Identification and Qualification of Shale Annular Barriers Using Wireline Logs During Plug and Abandonment Operations
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Abstract
It has long been recognised that during and after drilling through certain formations, the rock moves inward and begins to close off the well. Normally this phenomenon is considered undesirable since it can cause problems for drilling and casing running. It can however be put to good use as the mechanism to create an annular barrier behind casing.

In order to extend the life of a number of North Sea brown fields many well slots on production platforms and sub-sea templates are being re-used. This process involves permanent plug and abandonment of the old well track prior to sidetrack drilling into a fresh area of the reservoir. Norwegian Continental Shelf (NCS) regulatory requirements dictate that compliant procedures for well abandonment require the establishment of double barriers to avoid leakage from the reservoir. With a shortage of sufficient traditional cement barriers these wells often need costly remedial work in order to meet abandonment requirements.

Traditional sonic and ultrasonic azimuthal bond logging provides information on the material immediately behind the casing. Many such bond logs show solid material behind the casing far above the theoretical cement top. Clear correlation of this bonding pattern to shales, known to cause problems during drilling, indicates that the shale has sealed off the annular region and that it is the presence of such formation material that results in a good bond log response.

Logging and pressure testing sealed off zones in a number of wells allowed the bond log response to be qualified for a certain formation without further pressure testing. In this manner logs can provide a clear answer of whether shale successfully seals off certain zones and consequently provides a natural annular barrier. This technique has been employed successfully on over 40 wells, proving non-destructively that high quality natural annular barriers had formed, resulting in elimination of complex remedial work and substantial cost savings.

Introduction
Historically log responses indicating a good bond have often been observed on bond logs far above the theoretical top of cement. Many explanations exist for these responses and it is likely that there are a number of possible causes. The most frequent cause is believed to be formation displacement. This is supported by the following observations on the log:

- Good bond log response far above the top of the theoretical cement.
- Good quality bond correlates with shale rich intervals.
- Large and sometimes frequent changes in bond log response at the same depth as geological changes.
- Above the casing shoe of an outer casing string the log response changes from good quality bond to free pipe as the formation can no longer impinge onto the inner casing string.
- Sinusoidal patterns on ultrasonic bond log images imply geological beds impinging on the outside of the casing.

If the formation has been displaced onto the outside of the casing in a uniform manner around the circumference and over a sufficient interval along the casing, then this formation could provide an annular barrier to reservoir fluids. In order to provide an annular barrier the displaced formation must have certain physical properties. Such properties include sufficient rock
strength and extremely low permeability to fluids. It is also important to understand the shale displacement mechanism taking place, as this has implications on whether the formation is capable of creating an annular barrier or not.

The significance of the possible use of formation as an annular barrier was realised as producing fields on the NCS have matured. Typical production platforms and sub-sea templates were designed with limited well slots. As producing wells reach the end of their productive life there is a need to drill additional wells into un-drained regions of the field. Due to the limited number of well slots, existing wells are re-used by plugging and abandoning an old well track and then drilling a sidetrack through one of the intermediate casing strings.

Planning of typical plug and abandonment operations prior to sidetracking has revealed a shortage of annular barriers, or a lack of documentation supporting the existence of annular barriers. In order to ensure proper annular barriers are in place prior to sidetracking, a number of remedial solutions have been used which include:

- Perforation of the casing, cement squeeze followed by bond logging of the squeezed cement.
- Cutting and pulling the existing casing string followed by placement of a long cement plug above and below the casing cut point.
- Section milling of at least 50 meters of casing followed by placement of a long cement plug across the milled section.

Such solutions are time consuming and therefore expensive, they also damage the very casing which is desirable to use as part of the barrier element and experience shows they are sometimes problematic to execute and complete satisfactorily.

Using, and being able to observe, displaced shale as a barrier is therefore a desirable alternative, as it avoids the complex remedial work that is otherwise required, retains the casing integrity and is quick and simple to execute.

**Barrier philosophy on the Norwegian continental shelf**

Drilling and intervention operations on the NCS are governed by the Petroleum Safety Authority of Norway (PSA). The PSA is the regulatory authority for technical and operational safety, including emergency preparedness, and the working environment.

