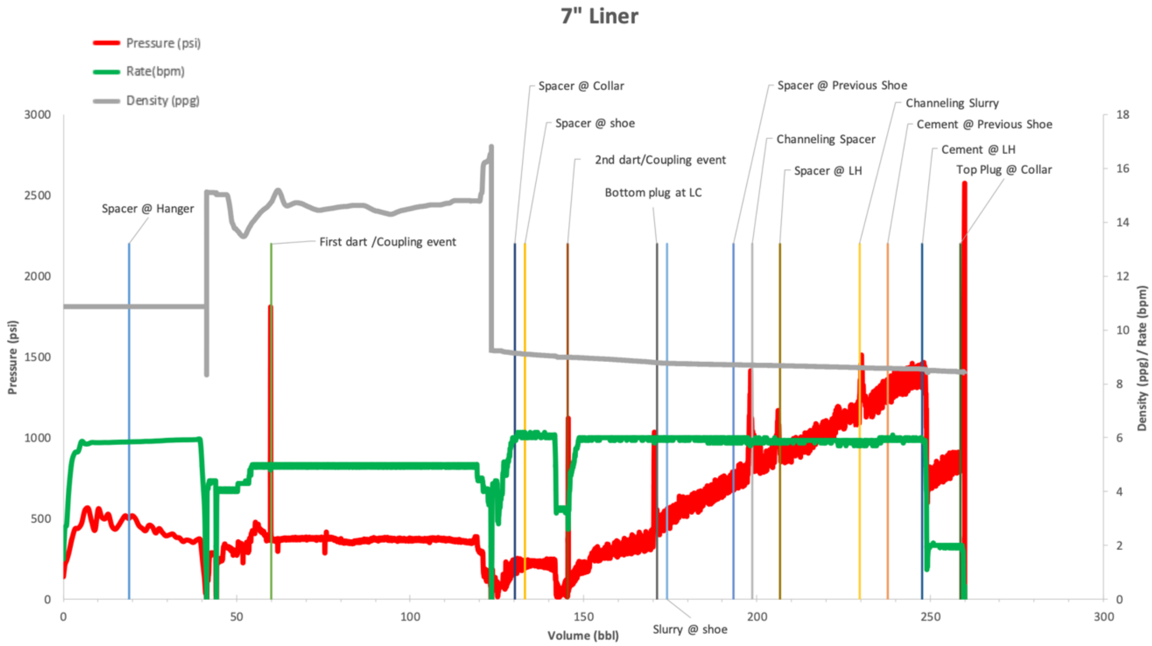

Figure 4: Software Predictive Pump Pressure Graph

Since rig data such as pump pressure, fluid densities, and surface toque can be used to calibrate the software model, logs can then be compared to software simulation results to assist with their interpretation. Displacement efficiency software calculations combined with logs allow for more confident identification of downhole events, such as the location of TOC and the presence of channeling.

Displacement efficiency calculation results for this well are shown below (Figure 5). Final fluid positions are shown on the left, with the mud/displacement fluid in brown, the spacer in green, and the cement in gray. The graphical 'tracks' from left to right are Fluid Mixing, Cement Concentration as an unwrapped annular view, Flow Pattern during pumping, Cement Concentration as a side view, and Cement Concentration as a simple line graph.

