Chapter 9
Barrier Verification

The main goal of a P&A operation is to restore the cap rock functionality by establishing competent barriers. When a barrier is established, its functionality needs to be verified. There are different test procedures to verify integrity of permanent barriers. Some include verification of annular barrier (barrier between casing and formation), some include verification of permanent plug inside casing, and some others include verification of barriers in open holes. The main challenge for barrier verification is the lack of direct relationship between laboratory verification and field performance testing. In the laboratory testing of cement, the following parameters are evaluated: mechanical properties (e.g. compressive strength, tensile strength, Young's modulus, etc.), shear bond strength, hydraulic bond strength and tensile bond strength, fluid migration analysis, static gel strength analysis, etc. In addition, most of laboratory experiments replicate best case scenario with respect to contamination of cement slurry. However, there is no simple way of accurately testing these parameters at expected downhole conditions. In fact, the only tests available to verify cement plugs in the field are hydraulic pressure testing, weight testing and tagging with workstring. The annular barrier is tested indirectly by logging. This chapter will review these field test methods.

9.1 Annular Barrier Verification

The concept of cross-sectional barrier has already been defined in previous chapters. In order to verify the cross-sectional barrier, barrier behind casing needs to be verified where casing exist. There are different methods to qualify the integrity of annular barrier. Acoustic logging of annular barrier, passive noise logging, temperature logging, and hydraulic pressure testing are the most commonly used verification method which will be reviewed in this chapter.

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9.1.1 Acoustic Logging of Annular Barrier

Acoustic logging of annular barrier technique is the prime method used in petroleum industry for verification of casing cement but also may be used for other types of barrier materials. Therefore, this technique will be discussed more in detail.

In acoustic logging method, an acoustic signal is emitted by a transducer, the emitted signal goes to a journey through casing fluid, casing steel, barrier behind casing, adjacent formation and all the way back to two receivers, Fig. 9.1. The receivers pick up the reflected acoustic signal and engineers process the collected data to check the quality of annular barrier.

The history of sonic logging goes back to 1950s when during formation evaluation by sonic logs the occurrence of skipped cycles were noticed where openhole and cased hole were evaluated [1]. Since then, the technology has advanced whereas ultrasonic tools have been developed and are in use. Nowadays, cement bond logs are run to determine cement to casing bonding, cement to formation bonding, and

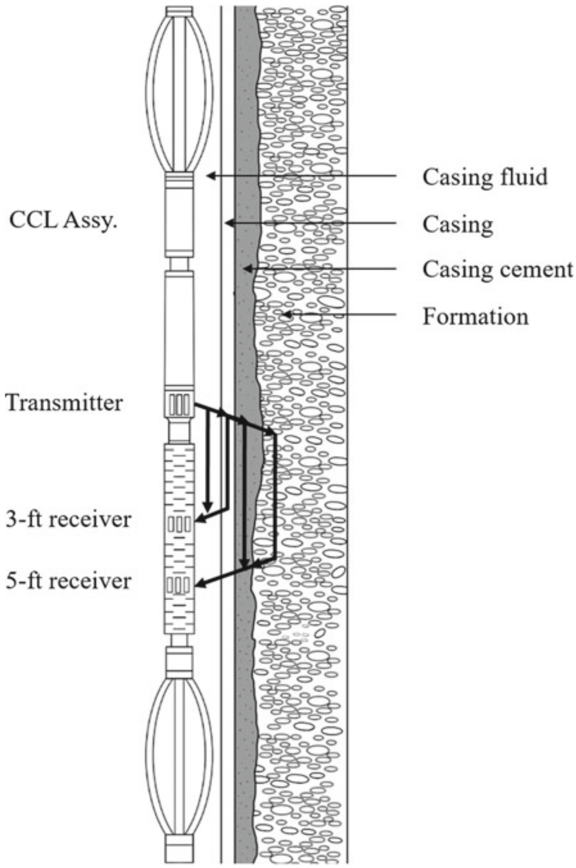

Fig. 9.1 A cement bond log (CBL) and variable density log (VDL) tool

evaluate cement conditions. The evaluation of cement conditions include detection of channeling, compromised cement (by gas cut, dehydration, etc.), top of cement, and micro-annuli.

Acoustic logging is a process of recording of some acoustic property of formation and wellbore. The result of process is displayed on an acoustic log which presents traveling time of acoustic waves versus depth in a wellbore. The acoustic logging of annular barrier can be through sonic, and ultrasonic (pulse-echo) measurements.

9.1.1.1 Sonic Measurements

Sonic tools are working in a frequency range of 10–30 kHz. An electrical signal is sent to a piezoelectric transducer, and the transducer generates an omnidirectional acoustic signal. Piezoelectric transducers are capable to receive electricity and convert it to acoustic signal and vice versa. Acoustic signals are sound waves which are categorized into compressional wave (P-wave), shear wave (S-wave), and plate wave, Fig. 9.2. Compressional wave (sometimes called longitudinal wave) is a wave that the motion occurs in the same direction or opposite direction to wave propagation. Compressional waves can travel through solid, liquid and gas. Shear wave (sometimes called an elastic S-wave) is a wave that the motion is perpendicular to the wave propagation. Large amplitude shear waves can travel only through solid phases. Plate wave (sometimes called Lamb wave) propagates in solid plates but slightly slower than compressional wave in steel plates.

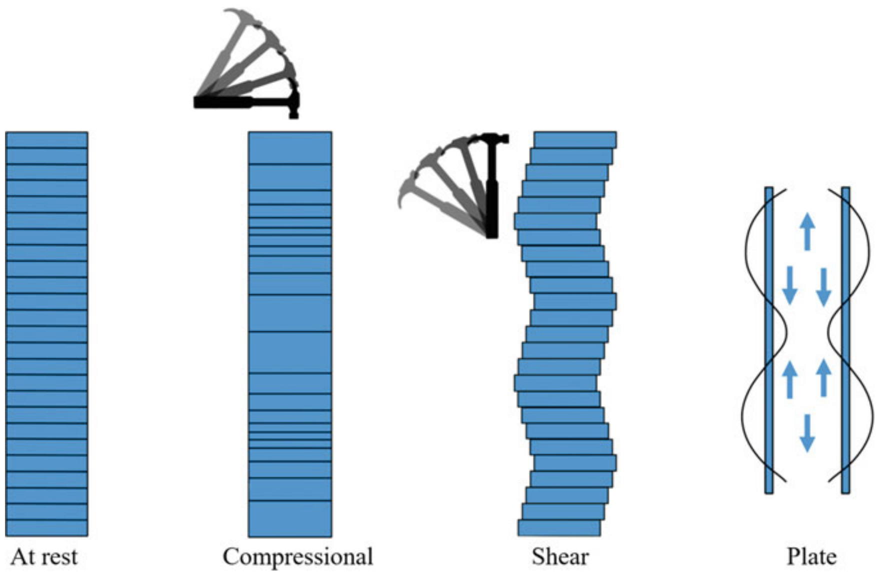

Fig. 9.2 Wave propagation modes [2]

Piezoelectric transmitter fires acoustic signal, compressional wave, and the wave propagates through casing fluid, casing steel, barrier material behind casing, and formation. The wave is reflected back through all of these medium toward the receivers (two piezoelectric receivers). Two receivers, placed 3 and 5 ft away from transmitter pick up the reflected signal, Fig. 9.1. The 3 ft receiver picks up the signal from casing arrival and casing fluid and the 5 ft receiver picks up the formation arrival. The recorded data are presented on a log which consists of a log heading, main log and repeat section, determination of logging pressure, before and after survey calibrations and parameter box, and log tail. A log heading is composed of four parts: API heading, remark box, well schematic, and tool schematic with sensor distances, Fig. 9.3.

