Case Studies in Evaluation of Cement with Wireline Logs in a Deep Water Environment

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Society of Petrophysicists and Well Log Analysists

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ABSTRACT

The evaluation of cement placement and zonal isolation in deep water environments is increasingly challenging. Traditional wireline evaluation methods rely on contrasting attenuation rates of sonic or ultrasonic waves to discriminate between cement and fluid behind pipe. In today’s deepwater environment, heavy synthetic based drilling fluids can have properties that render the evaluation of the typical lightweight cements extremely difficult. In addition, cement evaluation logs are often run within 48 hours of pumping the cement which results in lower acoustic impedance at the time of logging. This further reduces the contrast in acoustic impedance between the cement and heavy synthetic based muds that are used in this environment. As a result, traditional cement evaluation logs can be ambiguous and difficult to interpret which has led to industry suspicion regarding the application of these measurements. A recently developed ultrasonic measurement called flexural attenuation combined with traditional measurements addresses these uncertainties, and results in more accurate cement evaluation under these difficult conditions.

This paper focuses on the practical application and interpretation of this recently developed measurement and will detail case studies from Gulf of Mexico offshore wells comparing results from traditional CBL/VDL and ultrasonic measurements, with methods that include the utilization of flexural attenuation. The physics of measurement and limitations of each measurement are reviewed and a workflow is presented to integrate all of the data to provide quantitative cement evaluation. Examples are used to illustrate the reduction in uncertainty that can be achieved using this workflow and the combination of these measurements leading to a more definitive determination of zonal isolation.

INTRODUCTION

After the first question “Where is the cement and how good is it?” the second most common question that is asked of the log analyst who does cement evaluation is, “How sure are you?”. That little ‘How sure are you?’ part offers more than enough subject matter for another paper but here we’ll discuss some of the uncertainties in cement evaluation and the application of new technology and interpretation techniques to reduce those uncertainties.

The evaluation of cement quality with acoustic measurements dates back to the late 1950’s when the first CBL, (cement bond log), technology was introduced. Early tools utilized a single transmitter and two receivers spaced at 3ft. and 5ft., a spacing convention which continues even today for standard CBL tools. An article in the first SPWLA Log Analyst - Vol. 1 No. 1 published in 1960 described this ‘new’ technology and included the following quote, “Now when your calculated oil zone comes in water, you can prove it is a channel job”. The article even stated that the price of the new log would be 6 cents per foot.

It was a stretch to say that these early amplitude based CBL tools could prove there was (or was not) a channel, but at least techniques were developed to provide qualitative interpretation of channeling. Unfortunately, the list of uncertainties inherent with these techniques is long and the basic lack of azimuthal sensitivity limited their effectiveness. Still, the technology offered a big improvement in cement evaluation capability compared to earlier techniques.
that depended on monitoring surface cementing data like pumping pressure and fluid returns.

The next development addressed borehole compensation by utilizing an attenuation calculation based on the difference in received signal amplitude between the two receivers. This allowed some compensation for tool position and borehole fluid but these tools still had no azimuthal sensitivity. Cement bond tools were eventually introduced that provided either 6 or 8 segments of azimuthal sensitivity to address this shortcoming but their low resolution meant there was still a need for higher resolution measurements to fully characterize cement quality and to detect the presence and geometry of channels.

Ultrasonic tools that utilized small high frequency transducers housed in a rotating sub offered a step change improvement in vertical and azimuthal resolution to address this problem but they offered no information about the radial thickness of the cement or the radial extent of channel geometry. In other words, they still only provided information about two dimensions of a three dimensional problem. These measurements are also sensitive to the borehole fluid which adds uncertainty to interpretation.

The addition of high frequency flexural attenuation measurements addressed both of these limitations with a pitch-catch transmission methodology to compensate for borehole fluid and measurement of a third interface echo, called TIE, to provide information about the cement/formation interface. This new measurement combined with conventional cement bond log data and ultrasonic acoustic impedance greatly reduces the uncertainty in cement evaluation that existed with previous technology.