The PSA have developed and defined regulations for technical and operational safety. The PSA guidelines often refer to recognized local Norwegian and international standards, such as ISO, IEC, EN, API, NORSOK, DnV, and OLF as a way to fulfil the functional requirements in the regulations.

International standards, ISO and EN, form the basis of all activities in the petroleum industry. Experts from a wide range of Norwegian companies participate heavily in the development of ISO and EN standards, in order to define safe and economical design and processes. However, Norwegian safety framework and climate conditions require amendments to ISO and EN standards. The NORSOK standards are developed to form these necessary amendments. The NORSOK standards are developed by the Norwegian petroleum industry to ensure adequate safety, value adding and cost effectiveness for existing and future petroleum industry developments in Norway.

The relevant NORSOK standard to describe well integrity requirements during drilling and well operations is NORSOK standard D-010. This document describes the requirements for well barriers at all stages of drilling and well operations. Some of the requirements relevant to this paper are:

- A double barrier element approach is required at all times, such that if any barrier fails a second barrier exists to prevent well leakage.
- Each and every barrier element should be verifiable through some form of testing.
- If any barrier fails it must be repaired before other activities can be carried out.
- Permanent well barriers must be in place prior to well sidetracks, suspension and abandonment.

Chapter 9 of NORSOK D-010 describes the requirements for permanent well barriers during sidetracks, suspension and abandonment operations. It states that “permanent well barriers shall extend across the full cross section of the well, include all annuli and seal both vertically and horizontally. Hence, a well barrier element set inside a casing, as part of a permanent well barrier, shall be located in a depth interval where there is a well barrier element with verified quality in all annuli.” NORSOK D-010 also states that a permanent well barrier should have the following properties:

- Impermeable
- Long term integrity.
- Non-shrinking.
- Ductile – (non brittle) – able to withstand mechanical loads/impact.
• Resistance to different chemicals/substances (H2S, CO2 and hydrocarbons).
• Wetting, to ensure bonding to steel.

These standards do not define particular materials acceptable for a well barrier element. This allows the operator to choose the barrier element material providing its properties meet NORSOK requirements. More specifically this allows the use of shale as a barrier element since shale satisfies all the requirements. Furthermore the fact that certain shales are cap rocks for many NCS reservoirs indicates that shale is an excellent barrier material.

For shale to form an annular barrier the following requirements must be satisfied:
• The barrier must be shale. This can be demonstrated through electrical logs or cuttings description logs made during or after drilling.
• The strength of the shale must be sufficient to withstand the maximum expected pressure that could be applied to it. In practice this means calculating the worst case scenario by extrapolating the maximum reservoir pressure to the base of the expected shale barrier via an annular gas column.
• The displacement mechanism of the shale must be suitable to preserve the well barrier properties.
• The barrier must extend and seal over the full circumference of the casing and over a suitable interval along the well. This can be verified by using wireline ultrasonic azimuthal bond logging tools.

The methods to satisfy the above requirements are detailed below.

Formation displacement mechanisms
On the NCS and in similar international settings formation displacement is observed as a reduction in well bore diameter, both during and after drilling. This is common in the argillaceous Tertiary and Cretaceous sequences. This reduction of well bore diameter has been observed as both a rapid and a slow process.

The following displacement mechanisms are believed to occur in isolation or in combination (E. Fjær et al, 2004):
• Shear or tensile failure
• Compaction failure and/or consolidation
• Liquefaction
• Thermal expansion
• Chemical effects
• Creep

