Improving Lightweight Cement Evaluation in the Geothermal Environment

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ABSTRACT

Logging techniques using low-density foam cement require careful evaluation to ensure that they are being implemented and interpreted correctly. The challenge to the geothermal environment is that as low-density foam has gained popularity, its use and interpretation has become increasingly difficult to evaluate. Previous work[9] detailed the use of ultrasonic devices and evaluated new cement interpretation techniques in ten wells. These techniques include suggestions for log inputs, log quality control and the use of pressure to eliminate a potential micro annulus effect. In this paper three case studies applying these techniques are examined to reveal the effectiveness of cement evaluation and to recommend solutions to problems uncovered.

Introduction

Low-density foam cement use has increased in high temperature wells for two main reasons:

1. Foam cements have improved elasticity that can accommodate casing/liner thermal expansion and contraction.
2. Low-density foam cements can help minimize or prevent lost circulation during cementing and eliminate a costly two-stage cement job (geothermal wells historically have natural fractures and low fracture gradients; therefore, they often experience lost circulation during drilling).

Experience in the oil industry has shown that low-density foam cement integrity is difficult to evaluate. The geothermal environment, however, presents additional challenges to the interpretation of cement evaluation logs. These include large casing diameters, high temperature accompanied by large temperature variations, pressure buildup due to temperature increases following cementing, and in some cases the use of titanium liners inside of steel casing.

Furthermore, the geothermal industry uses and interprets cement integrity differently than the oil industry. While the oil industry uses cement primarily for zonal isolation, the geothermal industry assigns it three main tasks:

1. Provide casing support where large temperature variation could significantly change casing length.
2. Provide casing protection in harsh, corrosive environments. Higher temperature waters can contain many corrosive chemical species (for example carbon dioxide) that can destroy steel casing in less than a year.
3. Prevent the migration of geothermal waters to the surface and/or between casing strings. Trapped liquids could heat up, expand, and possibly crush, creating holes or splits in casing.

Environmental Factors and Inputs

Before discussing the critical evaluation of the three case studies, we must assess the near wellbore environment, including operator assumptions about this environment.

The data collected and the analyses performed are based on a model of the well bore environment. The model considers a sequence of layers of materials radially from the tool out to the rock. The data collected, the analyses completed, and the interpretation formulated depends on geometric considerations (for example thicknesses of materials), material properties (for example density and compressional wave velocity), and the nature of interfaces between materials (for example, open, closed, fluid filled or not, etc.).

Key near wellbore environment variables required for proper cement log interpretation includes the *acoustic impedance,* density and composition of the following materials in and near the wellbore. These materials include the fluid inside the casing, liquid behind the casing before cementing, solid cement after curing, and casing or liner.

Acoustic Impedance

In ultrasonic logs, the acoustic impedance (Z) of the material in annular space is determined as the product of the density times the compressional wave velocity, $Z = \rho V_p$. This is the standard output from ultrasonic logs. The impedance is based on an algorithm using the ultrasonic waveform to determine the impedance of the material in the annular space typically between the casing and the formation. This annular space may also be between a casing and a liner or two casings. This algorithm uses as an input the acoustic impedance of fluid inside the casing and the casing itself (values for these parameters are either measured or assumed). The standard interpretation of the impedance value depends upon whether cement and drilling fluid have sufficient acoustic impedance contrast. Note that lower density cements, with their lower acoustic impedance, could be misinterpreted as fluid.

When acoustic impedance contrast between fluid and cement is too low, new interpretation techniques from Schlumberger and Halliburton are utilized [9]. These interpretation methods compare the acoustic impedance variations in a solid (non-homogenous material) to those of a liquid (homogenous). More acoustic impedance variability is expected in lightweight cements due to the gas or lightweight rigid beads that are added to the base slurry to lower cement density. Additionally, there can be acoustic impedance variations near the casing surface due to contact between casing and a fluid, though potential for variations is greater with a solid-solid than with a solid-liquid contact. Finally, there are variations due to the casing surface variability, for example roughness, corrosion, etc.

Micro Annulus Effect of

In geothermal wells considerable changes in temperature causes fluids to expand and pressure to build after cement is in place. Temperature changes will cause thermal expansion or contraction of the casing. These changing in casing diameter will almost always cause a separation (as small as .001 in) between casing and cement to form a micro annulus, which could affect log response. The micro annulus may be filled with liquid, gas or slightly crushed cement due to casing expansion.

In all three case studies, logs were run under different pressures to determine the pressure effect. Increases in pressure caused a change in both the acoustic and ultrasonic log response, which was likely signaling a closing of a micro annulus with pressure. This pressure effect clearly indicates the presence of a micro annulus. It is then necessary that logs should be run under sufficient pressure for proper evaluation of the cement sheath. Logs that are not run under enough pressure preclude proper evaluation. In Case Study 1, Halliburton's log was run with 550 psi, while Schlumberger's was run with 1,000 psi. The different log responses observed resulted from different amounts of micro annulus closure.

It is a common misconception that the presence of a micro annulus does not affect the results of ultrasonic logs. The size of the gap and the fluid inside the gas (particularly gas) affect results on all ultrasonic tools. Figures 13a to 13c illustrate the changes on acoustic impedance values on interpretation 3 from Schlumberger. The logs presented were run at 0 psi (Figure 13a), 500 psi (Figure 13b) and 1,000 psi (Figure 13c). There is an increase in the calculated acoustic impedance (darker shades on Z mapping represent higher values) and associated increase in cement percentage shown on the interpretation with each pass. Schlumberger's "Micro Debonding" technique represents an interpretation of a solid (i.e. cement) based upon a level of variations in acoustic impedance. The interpretation presented in the darkest shade (green) represents material with low acoustic impedance but sufficient impedance variability to be considered as cement using the Micro Debonding interpretation technique. Lower acoustic impedances interpreted as gas are shown in red or the next to the darkest shade.

As pressure increases on the log, an increase in acoustic impedance is illustrated by an increase in the lightest shade (yellow for cement) on the % cement maps (Figure 13). Fre-

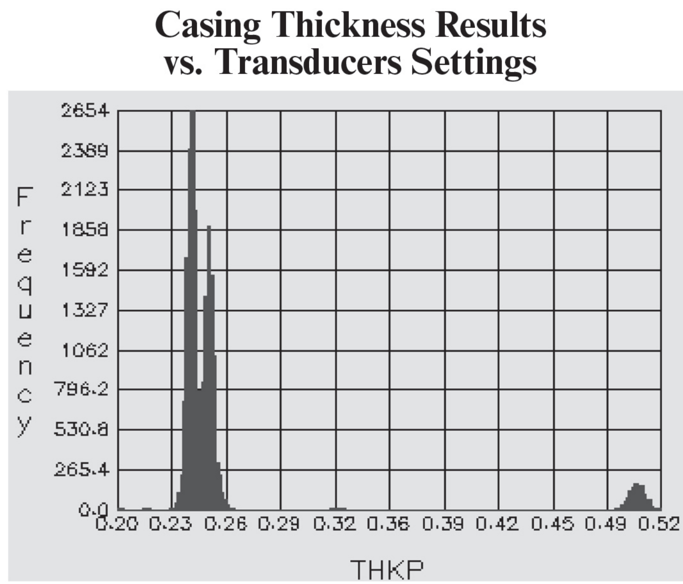

Figure 1a. Incorrect transducer frequency and location produced an inaccurate thickness measurement with a test pipe.