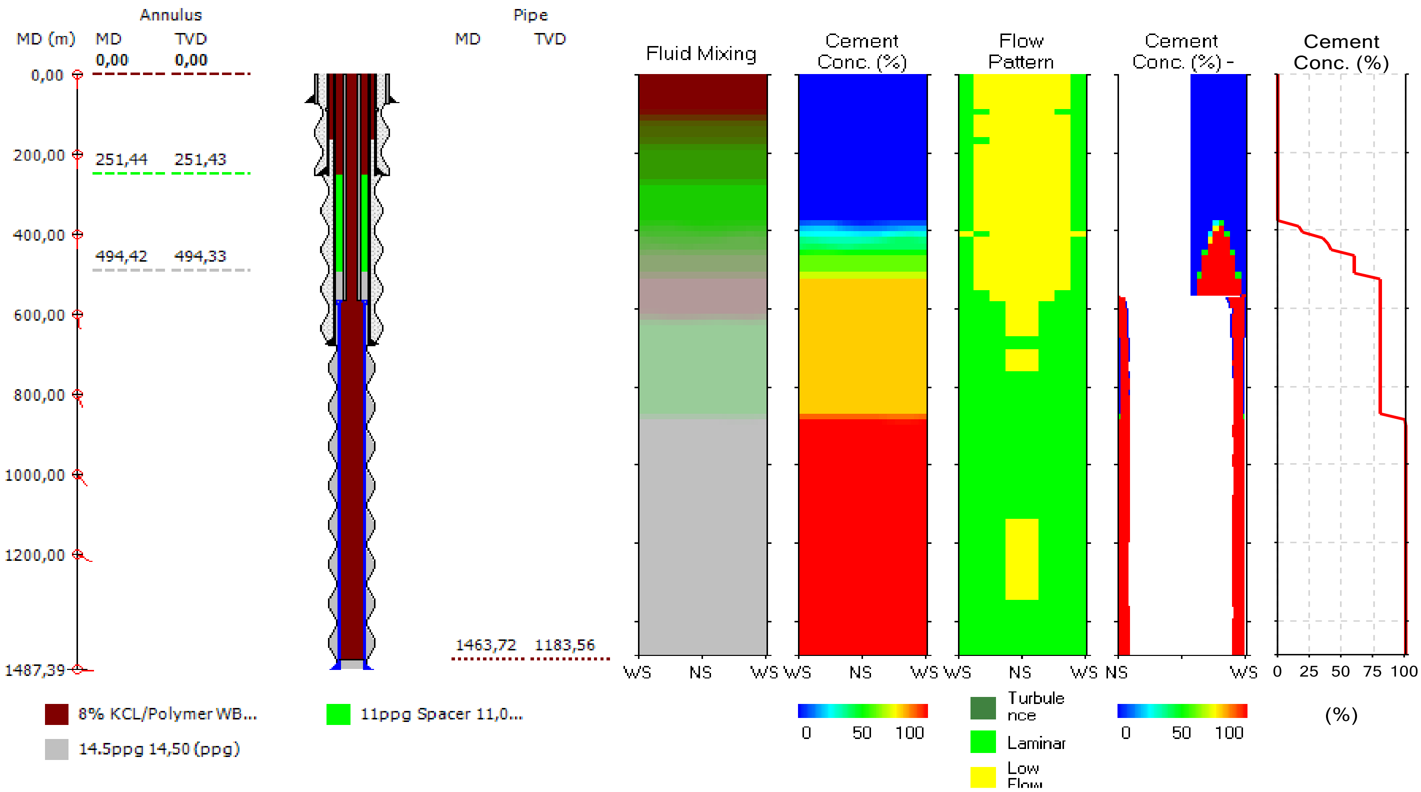

Figure 5: Software Predictive Displacement Efficiency Outputs

Two actual logs were taken following the cement job. VDL (density) and USIT (acoustic impedance) logs were taken from 566.5 m MD to 1,066.5 m MD. The density logs were used to verify the presence of cement, and the acoustic impedance log was used to verify the quality of the cement sheath. A synthetic log was also developed to evaluate the missing depths below 1,066.5 m MD to the shoe and for comparison with the actual logs.

A synthetic log is an image or profile equivalent to the graph produced by a cement log. These are made from the software's outcome of displacement efficiency (cement coverage). The output is based on cement's and other fluids' presence and concentration levels, measured via acoustic impedance. The impedance is directly proportional to the fluid concentration, making it possible to quantify to total acoustic impedance by a simple formula:

= Total acoustic impedance (to be compared to what's measured with the log) = % fluid1 x acoustic Imp. + % fluid 2 x acoustic impedance + % cement x acoustic impedance

This log can be compared with the actual log in trend and value. The synthetic log can validate the actual log measurements and vice versa. These logs can also provide a baseline to identify changes that occur later on after placement, potentially caused by pressure testing, formation interactions, and other events.

Field Results:

The measured surface torque is shown below as the blue line in relation to the right y-axis in thousands of ft-lbs. The surface torque was approximately 5,000 ft-lbs before the higher density fluids made it into the annulus vs. the software's predicted 4,400 ft-lbs. The increase in torque can be seen between 60 and 80 minutes into the job. The increase, absence of momentary jumps higher, rose more than the model's estimated 5,200 ft-lbs to approximately 6,200 ft-lbs.