The main log presentation consists of three tracks: Track 1 for quality control, Track 2 show the quality of bonding between cement and casing, and Track 3 which shows formation arrival (see Fig. 9.4). Depending on the logging tool used for logging annular barrier, more tracks may be distinguished, Fig. 9.4.

A repeat section is to examine the logging operation and the recorded length is usually 100 m which covers the zone where good sealing is expected. Sonic logs are always run under pressure in order to differentiate microannulus from channeling. As the pressure affects the amplitude of sound, the logging pressure is determined and presented on the log. The parameter box and sonic summary, before and after calibration, are presented on the log. The last section on a log presentation is a log tail which repeats the top part of the heading.

When transmitter emits an acoustic signal, an elapsed time is passed until the receiver can detect the first part of the wave arrival, which is exceeding a preset amplitude threshold. The elapsed time is known as *transit time*. Amplitude is the strength of the first arrival wave. When time passes, the amplitude recorded by receiver increases up to a level and then decreases. Time taken by an emitted signal to travel from transmitter to receiver is called *travel time*. Figure 9.5 shows the above-mentioned terminologies. When the emitted signal travels through different medium (e.g. casing fluid, casing, material behind casing), it loses the energy. The loss of sound energy, strength, is called *attenuation*. So, the higher the attenuation the lower the amplitude.

An acoustic logging tool may be configured with some complementary logging tools. The most common complementary logs include casing collar locator (CCL) and Gamma ray logs. Figure 9.6 shows two sonic logs equipped with CCL, GR detector and centralizers; however, tool centralization is valid in wells with inclination less than 50°. CCL is used to locate casing collar for depth calibration. GR detector is also used for depth and formation calibration. In fact, Track 1 does not provide any information regarding the cement quality but it is used for quality control.

A transmitter fires a compressional wave and it propagates spherically. A part of the compressional wave travels downwards along casing fluid along casing steel and a part reaches the casing and travels downward along the casing. Another portion of the wave which entered to casing steel travels further toward material behind casing and formation. If there is solid material behind casing, at the interface of casing and the solid material shear waves is generated. So, the generated shear wave and