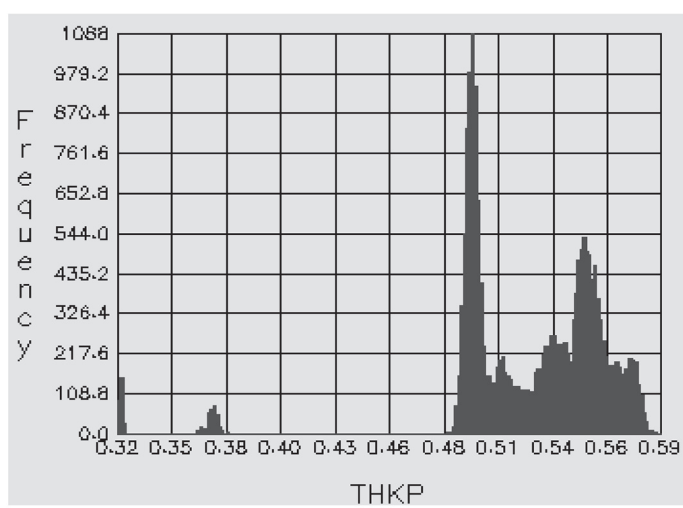

Figure 1b. Correct transducer frequency and location produced an accurate thickness measurement for the same 13 3/8 inch casing with estimatede thickness of .58 inch with same test pipe.

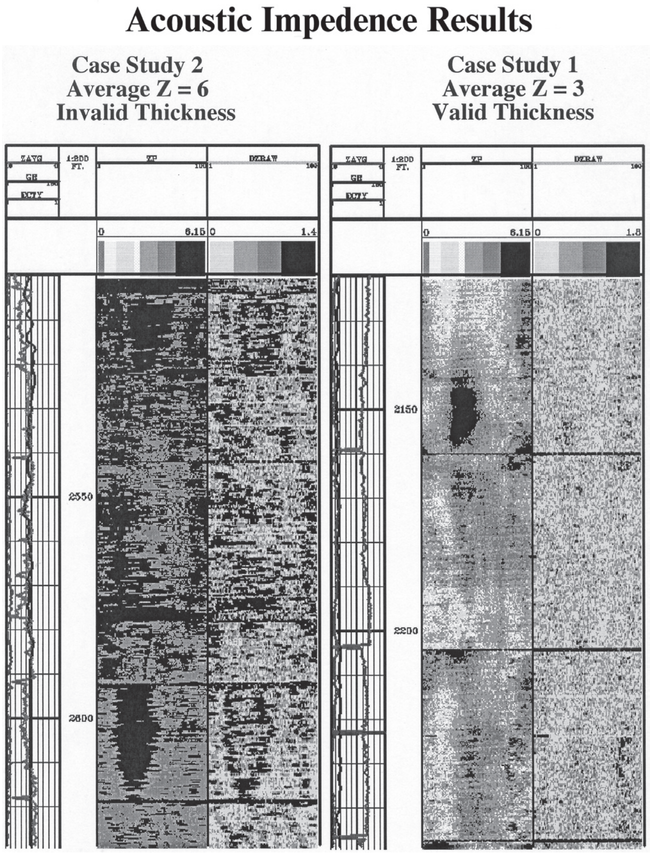

Figure 2. Acoustic impedance values unrealistically high for wellbore conditions and cement.

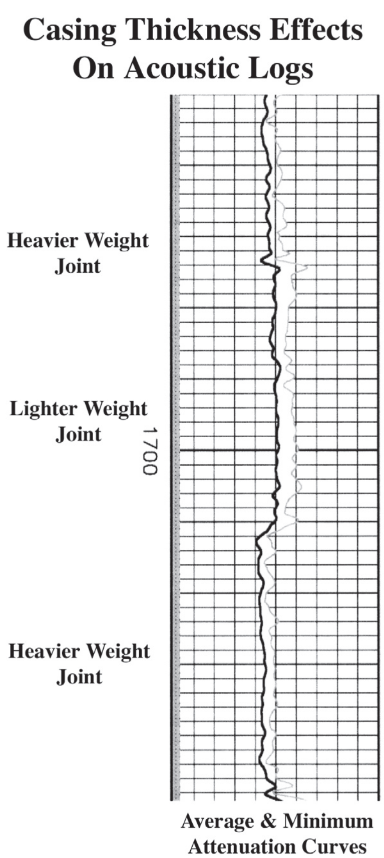

Figure 3. Changes in thickness are changing the attenuation for the SBT in free pipe

quently, higher acoustic impedance is interpreted as a solid (darkest shade or green color). Hence, the changes in pressure are changing calculated acoustic impedance values thereby reducing the necessity of newer interpretation methods for determining cement placement. While a 0 psi log run has indications of channeling on the left side of the % cement map in medium shades (Blue for liquid and Red for Gas), the apparent channel does not appear in the 1,000 psi log. Therefore, the ultrasonic log interpretation would not represent the cement placement downhole, if it were not run with sufficient pressure.

Casing Material

Another integral part of the near wellbore environment is the casing itself and attendant material properties. The ultrasonic tool selection and/or data processing algorithm can be based upon the material properties of steel casing. Since Case Studies 1 and 2 contained titanium liners, an equivalent steel weight and thickness is used in the analysis. For example, titanium with a thickness of .514 inches has a density of 44.7 ppf (pounds per cubic foot) whereas a steel casing of equal thickness has a density of 72 ppf. Therefore, the correct casing density algorithm (based upon steel) input for Case Study 2

Table 1. Equipment Selection for Case Study 1.

Schlumberger	
Ultrasonic Log	USIT with a large sub and 36 or 72 measurements in 360°. Uses inputs for titanium for casing impedance and casing travel time. Measures the impedance of the fluid while logging down and can then be used for input into calculating impedance of the fluid behind the casing.
Acoustic Log	A Cement Bond Tool or fluid compensated acoustic log with a five-foot variable density was run. The attenuation curve is a 360° average response with no means of correcting for titanium casing.
Halliburton	
Ultrasonic Log	CAST-V with a large sub and 100 measurements in 360°. No means of correcting for titanium casing for case studies 1 & 2. Measurements the impedance of the fluid during logging up and uses that as a direct input for determining the impedance of the fluid behind the casing.
Acoustic Log	Open hole sonic log combines with CAST-V. The sonic is then run as a cased hole CBL with a 3-foot amplitude and a 5-foot MSG. The amplitude curve is an average response for the 360°. However, the amplitude measurement gate is allowed to move over another peak and may not always measure the first amplitude traveling down the casing.
Temperature Log	A single point temperature measurement was measured following the cement log runs. This log represents a continuous the average temperature while logging down. This log was run only on Case Study 1.
Baker Atlas	
Acoustic Log	The SBT or Segmented Bond Tool was run. This is a fluid compensated device that has pads that allow an attenuation measurement over a 60° average. This tool has a 6 inch vertical resolution compared to 3 feet or 2.5 feet of the other acoustic logs. Above the SBT is a 5-foot spaced transmitter and receiver to obtain a VDL log.

Table 2. Schlumber and Halliburton Average Joint Thicknesses from Logs. Inspection Thickness was from Average Inspection at Site. Differences are Calculated from Inspection Thickness.

