Ensuring Zonal Isolation Beyond the Life of the Well

When zonal isolation fails, production or injection efficiency is severely degraded. In some cases, the well is lost entirely. No less significantly, such failures present environmental and safety implications since hydrocarbons or previously injected fluids may flow to the surface or into nearby aquifers. Therefore, it is not sufficient to obtain good zonal isolation; the resulting seal must last many years beyond the life of the well.

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Placed between casing and wellbore, a cement sheath is expected to provide zonal isolation throughout the life of a well. But its ability to do so depends on the proper placement of the cement, the mechanical behavior of the cement and the stress conditions in the wellbore. Even if the slurry was properly placed, changes in downhole conditions can induce sufficient stresses to destroy the integrity of the cement sheath. Over time, stresses are imposed on the cement by pressure integrity tests, increased mud weight, casing perforation, stimulation, gas production or a large increase in wellbore temperature.[1] Any of these events can damage the sheath.

Often, damage to the cement sheath resulting from these forces manifests as microannuli so small as to be nearly impossible to pinpoint and even harder to repair. Even the smallest microannulus can be large enough to provide a pathway for fluid migration. Remedial work for such cement failures has been estimated to cost more than $50 million annually in the United States.[2]

Despite changes in downhole conditions over time—both predictable and unexpected—obtaining long-term zonal isolation is not only possible, in today's fiscally and environmentally sensitive oil industry, it is mandatory. To do so requires the right technology, processes and evaluation because drilling a well disturbs long-settled and precariously balanced stresses. Drillers must compensate for this disturbance, to the degree that it is possible, by using drilling fluids to exert hydrostatic pressure on the formation. However, this pressure may be insufficient to maintain equilibrium with the far-field stresses, and the formation surrounding the removed volume will deform.[3]

Draining fluids from a formation during production may also change formation pore pressure and related stresses. Within the rock, the resulting increased loading leads to varying degrees of deformation or failure that can cause cement to break or debond at the formation interface. Production-induced stresses can also result in reservoir compaction, which may lead to tubular shearing and buckling of completion components.[4]

An obvious key to long-term zonal isolation is obtaining a good seal in the first place. To determine whether that objective has been achieved, standard sonic and ultrasonic logging tools have been developed and improved over time in an effort to quantify the cement-to-casing bond. Recent versions of ultrasonic tools can now detect the presence of channels within the cement sheath through which hydrocarbons can flow.

In this article, we will highlight the most recent development of these ultrasonic tools that can also indicate casing eccentricity, evaluate the material in the casing annulus and distinguish between new lightweight cements and drilling fluids of similar acoustic impedance. Case histories will also demonstrate the new ultrasonic logging tool's ability to offer improved characterizations of cement-to-casing bonds and annular fill.

This article also examines industry efforts to achieve long-term zonal isolation using specially formulated cements as annular sealing material. Of primary interest is a new, long-life, self-healing cement. Developed in response to what has been called the weak link in zonal isolation—the inability to correct defects after the cement has set—the new sealant swells in the presence of hydrocarbons to close cracks and microannuli that may form in cement sheaths as a result of changing downhole conditions. We also present laboratory tests and case histories that demonstrate the success of this development effort.

Preparing the Ground

Obtaining a good cement sheath demands adherence to well-established operating practices of hole preparation, casing centralization and casing rotation and reciprocation.[5] Successful zonal isolation first requires removing contaminants—principally drilling mud—from the wellbore. Since formation pressure must be contained during this hole-cleaning operation, the drilling fluids being removed must be displaced with a fluid of higher density—a spacer—pumped behind the mud and ahead of the cement.