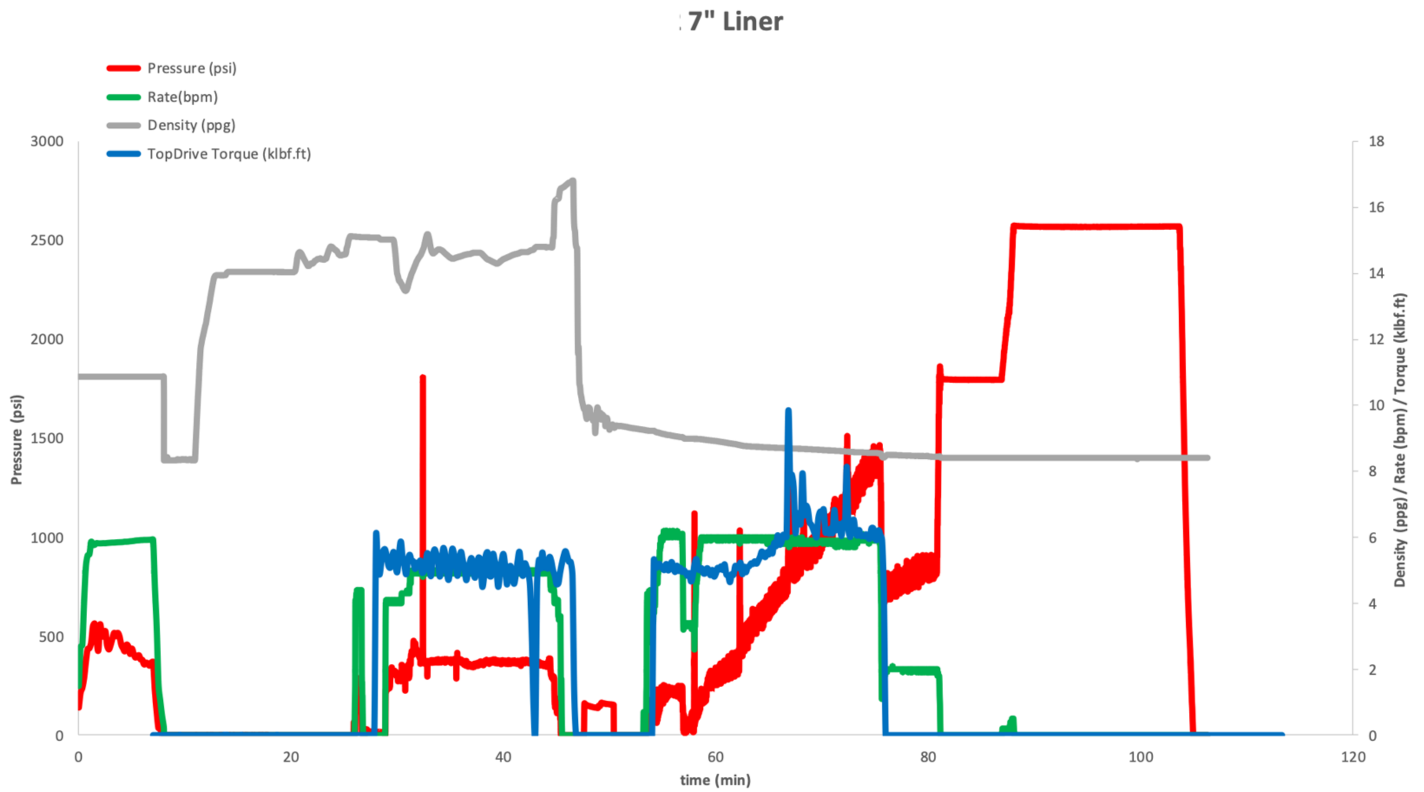

Figure 6: Measured Surface Torque Overlaid With Pressure, Rate, and Density

The actual pump pressure (blue) can be compared with the calculated pump pressure (red) in the below graph, related to the left y-axis. The flow rate (green) is also shown for reference, related to the right y-axis. For pump pressures, it is more important to match trends than actual values, in the authors' experience.