THEORY OF MEASUREMENT

The use of acoustic measurements for cement evaluation is based on laboratory measurements of acoustic waveform amplitude and attenuation in cemented and non-cemented casing. Examples of these measurements are shown in figure 1 below (Anderson and Walker, 1961):

![Fig. 1 ‘Pitch Catch’ flexural attenuation measurement uses an angled transmitter and two closely spaced receivers to provide high resolution borehole compensated flexural attenuation measurement and information on the formation interface, called the third interface](image)

The trend toward larger, thicker casing sizes combined with heavier drilling fluids and lighter cement slurries in the deepwater drilling environment create the perfect storm leading to increased uncertainty in cement evaluation. Given the prolific production rates and the difficulty of intervention or remediation of these deepwater wells, there is clearly a need to supply better solutions. New interpretation workflows combined with technologies available today reduce these uncertainties resulting in quantitative determination of cement placement and zonal isolation.

While the principles of interpretation for cement evaluation tools available today have been thoroughly discussed in the literature, the main focus of this paper will be to describe a recently developed measurement and a revised cement evaluation workflow designed to reduce uncertainty and to illustrate these applications using real world examples.

Fig. 2 Laboratory measurements showing acoustic amplitude and attenuation in cemented and non-cemented casing

One of the limitations of conventional CBL technology is the omni-directional nature of the measurement that relies on tool centralization to ensure that the first arrivals are simultaneous from all azimuths. The lack of azimuthal sensitivity also results in many
uncertainties in interpretation including the inability to distinguish between low-strength cement and high strength cement with a channel (Froelich et al., 1982).

This table shows a few of the factors that affect cement evaluation certainty/uncertainty and highlights the ability of various types of cement evaluation technology to address these factors. To keep it simple, green is good and red is bad. The standard CBL tools that were available back in 1960 show a lot of red.

**Fig. 3 Basic CBL ability to address various factors that affect cement evaluation shows high uncertainty**

Fortunately, technology has advanced considerably over the past 51 years and today a wide range of technology is available to reduce these uncertainties.

**Figure 4 Technology developed since 1960 addresses many of the factors that cause uncertainty in cement evaluation**

Ultrasonic measurements made with a rotating transducer brought high vertical and azimuthal resolution. Each transducer cycle responds to a 1.2” diameter area projected on the inner surface of the casing but the effective resolution is also variable as a function of logging speed.

A high frequency pulse travels from the transducer through the fluid inside the casing to the casing wall. When the wave contacts the wall, some of the energy is refracted through the casing while the majority is reflected back to the transducer. The amount reflected vs. refracted is determined by the acoustic impedance contrast between the fluid and the casing.

**Fig. 5 Ultrasonic transducer – travel paths, interfaces and resulting information**

Acoustic impedance (Z) is defined as the product of density and compressional velocity (Z = ρν). The first returned pulse is used to calculate the internal radius of the casing based on the signal transit time as well as information on general condition of the casing surface. The energy that is refracted through the casing travels through the casing wall until the acoustic impedance contrast between annular material and casing is reached. Once again, some of the energy is reflected and some is refracted based on the acoustic impedance contrast. This process continues as shown below until the returning signal is too small to detect. The exponential decay of the echo and rate of decay contains information on the Z of the annular material.

The rate of decay is also impacted by factors other than annular Z. These include non-normal angle of incidence, shear bonding, third interface reflections, dry microannulus, and casing properties that also affect the
response and need to be accounted for in the data analysis.

Hardware designed to measure flexural attenuation introduced in 2005 utilizes a transmitter firing at 250 KHz and two closely spaced receivers. The decay of the casing flexural mode is a function of the impedance contrast at the inner and outer walls of the casing. The decay of the flexural wave is driven by the fluid in contact with the casing and if present, the cement in contact with the casing. Since the flexural measurement is based on the difference between two receivers, it is fully compensated for the fluid in the borehole. Unlike conventional ultrasonic attenuation tools, enough energy leaks into the annulus to reflect off the third interface, or the formation face, to be detected by the receivers. This information can be used to create a map of the formation wall as shown below.

![Figure 6 TIE. third interface echo image shows an image of the casing and the borehole wall of the free pipe section from case 2 example below](image)

As described by Snell’s Law, when the velocity in the cement is faster than the flexural wave propagation in casing, the compressional wave in the cement will no longer be generated. This causes a sharp drop in the measured flexural attenuation at the critical Z value as illustrated below. This is also called the evanescence point.

![Fig. 7 Relationship between flexural attenuation and acoustic impedance: Evanesence - effect](image)

Due to this phenomenon, a combination of flexural attenuation and traditional acoustic impedance are used to eliminate ambiguities between fluid and well bonded high velocity cement. The flexural attenuation transmitter and receivers are mounted on the same rotating sub as the ultrasonic measurement ensuring the combination. The measurement is made at 10° intervals azimuthally providing a high resolution.