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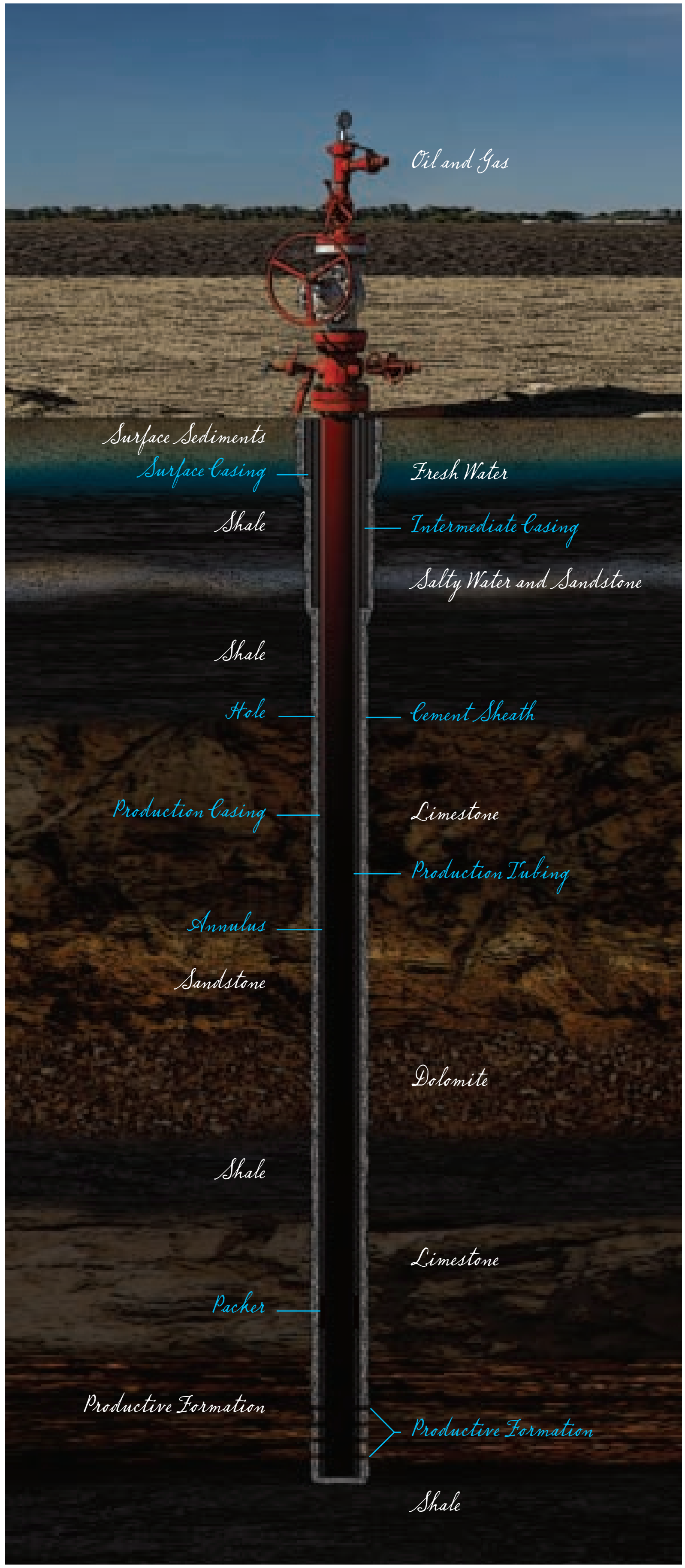
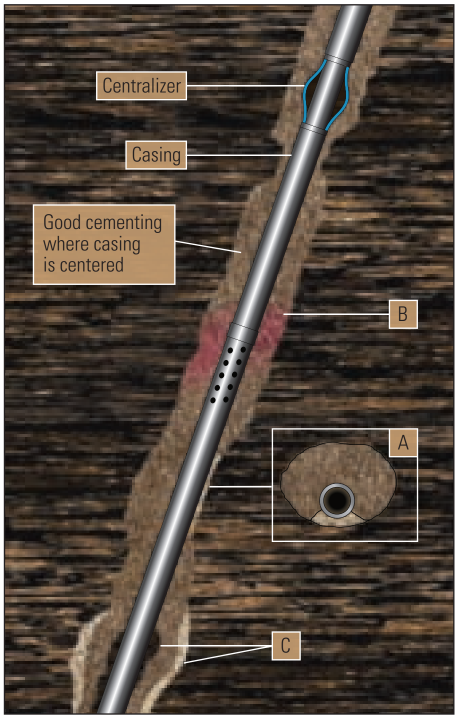
3. Gray KE, Podnos E and Becker E: "Finite Element Studies of Near-Wellbore Region During Cementing Operations: Part I," paper SPE 106998, presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, USA, March 31–April 3, 2007.
4. For more on formation stresses: Cook J, Frederiksen RA, Hasbo K, Green S, Judzis A, Martin JW, Suarez-Rivera R, Herwanger J, Hooyman P, Lee D, Noeth S, Sayers C, Koutsabeloulis N, Marsden R, Stage MG and Tan CP: "Rocks Matter: Ground Truth in Geomechanics," *Oilfield Review* 19, no. 3 (Autumn 2007): 36–55.