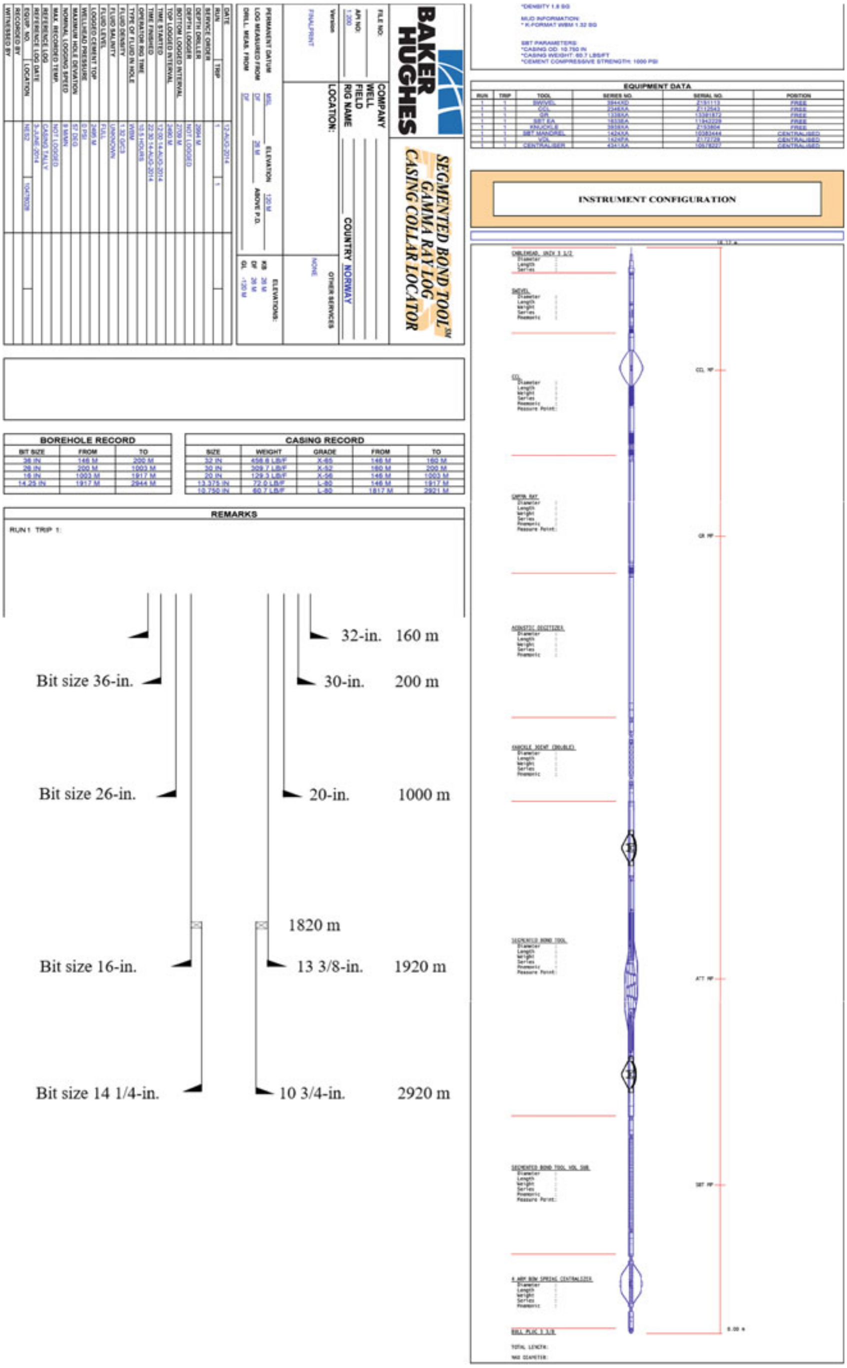

Fig. 9.3 A log heading

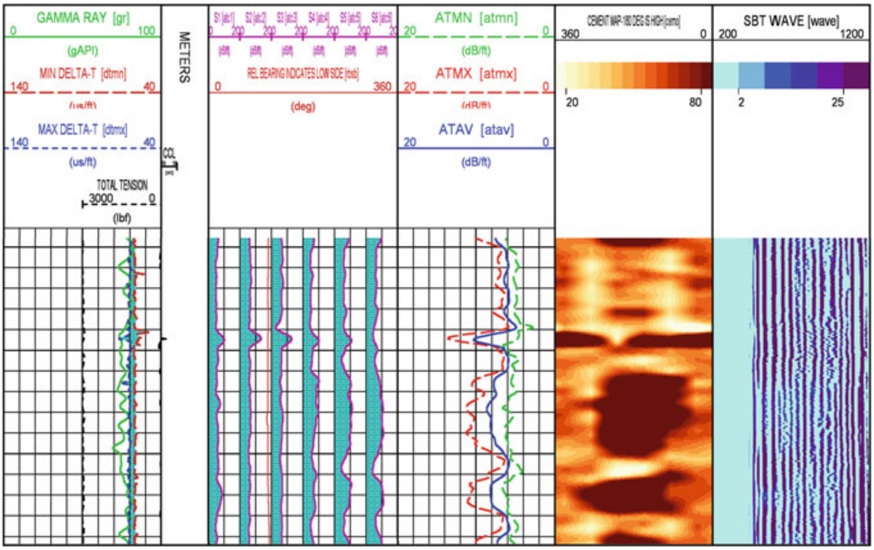

Fig. 9.4 A CBL-VDL log with radial mapping which includes five tracks

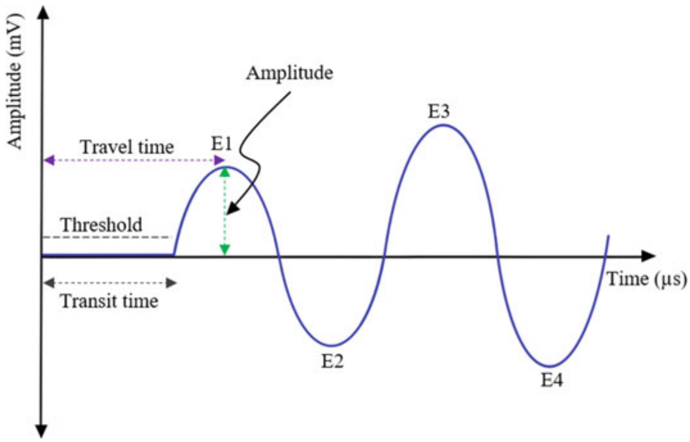

Fig. 9.5 Recorded amplitude of an acoustic signal

compressional wave continue to travel through the solid material behind casing and formation, and also downwards. But if there is no solid material behind casing, shear wave is not produced and only the compressional wave will travel through annulus behind casing to formation and downwards. In order to get the wave propagation inside the casing plate, the waves are emitted in a predetermined critical angel.

Example 9.1 In order to understand the concept behind acoustic logging of casing, you are asked to run an experiment. Pick up a pozzolan or steel coffee cup with a

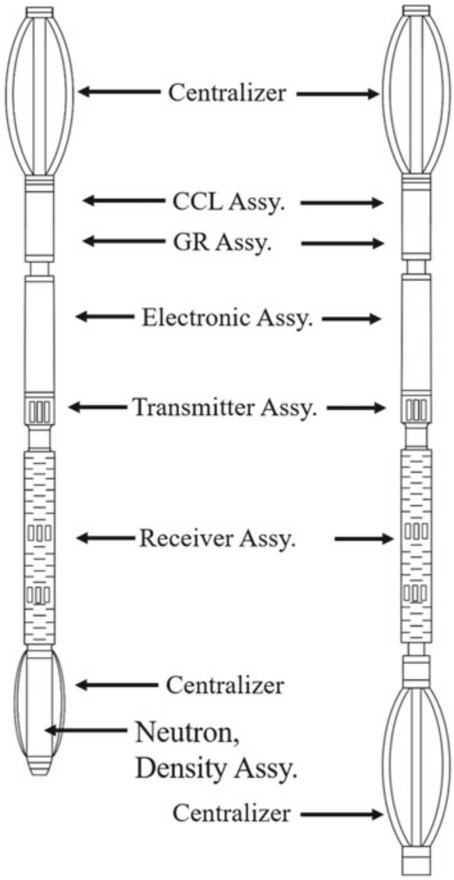

Fig. 9.6 A cement logging tool assembly [3]

teaspoon. Ask an assistant to hold the cup from its handle part with no hands around it, and hit the cup with teaspoon from inside and listen to the noise, Fig. 9.7a. For the second time, ask the assistant to hold the cup between his/her hand tightly. Again, try to hit the cup with the teaspoon from inside and listen to the noise, Fig. 9.7b.

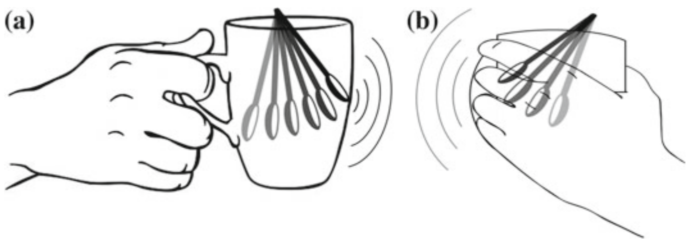

Fig. 9.7 Simulating reflected noise from an uncemented and cemented casing: **a** cup has no barrier behind it, **b** hand acts as barrier behind cup and absorbs the noise energy

Now assume that the cup is casing, teaspoon is transmitter, and hands around the cup is cement behind casing. Based on the experiments explain and interpret your observations.

Solution When holding the cup form its handle and hitting the cup wall with teaspoon, the sound energy is high. In other words, the reflected sound has high energy which is known as ringing. The same phenomenon happens when there is free casing, the casing rings.

When holding the cup tightly between hands, the emitted sound is absorbed by the hand and lower sound energy is reflected. When there is solid barrier behind casing, the emitted sound travels further and less energy is reflected back.

As described earlier, the transmitted acoustic signal is picked up by two receivers: 3 and 5 ft. 3 ft receiver picks up the reflected sound from casing and presented on Track 2, which is known as CBL log. The CBL log shows the quality of bonding between casing and the material behind it. When CBL log shows high amplitude (high energy), then the casing reflects back most of the transmitted sound because of poor bonding. In other words, the casing is ringing because of poor bonding between solid material adjacent to casing, whereas sound is not absorbed. But if there is good bonding between solid material in annulus behind casing and casing, the sound travels further to formation and it is picked up by the 5 ft receiver. The recorded data are presented on Track 3, which is known as VDL log. The VDL log records the amplitude of transmitted sound though casing fluid, casing, barrier behind casing, and formation (Fig. 9.8). When VDL log shows formation arrival, then there is a solid material in the annulus behind casing up to formation.