Joint Length	Joint Top	Joint Bottom	SCH Thick.	HAL Thick.	SCH Diff in %	HAL Diff in %	Inspection Thickness
14.95	1861.43	1876.38	0.537	0.549	test jt for logs		
36.48	1824.95	1861.43	0.528	0.549	4.8%	9.0%	0.504
38.74	1786.21	1824.95	0.512	0.539	-0.5%	4.6%	0.515
36.96	1749.25	1786.21	0.524	0.551	2.7%	8.0%	0.510
37.75	1711.50	1749.25	0.543	0.550	-1.8%	-0.5%	0.553
37.00	1674.50	1711.50	0.515	0.541	5.1%	10.5%	0.490
38.30	1636.20	1674.50	0.522	0.550	5.5%	11.1%	0.495
39.08	1597.12	1636.20	0.521	0.548	-2.4%	2.6%	0.534
39.21	1557.91	1597.12	0.504	0.529	-5.1%	-0.4%	0.531
37.63	1520.28	1557.91	0.516	0.547	-0.3%	5.6%	0.518
37.42	1482.86	1520.28	0.515	0.543	-3.3%	2.0%	0.532
36.61	1446.25	1482.86	0.510	0.544	0.0%	6.7%	0.510
37.82	1408.43	1446.25	0.524	0.556	4.7%	11.2%	0.500
35.89	1372.54	1408.43	0.524	0.556	-1.8%	4.4%	0.533
36.60	1335.94	1372.54	0.525	0.559	0.0%	6.5%	0.525
39.68	1296.26	1335.94	0.520	0.560	-1.6%	6.0%	0.528
39.85	1256.41	1296.26	0.531	0.565	4.1%	10.9%	0.510
39.42	1216.99	1256.41	0.519	0.562	-2.1%	6.1%	0.530
38.91	1178.08	1216.99	0.505	0.549	-2.9%	5.5%	0.520
39.58	1138.50	1178.08	0.509	0.557	-0.9%	8.3%	0.514
6.12	1132.38	1138.50	0.511	0.560	3.2%	13.2%	0.495
34.52	1097.86	1132.38	0.552	0.583	2.3%	7.9%	0.540

Test Joint Compared to Log Measurements

Laboratory Measurements were Made with Very Accurate Devices 7 Feet from the Top.

Casing Measured by Halliburton and Schlumber same Depth as Test Fixture.

Value Measured	SCH Measure*	HAL Measure*	Test Fixture Measure*	SCH Diff in %	HAL Diff in %
Thickness	0.533	0.551	0.525	1.5%	5.0%
ID	12.071	12.340	12.335	-2.1%	0.0%
OD (Calc)	13.137	13.443	13.386	-1.9%	0.4%

* Measurements are average of all measurements at depth

should have been 72 ppf. Figure 1 presents the results of two different frequencies using a titanium test joint of known thickness and diameter. The calculated casing thickness is used as an input for calculating acoustic impedance (Z); subsequently the log values based on smaller thickness measurements were unrealistically high as shown in Figure 2.

An algorithm based upon casing size and thickness is used to help select the proper transducer frequency and standoff. For Case Study 2, the transducer for the ultrasonic log was incorrectly chosen to have an inappropriate frequency: the casing thickness calculation subsequently was in error, and in turn impedance calculations were in error.

There were two titanium casing weights of 13 3/8 in titanium with diameters of .514 inches and .58 inches. In Case Study 1 the casing weights were asystematically mixed throughout the well. Log response is a function of casing thickness which in turn changes interpretation results. Figure 3 illustrates how casing density changes have affected acoustic logs such as the SBT (Segmented Bond Log, Baker Atlas). Table 2 illustrates casing thickness calculations from Case Study 1including Schlumberger and Halliburton average thickness calculations. Measured thicknesses and internal diameter calculation using both ultrasonic tools are compared with the same joint previously measured at the surface.

In addition, the inner surface of the casing must have a good reflective surface. In other words the surface must be virtually smooth in order for the reflections to return properly to the transducer. Thus, surfaces with rust, corrosion or ce-

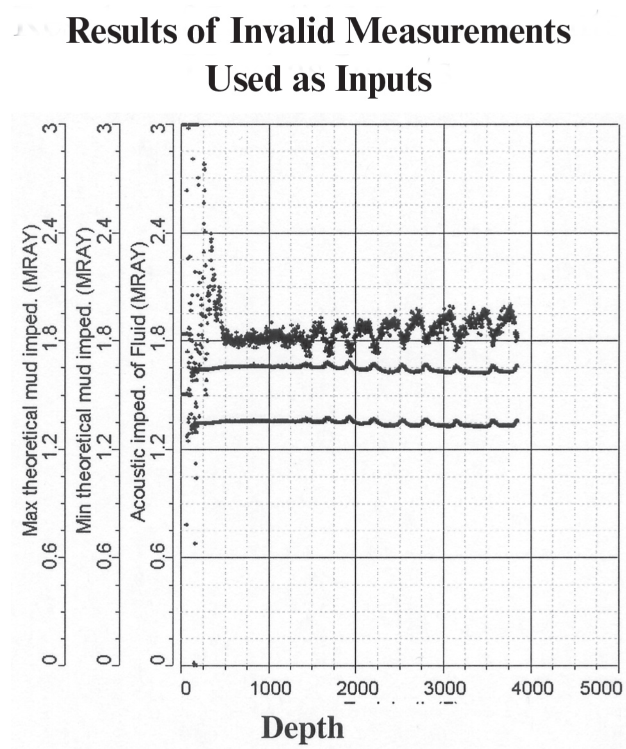

Figure 4a. The two lower solid lines are expected minimum and maximum values for acoustic impedance of drilling fluid. Measurement is greater than maximum value.

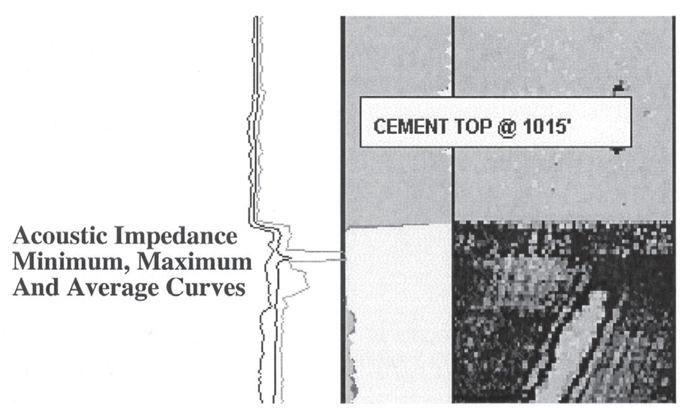

Figure 4b. Resulting high acoustic impedance values cause misinterpretation of cement top at annular fluid level.

Table 3. Ultrasonic Log Near Well Bore Environment Inputs.

Case Study Number 1	Fluid Inside Casing			Casing Weight	Casing Thickness		Cement Acoustic Impedance	Transducer Used
	Acoustic Impedance	Fluid Density	Fluid Velocity	Steel Equivalent			Expected Cutoff	
Schlumberger*	Z	Pounds/ Gallon	usec/f	Pounds/ Foot	Above 1,880 feet	Below 1,880 feet	Z	
Interpretation 1	1.84-1.96	8.3	200-205	81#/72#	0.58	0.514	2.6	9.625
Interpretation 2	1.5	8.3	200	81#/72#	0.58	0.514	2.6	9.625
Interpretation 3	1.5	8.3	195	72#/81#	0.514	0.58	2	9.625
							11.0 PPG	
Halliburton	1.72	9.5	200	72#	Calculated	Calculated	2.7	WHCH

Case Study Number 2	Fluid Inside Casing			Casing Weight	Resonance Calculated	Cement Density	Transducer Used
	Acoustic Impedance	Fluid Density	Fluid Velocity	Steel Equivalent		Expected Cutoff	
						14.5 PPG	
Halliburton	1.53	8.5	200	44.7#	Reso	2.7	BRCH

Case Study Number 3	Fluid Inside Casing			Casing Weight	Resonance Calculated	Cement Density	Transducer Used
	Acoustic Impedance	Fluid Density	Fluid Velocity	Steel Equivalent		Expected Cutoff	
						11.5 PPG	
Halliburton	1.66	8.7	192	72#	Resonance Calculated	2.7	WHCH

* Additional Schlumberger Inputs when Titanium Casing is Used		
Casing Denisty	**Casing Velocity**	**Casing Acoustic Impedance**
Pounds/ Cubic Foot	Micro Seconds / Foot	Z
283.3	50.2	27.55

Calculation for Cement Acoustic Impedance Using UCA & Density Inpus.