Observations in wells, test jigs and on logs make it possible to identify the key displacement mechanism occurring as follows:
• Shear and Tensile failure is seen in many different wellbore inclinations and azimuths. It is most often seen in shale sequences requiring mud weights higher than the pore pressure to remain stable with respect to shear failure calculations. The reduction of density of the mud behind casing over time may therefore be of significance when it comes to initiating this process. However, based on the fact that bond logs have identified distinct lithological layers which have not impinged on the casing in between layers which have, we can conclude that this is not a “rubble zone” as could be expected if shear failure alone was responsible.
• Once the process of the formation wall moving onto the casing has started, then compaction failure and consolidation are likely to occur. However this is not regarded this as an important triggering process, rather a consequence response.
• There is no evidence from logs or drilling experience that liquefaction is involved in the process. The fact that bond log responses indicating a solid material presence in the annulus is enough to indicate that liquefaction is not the key mechanism.
• Thermal expansion from production may be of minor importance, but the temperature differences involved here, from formation temperature to production phase, are typically small and therefore the effect is not believed to contribute significantly to the displacement observed. Thermal response could, however, be of importance in escalating the process in the shallower sections.
• The log responses show that the observed bonding appears regardless of the type of drilling mud used, therefore chemical effects are not considered to be a major contributor to the displacement process.
• A simplified description of the displacement process of the clay-rich rocks is that the formation is moving in a hydraulic way, much like a BOP pipe ram would do during closing. Of the above mentioned mechanisms it is thought that creep appears to best fit the observations, possibly in combination with shear failure.
Formation strength requirements:
In order to qualify a zone of bonded formation as an annular barrier it is important that the maximum reservoir pressure that could be exerted on the barrier is not higher than the minimum horizontal stress (σ₁h). In the planning phase of the qualification process the σ₁h is taken from the earth stress model of the actual field.

The first objective of the strength test is to ensure that a fluid communication system behind the casing does not exist. If communication appears to exist then the verification process has failed, as the barrier can not be confirmed. The second objective of the strength test is to verify that the formation strength is coinciding with the stress prognosis.

The strength test could be a Formation Integrity Test (FIT) but since both the communication issue and formation strength can be clarified as part of an extended leak off test (XLOT), this is the preferred option. If the strength test should give lower strength than expected, then the safety margin against reservoir pressure may become an issue and should be carefully evaluated.

Logging tools and log response

Cement Bond Log (CBL) and Variable Density (VDL) Logs
CBL and VDL logs are acquired with a sonic logging tool that has a monopole transducer and monopole receivers placed respectively at 3 ft and 5 ft from the transmitter (Fig. 1). The monopole sonic transmitter sends a low frequency (10-20 KHz) omni-directional pulse that induces a longitudinal vibration of the casing. The data recorded represents the averaged values over the circumference of the casing. It consists of the amplitude of the first positive peak (denoted by E1) of the sonic waveform received at 3 ft and the full waveform received at 5 ft. When bonded to a stiff material, the vibration of the casing is attenuated and the CBL E1 amplitude is small. The transit time (TT) taken by the wave to travel from transmitter to receiver is used to quality control the tool centralization and set the correct parameters for proper detection.

When the casing is fully bonded to a thick enough cement sheath or solid material, the attenuation of sonic signals travelling through the casing is proportional to the shear acoustic impedance of the cement. However, wellbore conditions also affect the attenuation of sonic signals. For instance, the bonded-pipe amplitude increases with casing thickness, decreases for larger casing sizes, and depends on fluid type and weight on either side of the casing. To minimize these effects when interpreting the CBL data, a calibration in a “free pipe” section is recommended to compensate for wellbore differences, assuming that wellbore conditions (casing sizes and weight and mud properties) remain constant over the entire well. Later, this can be assessed with the TT value, which varies with casing inner diameter and mud velocity.

In addition to wellbore conditions and acquisition parameters, the CBL amplitude is affected by centralization (for example, E1 is reduced by half, and TT by 4 μs for a 6.4-mm tool eccentricity), and a micro-annulus, which results in an increase of the CBL amplitude. This increases again with fluid-filled channelling in the cement sheath.

The characteristics of the entire waveform at the 5 ft receiver are displayed graphically on the VDL log. In a perfectly bonded situation, weak casing arrivals followed by strong formation P, and then S, arrivals are observed. In free pipe, however, the casing arrivals are strong and appear parallel on the log. Few formation arrivals are observed, and in front of the casing collar, the characteristic chevron pattern can be observed. In partially bonded casing (with channelling), both casing arrivals (accompanied by a high CBL) and formation arrivals may be present. This may also occur in the presence of a micro-annulus at the casing-cement interface. To differentiate between the two situations (channelling and micro-annulus), the casing pressure is typically increased and the log repeated. A decrease in E1 with vanishing casing arrivals and strengthening formation arrivals favours the micro-annulus hypothesis (with cement in the annulus) versus the channelling hypothesis.