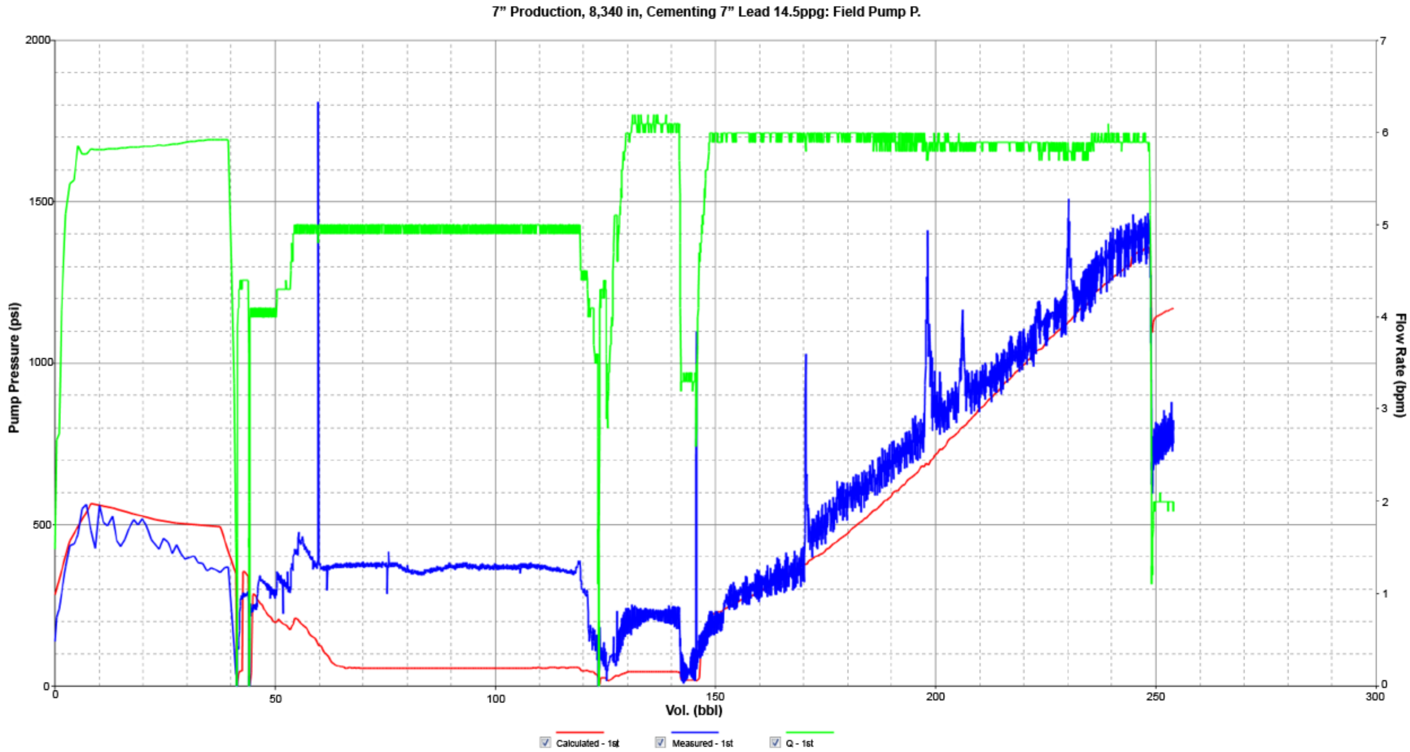

Figure 7: Measured vs. Predicted Pump Pressure

The actual pump pressure does follow the same downward trend until 50 bbls into the job, at which point the field and calculated values stay reasonably steady, despite the approximately 300 psi difference in value. Changes in the measure pump pressure can be seen directly following the pause in pumping when the plugs were dropped, at 40 bbls and just after 124 bbls into the job. The pump pressure can be seen climbing by 150 bbls into the job with the spacer in the annulus, and a slope change at 170 bbls when the cement turns the shoe. The calculated and actual pump pressures closely follow the final plug landing.

The measured and planned fluid densities at the surface are shown below in blue, with the pump rate in green for reference. The cement was pumped from 40 bbls to 124 bbls into the job and is the most important fluid to validate for density. Any errors in cement mixing or density changes before being pumped downhole would severely impact the fluid properties of the cement and, therefore, the cement's pumping, mud removal, and setting. The below graph lends confidence that the planned slurry is effectively what was pumped downhole.

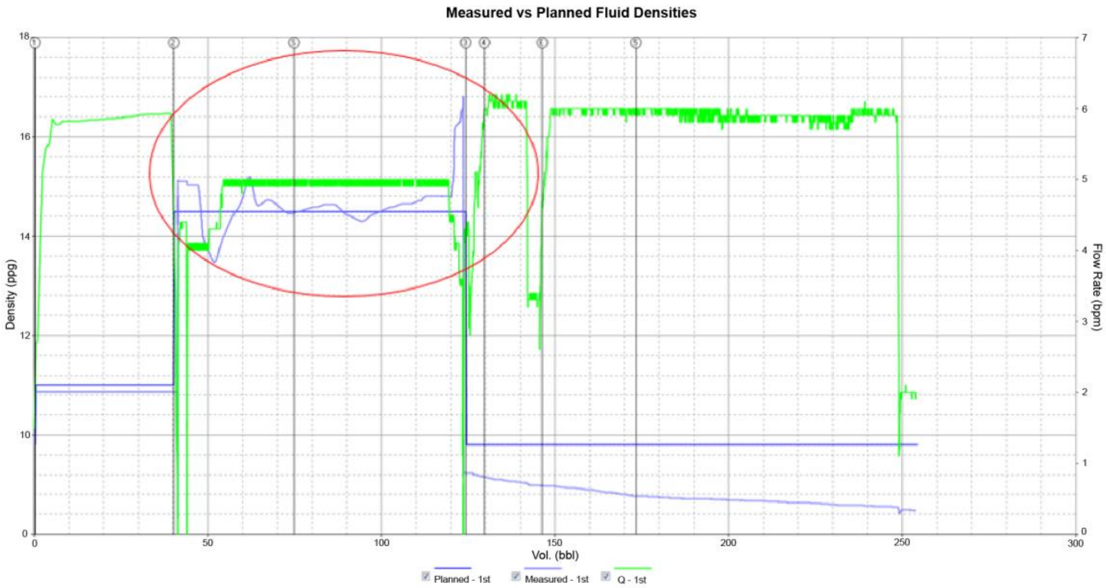

Figure 8: Measured vs. Planned Fluid Densities

The software displacement efficiency graphics (left) are compared to the acoustic impedance log (right) in the figure below. The presence of cement is expected from roughly 850 m MD and below in the leftmost unwrapped view of the annulus, with mixed spacer and cement from 600 m to 850 m MD. The rightmost unwrapped view shows the section of 100% cement coverage as red, from roughly 850 m MD to TD. The acoustic impedance log also shows poor cement in the upper section (light brown and the presence of blue, which will be described in more detail in the next section).

