Basic Cement Isolation Evaluation

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Cement evaluation requires more than just running a cement bond log or even performing a successful pressure test (Steiles, 2012). This document is an explanation of basic cementing evaluation tools and recognized and documented methods of evaluating cement isolation. It is, at best, a skeletal framework.

By understanding the needs of isolation and pressure support for the particular well over its lifetime, a fit-for-purpose cementing design can be initially delivered, but optimization of a cement plan only evolves if evaluations and case-by-case learnings are introduced into the design. Cement evaluation is a necessary part of the learning process.

Summary Points and Basics of Cementing

1. The only cement test method that can confirm zone-to-zone isolation is a pressure test.

2. The best overall quality check of both pumped cement and cement placement is an analysis of the cementing pump record of fluid densities, placement pressures, flow rates and returns.

3. Test wells designed purposely to test CBL and related tools (including wells at Amoco Research, Texas A&M and the EPA test well in Ada) have consistently shown that the CBL tools will not find all of the test channels within the cement sheath. Cement bond logs, and other Cement Evaluation Tools (CET) in specific cases, may give a reasonable estimate of bonding and a semi-quantitative idea of presence or absence of larger cement channels, but will not certify pressure or fluid isolation of a zone. Cement bond logs have been proven to miss a majority of smaller channels in cement, even under ideal conditions and interpretation.

4. To provide an effective seal and isolation of a zone, only part of the total cement column must be channel free. Cement channels may be present in parts of the cement, but as long as there are significant, continuous sections of channel-free cement, isolation of the zone along the wellbore will be adequate if proven by a pressure test and periodically monitored by annulus pressure checks.

5. Bond logs have failed to show bond in many wells that proved to be well isolated in a differential pressure test. The error is caused by a variety of formation influences and annular fill materials. Error within the application and interpretation of cement bond logs has resulted in numerous workovers to repair cement that was not faulty, resulting in high workover costs and a decrease in the well integrity by unnecessary perforating and attempts to block squeeze cement under high pressures.

6. Top of cement (TOC) can be established by several methods. Temperature logs are functional in vertical casing strings within a short time-window for determining top of cement. Density logs may show cement tops, but will confuse formation fill with cement. Bond logs may provide

cement top information but can be fooled by highly compacted cuttings, barite, formation collapse in the annulus and formations with fast sonic travel times.

7. With the exception of a pressure test, requiring a specific tool on every cement job appears to be a poor choice, with possible detrimental economic and structural consequences caused by squeeze cementing attempts made on wells with cement suspected by CBL investigation but proven effective by a pressure test.

Cement is a long-lived and versatile isolation material when used within the bounds of sound engineering judgment. Proper modifications of the cementing slurry can stretch the ability of cement to handle shrinkage, cyclic pressure applications, hotter, deeper, colder and acid gas environments. The first few cement isolation jobs in an area may need to be logged to determine bond, fill, gas channeling, microannuli extent and other placement objectives. Once the cement recipe is determined and the proper well set-up and placement details are worked out, there is little need for continuous logging unless a problem is indicated by the cementing pump chart.

An experienced engineer or foreman can often forecast the quality of a cement isolation step from the cement pump chart's recording of density, pump rate, pressure and a record of type and volume of returns. This type of early evaluation is immediately available, requires no added equipment or cost and is superior to nearly every combination of tools on the market.

Tests on ability of even relatively small amounts of cement to isolate pressures are scattered through the literature. One example is from extremely high pressure gas sands along the U.S. gulf coast, Figure 1, where 30 to 50 ft. (9.1 to 15.2m) of cement is shown to successfully isolate stacked pay zones with differential pressures of over 10,000 psi (King & King, 2013).

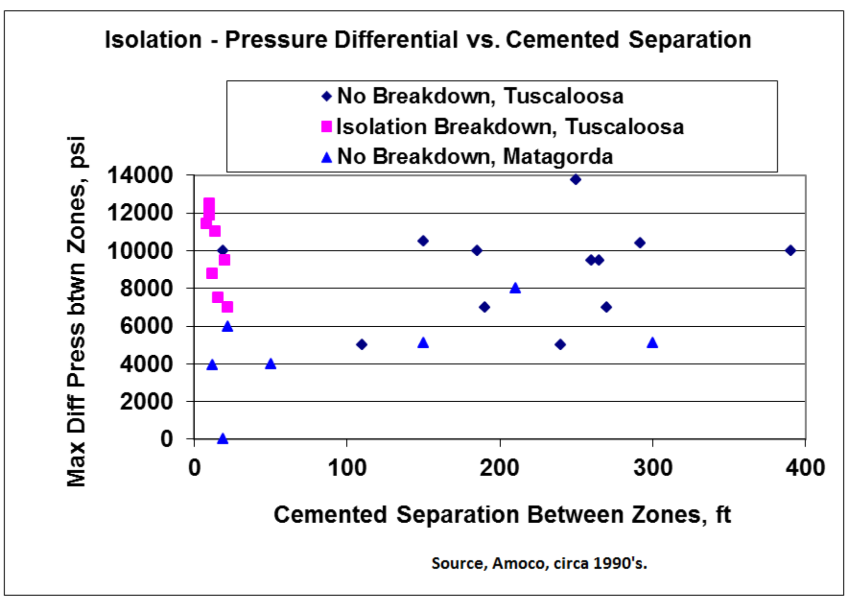


Figure 1 – Cement breakdown and isolation success for Tuscaloosa (on-shore) and Matagorda (Off-shore) gas fields.