![Figure 1: Cement bond log (CBL) tool and principle of operation.](image-url)
Ultrasonic azimuthal bong log

The ultrasonic azimuthal bong log uses a high-frequency pulse-echo technique. The tool uses a rotating 7.5-rps transducer which emits a broadband ultrasonic wave, perpendicular to the casing walls, to excite the casing into resonance mode. The ultrasonic wave frequency is adjustable between 250 and 700 kHz and the frequency used depends on the casing thickness and the amplitude decay. This is related to the acoustic impedances of the media on either side of the casing. The tool scans the casing with an azimuthal resolution of 10 or 5 degrees providing 36 or 72 measurements at each depth. These are processed to yield the casing thickness, internal radius, and inner wall smoothness (from the initial echo) as well as an azimuthal image of the acoustic impedance of the material behind the casing (from the signal resonance decay). The acoustic impedance is then classified as that of gas when it is typically less than 0.3 MRayl, or liquid when between 0.3 and 2.6 MRayl, or solid bonded material when it is larger than the upper liquid limit of 2.6 MRayl. The accuracy of the estimated cement acoustic impedance depends on the accuracy of the known mud acoustic impedance. This is estimated with the fluid measurement cell when the tool is lowered into the well and the transducer is flipped inward towards a reference plate of known thickness and elastic properties.

New generation ultrasonic azimuthal bond log

When the estimated acoustic impedance is low and close to that of the mud, it becomes difficult to conclude without ambiguity whether a solid (fluid-contaminated or lightweight or foam cement) or a liquid fills the annular space. More recent ultrasonic technology addresses these limitations. The new generation tool combines traditional pulse-echo technique with flexural wave imaging, increasing the range of cements and conditions which can be successfully analysed.

Flexural wave imaging relies on the pulsed excitation and propagation of a casing flexural mode, which leaks deep-penetrating acoustic bulk waves into the annulus. Attenuation of the first casing arrival, estimated at two receivers, is used to determine the state of the material coupled to the casing as solid, liquid, or gas (SLG). Third-interface reflection echoes arising from the annulus/formation interface yield additional characterization of the cased hole environment. Since acoustic impedance and flexural attenuation are independent measurements, their combined analysis provides borehole fluid properties, not requiring a separate fluid-property measurement.

CBL/Variable Density logs versus the Ultrasonic azimuthal logs

The main shortcomings of the ultrasonic azimuthal logs versus the CBL/Variable Density log are its limitations when operated in dense wellbore fluids that tend to heavily attenuate the ultrasonic signal (limits typically correspond to a maximum water-based mud...
density of 1.9 g/cm³ or an oil-based mud density of 1.4 g/cm³). The ultrasonic tools also have difficulty in the presence of a dry micro-annulus. Shortcomings of the CBL are its single averaged amplitude value, which is highly sensitive to tool centralization and micrometric micro-annuli. The CBL measurement does not allow differentiation between contaminated cement, channelling, or micro-annuli. Additionally, the CBL is affected by mud type and density and, when present, by concentric outer casings (in a double string configuration). The main advantage of the Variable Density log is its ability to detect formation arrivals even in the presence of a millimetric micro-annulus, which allows it to differentiate between a fluid-filled annulus and cement in the presence of a large micro-annulus. Given the different responses of the measurements to certain annular conditions, for evaluation purposes, the azimuthal ultrasonic, CBL, and Variable Density logs complement each other and should therefore always be run in combination.

**Calibration of log responses**

As previously discussed, for formation to be qualified as an annular barrier a number of requirements must be satisfied. In order to ensure the strength of shale observed on bond logs contacting the backside of the casing is sufficient to provide a barrier, it must be pressure tested. The pressure test must be made from below or near the base of the potential barrier. The pressure test must be made at a high enough pressure to exceed the maximum expected pressure that could be applied to the potential barrier from the reservoir. Practically this often means the pressure test will be made up to leak-off pressure in order to ensure possible leakage is not missed when applying a lower pressure.