Information of the compressional wave velocity allows engineers to measure compressional acoustic impedance (Z) of materials. Every material has its natural acoustic impedance property and by estimating the acoustic impedance of an unknown material, the material might be distinguished. This is the main driver of sonic logs for verification of annular barrier. The acoustic impedance of a homogenous, non-dissipative

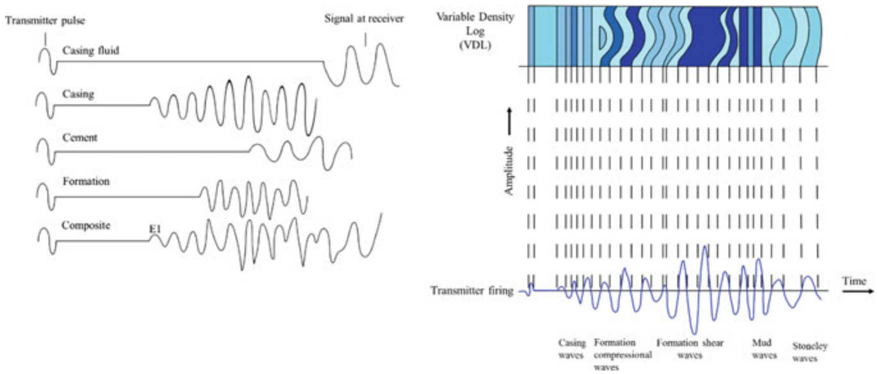

Fig. 9.8 Signal arrivals from casing fluids is the latest as sound travels slower in liquid phases, casing arrival is the first to arrive. Composite amplitude is presented on VDL log

medium, is given by:

$$Z = \rho v_P \tag{9.1}$$

where ρ is the material density (kg/m^3) and ν_P is compressional wave velocity (m/s). The acoustic impedance is expressed in $10^6 \left(\frac{\text{kg s}}{\text{m}^2}\right)$ which known also as mega-Rayleigh (MRayl).

When designing, executing and interpreting sonic logs, there are well parameters, organizational and operational factors, and human factors, which can affect the final result. The well parameters include, but are not limited to: temperature and pressure, wellbore-fluid properties, casing size and thickness, cement thickness, and surrounding formation. Organizational and operational factors may include selection of service provider, pre-job meeting and discussions, surface pressure (equipment and procedure used), detection setting, and log quality control procedures. All of these factors affect the reliability of the final logs and their interpretation.

Considering utilization of sonic logging tools in P&A, for verification of annular barrier, their reliability may be questioned if the logging tool is calibrated according to well conditions for primary cementing. This is due to change in properties of annular barrier over time, casing thickness changes, and formation subsidence. Therefore, calibration and re-evaluation of logs based on current well condition are expected. Advances of sonic logging tools has been in progress since their development and utilization. Re-evaluation of annular barrier, in place from primary cementing, with recently modified sonic logging tools could give a better understanding of annular barrier condition.

Example 9.2 In recent years, PWC technique has been developed and employed to avoid section milling. After barrier establishment with PWC, the internal cement is drilled out and annular barrier is logged with sonic tools. How can the perforated casing create difficulties and uncertainty in sonic logging?

Solution When casing is perforated, plate waves cannot effectively travel through casing unless they have very low shot density. In addition, generation of shear waves at the interface between casing and cement is disrupted. Therefore, increased attenuation of sound waves is expected which is caused by the holes created during perforation. One possible solution is to remove the effect of holes during Fast Fourier Transform processing.

Sonic logs have their advantages including: wireline operation, non-destructive technique, and safe operation. However, there are some limitations associated with utilization of sonic tools. Sonic logging provides a qualitative evaluation of cement quality and it does not show the direction of anomaly. In other words, the CBL-VDL graphs show an average of circumferential measurements. These tools are also sensitive to liquid-filled micro-annulus. Therefore, ultrasonic tools have been developed and are employed more often than sonic tools.

9.1.1.2 Ultrasonic Measurements

Ultrasonic pulse-echo (PE) techniques were introduced to the industry for cement evaluation in the early 1980s. These cement-mapping tools operate at much higher frequencies than acoustic tools, typically between 200 and 700 kHz [2, 4, 5]. The principle of the ultrasonic technique is to cause a small area of the casing to resonate across its thickness. In pulse-echo techniques, a transducer, acting as both a transmitter and a receiver, mounted in a rotating head, sends out a short pulse of ultrasound and picks up the echo containing resonance, Fig. 9.9 [6]. As ultrasonic tools provide peripheral rotation, a radial map (Track 4 in Fig. 9.4) is generated as result and defect location can be distinguished. In order to apply real time corrections for impedance calculations, ultrasonic tools provide real time measurements of fluid impedance in a built-in mud cell. The rate of decay of the resonance will be lower if there is fluid behind the casing whereas cement will damp the resonance faster [7].

A limitation with PE measurements is that they are only able to investigate the presence of cement behind a single casing string. Another known weakness of this ultrasonic sonic measurement technique is its sensitivity to the presence of small gas bubbles [8].

Viggen et al. [9] attempted to model ultrasonic pitch-catch measurements in a through-tubing logging configuration. In pitch-catch techniques, there is one transmitting transducer and one or more receiving transducers. They used a finite element model of a double-casing geometry with a two-receiver pitch-catch setup. In their study, they found that a cascade of leaky flexural Lamb wave packets appears on both casings caused by leaked wave fronts. Their study shows that the received pulse

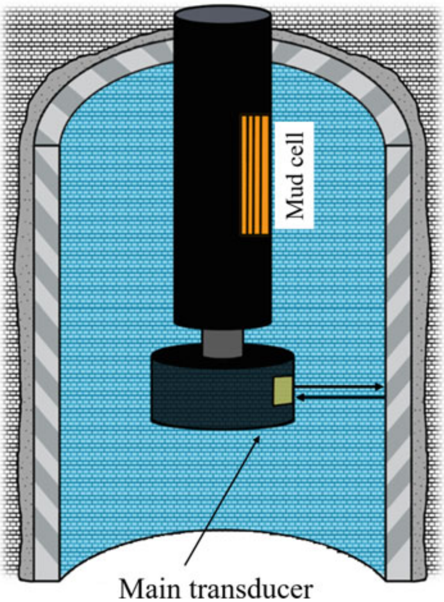

Fig. 9.9 Ultrasonic measurement, pulse-eco technology

from the second wave packet contains information about the bonded material in the outer annulus as well as the interface between cement and formation.

Viggen et al. [10] attempted to analyze outer casing echoes through simulations of ultrasonic pulse-echo measurements through-tubing. Their work examined the hypothesis that anomalies behind a second casing string can cause significant variations of pulse-echo. Their finding shows that variations of the outer casing interface echo with the outer casing thickness and the B-annulus material may be too subtle to be reliably applied to through-tubing logging. In addition, they found that eccentricity of the casing and transducer angle influence the travel time of the interface echo.

A recent development targets the utilization of electro-magnetic acoustic transducers (EMAT) for the generation of guided acoustic waves in the casing [11]. For this technology, a Lorentz force[1] is used to generate and measure acoustic waves directly. EMAT operate with a coil, a magnet and a conductive casing, and it can function both as transmitter and receiver. EMAT generate two fundamental wave modes; shear horizontal and lamb flexural (plate). In the shear horizontal wave mode, the particle motion is perpendicular to the direction of wave propagation; however in the lamb flexural mode, the particle motion is normal to the casing surface. The study of these wave modes is a direct measurement of the shear modulus of the solid material behind casing with a higher resolution compared to conventional acoustic techniques whilst eliminating sensitivity to the wellbore fluid or the need for physical contact of the transducers with the casing [12].