The question of how much cement to use in a well is often misunderstood by those without a background in subsurface monitoring and isolation over the life of a well. Regular class G & H cements, when mixed properly with water, have a slurry density of about 16 to 16.4 lb./gal. depending on specifics of cement grind (particle size) and type and composition of the mix water. This density translates into a pressure application of roughly 0.83 psi/ft (0.83 psi for every vertical foot of cement slurry in in the pipe or the annulus formed by the casing and the drilled hole).

Friction pressures generated by circulating the viscous cement slurry down the pipe and up the narrow annulus places added pressure on the bottom hole, over and above the density of the cement slurry. This friction-driven "equivalent circulating density" or ECD may add a pressure equivalent to 1 to 2 additional pounds per gallon (or a total of 0.88 to 0.93 psi/ft.) during the pumping phase, depending on pipe-to-hole clearance, circulation rate and cement type.

The pressure gradient to fracture most rocks is between 0.65 and about 0.85 psi per vertical foot depth with an average of about 0.7 psi/ft. If too much cement is used (or circulation is too fast), the density of the cement may fracture the formation resulting in large losses of cement, failure to generate reach the design cement top or loss of well control. The normal approach is to balance the density of the total height of the column of cement, the mud and the ECD to be less than the pressure that will fracture the formation.

If the annulus must be filled with cement from top to bottom because of needs for sealing shallow gas charged formations, to isolate corrosive saltwater or to meet regulations, a lower density cement or a two stage job must be designed. Low density cements are available but are weaker and may pose problems in evaluating with cement bond logs. Two stage jobs usually require perforating the casing or specialized tools that open a port in the casing to allow a second cement job to be pumped above the first job. These two-stage jobs create require an opening in the casing which may compromise casing integrity.

There are a few points that anyone who wants to understand cementing must know:

1. There is no such thing as every inch of cement in a well's annulus being perfect; and there is no need to have every bit perfect. To achieve effective isolation, cement needs to fill the area around the pipe and produce a channel-free, effectively bonded section of strong cement over a length of the cement column suitable to isolate zones and prevent leakage into or out of a protected zone. Channels may exist over short intervals in many cemented completions that are still effectively isolated. In many published case histories of cement isolation studies and several multi-well studies, logs of cement quality show channels over short zones, even where isolation has been proven by decades of production. Unless the channels extend through the entire length of the cemented column, the isolation potential of a cement column is still acceptable.
2. Effective cement life is a function of the conditions in the well over its lifetime including the surrounding formation fluids and stresses. Cement can be strong as or stronger than the rock that has provided a seal that has kept gas, oil and saltwater in place for millennia. There are records of cemented wells still effectively isolated after 70 to nearly 100 years. Older records are

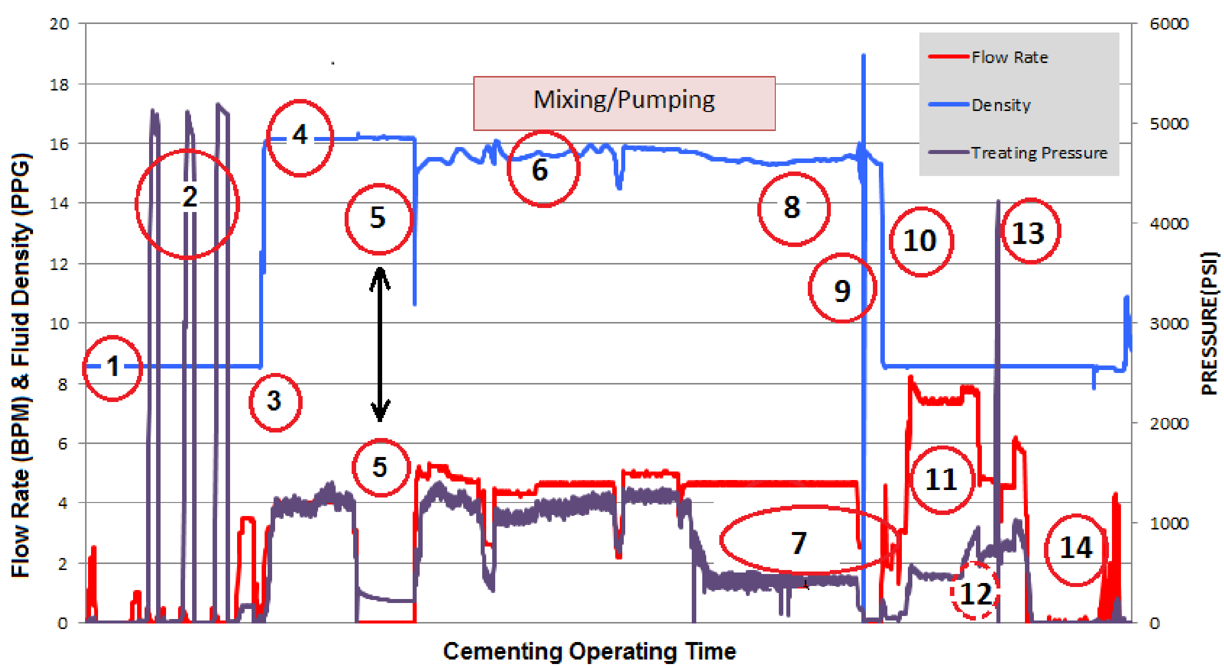
simply not available since the first use of cement in an oil, gas or water well was in 1903 and was not required by newly developed regulatory agencies until time periods varying from 1915 to 1935, when the U.S. Interstate Oil and Gas Compact Commission (IOGCC) was formed and began its mission of assisting member states to efficiently maximize oil and natural gas resources through sound regulatory practices while protecting our nation's health, safety and the environment. Correct selection and use of cement composition and additives can prevent shrinkage, microannuli, gas channeling, acid gas reactions, and other deteriorating effects.