Input Travel Time from UCA in micseconds per foot
Input density of sample tested in UCA in pounds per gallon
Acoustic Impedance is calculated in units of 10E6 kg/m3 sec (Mega-Rayleigh or Mrayl)

Input TT	10.5		
Input Density	14.5	Calculate Z	4.2

ment inside the casing could cause a poor signal reflection. For Case Study 1 a bit and scraper was run prior to logging in order to improve the inner surface. However, titanium is naturally significantly rougher than the inner surface of steel adding another degree of difficulty for proper cement sheath interpretation.

Equipment Selection

Several tools from various service companies were used to log in these case studies. Three companies and their respective tools were used on Case Study 1 while Halliburton logged Case Study 2 and 3. Table 1 is a list of those logging tools used for each well.

When gathering ultrasonic data from Schlumberger's Ultrasonic Imaging Tool (USIT) or Halliburton's Circumferential Acoustic Scanning Tool (CAST-V), it is important to have the greatest signal to noise ratio for quality data. Two important factors that are critical to assure quality data are the distance from the transducer to the casing (standoff), and the frequency that generates the ultrasonic pulse.

Ultrasonic Logging Information

Table 3 lists various inputs used representing the near wellbore environment inputs by both Schlumberger and Halliburton algorithm inputs.

Schlumberger

Each of Schlumberger's three interpretations for Case Study 1 is based upon different assumptions/inputs for the near wellbore environment. Values of the borehole fluid acoustic impedance, cement expected acoustic impedance and casing thickness were in each interpretation. A Schlumberger log measured borehole fluid acoustic impedance of 1.8-1.9, rather than a more appropriate value of 1.5 for fresh water with a density of 8.4 ppg (Figure 4a).

Interpretation # 1 was made using a Z of 1.8-1-9 for the borehole fluid (using measured values) where Interpretation # 2 used a value of 1.5, for the same parameter. All other inputs were the same for Interpretations 1 & 2. When invalid values for fresh water of 1.8-1.9 were used the fluid level was misinterpreted a cement top as shown in Figure 4b.

When a value for borehole acoustic impedance of 1.5 (Interpretation 2) was used a more reasonable interpretation is obtained (Figure 5a, overleaf). However, interpretation 2 falsely indicated primarily liquid above the fluid level rather than gas.

The primary difference between Interpretations 2 and 3 was values chosen for acoustic impedance threshold for gas and the

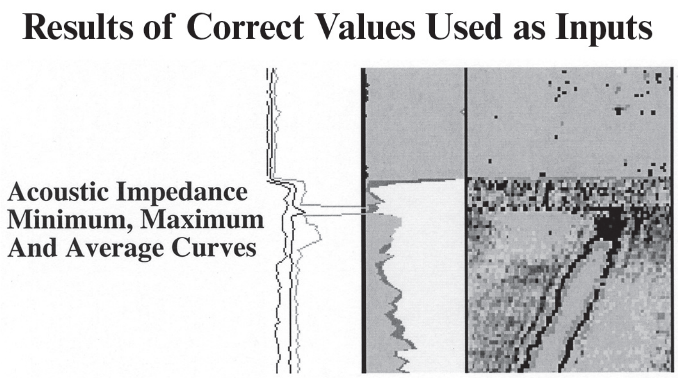

Figure 5a. Changing drilling fluid value to 1.5 acoustic impedance values are lowered, but gas continuing to be interpreted as a liquid.

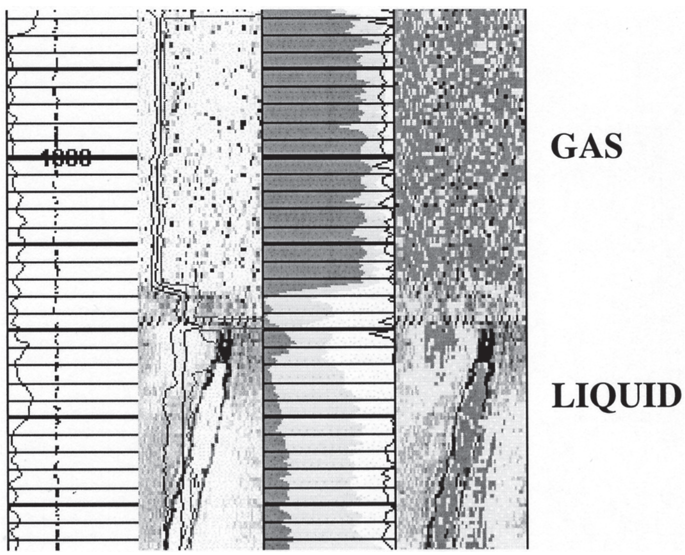

Figure 5b. Using 1.5 for drilling fluid and changing expected cement value to 2.0 from 2.6 liquid and gas are both correctly interpreted. Red or darkest shade is gas.

cutoff between a slurry and solid. The cement acoustic impedance of 2.6 was too high (Interpretation 1 and 2) for foamed 11.4 ppg cement slurry. Higher input values resulted in calculated acoustic impedance values which are too high. In turn these higher values resulted in gas being incorrectly interpreted as liquid and liquids being incorrectly interpreted as a solid. However, the last interpretation (Interpretation 3) correctly identifies the fluid as gas by using a more appropriate acoustic impedance value of 2.0 for lightweight cement (Figure 5b).

Two casing thicknesses were used in the three interpretations. For Interpretation 3, the thicker (.58 in ID) casing was assumed to have been used below the crossover around 1,880 ft. For Interpretations 1 and 2 the opposite was assumed. In Interpretation 3 the thickness inputs corresponded to those used for the wellbore. Unfortunately, there were unrecorded thickness changes at various places throughout the well. Figure 6 illustrates the response from an interval with gas in the liner-casing overlap. The interpreted response changes from gas to liquid and back again due to actual casing thickness changes that were not modeled correctly.

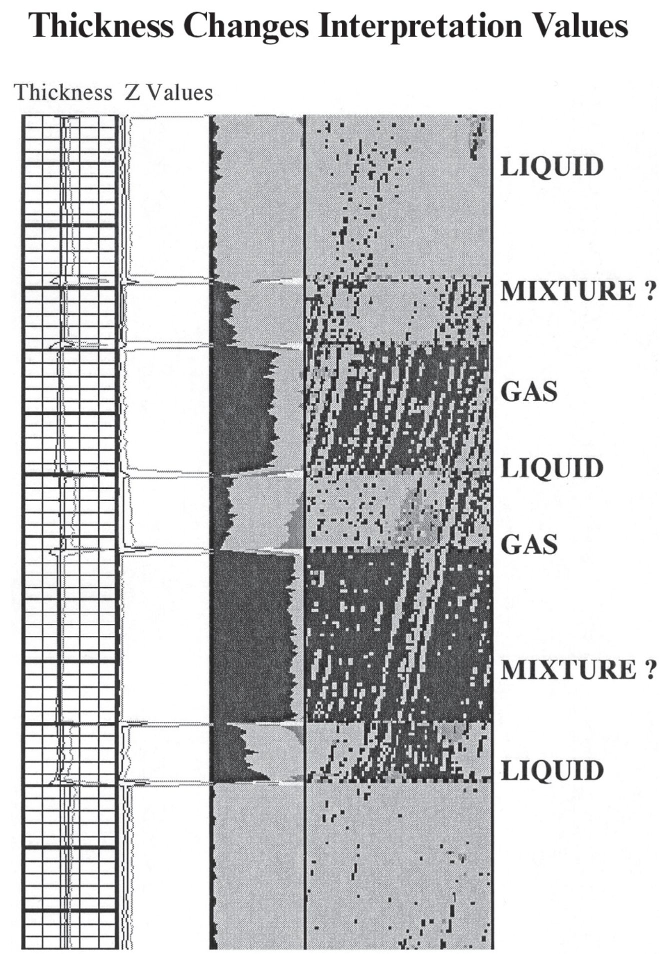

Figure 6. Interpretation 2 changes from liquid to gas based upon thickness, when annulus fluid is gas. Interpretation 3 has fewer changes by changing thickness search window.