9.1.2 Noise Logging Measurements

When a leak occurs through cement defect, noise may be generated which depends on the defect size and geometry, leakage rate, and surrounding materials. If the generated noise is above a threshold level, it can be detected and analyzed; either by passive noise logging or active noise logging.

9.1.2.1 Passive Noise Logging

Fluid flow through a leakage pathway generates noise with two measureable parameters; intensity and frequency. Noise intensity, also known as acoustic intensity, is defined as the energy carried by the sound wave per unit area. In the context of leakage, noise intensity depends on fluid flowrate and differential pressure driving it, while noise frequency depends on the geometry of leakage pathway. As a rule of thumb, when fluid flows with ease through a large area, a low frequency noise is generated whereas fluid flowing with difficulty through a narrow space generates a

[1] It is an electromagnetic force that acts on a charged particle which is moving with a velocity through and electric magnetic field.

high frequency noise. There are a variety of tools able to record noise generated by leaks over a wide frequency range with a high resolution and high sensitivity.

9.1.2.2 Active Noise Listening

Active listening is an acoustic technique whereby a very short acoustic pulse is fired at the region being examined and the reflected signal is thereafter recorded. After a short waiting time, the same region is examined again by an identical signal and the reflected signals are thereafter subtracted from each other. If there is no difference in the reflected signals, it means that there is no motion or other changes in the material behind the casing. In other words, motion in the material during emitting the first signal and the second signal will result in an incoherence in the signals at the same depth. The strengths of this technique compared to conventional noise logging is that it is sensitive to a wider range of flowrates, provides a quantitative estimate of flow velocity, the distance to channels can be estimated and gas migration through a column of liquid in the channel can be detected.

9.1.3 Temperature Logging

Temperature logs are used to detect the temperature anomalies behind casing caused by cement hydration or leakage of fluids. Of temperature logs, cement hydration detection, communication indicator, radial differential temperature, active temperature logging and distributed temperature sensing are the most known temperature logging techniques [8].

9.1.3.1 Cement Hydration Detection

Temperature logs are used to detect the temperature anomalies behind casing caused by cement hydration or leakage of fluids. Cement hydration occurs over a period of six to twelve hours after initial mixing of cement and is an exothermic chemical reaction which generates considerable heat. It is the temperature rise inside the well due to the heat conducted by the casing from the cement that is readily detected by temperature logs. Temperature logs recorded at a suitable point in time can be used to detect the TOC, however, complete verification of the seal quality of a primary cementing operation is challenging. Detecting cement hydration must be performed before the temperature increase due to hydration has dissipated and this technique is not therefore suitable for inspecting the casing cement later in the well life.

9.1.3.2 Communication Indicator

When fluids leak through a defect, the temperature of the surroundings is affected. In thermodynamics, the Joule–Thomson effect describes the temperature change of a real gas or liquid when it is forced through a restriction. A condition of the Joule–Thomson effect is that the enthalpy, H, remains constant:

$$H = U + PV \tag{9.2}$$

where U is internal energy, P is pressure and V is volume. According to the Joule–Thomson effect, the change in PV shows the work done by the fluid. When a fluid passes through a defect, the PV is increased and to keep the H constant, U is decreased. This means that cooling due to expansion is expected if gas flow occurs. A conventional temperature log measures the fluid temperature inside the well and the recorded data is plotted versus depth. By comparing the obtained data with the geothermal temperature gradient the depth of anomalies can be identified that might be related to fluid leakage through defects in the cement. Temperature gradient differences can also be created by injected fluid flowing in the channels.

9.1.3.3 Radial Differential Temperature

Radial Differential Temperature (RDT) logging is a modified version of conventional temperature log for detecting channels. This method utilizes two sensors (in addition to a sensor in the center of well) to measure the pipe wall surface temperature around its circumference. The difference in temperature between casing wall and sensor in the center of pipe is measured and plotted versus depth. Deviation of recorded temperatures from geothermal temperature can be used to locate channels near to the casing.

9.1.3.4 Active Temperature Logging

Active temperature logging uses short-term local inductive heating of the metal in the casing to give the reservoir fluid a thermal signature that can be detected during production. As a result of inductive heating of the casing, a thermal anomaly is induced both inside the well and in the fluid moving behind the casing which can be detected by sensors once the fluid is produced into the well. Figure 9.10 shows an active temperature logging tool equipped with inductor, distributed temperature sensors; T1, T2 and T3, collar locator, gamma ray detector and water resistivity recorder.

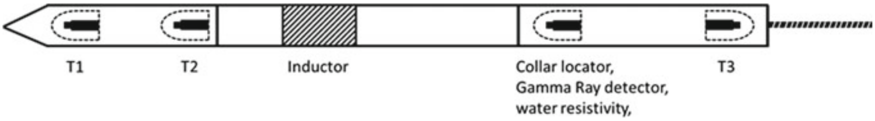

Fig. 9.10 Active temperature logging tool with its inductive heater

9.1.3.5 Distributed Temperature Sensing—Fiber-Optic Sensing

Pulses of light generated by a laser sent through an optical fiber are reflected repeatedly from the fiber walls. The fiber and its coating form a wave guide with total internal reflection such that light is not lost through the fiber walls. A sensor or combination of sensors can be placed along the fiber and record measurands such as; pressure, temperature, seismic, mechanical stresses, chemicals, and flow [13, 14]. Figure 9.11 shows three main types of fiber-optic sensor arrangements; single point sensor, multi-point sensors, and distributed sensors. The single point sensor measures the parameter of interest at a single point in space typically at the end of the fiber. The multi-point sensor measures the measurand at a number of fixed, discrete points along a single fiber-optic cable. The distributed sensor measures the measurand with a certain spatial resolution at any point along the fiber-optic cable. In the latter case, the fiber cable itself is the sensor and backscattered light carries information. Distributed sensing has the potential to identify leakage pathways and thereby cement defects. Two different distributed sensing systems are Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS).