3. Requirements to cement the annulus of every well to the surface may prevent effective pressure monitoring of the annulus and will be detrimental to detection and repair of leaks.

Cement Evaluation and Monitoring Methods

Cement Bond Logs or CBLs, are often proposed by a few regulators and some NGOs to be a necessity, but these tools, while useful from an investigative view in early cement design or to help find problems, can give false readings, miss small channels completely and are notoriously difficult to run in an effective and repeatable manner. A false reading by a CBL may initiate a cement repair where none is needed and those operations may weaken the casing and leave a potential leak path where none existed before.

The best cement quality prediction method uses information from the pump chart, Figure 2, and a pressure test after the cement is placed.



Source: slide from Mike Cowan, interpretation from Mike Cowan and Loran Galey

Figure 2 - Analysis of a cement job pump chart can show expected behavior or potential problem areas.

Explanation of numbered points:

1. Filling the surface equipment with fresh water prior to the pressure test.

2. Surface equipment pressure check – testing to a pressure above maximum expected for the cement job. There are two failed pressure tests, probably incompletely made-up connections art surface and the final successful test, showing only expected temperature cooling while holding pressure.
3. Start of spacer to separate mud from cement.
4. Example of constant density of spacer.
5. Shut down to switch over to drop the bottom plug and start pumping cement that is mixed on the fly.
6. Pumping cement mixed on-the-fly. Holding cement density as constant as possible. Target is +/- 0.2 lb./gal with automatic density control equipment, but may vary +/- 0.5 lb/gal in some cases. Batch mixing provides the most consistent density but may be too slow for large jobs.
7. Cement free fall, a routine occurrence in many vertical strings with wide differences between mud and cement density, is the result of high-density cement slurry overbalancing the density of the mud that is being displaced by the cement and pushing the mud out of the well faster than incoming pump rate, which stays constant in this example (Beirute, 1984).

   Note – Depending on well geometry, fluid properties, etc., there may be little or no free fall on a horizontal well production casing cement job. Cement is a thixotropic fluid which shear thins when moving and develops gel strength when it stops moving. The cement may go static inside the casing during even a short shut-down while up the surface line to the rig floor. In smaller casing, such as 4-1/2", this is a very undesirable situation because the surface pump pressure required to break the cement's static gel strength (and get in moving again) may be very high (several thousand psi).

8. Cement density variance of concern unless cement type/grade has been changed for a specialty tail-in slurry.
9. Shut-down to wash up surface lines and release the solid top plug.

   Note – the entire cementing volume is often contained inside the casing before the cement starts moving up the annulus (backside) between the casing OD and the drilled hole. For an example of 5-1/2" (OD) 20 lb./ft. casing (4.78" ID) in a 7" drilled hole with no hole washouts (a "gauge hole"), the annular volume would be about 1200 gallons per thousand feet of annulus to be cemented; this 1200 gallons of cement for 1000 ft. of annulus would only occupy 108 feet of casing volume inside the 5-1/2" casing.

10. Displacement of cement slurry by water after calculated volume of cement has been pumped into the well. The top plug separates cement slurry and displacing water or clean mud pill. As the bottom plug lands in the shoe track, the rupture disk or diaphragm in the bottom plug ruptures, allowing cement slurry to "turn the corner" and start moving up the annulus.
11. The volume of the vertical wellbore evacuated by the free fall of heavy cement slurry must now be made up as the pressure balance is evened out by cement leaving the casing and moving upward in the annulus displacing mud. The flow recovery during this period (if free fall occurs)

will decrease as the mass balance of fluid volumes evens out. Flow rate is often increased (where permitted by equivalent circulating density) to help sweep annular hole volume more completely.

12. The cement lift pressure in this example is much too low if the job is a long surface string cement job. Pressure during the displacement of cement up the annulus is expected to be at or above the surface line pressure while mixing and pumping cement. The cause may be gauge related or could be cement lost to the formation resulting in incomplete coverage of the annulus. The mass balance of fluid in and out of the well during the cement job should be checked and/or the well should be logged to determine top of cement. See Figure 3 for an example with significantly higher cement lift pressure.
13. The top plug "bumps" or hits the bottom plug and the cement placement is complete.
14. Flush of equipment and holding pressure if check valve in float shoe/collar fails (not in this case).