   For more on reservoir compaction: Doornhof D, Kristiansen TG, Nagel NB, Pattillo PD and Sayers C: "Compaction and Subsidence," *Oilfield Review* 18, no. 3 (Autumn 2006): 50–68.
5. Casing rotation and reciprocation refer to any movement of the casing to help remove drilling fluids from the annulus while cement is being pumped downhole.





^ Failed isolation. Problems that occur while running casing and cementing can create conditions that may lead to loss of zonal isolation. Among the most common of these is casing eccentricity from poor centralizer positioning. Cement, like all fluids, seeks the path of least resistance and so flows to the more open side of the casing, creating a narrow space between the casing and the formation that can become fluid-migration paths (A). Inadequate slurry density can also allow formation gas (red) to enter the wellbore (B) and create weak points or gaps within the cement that fail when stresses are imposed on the cement sheath by changing downhole temperatures and pressures. The geometry of washed-out areas (C) often results in inefficient flow rates during wellbore cleaning operations that leave drilling fluids behind. These contaminants also lead to weak spots in the cement sheath and, if large or numerous, can create channels through which formation fluids may flow.

The spacer is designed to keep the drilling fluids and cement apart while the cement is being pumped through the casing and into the annulus, and is generally formulated with a viscosity close to or greater than that of the drilling fluid. Besides maintaining well control, the spacer also serves as a chemical wash to clean leftover drilling mud from the casing-casing and casing-wellbore annuli. If the spacer leaves drilling fluids behind, or if it allows them to mix with the cement, then good bonding between cement and formation or casing is unlikely. Since these contaminants remain in a liquid state, they are liable to form channels of communication between zones along the borehole or casing (left).[6]

Efficient borehole cleaning is not the only requirement for good zonal isolation. A poorly drilled hole, for example, may have washed-out areas that are difficult to clean and that may contain pockets of gelled drilling fluids. These gelled fluids can be pulled into and contaminate the passing cement slurry. Poor casing centralization can contribute to a poorly placed cement since it can be difficult to remove fluids from the side that is closest to the borehole wall in eccentrically positioned casing. Since the 1940s, research and development efforts have gone into developing recommended standards for centralizer placement along the casing string to be cemented. Those practices are now being tested by new cement evaluation tools that provide casing eccentricity measurements. These measurements can be compared with traditional calculated standoff values that rely on unlikely assumptions such as a perfectly in-gauge wellbore.[7]

To avoid leaving behind a heavy filtercake that is impossible to remove, the properties of the drilling fluid must be altered to match those more suited to hole cleaning. For best results, the mud density, yield stress, plastic viscosity and gel strength should all be reduced.

Mud rheology may be reduced by adding water or dispersants to the system and circulating the fluid until its properties reach the desired range. This requires circulation of at least one borehole volume and, when possible, should be performed before removing the drillpipe to prevent mud from gelling while it is static during pipe-pulling operations.