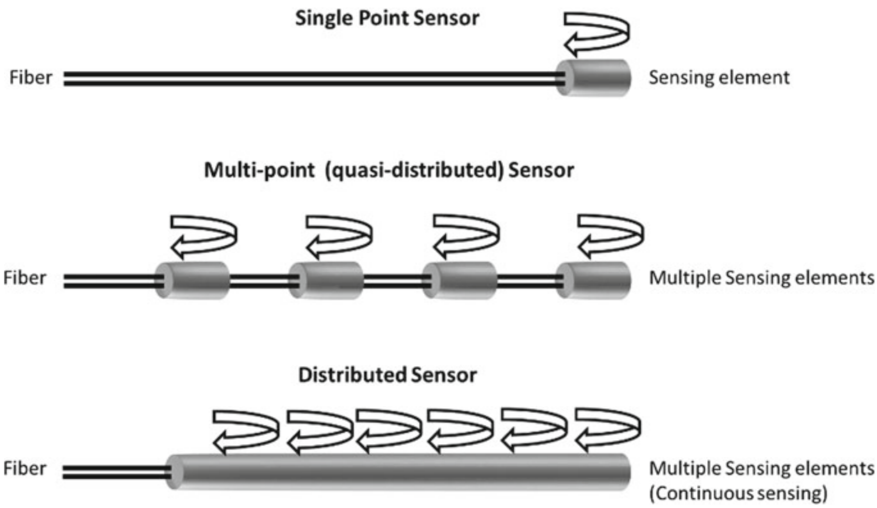

Fig. 9.11 Different modes fiber-optic sensing

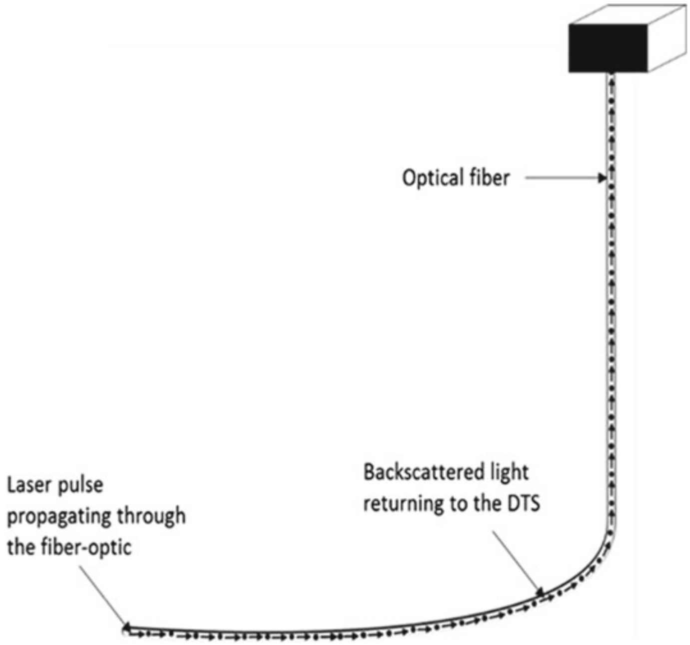

Fig. 9.12 Graphical schematic of DTS system

In the DTS system, a short pulse of light is launched into the fiber. The forward propagating light generates Raman backscattered light at two distinct wavelengths, from all points along the fiber, Fig. 9.12. These two wavelengths are named "Stokes light" and "anti-Stokes light" and are generated due to inelastic scattering of a photon. Anti-Stokes light is temperature-dependent, while the Stokes light is weakly temperature-dependent. The local temperature of the optical fiber is calculated from the ratio between the amplitude of the Stokes and the anti-Stokes detected light.

One of the challenges for temperature logging tools is high-temperature wells where the generated temperature during cement hydration or temperature anomaly caused by leakage is difficult to identify from the high geothermal temperature.

9.1.4 Hydraulic Pressure Testing

Inability to log annulus behind the second steel string, Fig. 9.13a, is one of the main challenges associated with the current acoustic logging technologies. So, utilization of rig might be inevitable to examine the annular barriers, red boxes shown in Fig. 9.13a. Therefore, rig is required to retrieve the production tubing to log the annular barrier behind the production casing, the solid red boxes in Fig. 9.13b. But

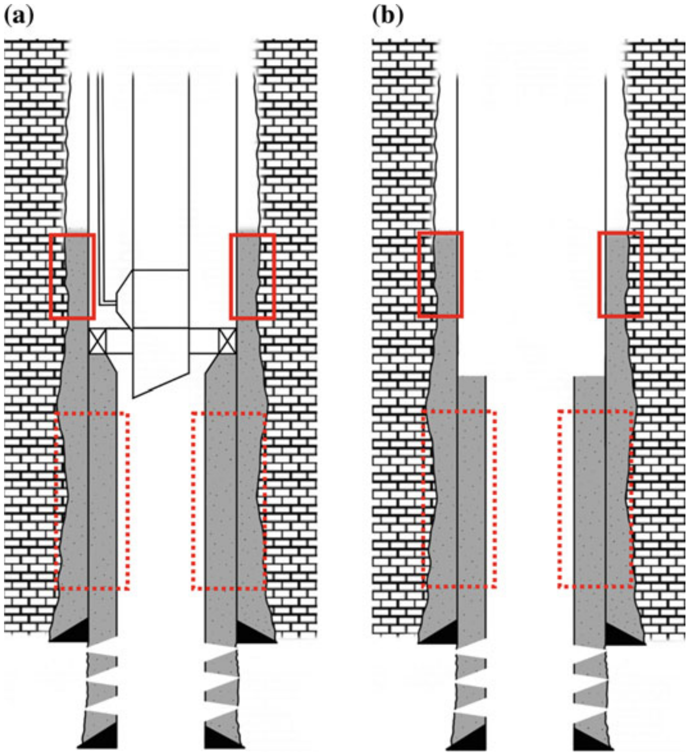

Fig. 9.13 Acoustic logging tools are not capable to log through two strings of steel; **a** rigless operations is not possible due to technology deficit of acoustic logging tools, **b** rig is required to retrieve the production tubing and only logging the red box marked with solid line. The dotted-line-box area cannot be verified even after removal of production tubing

logging the annular barrier behind the production casing, across the liner (the dotted red box in Fig. 9.13b), still remains unsolved due to technology deficit.

When utilization of acoustic logging tools for verification of annular barrier is impossible or may create extra work, hydraulic pressure testing (known as communication testing) might be an option [15]. Such circumstances may include, verification of casing cement when production tubing is in place, verification of annular barriers behind the second casing string, or when PWC technique is used to establish both internal and external barriers [16], Fig. 9.13a.

In hydraulic pressure testing method, a bridge plug is installed at the base, where base of annular barrier is supposed to be. The installed bridge plug is pressure tested and when it passed the pressure testing, above the bridge plug a small window is perforated. Another bridge plug which is equipped with a wireless pressure gauge is installed away above the created perforations. This bridge plug also needs to pass pressure testing. A new window needs to be perforated above the second bridge plug, Fig. 9.14. The distance between the windows of perforations depends on the required

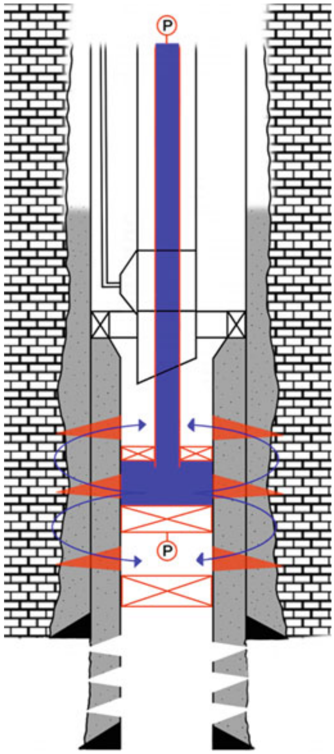

Fig. 9.14 Hydraulic testing, communication testing, of annular barrier behind second casing string

length of annular barrier to be verified. A workstring, equipped with a packer is run and the packer is engaged above the second perforations. A fluid is pumped through the workstring and pressure changes are monitored. If the downhole pressure gauge and surface gauge do not record any changes, the annular barrier is qualified.