The flexural attenuation measurement is relatively insensitive to the amplitude variations caused by tool ecentering or internal casing rugosity that affect other measurements. Second the dual receiver geometry and flexural wave properties reduce the effect of variations in casing properties such as surface condition and thickness. Third and most importantly, the ability to measure a transit time in the annulus to the third interface introduces a new dimension in diagnostic capability:

- Annular velocity can be estimated and correlated to the attenuation measurement
- Depth of channels can be imaged allowing cross sectional area to be estimated
- Position of the casing in the borehole can estimated and used to analyze cement placement, and one of the primary causes of channeling

**CEMENT EVALUATION WORKFLOW**
The basic steps in cement evaluation include:

1. **Determine the objectives of the cement job and evaluation program**

2. **Review the data**: Open hole log data, drilling reports, pore pressure profile, casing reports

3. **Choose the appropriate cement evaluation tools**

4. **Gather information on the cementing operation**: expected top of lead and tail, density of lead and tail slurries, information on returns and pump pressures, wellbore fluid acoustic properties, spacer acoustic properties, annular fluid acoustic properties

5. **Quality control and interpret the data**

The focus here is on the last step, quality control and interpretation of the cement evaluation data. While the basic relationship between acoustic attenuation and cement quality may seem simple, it is far more challenging to account for factors other than the cement that affect the measurement including:

- Wellbore fluid
- Casing wall thickness
- Internal casing rugosity
- Tool eccentricity
- Annular fluid
- Pressure and temperature effects on the transmitters/receivers/transceivers
- Casing metallurgy
- Tool to casing standoff
- Annulus thickness
- Waveform gain and offset
- Microannulus

Additionally, the effect of these factors varies by tool type and the frequency of the transmitted waveform.

The most recent addition to cement evaluation technology is the measurement of flexural attenuation which is less affected by some of these factors:

- Reduced sensitivity to tool eccentricity
- One third as much standoff effect
- Increased precision and accuracy
- Less affected by water filled microannulus
- Less sensitive to heavy casings

This results in less variation in the measurement of flexural attenuation due to casing manufacturing variations such as surface roughness and thickness.

Most important, flexural attenuation is direct measurement that does not require input of any parameters compared to the acoustic impedance measurement which is derived from recorded waveform and depends on theoretical model used and many input parameters to this model.

In addition to attenuation measurements, flexural attenuation measuring tool provides third interface echoes. By analyzing them, information about casing position in the annulus can be derived.

The methodology illustrated in the examples provides more consistent answers which are not driven by processing parameter choices. Condensed depth plots show the changes due to fluid, pressure, and temperature and simplify interpretation of each parameter. In addition, identification of the cement top can be more apparent in many cases.

**Case I**

Zonal isolation was required across reservoir intervals in a section that covers about 400 ft gross interval. In addition, some sands had greatly reduced formation pressures due to production in the field. 7” X 5.5” tapered liner, (P110-32 lb, 6” ID) and (23 lb, 4.5” ID), was run to total depth to cover the field reservoirs. The 7” liner covered the intervals that were suspected to have substantially reduced formation pressures and 5.5” liner was run across additional reservoir intervals to total depth. The multiple casing sizes necessitated two separate descents.

The objectives of the cement evaluation program were to ensure isolation between the zones with reduced pressures in the 7” and the original pressured zones in the 5.5” liner. In addition, the optimal depth for taking reservoir pressure through-casing in the 5.5” liner with acased hole formation test tool needed to be selected. Pressure data was crucial for planning completion operations and it was important to drill the hole for the formation test in an interval with no channels and good quality cement.

Interpretation of the standard low frequency attenuation based CBL data suggested very poor bond with an average attenuation less than 2 dB / ft. throughout the entire interval.
Fig. 8 Attenuation based CBL field shows very little contrast and less than 2 dB/ft attenuation over the entire interval, bond index calculates less than 15%. A close look at the attenuation and bond index highlights the problem; there is no contrast on the conventional CBL log. Where is the cement? Do we have zonal isolation? Much less, what is the certainty of any cement evaluation? Without additional data we are limited to guessing.

An experienced log analyst might identify the top of cement correctly using this expanded plot of CBL attenuation, but the interpretation still leaves several possible choices and there are anomalies in the data that are impossible to explain in the absence of additional data. Even if we assume that there is good cement somewhere in the interval, and that would be a very big assumption, it is impossible to tell if there is good zonal isolation for the formation test or subsequent completion operations.