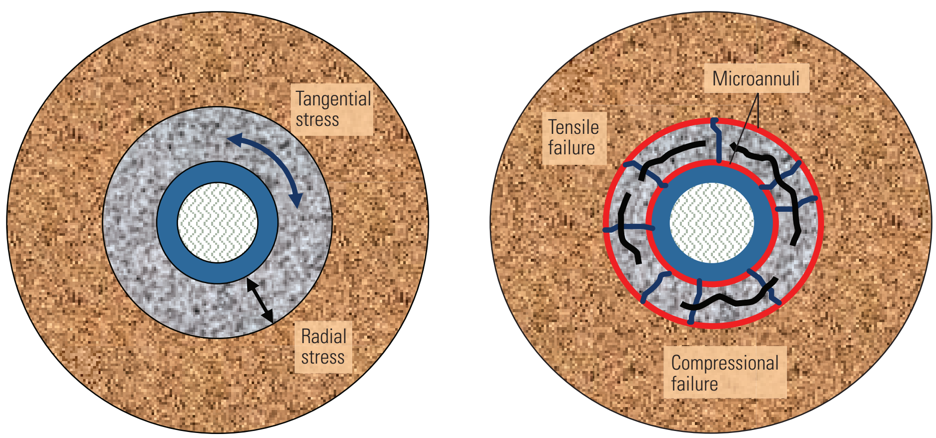
Mechanical steps are also recommended to help remove contaminating fluids prior to cementing. Moving the casing frees mud trapped in narrow sections of the annulus. Attaching scratchers, scrapers and wipers to the casing also helps remove gelled and dehydrated mud as the casing is rotated and reciprocated.

The optimum wellbore for cementing purposes, then, is one with controlled subsurface pressures and minimum doglegs, is in-gauge, stabilized and free of drill cuttings, and has a thin dynamic filtercake across permeable zones.[8]

Sound Technologies

Following industry best practices does not guarantee that the resulting cement sheath will be up to the tasks—casing support, corrosion protection and, most critically, zonal isolation—for which it was designed. Determining contamination, continuity and bonding quality of the cement behind the pipe is therefore tantamount to protecting the asset and the environment by recognizing the need for remedial operations before the well is brought on production.

Finding the top of the cement behind pipe where expected is a reasonable indication that the volumes displaced match those calculated and that the annulus is filled with the correct amount of cement. Since cement hydration is an



^ Cracks and microannuli. Over time, as downhole stress conditions change, primarily in response to temperature and pressure changes, even a successful cementing operation can fail. Large increases in wellbore pressure or temperature and tectonic stresses can crack the sheath and even reduce it to rubble. The interplay of tangential and radial stress changes may be caused by displacement of casing as a result of cement bulk shrinkage or temperature or pressure decreases (*left*). These stress changes can cause the cement to fail in tension or compression, or to debond from the casing or formation, creating microannuli (*right*).

exothermic reaction, this can be done using a temperature survey. This method, however, reveals little else about the results of the cementing operation.