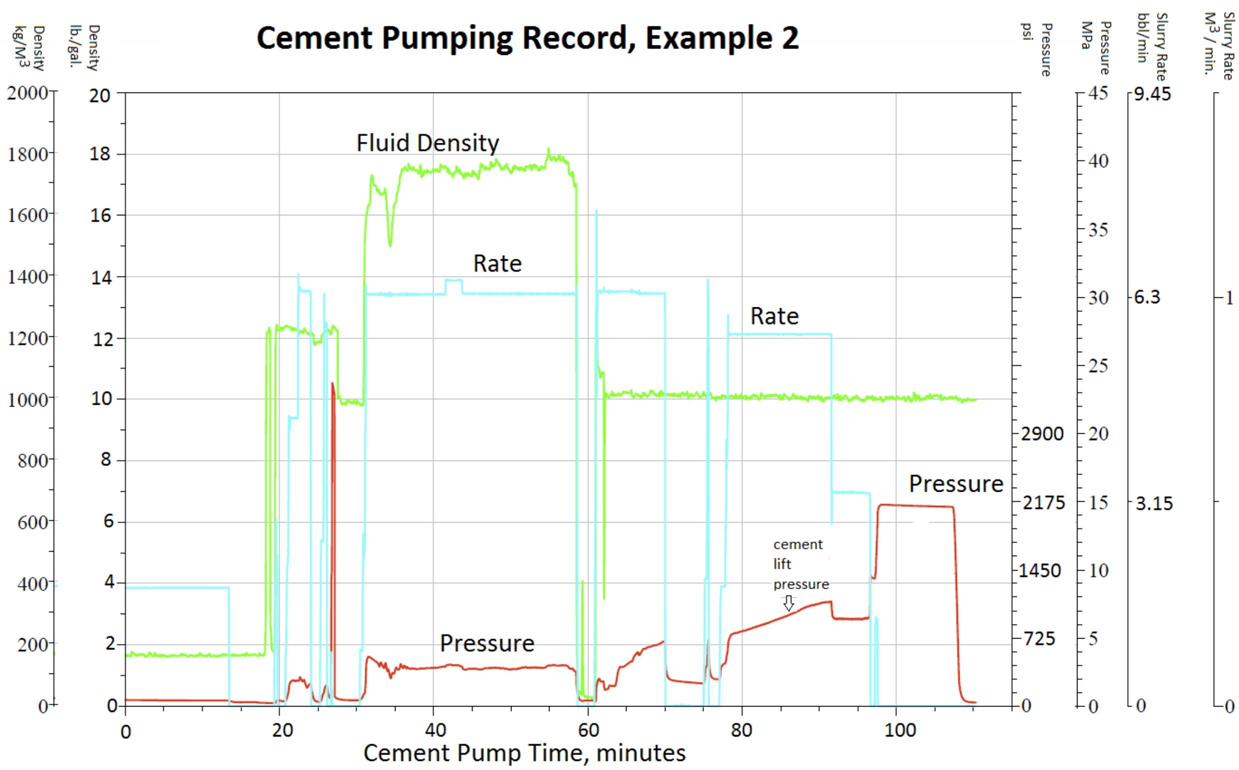


Figure 3, Pumping Record – Example 2

Pressure required to lift the cement reflects the imbalance of cement in the annulus being moved upward in the annulus by lower density displacement fluid in the casing.

Cement Testing and Logging Methods – What They Do and Their Limitations

Pressure testing of the wellbore after a cement job provides a record of whether the wellbore between the top and bottom exposure points will hold a pressure equal or greater than the highest pressure that the specific cemented string will experience during subsequent drilling, stimulation operations or production. This is the most reliable isolation test, quickly separating adequately isolated casing strings from those that need repair to pass isolation tests. During well construction, a required pressure test must be passed before drilling or stimulation can proceed. Repair frequency during the construction phase depends on the area and geologic variations. Repairs in offshore areas with less consolidated formations may be needed in 10% to 20% of wells (Harris, 2001), while on-shore wells in highly consolidated areas may exhibit a repair frequency during well construction of less than 1% (King & King, 2013).

Pressure tests are a standard during well construction and, if the test pressures are more than subsequent operational pressures, the test offers documentation of isolation. The area that is tested in this manner is the casing string exposed to the test and the zone in contact with the pressuring fluid, which is typically the bottom section or casing "shoe". There are different types of pressure tests and care is needed to accurately describe the type of test and how to vet the outcome (Postler, 1997; Thornhill, 1987).

Cement evaluation behind the pipe began with the calculation of cement tops. Properly run temperature surveys can identify the top of cement or TOC, but distribution of cement-e.g., vertical isolation through zones of interest-is difficult to ascertain. The most critical factor in the evaluation technique is the timing of the survey. Heat dissipates rapidly from the exothermic reaction as cement sets, thus temperature measurements must be taken within a few hours. Laboratory tests indicate a return to near normal temperatures in 24 hours. Early surveys also showed the effects of time, bottom hole temperature, circulating time, and thermal conductivity of the surrounding formations on the temperature profile. The temperature log remains an economical and effective way to determine the TOC and intervals of cement accumulation. The temperature log is not a direct measure of vertical isolation across hydrocarbon-bearing zones; however, if a four-arm caliper is available, it is possible to infer good cement displacement if the TOC agrees closely with the calculated top and full returns were present during pumping and displacement of cement. Top of cement investigation are usually run only in the first few wells in an area until cementing operations are understood.

Tracer surveys for cements containing very low energy level, short half-life gamma ray emitting tracers are possible, but would require licensed appliers. These tracers, with half-life of 30 to 60 days have the same limitations as temperature logs; i.e., shallow investigation and short window of opportunity to measure the weak gamma signal. There was no record located of this technique being used in the past 70 years.

Cement Bond Logs

Cement bond logs (CBL), which may be sonic or ultrasonic, range from simple averaging instruments similar to those that came out in 1960 to the more sophisticated models that investigate 60^o segments of the cemented annulus around the tool (Grosmangin, et.al., 1961; Flournoy & Feaster, 1963; Steiles, 2012; Pilkington & Fertl, 1975; Pilkington, 1992; Fitzgerald, 1985; Frisch, 2000; Froelich, 1982; Griffith, 1992, Jutten, 1989; Jutten 1987; Morgan, 1963; Pardue, 1963; Winn, 1962)).

The bonding investigation theory behind the CBL is basically sound but application and tool investigation problems show the inability of any CBL to find all of the small channels in cement (Thornhill & Benefield, 1987).