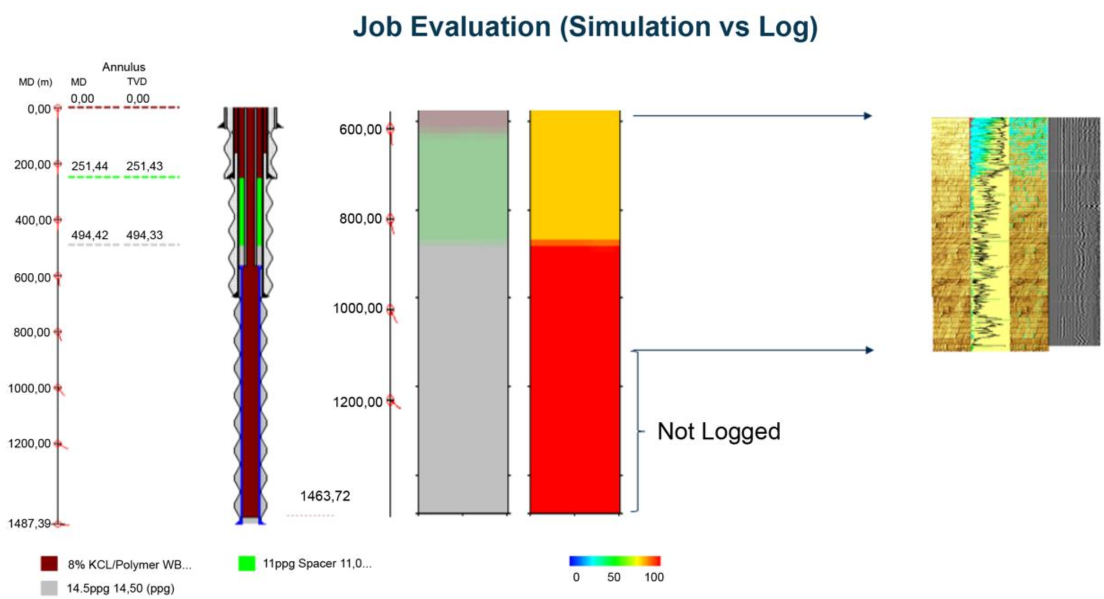

Figure 9: Software Displacement Efficiency Output (left) vs. Acoustic Impedance Log (right)

In the below figure, a comparison is made between the acoustic impedance log and the synthetic log. The uppermost horizontal section is the VDL, which shows cement in the entire interval. This is helpful because it verifies cement presence and allows the other logs to be evaluated for the bond quality between the casing and cement.

The USIT (lower graphic) shows the acoustic impedance max (gray; upper), min (purple; lower), and average (blue; center). In the upper horizontal section of the graphic labeled VDL, the light brown shows poor cement, and the darker brown shows good cement. The blue line represents mud's acoustic impedance threshold, indicating mud's presence in the annulus.

The yellow background represents a good bond, and the blue background a poor bond, with the green in between less than desired quality cement. Higher acoustic impedance is desired, as they are linked to density. The existence of a Max and a Min indicates the casing's eccentricity, or how centered it is in the hole. When placed, the cement will flow more on the wide side of the annulus and less on the narrow side, leading to a better cement sheath on the wide side and less cement coverage on the narrow side.