Halliburton

Halliburton's real time processing is based on steel casing without allowances for other casing material and have as key inputs fluid density and casing weight. Tool calculation of thickness and ID compared favorably to the test joint in Case Study 1. Apparently the difference in casing material did not affect the thickness calculations (Table 2) as expected. However, there still may be uncertainty regarding the calculations of acoustic impedance. None-the-less, the difference between a liquid a solid can be determine with post processing.

With ACE post processing variations in annular material properties can be used as a tool to evaluate whether the material is a solid or liquid. The materials of a titanium liner have rough inner and outer surfaces as compared to steel. The resultant reflections have an additional variance unrelated to materials in the annular space. Due to casing roughness Halliburton's initial interpretation for Case Study 1 indicated a solid when there was actually liquid behind the casing (Figure 7).

A new technique was developed by Halliburton to eliminate this additional variance resulting in a more accurate interpretation. This method utilizes ultrasonic waveform amplitude in conjunction with variance. When a reflection occurs from a rough surface it comes back at angle of reflection other than

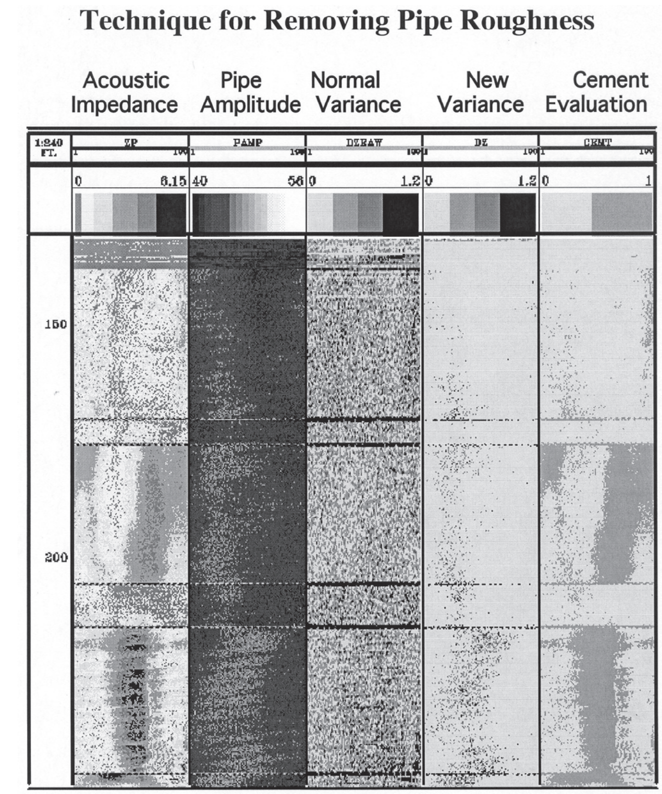

Figure 7. New technique from Halliburton for removing the effect of pipe roughness from the variance calculation. Low amplitudes are presented in the darker colors.

the preferred 90° resulting in a lower amplitude signal. This is similar to the response expected in corroded steel casing. Figure 7 illustrates the interpretation difference with the result of the casing inner surface roughness considered.

Cement Slurry and Wellbore Casing(s)

Case Study 1

This well was cemented with conventional latex cement foamed for an estimated downhole density of 11.4 pounds per gallon (PPG). A 13 3/8 in titanium liner was hung inside a 16 inch (OD) steel casing with an inside diameter (ID) of 15 inches. The titanium liner was placed without centralizers. The distance between the two strings would be .625 inches for the ideal case with perfect centralization. All cement evaluation logs require ¾ in of cement for proper logging tool response. When cement thickness is less than ¾ inches signal interference will occur due to the material on the outside of the cement sheath. Due to these wellbore conditions a large influence from a thin cement annulus was noted on the logs where the liner was not well centralized. During cementing operations cement began to set up and was not circulated to surface.

Case Study 2

This well was cemented with Thermalock™ cement foamed for an estimated downhole density of 11.4 PPG. Case Study 2 also had a 13 3/8 in OD titanium liner inside a 16 inch casing steel casing with an ID of approximately 15 inches. The completion was exactly the same as Case Study 1 except the titanium liner was centralized. The distance between the two strings would be ideally .625 with perfect centralization. There were no operational problems with the cement placement.

Case Study 3

This well was cemented with cement slurry for higher formation temperatures. Cement was foamed resulting in an estimated downhole density of 10.5 PPG at the bottom to 11.8 PPG near the end of the foaming operation. A 13 3/8 inch steel liner was run to over 3,500 ft with approximately a 750 ft overlap with a 20 inch casing from the surface. This cement was pumped in a reverse direction to minimize force created from cement slurry hydrostatic pressure and friction during pumping on a low fracture gradient formation.

Case Study Evaluation

Case Study 1

Case Study 1 was used as a control well. A titanium joint was evaluated for thickness and internal diameter before running in the hole. This procedure allowed comparisons

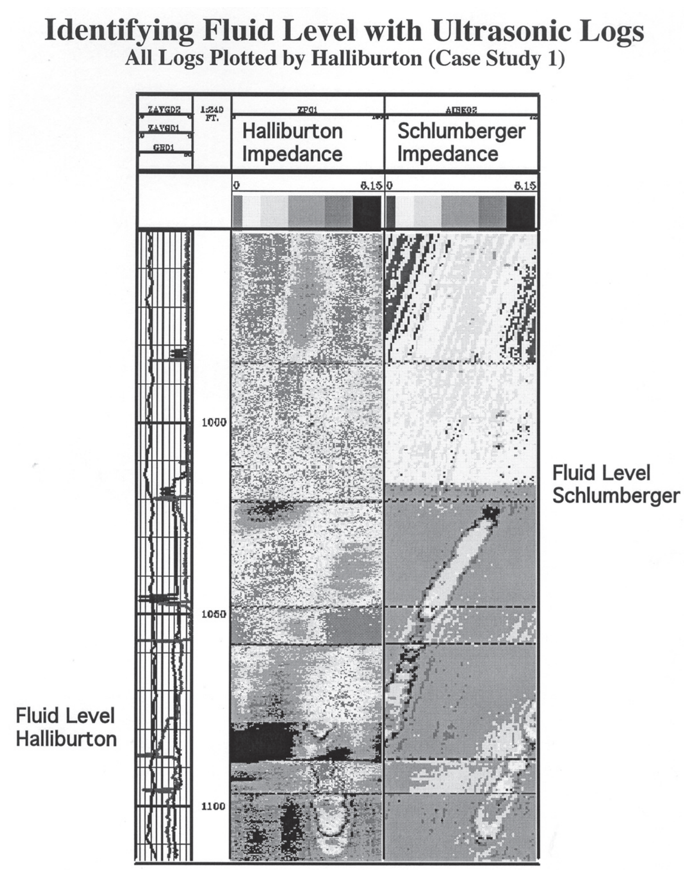

Figure 8. Both Halliburton and Schlumberger have interference patterns when liquid rather than gas is in the annular space. The water level changed between logging runs.

between the surface measurements to the same measurements made downhole by the logging tools. These measurements are compared in table 2.

No pressure was applied or maintained following the cement job, causing nitrogen to break out of the cement slurry. This resulted in an annular space containing air and water along with cement. Also, there were large vertical variations in cement density between the top and bottom of the well with the top cement having an abnormally low density. The approximate cement top was determined using engineering judgment and is described in the next section.