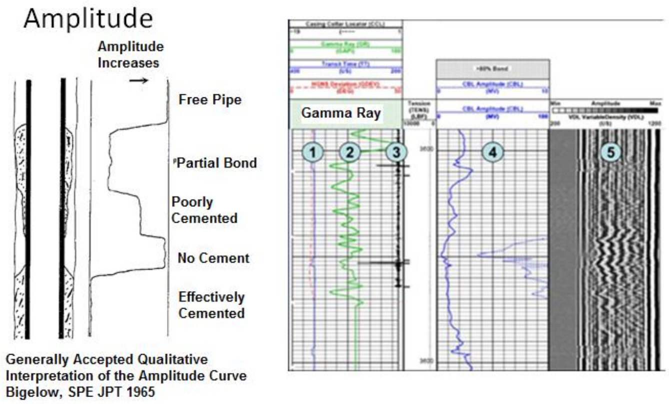
CBL Tool Use

In conventional CBL tools, a transmitter is pulsed to produce an omni-directional acoustic signal that travels to a set of receivers along various paths through the borehole fluid, pipe, cement and formation. The logging system records the receiver waveforms and displays them on the log along with a pipe-amplitude curve. Interpretation of the CBL signals uses these two measurements to indicate two bonds; the pipe-to-cement bond and the cement-to formation bond.

An additional measurement is the sound travel time, which confirms cement presence, tool centralization and is an indication of cement-to-pipe bond. The pipe amplitude curve displays the amplitude of the acoustic signal that has traveled through pipe, but not through cement and formation, to arrive at the receivers. Conventional cements will have an amplitude measurement of less than 10 mV for good bond. Foamed, nitrified cements and cements containing light or heavy weight components will affect the amplitude measurements of the CBL (Bruckdorfer, 1984).

Ultrasonic tools provide the most beneficial data when evaluating cement placement and bonding. Instead of a separate source and receiver, the ultrasonic source and receiver are packaged together as a transducer. When a signal emitted by a transducer encounters an acoustic interface (for example, between casing and annular material outside casing), some of the signal energy is reflected at the interface, and some is transmitted across the interface. The fractional amounts of reflected and transmitted energy depend on the acoustic impedances of the materials at the interface. The signal strength received at the tool, the acoustic impedance, or Z, is a function of the bulk density of the material through which the sonic waves travel (Frisch, et.al., 2000).

The CBL presentation in Figure 4 shows the five logging tracks that make up a good CBL report.



1. Transit Time
2. Gamma Ray Log
3. Collar Locator
4. Amplitude
5. Variable Density Log

Figure 4 – the log tracks of a CBL.

The raw transit time data helps distinguish between cement measurements and interruptions from “fast formations” (faster sound travel than steel pipe) (Steiles, 2012). The gamma ray is a gamma emission measurement log that reports natural radioactivity of a formation and is a good depth correlation. The CCL is a casing collar locator log that correlates the thicker steel collar locations (affects sonic travel and cement thickness). The amplitude is the strength of the signal after loss of signal due to attenuation of the transmitted sonic or ultrasonic signal. The VDL or variable density log is a recording of the bond log interpretation. Amplitude is the magnitude or loudness of the signal when dealing with sound waves. Attenuation is the loss of energy during transmission of the signal. Density of cement and formation are two of the variables.

The difference in the speed of the sonic or ultrasonic signal in the specific media (formation, cement, steel, mud, etc.) must be known to make the bonding calculation accurate. Errors in the information from variances in the materials or inaccurate measurements create significant error potential in the CBL measurement.

Newer tools such as the Segmented Bond Tool (SBT) and ultrasonic imager are definite improvements, but the small channel detection problem remains. Other developments may include more sophisticated tools, such as the cement volumetric scan tool. Each logging technique currently in use has limitations and none will measure isolation except a pressure test (Fertl, 1974; Pilkington & Fertl, 1975, Pilkington, 1992).

Frisch described the industry problem with cement investigation tool with this statement: “Previous conventional cement evaluation techniques that rely on combined data from a traditional acoustic cement bond logging (CBL) tool and modem ultrasonic tools can be problematic. It is important to accurately evaluate the downhole placement and bonding characteristics of any type of cement to ensure zonal isolation of economic fluids from undesirable fluids. Inaccurate evaluation can lead to unnecessary and expensive remedial cementing operations. It is estimated that the industry spends about $200 million per year on remedial cementing. Of this amount, between $30 to $40 million per year is wasted because of misinterpretation of cement evaluation logs” (Fritch, et.al., 2000).

Limitations

Field performance for a properly run and calibrated CBL is about 90% in finding small channels, particularly those covering six degrees or less of the 360 degree radial aspect of the pipe. Smaller annular channels are not easily identifiable to a bond log because of variations in cement composition that create density differences in the cement and by the investigative nature (averaging) of the tools. These channels may or may not compromise cement seal (isolation) integrity depending on their extent and connectivity along the annular cement sheath. Only a pressure test will determine if a leak exists.

This major limitation of the CBL in identifying small channels practically eliminates it as a reliable test for isolation. Many of the early and current problems with CBL's came from poor running and interpreting techniques as well as mistakes in selecting correct time and place to run the logs. Early work indicated several false signals, particularly in thinner cement sheaths and hydrocarbon contaminated cement (pockets). In multiple well studies, the cement bond log often indicated poor bonding when well performance and zone pressures were clearly isolated by cement. This finding was proven by long-term production without problems, water-free well performance (water isolation) and pressure measurements over time (Flournoy & Feaster, 1963).

Data in these field tests showed many wells with effective isolation even though the percentage of acceptable bond ranged from 31% to 75%. Even a few sections of good bond established isolation are adequate seals between zones, as proved by pressure readings and long term water avoidance that were only tens of feet away (Flournoy & Feaster, 1963).