There are a number of ways such a pressure test could be practically performed. Some of those methods are:

- Perforate the casing at the base of the potential barrier identified from logs. Apply pressure in the well until either a pressure response is seen at the casing annulus at surface, or a leak-off response is seen.
- Perforate the casing at the base of the potential barrier identified from logs. Perforate the casing at the top of the potential barrier. Run a test string and packer. Set the packer between the perforations. Apply pressure in the test string until either a pressure response is seen at the test string annulus, or a leak-off response is seen.
- Run a cased hole formation tester with pump-in capability. Make a hole in the casing at the base of the potential barrier. Monitor formation pressure to ensure no connectivity to other pressured zones. Pump into the hole until leak-off pressure is reached. Repeat the measurement to ensure good quality.

Once a particular shale horizon has been pressure tested successfully, the bond log response associated with the now proven barrier is assumed to indicate the required minimum acceptable bond log response for barrier confirmation in subsequent wells. Experience has shown that when an acceptable bond log response is observed in a shale zone, repeating such pressure tests on a number of wells in different fields consistently proves an annular barrier is present. In other words the bond log response is now qualified to identify an annular barrier in a particular shale horizon without a pressure test.

The supposition that a bond log response indicates an annular barrier relies on the assumption that the log only indicates a “good bond” when a solid material is pressed hard enough onto the outside surface of the casing to prevent migration of well fluids in the annulus. In order to confirm this assumption a test jig was built to observe bond log responses when different materials were present in the annulus. The main purpose of the test was to show that non-consolidated granular materials in the annulus such as sand and shale fragments would not produce a log response that could falsely indicate a good annular barrier, as loose annular material of this type is unlikely to create a suitable annular barrier (at least over a relatively short interval).
The test jig was designed to allow bond logging tools to be inserted inside a water filled 9 5/8” casing which could then be pressurised to allow correct functioning of the tool acoustics. The annulus was built by centralising the 9 5/8” casing inside a section of 20” casing. The annular space between the 9 5/8” and 20” casing could then be filled with unpressurised material.

Water was first tested as the control medium in the annulus. Following the water test the annulus was filled with sand. This sand was mixed grain size and had a low pore volume of around 25%. The pore space contained water and some small air bubbles due to the process of pumping the slurrified sand into the annulus. After the sand had been allowed to settle in the annulus, the log responses from different bond logging tools were recorded.

With sand in the annulus the CBL showed only a slightly lower signal than free pipe of around 48 mV. This is assumed to be because the loose sand did not prevent compressional vibration of the 9 5/8” to any significant extent. The VDL signal showed slightly more attenuation than the VDL in the water. The ultrasonic azimuthal bond log showed a very low acoustic impedance result indicating a mixed fluid and gas in the annulus. This was unexpected as it was hypothesised that the result would show the average acoustic impedance of the sand and fluid mix. The presence of small gas bubbles in the sand much smaller than the ultrasonic beam diameter appears to have a large effect on the log response. It is assumed that if the annulus had been pressurised and the gas bubbles compressed to a very small size, the acoustic impedance reading would be significantly higher.

It can be concluded however that the presence of fluids between the grains and wetting the outside of the 9 5/8” casing has a considerable effect on the log response and that a good bond consistent with an annular would not result in the presence of non consolidated granular materials filling the annulus.
Calibration of bond logs in well conditions

To measure and calibrate the bond log response in displaced shale which has formed an annular barrier, both logging and pressure testing are required to be carried out in the same well. This process was carried out successfully in three NCS wells. In subsequent wells the calibrated log response was used to identify shale annular barriers without pressure testing. The first calibration test was carried out on a NCS well on a production platform undergoing a sidetracking operation.