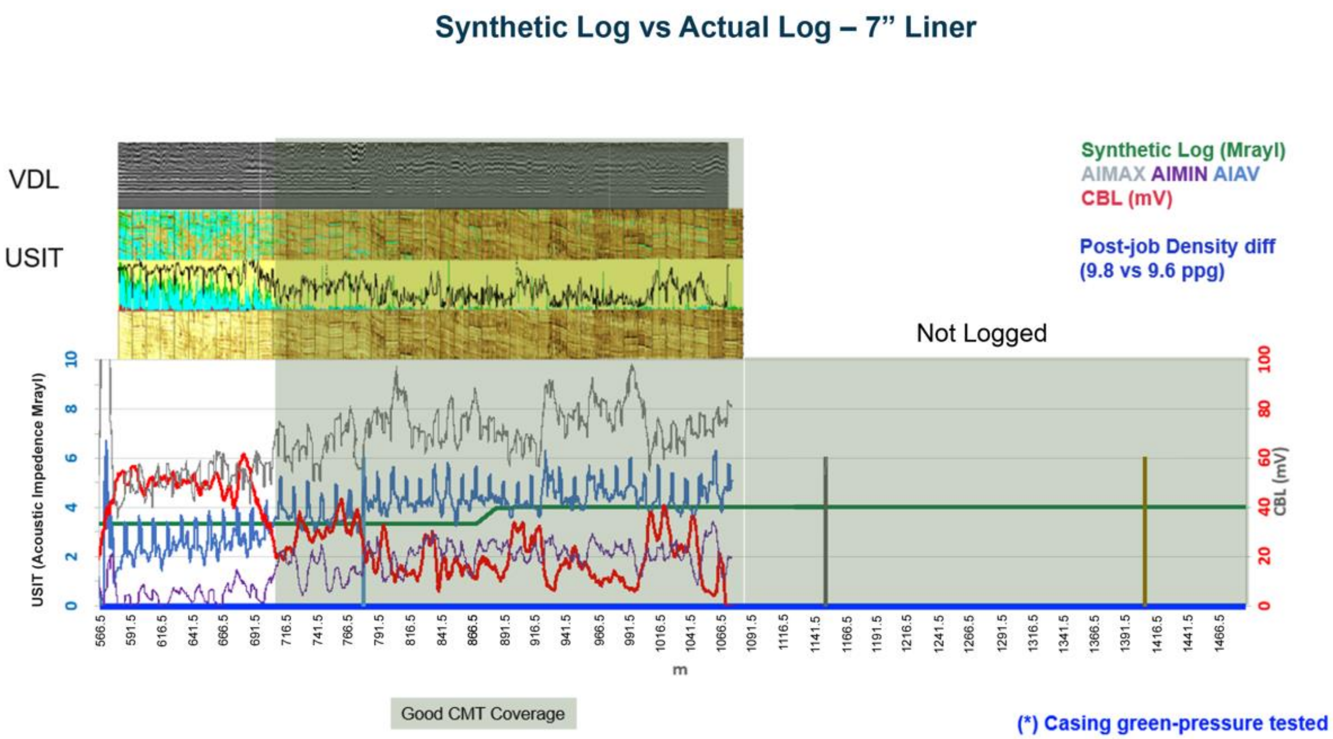

Figure 10: Synthetic Log vs. VDL and USIT Logs

In the bottom section, the actual log shows the synthetic log as green, the CBL as red, and the min/max/average USIT lines (purple, gray, and blue, respectively). The proximity of the AIAV and the green line evaluates the cement using the software as executed (in playback). This validates the placement and is shown as the darker shaded area below 716.5 m MD.

Above the shaded area, something happened to cause micro-annulus formation, likely post-job. Lower CBL values are better, with increased levels undesirable. The CBL (red line) reacts more violently when micro-annuli are present, which occurs when the formation interaction between the cement and a permeable zone occurs. CBL is sonic and is more sensitive to the presence of micro-annuli.

The upper log in Figure 11 below indicates the presence of gas. Looking at the uppermost horizontal section, it can be seen that the presence of gas is primarily in the unshaded zone, from roughly 1,080 m MD and below. Since the shaded area has been confirmed as having a high level of cement coverage, the gas zone is known to be covered by a good quality cement sheath.

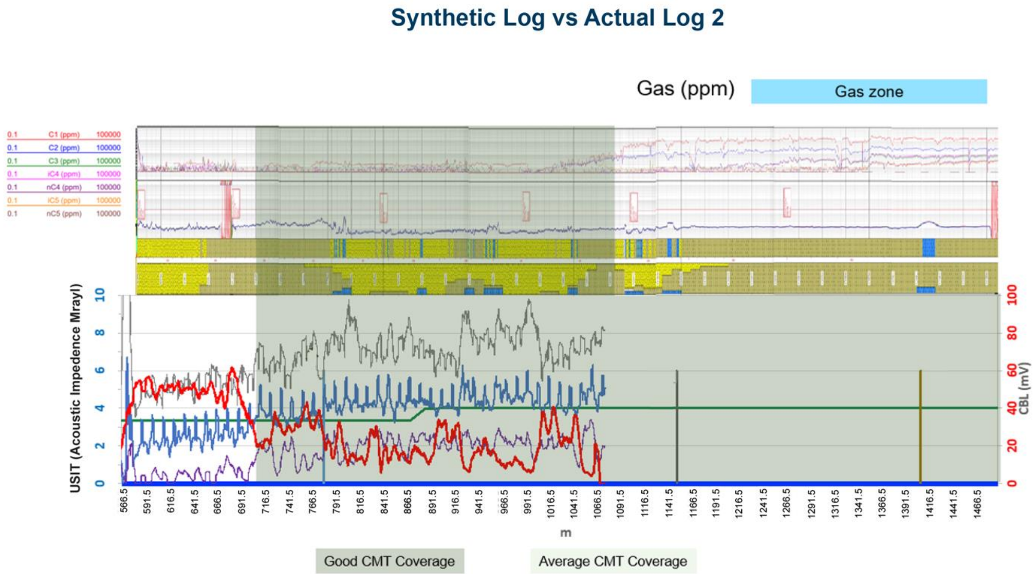

Figure 11: Synthetic Log vs. Actual Log

The USIT log (Figure 12) is shown at the bottom and was not logged below approximately 1,070 m MD. Without an actual log below 1,070 m MD, this leaves the synthetic log as the only usable log going all the way to the shoe. Using the below comparison between the actual and synthetic logs in the shaded area of the actual log, the synthetic log is considered to be a good representation from 1,070 m MD to the shoe.