Field examples of cementing practices showed a correlation between mud removal operations and better bonding, to the point where a good cementing program was more important, and more reliable, than running and trying to interpret a cement bond log. The bond log was highly useful in measuring bonding trend improvements in cementing application where there were demonstrated problems with cement isolation and are used in some areas to measure improvements in cementing operations. The information that is needed to assess isolation is whether a significant portion of the wellbore is channel free and the cement fill, bond and strength are sufficient to contain pressure. A CBL will not reliably answer those questions as a stand-alone piece of data.

Well cementing technology in both relatively straight and high-angle directional holes has advanced dramatically since the first casing was cemented in 1903 (Fertl, et.al. 1974). The basic requirements for obtaining a successful primary cement job have been known for years. Good design characteristics are based on knowledge of formation, cement, and pipe properties, and controlled placement techniques that consider fracture gradients. Also important is an understanding of (1) minimum practical mud density and viscosity, (2) cement type, (3) turbulent flow conditions, (4) the optimum size of preflushes, (5) centralizing of casing, (6) pipe movement where possible (mostly on surface strings), and (6) the proper choice of casing.

Basically, the utility of cement bond logs is in determining the presence of cement and information on cement bonding across the zone of investigation. The best measurements with a CBL are in deeper sections with more stress contrast and on cements with higher strength. A CBL cannot not predict or confirm pressure isolation.

EPA Test Well Evaluation of CBL, RBT, and PET Tools

In July 1981, a research project was stated by the US EPA at their facility near Ada Oklahoma. A dedicated well was designed and equipped with plastic tubes on the outside of the well to simulate channels and service companies were invited to run their tools and provide information on their ability to find the "channels" in the cement. This was actually the third attempt to test CBL tools in such a well, the first two being Amoco Research (Tulsa, Oklahoma) and a similar reported well at Texas A&M. In each well, CBL tools failed to find all the test channels, specifically the smaller channels.

Albert et.al. (1988) describes the EPA well configuration: "The EPA logging well was constructed to evaluate the ability of industry tools to determine the mechanical integrity of injection wells and was designed with several commonly used sizes and weights of casing with specially constructed flaws on the casing circumference to simulate channels in the cement. The channels were represented by water-filled PVC pipes attached to the outside of the casing. The PVC pipe, either ¾ or ½ in. [19 or 13 mm] in diameter, was sealed on one end, filled with water, and capped. The PVC pipe was then attached to the outside of the casing so that the channel would cover either 90, 60, 30, or 6° [1.57, 1.05, 0.52, or 0.1 rad] of the 360° [6.3-rad] radial surface of the pipe."

The EPA report concluded that the tools found many of the channels but none of the tools found the small 6^o (0.36" width channel in a 7" pipe) channels (Thornhill & Benefield, 1987): "None of the logging tools presently available positively identified any of the 6 degree channels; the 'second generation' tools located all of the 30,60, and 90 degree channels designed into the well and identifiable; and a calibrated single transmitter/dual receiver CBL tool with three foot/five foot spacing located the 60 and 90 degree channels and all but one of the 30 degree channels. The research indicates the ideal approach for evaluating the cement in an injection well is to run both the 'second generation' tool and a calibrated CBL tool with single transmitter/dual-receiver three foot/five foot spacing. It was determined that calibration of both tools is imperative for reliable data to be produced. This is a critical area if these tools are to be used to evaluate the cement in an injection well. In addition, the inability of any of current cement evaluation technology to detect channels smaller than 30 degrees is of concern since channels of this size could represent a significant avenue for movement of fluids."

Cementing

A partial list of drilling, casing and cementing activities that influence the outcome of a cement isolation step are offered in Table 1. This list does not cover hydraulic calculations, specific displacement rates and volumes, thickening time, fluid loss control or final pressures, all of which are specific to individual jobs.

Table 1 – Factors in Establishing Cement Isolation

Factor	Reason	Casing String Target
Pipe Rotation and / or Reciprocation	Most effective physical removal of drilling mud and replacement of mud with cement during pumping.	Surface casing, intermediate & deeper vertical strings & liners
Casing centralization	Need to hold the casing off the borehole wall. Solid body centralizers may be preferred. 70% standoff is customary.	Surface and intermediate strings. Other strings where possible.
Minimum flow rate	Helps breakup mud cake and gelled mud after displacement flushes.	All strings
Mud conditioning	Circulation at proper rate helps remove gelled mud and gauges circulated hole volume	All strings
Preflush packages	Mud thinning flushes, filter cake disaggregation and separating dispersed mud and solids from cement during removal improves cement strength. Contact time is critical for chemical reaction.	All strings
Within well control & frac gradient window	ECD (equivalent circulating density) must be less than fracture gradient for exposed zones.	All strings
Casing to Hole clearance	Min. hole diameter >/= casing OD +1.5” Max. hole diameter </= casing OD + 4”	All strings
Fluid density consistency	All fluids pumped within +/- 0.2 lb/gal	All strings
Two plug system	Separation of mud/cement/flush	Where isolation is critical
Float shoe & collar	Insures strong uncontaminated cement around the bottom of the well.	All strings where isolation is critical.
Fluid loss control	Prevents water loss from the circulating cement slurry and the weak dehydrated cement that results.	Any string across a permeable zone, especially those that are pressure depleted.
Gas migration prevention	Prevents gas channels in the cement.	Any casing string across a gas charged formation.
Returns arrive as per design	Circulated volume and injected recovered fluid balance indicates amount of volume not circulated and therefore if voids or channels are an issue.	All strings. Critical for surface strings and critical isolation cases.