The sidetrack was planned to be made at the 13 3/8” casing shoe at 1865m by first cutting and pulling the 9 5/8” casing and then using a whipstock to mill through the 13 3/8” casing in order to drill a new well track in a less depleted portion of the reservoir. The old well track was completed with a perforated 7” liner set just above the 9 5/8” casing shoe at 3704m. The primary annular barrier behind the intermediate 9 5/8” casing string was the primary cement job with an estimated top around 3184m. Prior to abandonment of the old well track a second barrier was required to meet NORSOK requirements on the NCS. No suitable barrier existed in this well. Instead of carrying out remedial work a known tertiary shale sequence (Hordaland Green clay) which had created tight wellbore conditions during drilling was suggested as a possible candidate for an annular barrier. This sequence was deep enough and estimated to be strong enough to provide an annular barrier.

Figure 6: Well sketch of first calibration well

The potential barrier section was pressure tested by perforating approximately 10 meters below the top and 10 meters above the base of the Green Clay sequence. A test string with a retrievable packer was run. The packer was set above the lower perforations and pressure applied through the test string. No pressure increase was observed in the test string or the 9 5/8” casing annulus. The pressure response observed and the volumes pumped through the test string were interpreted to represent formation leak-off in the Green Clay. The leak-off value was consistent with previous knowledge for this formation and indicated that an annular barrier had formed.

Bond logs were run which showed good bonding over the entire Green Clay interval; however the CBL and impedance values were lower than would be expected in good cement. The higher CBL value in shale then cement is most likely due to shale being less stiff than well set cement. This would allow a little more axial compressional wave casing motion with shale than with cement. The lower acoustic impedance values observed on the ultrasonic azimuthal bond log is explained because the acoustic impedance of shale is significantly lower than standard class G cements. Good bonding was also observed in the shales above the Green Clay. Above the 13 3/8” casing shoe a free pipe response was observed, indicating no displaced shale. This is simply explained by the fact that bond logging tools only respond to the primary annulus which was now shielded from the formation by the 13 3/8” casing . The change over from poor bond below the Green Clay to a good bond coinciding with the base of the Green Clay and the change from good to poor bond at the 13 3/8” casing shoe is clear evidence of the capability of these tertiary shales to create an annular barrier.
Good bond log response due to displaced shale pressing on the outside of the 9 5/8" casing. CBL reading average of 15mV, low contrast VDL pattern and acoustic impedance average of 4 MRayl with good azimuthal coverage.

Figure 7: CBL/VDL and ultrasonic azimuthal bond logs over an interval in the Hordaland ‘Green’ Clay
This calibration process was repeated in a number of other wells with remarkably similar results. Similar annular barriers were observed and tested in all cases. Bond logs with similar responses were associated with the tested annular barriers. These observations built confidence that a positive bond log response similar to or better than the response observed in these wells could be used to determine the presence of an annular barrier without subsequent pressure testing.

Despite the fact that remarkably similar log responses associated with positive pressure tests have been observed in a number of geologically different shale horizons, it is prudent to re-calibrate the log response in a "new" shale by means of a pressure test. Due to the variation in the mechanical properties of different shales the possibility exists that a good bond response may not be a clear indication of an annular barrier. Practically this means a positive pressure test should be made in a "new" area before bond logs can be used alone to identify and qualify shale annular barriers.

**Results and examples**

Following the verification of the collapsed Hordaland ‘Green Clay’ as an annular barrier in the first field, qualification procedures have been carried out in additional fields that penetrate other clay rich formations on the NCS. Following these qualifications, a significant number of wells have been logged to confirm the presence and quality of the formation bonding in line with the barrier requirements. In all but three of these wells a good formation barrier has been observed. In those three where it was not, remedial action was required to put sufficient well barriers in place. This experience further underlines the need to confirm the barrier quality with log measurements. In this section examples from two wells are presented.

**Example #1 Shetland Clay**

Cement Bond logs were recorded in a 9 5/8” casing as part of a plug and abandonment program to recover the well slot for a planned sidetrack. Logs were run to verify the formation to casing bond in the Shetland clay sequence and confirm the displaced Shetland formation as the secondary well barrier to the reservoir.

The log graphic shown in Figure 8 shows the CBL/VDL and ultrasonic log responses over a representative interval in the Shetland Clay. First to note is that the Ultrasonic images indicate a good formation to casing bond, with well bonded, high impedance material present all around the annulus. The CBL and VDL log responses support this, with low CBL amplitudes and a VDL image showing clear dampening of the casing arrivals in combination with strong formation arrivals. The observed log responses are in fact almost identical to those expected in well bonded Class G cement.