The results of Schlumberger's interpretation are discussed throughout this paper and can be seen in Figure 4-6. Halliburton's interpretation includes a process for removing pipe roughness as discussed earlier and can be seen in Figure 7. A comparison of the fluid level (behind the liner) between Halliburton and Schlumberger resulting from fluid level changes during logging can be seen in Figure 8. Figure 9 compares the apparent cement top from Halliburton, Schlumberger and Baker Atlas with all logs plotted by Halliburton.

Log interference patterns from thin cement sheaths and casing weight changes are seen in Figures 3, 6, and 10 and 12. Micro annulus effects on ultrasonic logs are illustrated in Figure 13. Figure 11 shows the variable density response using a variance technique from Halliburton on all CBL/VDL logs for estimating a cement top.

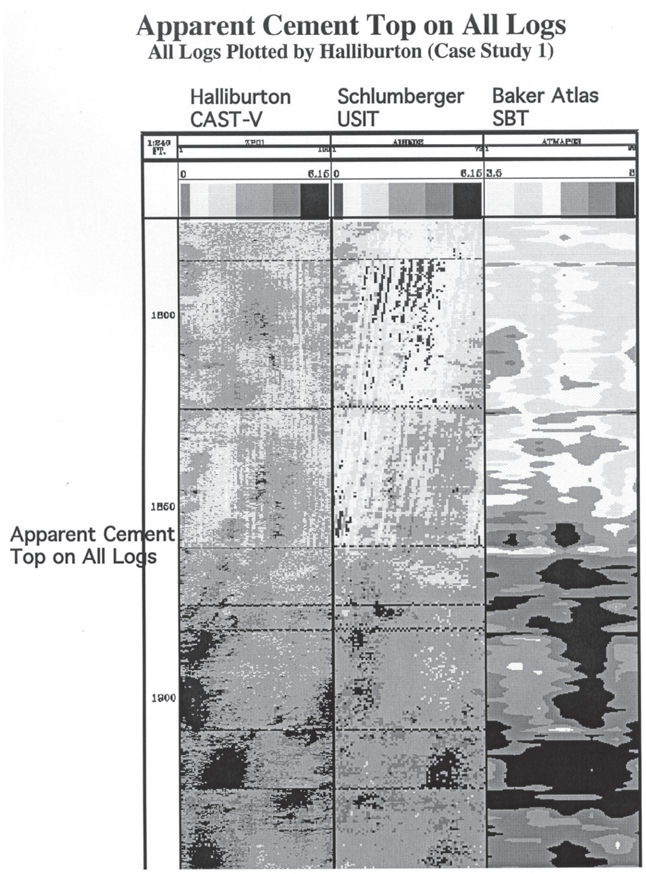

Figure 9. Actual cement top was higher level, but cement density was too low to be detected by normal meals between the titanium liner and steel casing.

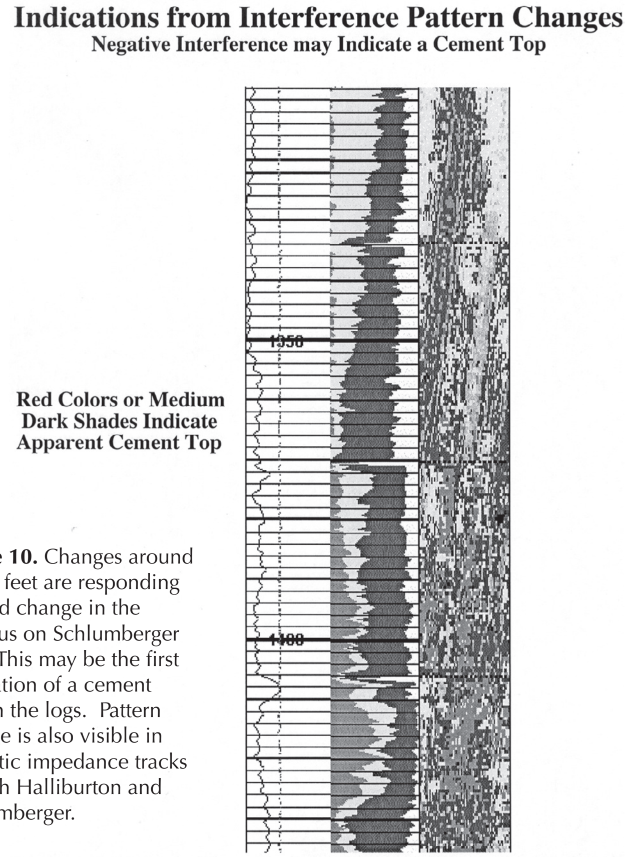

Figure 10. Changes around 1,370 feet are responding to fluid change in the annulus on Schlumberger log.. This may be the first indication of a cement top on the logs. Pattern change is also visible in acoustic impedance tracks in both Halliburton and Schlumberger.

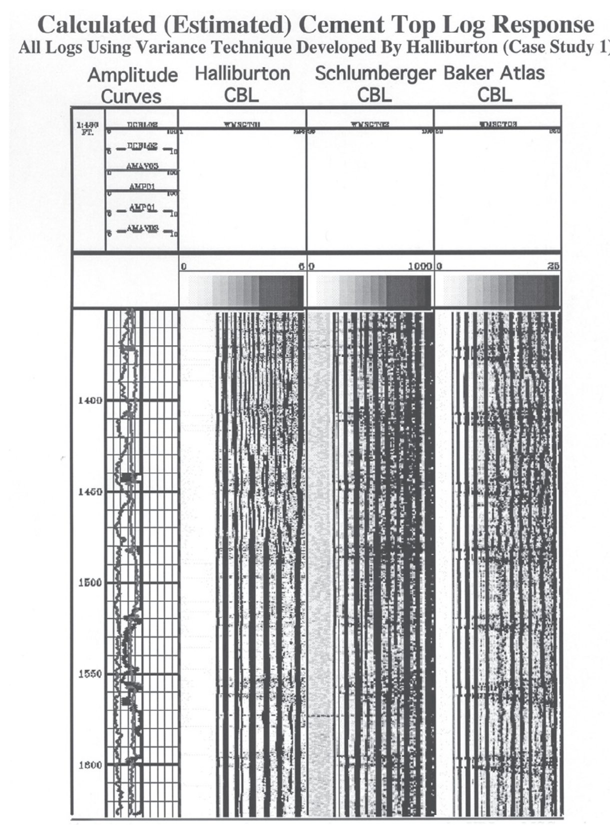

Figure 11. Calculated cement top from unusual means suggests the VDL or MSG variance presentation from Halliburton illustrates a change in attenuation at a depth near 1,470.

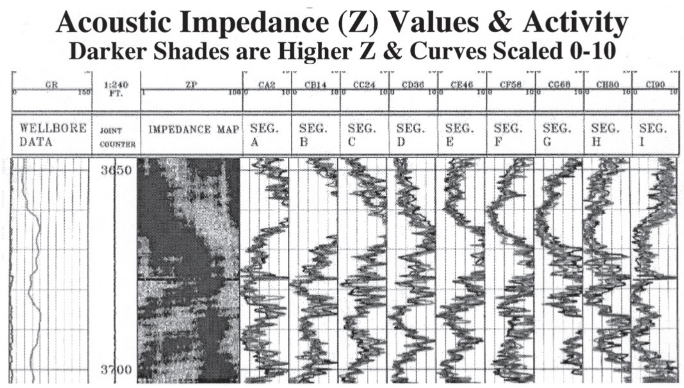

Figure 12a. Impedance Too High from Thin Annulus Interference.

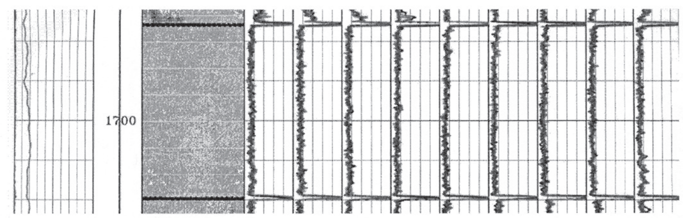

Figure 12b. Low Impedance Values and Low Variance.