Fig. 9 Plot of the CBL attenuation shows more than one possible top of cement as well as other anomalies that can’t be explained without additional data.

The VDL showed casing arrivals and collar chevrons throughout the section suggesting poor cement quality. It was difficult to identify the top of cement on the raw logs, but a best estimate was approximately 110’ below the top of the cross over where there was a shift in the VDL and a vague appearance of formation arrivals.

Fig. 10 Attenuation based CBL field log does not read free pipe, but interpretation is impossible due to low contrast in between free and cemented pipe

Confidence in the top of cement interpretation improved slightly when it was supported by the
acoustic impedance map that showed a small increase at the same depth.

Closer scrutiny using a condensed plot of the minimum ultrasonic impedance shows some indication of the top of cement, but once again, the wide variation in free pipe acoustic impedance combined with low contrast from the cemented section makes evaluation of cement quality and zonal isolation highly uncertain.

When the minimum acoustic impedance falls into the free pipe range below the cement top, it should indicate channeling or poor cement but unfortunately as is common in the deepwater environment, lightweight cement combined with heavy wall pipe and heavy borehole fluid reduce the contrast between free pipe and cemented pipe. This results in an overlap of the free pipe range and the cemented pipe range. Variations in pipe thickness and irregularities on the inner surface from the manufacturing processes add noise to the measurement and the width of the free pipe attenuation range increases to make it impossible to differentiate between free and cemented pipe.

Despite these complications, the interpretation becomes easier with the addition of the flexural attenuation map shown below in the right track, darker blue for low attenuation, red for high attenuation. Now we see a strong contrast at the cement top which gives a high level of confidence in the earlier estimates for TOC.

**Fig. 11** The ultrasonic acoustic impedance image on the field log shows some indication of cement, but confidence remains low due to very low contrast from free pipe to cemented pipe.

**Fig. 12** A plot of the minimum acoustic impedance with projected free pipe attenuation range through the cemented section shows a wide variation of attenuation in free pipe and little contrast between free pipe and cemented pipe.
Fig. 13 The flexural attenuation map in the right track shows a strong contrast at the top of cement highlighted by the red line.

An expanded plot of minimum flexural attenuation shown below adds another indicator for the top of cement, but now the range of values in free pipe is narrow with very low noise levels. The projection of the free pipe range through the interval shows a very strong contrast compared to the cemented section which leads to a high level of certainty in the interpretation of cement quality and zonal isolation.

Fig. 14 Plot of minimum acoustic impedance with the addition of minimum flexural attenuation showing the range of values in free pipe projected to the bottom of the interval.

Comparison of the uncertainty range based on the reading in free pipe shows the added precision of the flexural attenuation. It also shows the clear contrast with the cemented section. Possible sources of the higher noise level on acoustic impedance include:

- Sensitivity to borehole fluid
- Sensitivity to pipe surface irregularities
- Sensitivity to pipe thickness variations

Fig. 15 Comparison of uncertainty range of minimum acoustic impedance and minimum flexural attenuation.
The flexural attenuation image shows a channel that caused the cased hole formation test point to be moved 21 feet to an interval with good cement quality. Data from conventional bond tools would have caused this test to be completely aborted when they indicated poor cement quality throughout the interval. Data from the TIE or third interface echo shows that the channel was caused by casing positioning that was near the borehole wall. The TIE plot shown below is a 3D model based on the time domain.

![Third Interface Echo: TIE](image)

**Fig. 16 Channel indicated on flexural attenuation map, (also confirmed within free fluid range on fig 11 above). TIE-Third Interface Echo image shows the casing is close to borehole wall in this interval which is the cause of the channel.**

After initial review of the field logs, zonal isolation was still in question but the after additional scrutiny of the data using these expanded data plots was completed, zonal isolation was confirmed and top of cement was identified with a very high level of certainty.

The conventional CBL and ultrasonic field data that suggested poor cement quality would have caused the formation test to be completely aborted while flexural attenuation combined with this workflow showed that the cement was adequate to perform the test. Furthermore, a channel identified at the planned depth for the formation test in the 5.5” allowed the test to be moved 21 ft to a zone with good cement quality. While the flexural attenuation map was the key component in this interpretation, the ultrasonic and flexural data were in agreement providing a more confidence in the final interpretation.