The pressure testing is a cycle of extended leak-off and drawdown tests, Fig. 9.15. The pressure test data can be used for both investigating the hydraulic communication between the perforations, and corresponding the pressure data to expected formation strength.

Hydraulic communication test—When fluid is pumped through middle perforations, any pressure changes above the packer attached on workstring or between the bridge plugs means failure of annular barriers. However, no pressure changes means intact and subsequently verified annular barriers.

Extended leak-off test—The extended leak-off tests are conducted to make sure that perforations reached to the adjacent formation. This can be examined by increasing the injection pressure until leak-off occurs. If the leak-off and breakdown pressures are corresponding to expected formation strength, it means perforations penetrated to formation. In addition, extended leak-off test is conducted to make sure that annular barriers can hold the maximum anticipated pressure.

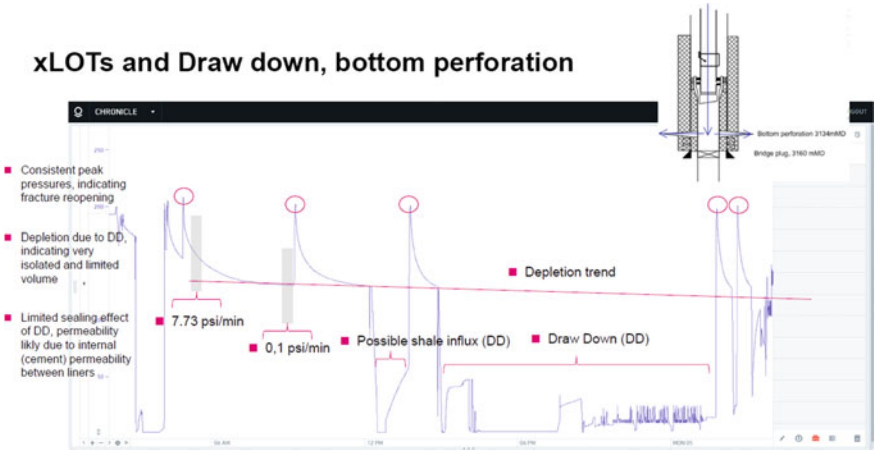

Fig. 9.15 Extended leak-off test and drawdown test to verify annular barriers, shown in Fig. 9.14, by hydraulic testing

9.2 Internal Barrier Verification/Plug Inside Openhole or Casing

9.2.1 Hydraulic Pressure Testing

Pressure testing is applied to plugs installed inside casing, openhole plugs which are extended to casing or plugs installed entirely in openhole, Fig. 9.16. Pressure

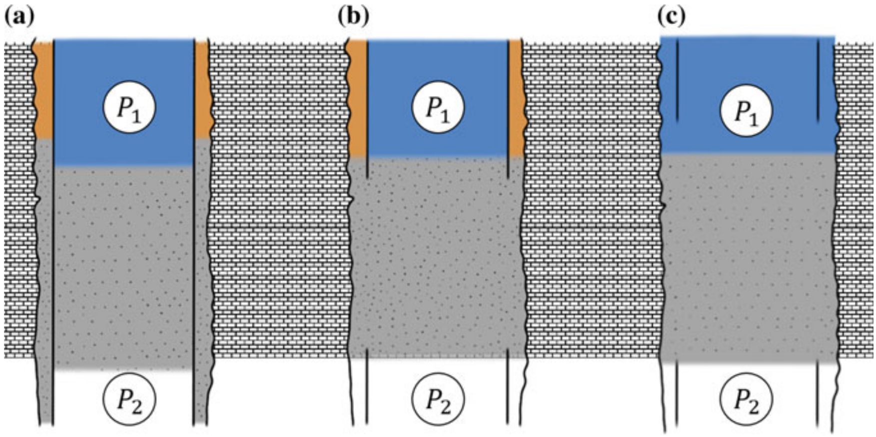

Fig. 9.16 Cement plug installed in wellbore; **a** cement plug is installed inside casing across a qualified annular barrier, **b** cement plug installed in an openhole but extended to casing, **c** cement plug entirely installed in an openhole

testing has other names such as pump pressure testing and hydraulic testing. Where mechanical plug is used as foundation for cement plug and the foundation passed the pressure testing, pressure testing of plug is meaningless.

There is a misunderstanding about information obtained by carrying out pressure testing. Pressure testing gives an insight about sealability of cement plug and sealing capability at the interface of cement plug and adjacent element [17]. But it does not necessary provide information about the hydraulic bond strength (for more information regarding hydraulic bond strength refer to Chap. 3) of entire plug length.

Depending on the direction of applied hydraulic pressure, positive pressure testing or negative pressure testing can be distinguished.

9.2.1.1 Positive Pressure Testing

In positive pressure testing, fluid is injected by surface pump whereas pressure above the plug is higher than the pressure below, P_1 is higher than P_2 (see Fig. 9.1) [18]. When the ΔP across fulfills the requirement asked by local authority, the pressure is monitored for some minutes and if a stable pressure is reading, the plug is a qualified plug. The positive pressure testing is carried out on plugs installed inside casing and across a qualified annular barrier, and plugs installed inside openhole but extended to casing string (see Fig. 9.16a, b). Pressure testing of plugs installed entirely in openhole is meaningless (see Fig. 9.16c). The reason is that when subjecting the openhole plug to the injected fluid, the fluid can penetrate the surrounding formation, Fig. 9.17.

There are some concerns associate with the positive pressure testing technique including, but not limited to uncertainty associated with sealing capability of casing connections, casing corrosion, and ballooning effect of casing. When hydraulic pressure is applied, the injected fluid can leak thorough casing connections and stable pressure reading may not be reached (Fig. 9.18). In this case, it is difficult to

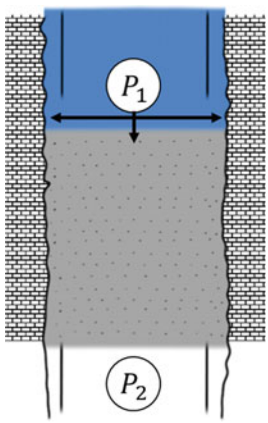

Fig. 9.17 Positive pressure testing of the plug installed entirely in openhole is meaningless

Fig. 9.18 Potential leak path through threads in positive pressure testing

identify the source of leak; casing connections or a failed plug. Where casing experiences small holes cause by corrosion or caused by mechanical wearing, the applied hydraulic pressure leaks through the casing and pressure monitoring does not show a stable reading. Ballooning effect is susceptible when there is liquid in the annular space behind casing and casing thickness has been affected over years. In this scenario, the casing can expand if the applied pressure exceeds the casing design criteria such as its elasticity (Fig. 9.19).

Positive pressure testing can also be used to estimate the shear bond strength between plug and the adjacent material by following equation:

$$Shear\ bond\ strength \geq \frac{P_p \times A_p}{\pi \times D_i \times L_p} \tag{9.3}$$

where P_p is the pump pressure, A_p is the surface area of plug, D_i is the inner diameter of the geometry plug placed inside, and L_p is the plug length. However, this is valid when the material sealability and the material mechanical strength is higher than the shear bond strength of the entire plug.