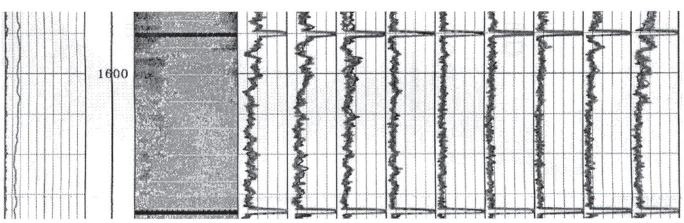

Figure 12c. Low Impedance Values and Higher Variance.

Cement Top Estimate in Case Study 1

After Halliburton and Schlumberger logged Case Study 1, the annulus was filled with water prior to running the Segmented Bond Tool from Baker Atlas. Annular fluid level was estimated to be 1070 ft following Halliburton's log by measuring the volume of water to fill the annulus. Fluid level (water behind the casing) was dropping while the well was being logged due to an increase in wellbore temperature. Figure 8 illustrates a fluid level from Halliburton at 1075 ft while Schlumberger, who logged the well first, shows it at 1020 ft.

Once fluid is in a liner-casing annulus several interference patterns are apparent on all ultrasonic logs (Figure 8). This eyeball or knothole pattern will be present on ultrasonic logs and can also be seen on many CBL waveforms (Figure 11). Rings of alternating colors or darkness due to thin cement annulus and casing to casing contact can be clearly seen. Interference of this nature could be the result of two casing strings or casing being too close to the formation. This interference is both positive (Z calculations too high) and negative (Z calculations too low) and hence the alternating bands or darker and lighter shades or colors. Changes in this interference pattern are used to find the cement top.

After logging, producing the geothermal well a few weeks removed all water from the annulus. The annulus was then

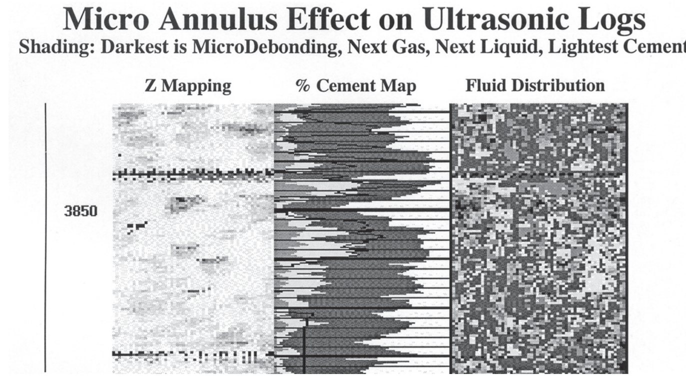

Figure 12a. Impedance Too High from Thin Annulus Interference.

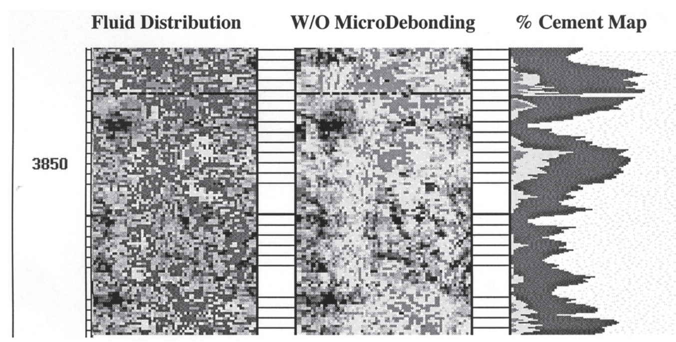

Figure 13b. Logged with 500 PSI Pressure.

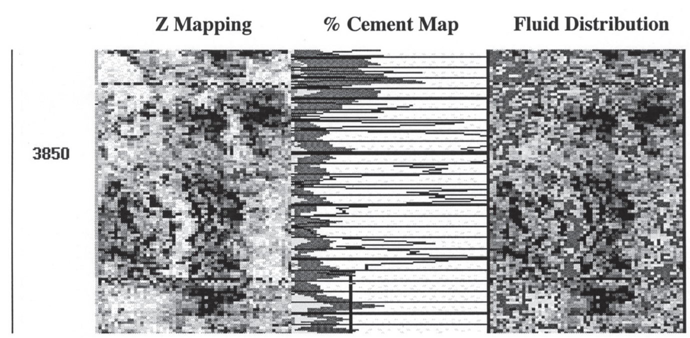

Figure 13c. Logged with 1,000 PSI Pressure.

filled with sand to support the liner and a 1,450-foot cement top was estimated from the sand volume. Later the casing was pulled from a depth of about 1,100 ft; hence the cement top had to be deeper than 1,100 feet.

Since the cement density near the cement top is extremely low, using both conventional and newer lightweight techniques did not indicate a cement top above 1,450 ft depth. A review of the logs did not identify a cement top using these methods until cement acoustic impedance had reached sufficient quantity around 1,850 ft (Figure 9).

Thin annulus interference patterns illustrate a different response when a liquid versus a solid is present in the liner-casing annulus. This reduced response is seen on both Halliburton and Schlumberger ultrasonic logs indicating cement top at a depth near 1,470 ft. Schlumberger's Interpretation 3 (inputs from Table 3 and discussion above in Case Study 1 Interpretation) has significant amount of destructive interference (low acoustic impedances) near the cement top. Figure 10 illustrates this destructive interference effect resulting from a thin cement annulus. The resulting low acoustic impedance values suggest that cement may be as high 1,350 ft.

The reflections and refractions of sounds wave at a collar create what is known as a "chevron" pattern on a CBL Waveform or Micro Seismogram (MSG) or Variable Density Log (VDL). This pattern is usually associated with liquid in the annulus rather than cement. However, when applying pressure inside the casing does not effectively eliminate a micro annulus this response may also be present. When Halliburton's variance technique [8] is applied to a CBL waveform all changes are enhanced. Figure 11 shows the reflection pattern and subsequent changes in the pattern are easier to detect and interpret. Figure 11 illustrates when this technique (part of Halliburton's ACE Program) is used, all 3 logging companies indicate the cement top by means of the results of CBL waveform responses.

Case Study 2

The cement slurry placement in Case Study 2 was without problems and was able to return cement to the surface. The liner was centralized inside the casing and the cement placement should have been more comparable to Case Study 1; the logs should have little to no interference from a thin cement sheath in the casing/liner overlap.

The CBL-MSG log generally looked good: sound attenuation was good throughout the log and there were no "chevron" patterns indicated on the MSG. This indicates that micro annulus effect had been eliminated by logging with casing pressure and consistent with a solid rather than a liquid in the annulus. Therefore, the log was consistent with good cement placement.

However, there were some variations in the strength of the MSG signal. This could indicate changes in tool centralization, cement acoustic impedance or effects from a thin annulus in some sections of the liner/casing overlap.

The CAST-V log was run with an incorrect transducer frequency for the titanium liner thickness. Therefore, it cannot be used for an interpretation. As a result of this wrong selection resulting casing thickness calculations were too low and acoustic impedance calculations were too high. Acoustic impedance results from this log can be seen in Figure 2 and are compared to similar conditions in case study 1. There were two indications of problems with the CAST-V apparent using the following results:

1. Thickness calculations were on the order of .34 inches when the titanium thickness was about .58 inches. The results using a different transducer and frequency to obtain thickness can be seen in Figure 1.
2. Acoustic impedance values were averaging 7 to 7.5 most of the time (see Figure 2) and on occasion were reaching values of 10 or greater. All of these values are outside the range for the base slurry cement and foaming would lower the acoustic impedance significantly. The base slurry cement would have impedance ranging from 3.5 to 4.5 and after foaming it would be expected to be 2 or less. This is a direct result of both the improper transducer selection and resulting casing thickness calculation.