The cased hole formation testing operation proceeded as planned with 4 pre-test pressure readings. The four (4) pressure draw-downs and buildups yielded a formation pressure of 8,446 psia. This pressure was higher than expected but still well below hydrostatic. The nature of the build-up and draw-drown charts along with the volume indicate the pressures were indicative of formation pressure. The hole drilled in the casing for the formation test was plugged and subjected to a 3000 psi negative test and a 2600 psi positive test indicating a good seal.

**Case II**

An existing deepwater well was being re-entered for the purpose of a geological sidetrack. A decision needed to be made whether to mill a window or cut and pull the existing casing. Milling the window, if successful, would save significant rig time. However, laboratory tests indicated a low compressive strength cement of around 300 psi. This would indicate a potential difficulty with traditional cement evaluation tools due low contrast between free pipe and cemented pipe leading to an ambiguous interpretation. Selection of the optimum interval for the milling operation that would also provide pressure integrity would be highly uncertain.

The proposed interval of interest for milling a window for sidetracking operations was between 12,300 and 12,800 ft. - ideally at 12,450 ft. This depth was picked to meet the dual objectives of landing the S/T well in the geologic targets following a simple build and hold directional plan. It was also below the shoe depth for the 22” outer conductor casing string.

The original well had been drilled with an 18.125” bit size which was then switched to a 12.25” BS several hundred feet below the base of a salt section. The 12.25” bit size was then used to total depth. 9.625” production casing was run from total depth to surface.

This planned interval for milling the window was approximately 2,000 ft. above the hole diameter change from 12.25” to 18.125”, in an interval where channels were likely due to the hole diameter change, wash-outs, the cement pumping program and quality of the cement that was pumped.
An 8 1/2" clean out/ drill out assembly was run in the well and a cement plug that had been previously placed in the well was drilled out. After the cement plug was drilled, the borehole fluid was displaced with 11.2 ppg synthetic base mud.

One possible danger with the planned milling operation was, if the window was milled and there was no cement in the 9.625" casing annulus, the 8.5" sidetrack bit could follow in the annular space and not drill the formation, causing a well operations problem that would have to be mitigated.

Cement evaluation logs including attenuation based CBL, ultrasonic impedance and flexural attenuation were run evaluate the cement quality for the purposes of determining the ideal place for window milling.

The top of any cement was noted below the 22” shoe, with the top of any significant cement that could possibly provide isolation approximately 750 ft above the intended window milling depth.

As anticipated - a probable channel was observed through this entire interval.

The CBL and VDL plots are shown below.

**Fig. 17** Transition near top of cement is not clear based on attenuation based CBL field log

Attenuation data from a recent generation array sonic tool shows improvement in data quality compared to standard tools shown in figure 17. The highlighted section from 12,600’ to 13,000’ is the ideal interval for the sidetrack operation based on this data.
Attenuation data from a recent generation array sonic, highlighted area shows best choice for sidetrack operation

Average acoustic impedance shown below supports the CBL results shown above for both top of cement and the choice of the ideal sidetrack location. Two potential cement voids in the interval of interest between 12,500’ and 13,000’ are suggested by the linear decrease in acoustic impedance. These intervals will need to be viewed using the acoustic impedance and flexural attenuation maps.

The next plot shows the minimum acoustic impedance which identifies possible channels in the interval of interest but also clearly shows other intervals that are not channeled. It can be seen on closer observation that intervals 12,600’ to 12,700’ and 12,850’ to 12,950’ are not channeled. The cement maps from the acoustic impedance and flexural attenuation will need to be analyzed for the possibility of channeling.
The next plot of average flexural attenuation supports the previous plots showing two intervals that intercept the fluid gradient, both of which are outside the interval of interest.

![Plot of Average flexural attenuation supports the previous plots](image)

Fig. 21 Plot of Average flexural attenuation supports the previous plots

After evaluation of the annular acoustic impedance, flexural attenuation and CBL, the interval from 12,590’ to 12,670’ was shown to be the best area for the milling operation. After the interpretation of all the cement evaluation logs, the revised window milling depth was adjusted approximately 200 ft. deeper than the originally planned depth. The revised depth still met the planned geologic and drilling objectives and the window was subsequently milled and the sidetrack was drilled to planned total depth.