This log example is also interesting in that it shows three distinct intervals where the formation has not impinged on the casing. These three intervals remain liquid filled with well bonded displaced formation above and below. The sinusoidal appearance of these intervals on the image logs indicate that these are geological beds, which can be identified as layers of Shetland Chalk. The fact that these chalk layers appear as liquid filled pockets further supports the plastic creep theory as we see no indication of ‘rubble’ fill which would have been expected with a shear/tensile failure mechanism. In addition any thermal expansion would have been expected to affect both the shale and the chalk formations to a relatively similar degree. A subsequent pressure test procedure (the same procedure as carried out in the first Hordaland ‘Green’ clay well) confirmed the annular barrier created by the displaced Shetland formation to meet all of the NORSOK requirements.
Figure 8: CBL/VDL and Ultrasonic Cement Bond Logs over an interval in the Shetland Clay

Chalk Beds that have not displaced appear as liquid filled pockets. Sinusoidal appearance due to well path cutting the chalk beds at approximately 60 deg

Shetland Clay displaced against the casing. The ultrasonic images show high measured impedance values around the entire annulus. Low CBL amplitudes and strong formation arrivals on the VDL image from the sonic tool support the ultrasonic interpretation, namely that the clay is ‘hard’ packed against the casing. This was subsequently verified as a barrier element through pressure testing.
Example #2 Shetland Group (Nise Clay) Example

In the next well example a procedure was undertaken to qualify the displaced Shetland (Nise clay) formation as an annular hydraulic barrier. Historical cement bond logs had, once again, shown good bonding high above the theoretical top of cement and qualification of the Shetland (Nise clay) formation as a barrier would allow significant efficiency savings related to slot recovery operations. The procedure involved first logging the 9 5/8” casing using both a CBL/VDL and an ultrasonic azimuthal bond logging tool which would determine the extent and quality of the formation bond. If an acceptable bond quality was identified over a sufficiently long interval then a second logging run with a cased hole formation testing tool would be undertaken to verify the barrier through pressure testing.

The CBL/VDL/Ultrasonic data from the first run showed that the formation had displaced and had formed a ‘hard packed’ bond against the 9 5/8” casing, it also showed that the bonding extended over a sufficiently large interval (>200m). Based on these results a test depth was chosen from the logs and a pressure testing procedure was carried out with the cased hole formation tester. Figure 10 shows a section of the CBL/VDL and Ultrasonic logs illustrating the good formation bond, it also shows the depth chosen for the subsequent pressure testing (3275mMD). The pressure testing procedure involved first observing the annular pressure after communication to the annulus had been achieved, this pressure was found to be significantly higher than that of the depleted reservoir below, indicating that a hydraulic barrier existed in the annulus between the reservoir and the test point. An extended leak of test then followed. Details can be seen in Figure 9. This test confirmed no communication via the annulus and that the formation strength was sufficient with respect to the reservoir pressure. The XLOT was then repeated giving the same results. The results from this testing procedure confirmed that the Shetland (Nise clay) formation satisfied all of the NORSOK annular barrier requirements and subsequent use of this annular displaced formation as a barrier element will offer significant savings related to future plug and abandonment operations on this field.

Figure 9: Test sequence performed with cased hole formation tester at a probe depth of 3275mMD

1. Pressure indicates annular isolation from depleted reservoir below
2. XLOT test first confirmed no annular communication. Interpretation of fall off data after breakdown also confirmed formation strength at this depth to be as expected and therefore sufficient w.r.t. reservoir pressure. This test therefore confirms the annular barrier to be compliant.
3. Repeated extended leak off test confirms results from the first test.
Ultrasonic logs show high impedance and high flexural attenuation all around the annular circumference. The solid/liquid/gas map, which is computed using both the independent attenuation and impedance measurements and a prior knowledge of the properties of all the possible materials behind the casing, also shows that there is solid material around the whole of the annulus.