Pipe Movement

Pipe movement assists both the displacement of drilling mud from normally uncirculated pockets of gelled mud on the low clearance side of the casing/hole annulus with cement and lifting mud and cement up the hole. The importance of pipe rotation has been recognized since the 1950’s and documented widely in the 1970’s. Once felt to be critical to a good cement job, pipe movement has declined in use and necessity with improvements in chemical washes that disaggregate, liquefy and disperse mud and wall or filter cakes prior to flow of cement slurry. Current understanding is that pipe centralization, flush selection and application, and displacement rates are more important than pipe movement.

Centralizers

Centralizers help center the casing in the drilled hole so fluids can flow more evenly around the entire casing string. The type and number of centralizers used on a casing string depend of the well deviation and the weight and length of the casing string.

Minimum Flow Rates

Flow rate during cement placement should as high as possible to assist in removal of mud and or mud residue, but the rate must be kept low enough to avoid fracturing any exposed formation.

Mud and Hole Conditioning

Circulating the mud, especially while moving the casing helps remove gelled, solids-laden or dehydrated mud. Clean mud or treated mud may be used in special cases to help sweep the annulus. Time to condition mud depends on the mud system, the depth of the well and other factors (Beirute, 1991).

Chemical Treating Stages

Removal of the last vestiges of mud is important to develop both strong cement and a bond between casing and cement, and cement and the borehole wall. Many drilling muds, when mixed into cement slurries in even small quantities can indefinitely prevent cement from setting. Gelled or thick muds, if not displaced will form mud channels. Oil based muds and some additive-laden muds are particularly troublesome in preventing cement from settling. When mud conditioning steps fail to remove the mud, special chemical stages are available to thin, disaggregate and displace mud components to prepare an area for high quality cementing. Each of these steps requires a specific contact time depending on the mud, degree of gelling and the clearance between pipe and borehole. The contact time is achieved with attention to treating clearance between hole and casing with the fluid volume and time of contact set by the pump rate (Schumacher, 1996).

Well Control and Fracture Gradient Operating Window

The cement density must be high enough to control the maximum exposed pore pressure and low enough not to fracture the weakest exposed zone. The density of class G or H cement as a slurry mix with fresh water is about 16.4 lb/gallon, which translates into a fracture gradient of 0.83 psi/ft. Fracture gradient of most formations varies from about 0.65 to 0.85 psi/ft/ thus a full column of regular cement, even a static column, would fracture the well in at least one place. As cemented is circulated, there is always friction pressure so the effective circulating density of a fluid, particularly a viscous one like cement, would be higher than the static density.

Lower density cements are available but may not register on some cement inspection methods. Some of the lightest weight cements are also compromised by higher permeability and lower strength.

Cement Density

Correct cement slurry density is achieved when the added water volume matches the requirements of cement as set by the type of cement and the "grind" or size of the cement particles. More water can be added to the cement but the excess water will be expelled as the cement sets. The water separates to the top of the slurry and a water channel can form along the top of a cemented column in a deviation of even 1 degree. Less water than optimum will create a thicker cement slurry that is more difficult to pump and does not create design strength. Holding the cement density steady in an on-the-fly or jet-cone mixer requires an experienced operator. Batch mixing of cement is slower but yields more consistent results.

Two Plug System

The patent on using a top and bottom plug system was granted in 1911 to Almond Perkins and has been at the center of effective cementing for the past 100 years. The bottom plug, which used to separate the mud from the cement slurry, is hollow with a rupture disk or diaphragm in the top. When the bottom plug lands in the shoe track, the diaphragm ruptures, allowing the cement to leave the casing and enter the annular space between the casing OD and the borehole wall. The cement is displaced by water or mud with the solid top plug between the cement and the displacing fluid, which stays in the pipe. When the top plug lands or "bumps", the displacement is over and a check valve in the bottom of the casing prevents backflow of the heavier cement back into the casing.

Shoe Track - Float Shoe and Float Collar

A check valve in the float assembly prevents backflow of the cement slurry into the casing from the higher pressure exerted in the annulus by the liquid cement slurry.

Fluid Loss Control

Drilling mud prevents fluid losses from the mud by forming a fluid loss filter cake of wall cake on permeable formations as the liquids from the circulating fluids penetrate the formation and leave their entrained solids on the formation. Although the filter cake is effective in preventing losses, the mud cake must be removed to achieve an effective seal and bond between the cement and the formation. When the filter cake is removed, fluid loss will increase. Since water content of the cement is critical to strength development, fluid loss in the slurry must be controlled at the cement is circulated. Failure to quickly develop fluid loss control in cementing can lead to dehydrated cement blocking the annulus flow path and ruining the cement job.

Gas Migration Prevention

As the cement slurry sets, the hydrostatic pressure from the density of the cement slurry column is lost and for a short time some gas from a gas-charged formation may enter the thickened but unset cement slurry, creating weak cement or gas cut channels in the cement. Swell packers in the annulus, expandable liner sections, cement set accelerators, additives, holding back pressure and other methods are used to minimize gas entry, gas migration or the length of channels (Beirute, 1990; Sutton, 1984; Tinsley, 1980; Watters, 1980).

Monitoring Returns

The amount, type and arrival time of returns during cementing can help confirm the effectiveness of the cement application. Centralizing the casing and removal of the mud and gelled mud, are the most important steps in placing the cement job.

Post-Job Cement Investigation

In the first few wells in a geologically challenging area, finding the best cementing design may require several investigative techniques or tools. As the design progresses and is optimized, less investigation will be needed if the field personnel are familiar with the steps and the responses that describes an acceptable job.