Case Study 3

In this case, cement was pumped down the annulus and not displaced. This method affords another unique opportunity for log evaluation; with the last cement pumped being at the top of the well rather than at the bottom.

The Case Study 3 CAST-V indicated a cement of higher than normal acoustic impedance. However the higher values were mostly near the bottom rather than near the top where they would be expected. The average acoustic impedance over the lower 600 ft was approximately 4 or greater, which compared favorably to the unfoamed base slurry (14.5 PPG) using a UCA (ultrasonic cement analyzer). The response is similar to when cement is pumped in a normal direction plus it was unexpected for foamed cement and is illustrated in Figure 12a. A 200 ft interval near the top indicates acoustic impedance values near those expected for the unfoamed base slurry as was expected. This corresponds with the last 30 barrels of cement, which consisted of the standard base slurry without foaming. This material is considered cement in the analysis due to its higher acoustic impedance with values greater than those for liquid.

In the bottom 200 ft the acoustic impedance values were the highest in the entire well with values occasionally exceeding 10 (Figure 12a). These very high values are likely the result of a thin cement sheath due to well deviation exceeding 13^{o}. This same interval has a dogleg severity of 3.2 in one instance. Although there were centralizers on every third joint through this section there still may be sections between centralizers where casing is not well centralized.

As expected for this density of foam cement, much of the rest of the log has low acoustic impedance ranging from 2 to 2.5. Between 1,650 ft to 1,900 ft there are several intervals, with acoustic impedance values lower than 2 and as low as 1.5. These values usually indicate liquid, so the variance with surrounding values must be sufficiently high in order to be interpreted as a solid. The liquid value cut-off for variance is determined from the log response in a liquid zone. This value will be different depending upon casing condition, fluids behind the casing, tool differences and wellbore fluids. Because of unusual environment with 13 3/8 casing and cement rather than liquid hypothesized in the annulus, more work should be done to better define this constant.

Figure 12b is an example of low acoustic impedance values, which have a low activity level. This interval would normally be interpreted as a liquid response or free pipe. These variance interpretation techniques are discussed in an earlier paragraph, but are discussed in more detail in a previous GRC paper (Reference 9). Figure 12c also shows low acoustic impedance value, but with a higher activity level. The higher activity level would be interpreted as a solid. There are occasional fractured zones through this interval and they could be playing a role in the cement behavior once it is placed downhole. However, from these results it remains unclear how ultrasonic log results are affected by both casing and hole size.

Quality Control

Certain effects due to poor quality control have been presented earlier and are reviewed here. Case studies in this paper have three illustrations of poor inputs used for model interpretation.

1. Invalid inputs for acoustic impedance of drilling fluid and cement.
2. Invalid inputs for casing parameter such as composition or thickness.
3. Invalid measurements (of borehole fluid) used for inputs.

Proper information concerning the near wellbore environment would have ensured a proper operation and valid interpretation. Schlumberger's interpretation model requires several valid inputs to produce valid outputs. Halliburton's model, although it is self-calibrating has important inputs. Inputs used by both companies are listed in table 3. Two methods should be used to validate log data:

1. Verify inputs by using all available data on the well. These include those key casing and fluid parameters listed in the section on near wellbore environment. For example the Z of fresh water should be 1.5 although the tool may have calculated it differently.
2. Validate the calculated data with known information. For example the thickness of the casing is a key indicator of quality. When the thickness information is wrong it could carry through into an invalid acoustic impedance interpretation.

Further, it has been demonstrated that specific acoustic impedance of cement is sometimes unknown, but a range of values should be well understood. Conversely, liquid's acoustic impedance should not exceed 2.5 except in the case of very heavy mud (greater than 14 ppg). It would be particularly unlikely for foam cement to have values as high those calculated in Case Study 2 (Figure 2). When acoustic impedance values as high as 7 or 8* are determined, a check of the near wellbore environment should be made to determine if these values are likely. (*Acoustic impedance algorithms are more accurate for low values of acoustic impedance. However, extremely high acoustic impedance values are sometimes seen in Case Study 1 and 3, and are due to log interference with a small liner-casing or casing-formation annulus resulting in a thin cement sheath.)

Case Study Summary

The results from three case studies indicate several critical areas necessary for valid log acquisition and interpretation of lightweight cement. These areas include:

1. Correct inputs for both data acquisition and interpretation.
2. Complete data set concerning the near wellbore environment in geothermal wells. Foam cementing data particularly needs to be very complete since there could be considerable variability of downhole density, foam quality and subsequent cement acoustic impedance.
3. The presence of a micro annulus was confirmed in all three cases. It was determined that it is necessary to run future logs with sufficient pressure for proper cement sheath evaluation.
4. Due to problems with cement placement in Case Study 1 ultra lightweight cement resulted in the annulus. A thorough knowledge of the wellbore environment allowed the use of additional interpretation techniques to determine a cement top where previously impossible.
5. Five different cement evaluation logs from three different logging companies were run on Case Study 1. These logs presented a unique opportunity to evaluate different techniques used by logging companies for gathering and interpreting cement sheath data.

Conclusions

Interpretation problems associated with lightweight cement in the geothermal environment are among the most difficult. However, these case studies have shown that lightweight cement can be interpreted successfully, but this success relies on more than just running a log and gathering data. Here it has been shown that acoustic and ultrasonic logs in conjunction with newer interpretation techniques are paramount to success, and these processes require close attention to detail.

This study shows how a micro annulus affects both sonic and ultrasonic logs. Careful attention should be paid to casing pressure following cementing operations; not only for pressure applied for testing casing, but also for pressure created within the casing from heat buildup during cement curing. In Case Study 3 pressure was allowed to build to at least 1,400 PSI according to wellhead gauges. Because of pressure limits on a wellhead valve at the time of logging the log could only be run with 1,000 psi of internal casing pressure. When a log is run with insufficient pressure the results could be a log that resembles a casing free of cement.

New interpretation techniques presented here, involving response to interference patterns and enhancement of changes in reflection patterns, represent additional methods for determining a cement top. These techniques are of particular importance when the cement density is too low for any previous techniques to be used to make such a determination. Determining a cement top has been very difficult in the past when two strings of casing are present. This study provides an initial interpretive attempt using only one data set; therefore, more experience is needed to validate these techniques.

Details concerning the near wellbore environment are critical for proper data gathering and interpretation using ultrasonic logs.

1. Proper tool frequency and standoff and data timing begins with knowing the casing size, thickness, density, and material makeup. For titanium casing, the casing density input will need to be a steel equivalent density with the same thickness as titanium.

2. Acoustic impedances of materials in the annulus are not measured but calculated using specific algorithms. These algorithms require proper inputs for the acoustic impedance of the fluid in the wellbore (measured), casing thickness (calculated) along with the casing acoustic impedance (normally assumed to be steel), and anticipated cement acoustic impedance. These inputs will vary between service companies and may not all be necessary.
3. Measured or calculated values used for these inputs (2) should be verified by other means. For example, base cement acoustic impedance should be available (prior to foaming) and density of the fluid in the wellbore should have a limited range of acoustic impedance values. (A formula for calculating the acoustic impedance of base cement slurry is included in Table 3. This formula uses cement density and travel time from an Ultrasonic Cement Analyzer (UCA) used in the lab to evaluate cement.)
4. Geothermal wells will very likely have generated a micro annulus outside the casing. The required casing pressure used for eliminating this effect should be close to the maximum pressure that the casing has experienced since cement was pumped.

Finally, quality control should be used throughout the entire process of tool selection, data gathering and field processing and post interpretation processing. Catching and correcting any errors as soon as possible will provide the most valid interpretation of any cement sheath.

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