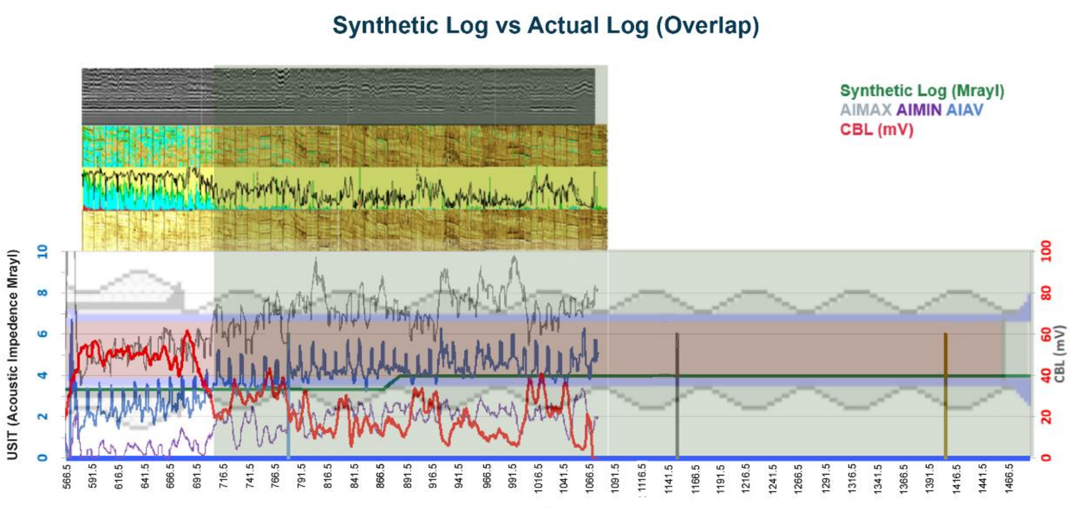

Figure 12: Synthetic Log vs. USIT Log

The software was calibrated to the rig data to match pressures, which is expected to give a reliable indication of accurate downhole values.

The graph below shows the formation of pore and frac pressures in the annulus in red and blue, respectively. The minimum equivalent mud weight (EMW) is shown in gray, which is the mud weight and is higher than the pore pressure.

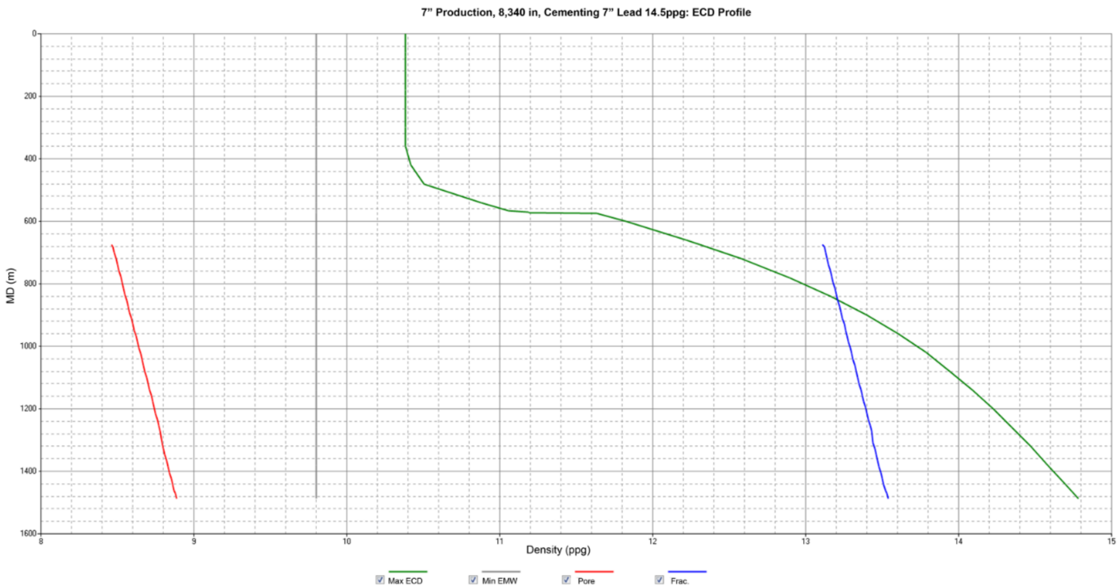

Figure 13: Calibrated Software EMX and ECD Outputs

The maximum equivalent circulating density is shown in green at the end of the job with the high-density cement in the annulus. The max ECD was expected to exceed the formation frac pressure, indicating the possibility of damaging the formation and cement/fluid losses to the formation. The ECD can be lowered during the job by reducing the pump speed, often done towards the end of the job as the pump pressure builds.