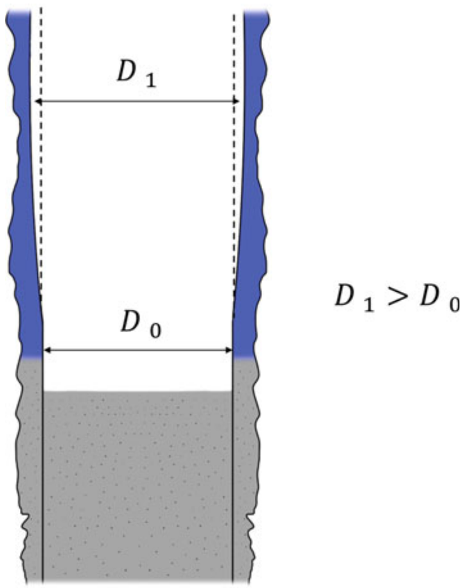

Fig. 9.19 Ballooning of casing while carrying out the positive pressure testing, D_0 is the origin casing diameter and D_1 is the diameter after ballooning

9.2.1.2 Negative Pressure Testing

In negative pressure testing (also known as inflow testing), the hydrostatic pressure above the plug is decreased so that pressure below the plug (P_2) will be higher than pressure above the plug (P_1), see Fig. 9.16. Then, the changes in pressure is recorded. A stable pressure means a sealed plug. If a transparent fluid is placed on top of plug, possible leak can be seen directly by use of downhole camera. Negative pressure testing is used where integrity of connections or casing string above the plug is questioned and positive pressure testing cannot be performed. In addition, when plug is entirely placed in openhole, which positive pressure testing is not feasible, negative pressure testing may be performed. The challenge associated with this method is that the current pressure, below the plug, might be lower than the expected final pressure. Therefore, plug is not qualified based on the estimated future pressure but the current pressure.

9.2.2 Weight Testing

When plug is installed, it is necessary that the plug keeps its position and does not move due to increase of pressure below it. Weight testing is a method to measure the positioning, bond strength to adjacent element, and also measures the plug location. Where cement plug is entirely placed inside openhole, it is not possible to positive pressure test it or even sometimes negative pressure test it. Thus, weight testing is carried out to check the positioning of the plug; however, weight testing does not provide any information about the hydraulic sealability of plug.

Weight testing measures the shear bond strength of plug to adjacent material. So, the required shear bond strength measured by drillpipe during weight testing is defined as drillpipe tag weight, W_{dp}, divided by circumferential area of cement plug and is given by:

$$Shear\ bond\ strength \geq \frac{W_{dp}}{\pi \times D_i \times L_p} \tag{9.4}$$

The main challenge to estimate the shear bond strength is the plug length, as the theoretical plug length is different from plug length retained from contamination.

Studies show that much larger amount of shear bond strength is achieved for short cement plugs when placed inside small diameter geometries. Studies also show that by increasing the plug length placed inside a constant diameter geometry, the required shear bond strength decreases.

Weight testing is operationally feasible in rig-based operations by use of drillpipe but it might be feasible to carry it out in rig-less operations by use of coiled tubing or wireline.

9.2.2.1 Drillpipe

It is a normal practice to weight test the plug when drillpipe is available on site. To avoid any challenge introduced by contaminated cement on top of plug, top of cement is drilled to reach hard cement. This operation is known as cement dress-off. The required weight is calculated carefully to avoid any damage to the cement plug. By using a part of drillpipe weight, the pre-determined weight, positioning of plug is tested (see Fig. 9.20a). In fact, weight testing provides the shear bond strength between plug and adjacent material. If the plug can hold the applied weight without being displaced, its positioning is qualified.

9.2.2.2 Coiled Tubing

Coiled tubing can be used for weight testing where drillpipe is not available. To dress-off cement plug, a downhole motor is used. One of the main limitations of coiled tubing to be used in weight testing is the maximum weight that can be created. In addition, coiled tubing may be susceptible to helical ramp or tortuosity (see Fig. 9.20b) and difficult to apply more weight.

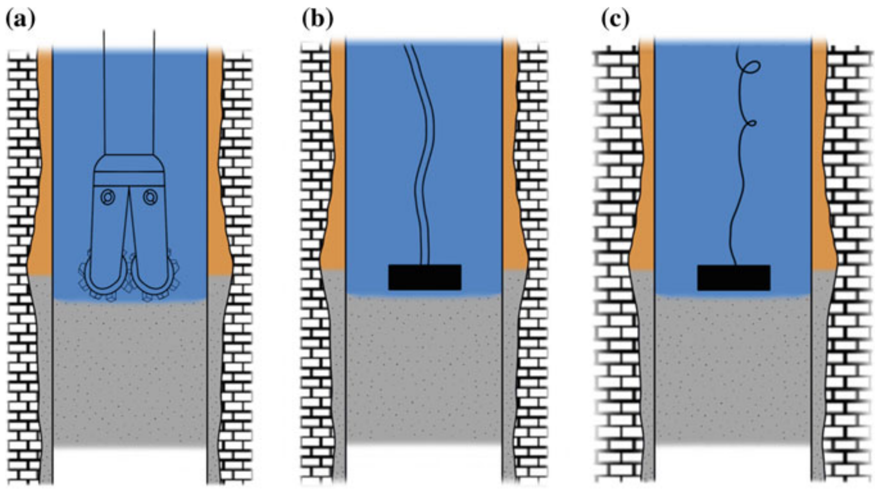

Fig. 9.20 Weight testing of cement plug placed inside casing; **a** drillpipe, **b** a heavy weight may be used with coiled tubing but coiled tubing may experience helical shape due to its design factors, **c** limited weight can be used for wireline

9.2.2.3 Wireline

Wireline may also be used for weight testing where there is no drillpipe nor coiled tubing unit. A downhole motor is used to dress-off the plug and then a limited weight is applied on the plug with no chance to apply additional weight (see Fig. 9.20c). Compared to drillpipe and coiled tubing, the use of wireline for weight testing is not accepted by many regulators due to the limitations of exerted weight. However, wireline can be used to confirm the depth of top of cement.

9.3 Hydraulic Pressure Equivalent to Drillpipe Tag Weight

As mentioned earlier, in some cases is difficult to perform positive pressure testing and weight testing needs to be carried out instead. In fact, weight testing and positive pressure testing impose the force on top of plug; weight testing is a mechanical way and positive pressure testing in a hydraulic way of doing it. So, it is possible to estimate the equivalent hydraulic pressure to drillpipe tag weight, Eqs. (9.3) and (9.4) can be equal:

$$\frac{P_p \times A_p}{\pi \times D_i \times L_p} = \frac{W_{dp}}{\pi \times D_i \times L_p} \tag{9.5}$$

and simplification of the equation gives:

$$P_p = \frac{W_{dp}}{\frac{\pi \times D_i^2}{4}} \tag{9.6}$$

Equation (9.6) shows that the required pump pressure to estimate the tag weight and the equivalent pump pressure is independent of plug length.

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