![Acoustic impedance map shows best cement quality interval for sidetrack](image)

Fig. 22 Acoustic impedance map shows best cement quality interval for sidetrack

**CASE STUDY SUMMARY**

Cement evaluation was critical for well design and planning on both wells described in these case studies. In Case I, the completion design required zonal isolation between the depleted reservoir sands and higher pressured zones. Additionally, it was critical to obtain reliable reservoir pressure measurements to determine if the zone selected for completion was depleted or was at original pressure.

In Case II the cement evaluation was used to select the optimal depth for milling the window and planning the subsequent sidetracking operation. One of the risks with this operation was the possibility of milling the window where there was no cement in the annulus which could have caused the 8.5” bit to follow the annular space instead of drilling the intended sidetrack.

In Case I, a good location for the through casing pressure test was selected which was critical to the well completion. In Case II, the whipstock setting depth was validated and the casing was milled without problems. The sidetrack was subsequently drilled to planned total depth.
CONCLUSION

When the presidential commission recently asked for information about cementing and cement evaluation, they started by saying that oil company representatives they interviewed told them that cement bond logging was so ambiguous that they might get three different interpretations from three different industry experts even when using the same log data. Unfortunately they were right. We all know that this can happen when data is limited and conditions are difficult. We also know that conditions in deepwater environments are the most difficult on the planet with many factors that add up to make cement evaluation extremely complex. Big heavy casing and heavy borehole fluids combined with lightweight cements stacks the deck against the log analyst; but the good news is that technology is available today to greatly reduce these uncertainties.

A more complete analysis of all of the uncertainties is a subject for another paper, but in 50 years technology allows a much more definitive answer to the classic ‘How sure are you?’ question.

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Charles L. Russell is the Well Operations Contract Manager for ENI US Operating Co., Inc. In the previous position as Subsurface Manager he supervised the petrophysics, pore pressure analysis and geological operations for Gulf of Mexico and Alaska. In this capacity all formation evaluation, wireline and logging while drilling, conventional coring, reservoir pressure and fluid acquisition and petrophysics, for the Gulf of Mexico and Alaska were under his responsibility. He has over 25 years experience in Exploration, Development and Operations with two major oil and gas exploration companies, and 3 years experience as assistant lab manager at Core Labs. Charles Russell has co-authored approximately twenty (20) technical papers ranging from LWD and wireline acquisition, Geomechics, Open Hole and Cased Hole formation sample acquisition and log data management. His papers were published in several different venues and conferences including SPWLA, SPE, DOT, OTC, OMC and World Oil. He was a presenter at the HGS “Dry Hole – Gulf of Mexico” seminar on November 2000. He has served on several customer advisory boards for wireline logging tool development. He received a BS degree from Midwestern State University and attended the University of Houston for Post Baccalaureate studies.

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Pavel Shaposhnikov is Schlumberger’s N. America Offshore Well Integrity Champion. He joined Schlumberger Wireline in Raduzhniy Russia in 1997 where he worked as a field engineer and since then, he has served in various assignments including land and offshore open hole and cased hole Engineer, deepwater offshore coordinator, Field Quality Champion. He was involved in development of Lean and standardized well integrity evaluation operations in Gulf of Mexico. He received a MS in physics from Saint-Petersburg State Technical University.

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APPENDIX

NOMENCLATURE

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AI</td>
<td>Acoustic Impedance borehole fluid</td>
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<tr>
<td>CBL</td>
<td>Cement Bond Log Amplitude</td>
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<tr>
<td>VDL</td>
<td>Variable Density Log</td>
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<tr>
<td>TIE</td>
<td>Third Interface Echo</td>
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<tr>
<td>Z</td>
<td>Acoustic Impedance</td>
</tr>
<tr>
<td>Z1</td>
<td>Acoustic Impedance drilling fluid</td>
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<tr>
<td>Z2</td>
<td>Acoustic Impedance casing</td>
</tr>
<tr>
<td>Z3</td>
<td>Annular Acoustic Impedance</td>
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<tr>
<td>MRays</td>
<td>Measurement unit for acoustic impedance</td>
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<tr>
<td>SBM</td>
<td>Synthetic Based Mud</td>
</tr>
<tr>
<td>TOC</td>
<td>Top of Cement</td>
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FORMULA

Acoustic Impedance: $Z = \rho v$

Reflection Coefficient: $R = \frac{(Z2-Z1)}{(Z2+Z1)}$

$I1 = 10 R1$
Reflection Coefficient of outer casing to annular material: $R_2 = (Z_3 - Z_2) / (Z_3 + Z_2)$