The results therefore showed that the Shetland (Nise clay) formation had displaced and filled the annulus and that it had bonded well to the casing. Given the results of the ultrasonic logging it was decided to continue with the XLOT testing procedure to allow verification of the annular formation material as a qualified barrier.

Depth selected for XLOT testing with a cased hole formation tester - 3275mMD

Figure 10: Ultrasonic Cement Bond Logs over an interval in the Shetland (Nise) Clay
Changes in steering documentation
In order to ensure appropriate and correct application of the methods described above, it was important and necessary to modify the operating company internal steering documents and best practice procedures.

A new steering document section was written to describe the requirement to verify formation as a permanent barrier element. This section is as follows:

If competent formation is considered used as a permanent barrier element, position of displaced formation shall be identified and seal ability verified.

Methodology
- Position and extent of collapsed formation shall be identified through appropriate logs.
- Two (2) independent logging measurements/tools shall be applied.
- Logging tools shall be suitable for applicable well conditions e.g. number of casing strings, casing dimensions and conditions, fluid types and densities.
- Logging tools shall be properly calibrated.
- Logs shall be interpreted by personnel with sufficient competence.
- Log response criteria for good bonding shall be established prior to initiating the logging operation.

Log interpretation
- Both log measurements/tools show continuous good bonding of minimum 50 meter = Barrier element verified.
- Less than 50 meter continuous good bonding and/or non-unambiguous log response = Verify collapsed formation through pressure test or inflow test.
- No/poor bonding identified. No barrier element identified = Further action to be determined.

In addition best practice procedures were written. These procedures describe the logging procedures with particular logging tools. They also list particular geological formations which have been qualified through both logging and pressure testing to be able to form suitable annular barriers.

The cut off value of bond logging responses has been calibrated against successful pressure tests in a number of formations and has found to be remarkably consistent in different formations. The following readings are suggested as guidelines.

<table>
<thead>
<tr>
<th>Cement bond log amplitude</th>
<th>Variable Density log</th>
<th>Ultrasonic acoustic impedance scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Barrier</td>
<td>CBL less than 20 mV over 80% of interval</td>
<td>Low contrast casing signal and clear formation arrivals</td>
</tr>
<tr>
<td>No Barrier</td>
<td>CBL reading within 20% of free pipe reading</td>
<td>High contrast casing signal and weak formation arrivals</td>
</tr>
</tbody>
</table>

Table 1: Calibrated bond log values

Conclusion
Tradition methods of checking or creating annular barriers during plug and abandonment operations are time consuming, expensive and not practical. Using shale that has collapsed against the casing via the mechanism of plastic creep due to overburden pressure provides a practical and effective annular barrier.

The presence of such barriers can be proven by using wireline logs. These logs are used to identify shale formations and identify zones of sufficient length and azimuthal coverage which have collapsed and are squeezed hard onto the outside of the casing.

Prior to being able to determine that an annular barrier identified by bond logs is good enough to withstand the pressures it may be exposed to, a particular geological formation must be “calibrated” by pressure testing to determine the barrier observed on logs is real. In addition the particular formation must be limit tested to determine the formation strength. This process was carried out on key NCS tertiary and cretaceous shales successfully.
These new procedures were accepted by the Norwegian PSA and the operating company steering documents and best practice documents were appropriately updated.

Regular use of bond logging to identify shale barriers during P&A operations on the NCS has been carried out during 2007 and 2008. Over 40 P&A operations have used this method with a success rate of over 90% of proving shale annular barriers. In some cases good annular barriers have been proven within a few weeks of setting the casing indicating that the process of creep can in some cases occur quite rapidly.

The results of this method has given significant rig time and operating cost savings, prolonged well life in some cases and an overall improvement in the quality of well integrity.

Identifying, qualifying and making use of nature’s own barrier provides a solution which is extremely durable, self-healing and more robust than man made barriers.

References:

1. The Petroleum Safety Authority of Norway (PSA), http://www.ptil.no/

2. The Standards Organisation in Norway (NORSOK) - standard D-010, Well integrity in drilling and well operations (Rev. 3, August 2004), http://www.standard.no/imaker.exe?id=5738