CONCLUSION AND ACHIEVEMENTS:

- Comparing rig data, software simulation, actual logs, and synthetic logs enabled the identification of formation interaction that occurred after placement. During previous jobs, this same occurrence affected the quality of the cement sheath but had not been identified. Once the problem was known, a different cement slurry was designed, and the cement quality post-placement improved significantly.
- The effect of centralization and standoff simulated by the software was linked to the log output, allowing the custom design of a centralization scheme, properly balancing casing running and cementing objectives.
- Historically, progressive improvement has enabled the achievement of the desired cementing results for similar wells in the area.

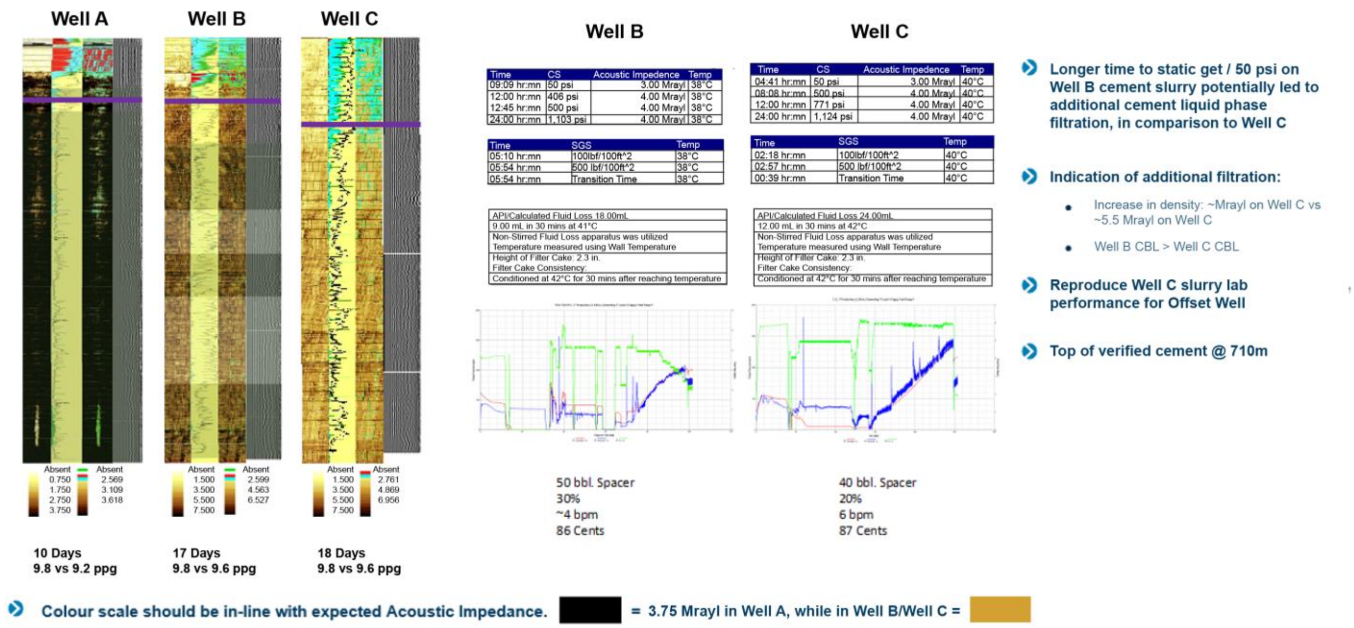

Figure 14: Log Comparison (left); Well B and C Results Comparison (center and right)

<u>Well A</u>

The methodology of using software simulation to validate the job execution by matching it to rig pressures was used to identify necessary changes in the cementing program. A family of offset wells with similar casing setups ended with Well A (9 5/8" liner), and the learnings were then implemented in the new set of wells, Well B and Well C. These new wells implemented 7" liners in similar hole deviations and the same methodology matching job pressures to the software simulations was used. These changes led to progressive improvements for Well B, ultimately achieving all the cementing objectives for zonal isolation. And finally, Well C is the case study presented in this paper.

<u>Well B</u>

Well B was the first 7" liner cemented using the learning from the Well A type 9 5/8" liner, and results were significantly better than similar wells in previous campaigns. The cement slurry had also been modified according to the well conditions, with the resulting undesired effect of taking longer to develop static gel and compressive strength. The cement log proved cement was present throughout the desired interval. However, the delay in cement development was believed to have led to filtration of the liquid phase during the transition time, leading to a micro annulus type of signal seen on the CVL/VDL log. The cement log proved cement in the interval.

<u>Well C</u>

Using the learnings from Well B, Well C, the cement slurry was optimized to reduce the time to develop compressive strength and static gel strength. This resulted in reduced formation interaction (filtration after placement), which provided a much better CBL/VDL log. Well C had a shorter deviated section than Well B.