Other Cementing Issues

There are several thousand oil field cementing papers in the literature. Specific papers that address a few of these topics follows.

- Self-Healing & Flexible Cement: Cavanagh, 2007; Reddy, 2009; El-Hassan, 2005.
- Cement Shrinkage and Control Additives: Beirute, 1992; Lyomov, 1997; Reddy, 2007, Sabins, 1991, Talabani, 1995.
- Microannulus Control: Bois, 2009; Jutten, 1987.
- Channel Locating & Testing: Fox, 1999; Badruzzaman, 1998; Blount, 1991.
- Mechanical Integrity Tests: Postler, 1997; Thornhill, 1987
- Cement Strength, Time, Gel Strength: Sabins, 1986.
- Horizontal Well Cementing: Sabins, 1990, Sabins, 1993.

Fully Cemented or Partially Cemented Annuli

Although a fully cemented annuli may seem the best approach as first thought, this may not be a good choice in many applications. The partly cemented annuli offers both a more effective may to monitor annular leaks and pressure, plus several options to repair microannuli, deteriorating cement, or pipe damage.

A comparison in Figure 5 shows an example of zones that may require increased monitoring. The casing design is excessive in this example but serves to illustrate extreme methods of separation that may be necessary in some cases.

The fully cemented annuli will likely require two-stage cementing, especially the longest full casing strings. This will result in an least one and maybe two multi-stage cement jobs that will leave cement filled holes in the casing barriers separating the protected water (which is assumed to be protected if TDS <10,000 ppm) and saltwater. If there is behind the pipe flow of any type, two strings of casing and cement will need to be perforated and a block squeeze attempted, assuming that there are methods of investigation that will find the leak. Cement squeezes through two pipe and cement layers are problematic.

In the monitored annuli on the right of Figure 5, pressure can be measured and fluid type of a leak can be determined, which can be traced to specific formations. Repair options may range from down-squeezes of sealant in the annulus, to relatively simple upper pipe removal to allow a full-bore repair (lower cost and higher success rate than a cement squeeze.

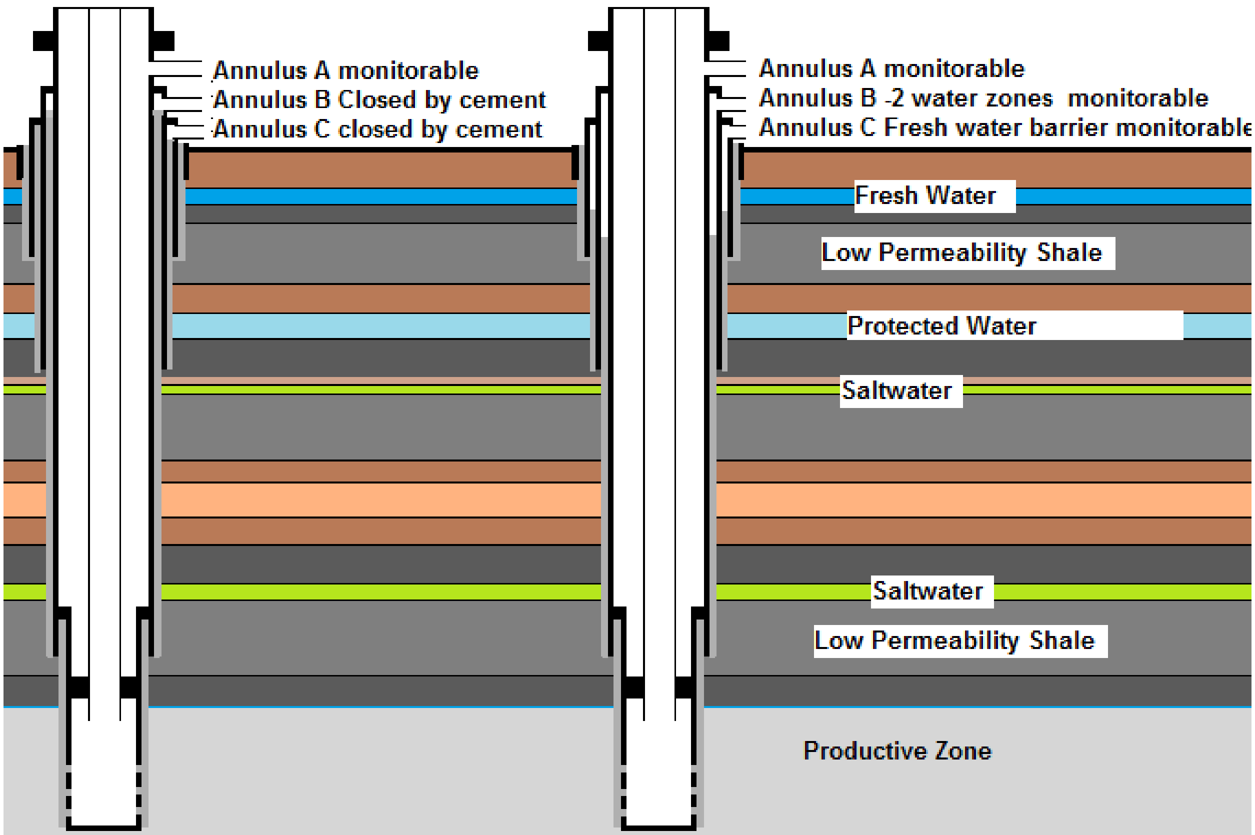


Figure 5 – Comparison of fully cemented and monitored annuli.

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