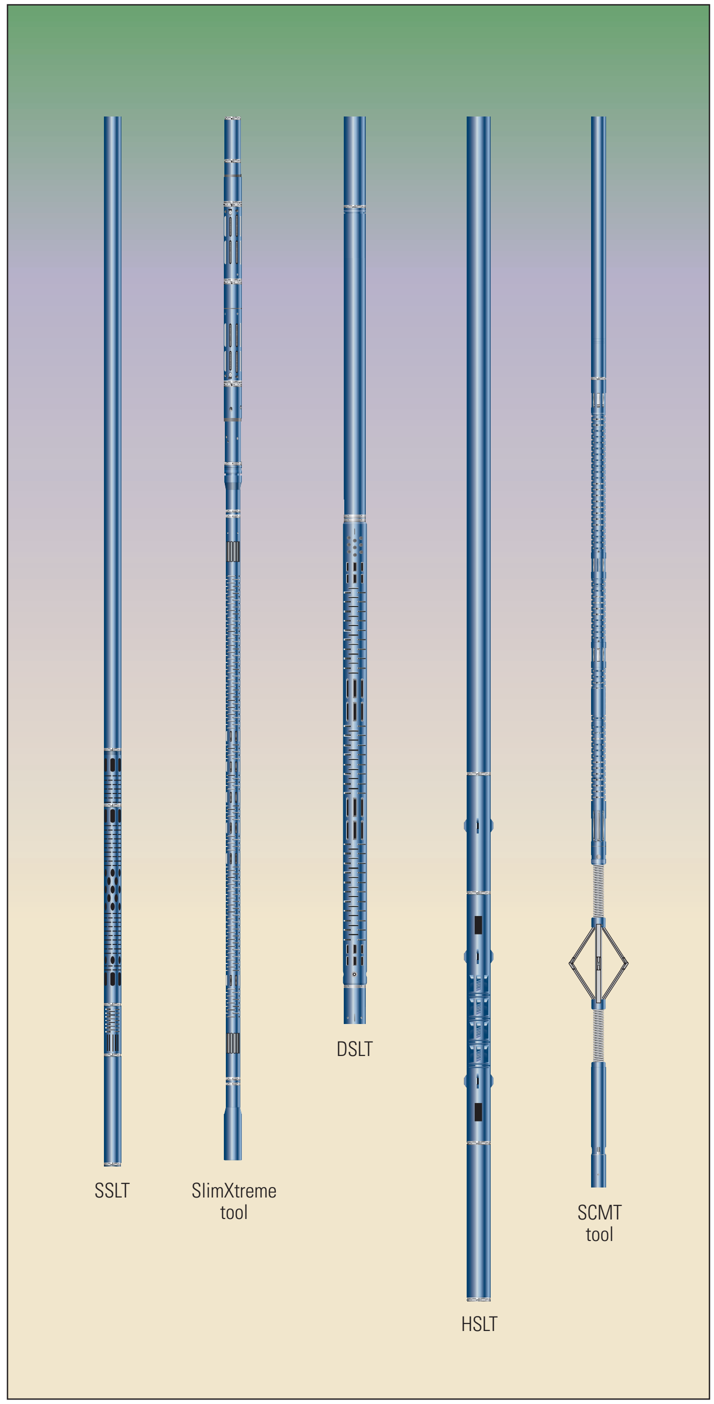
Hydraulic testing—a common test of zonal isolation—applies internal pressure along the entire casing string. But pressure can expand the casing, causing the cement sheath to experience tensile failure. This may lead to radial cracks and local debonding of the cement and casing in areas where the cracks are near the casing wall (previous page, bottom).

Because of the limitations of the other techniques, acoustic logging has become the industry's tool of choice for detecting cement behind casing and assessing the quality of the bonds between casing, cement and formation. Acoustic logs help indicate nonintrusively the depth interval at which cement has been placed around the casing, measure acoustic impedance of the cement bonded to the casing, and quantify the percentage of pipe circumference bonded to the cement.

These characteristics inform the operator of faults in the cement sheath that may require remedial measures—commonly a squeeze operation in which cement is pushed through perforations into the annulus to fill gaps along interfaces at the casing, formation or within the annular material itself.

Cement bond logs (CBLs) and variable density logs (VDLs) are acquired using a sonic logging tool (right). Standard CBL tools, which comprise those that measure signal amplitude or attenuation, have a common theory of measurement and interpretation. The principle behind them is to measure the amplitude of a sonic signal produced by a transmitter emitting a 10- to 20-kHz acoustic wave after it has traveled through a section of the casing as an extensional mode.[9]

Measurements are displayed on the CBL log in millivolts (mV) or decibel (dB) attenuation, or both. Increased attenuation indicates better quality bonding of the cement to the outer casing



^ Traditional sonic cement bond log tools. The slim array sonic tool (SSLT) is a digital sonic tool that provides conventional openhole sonic measurements, standard cement bond log (CBL) amplitude and a variable density log (VDL). The SlimXtreme slimhole well logging platform provides the same measurements as the SSLT for evaluation of the cement bond quality in high-pressure and high-temperature environments. The digital sonic logging tool (DSLT) uses the sonic logging sonde to measure the cement bond amplitude and provide a VDL display for evaluation of the cement bond quality. The hostile environment sonic logging tool (HSLT) provides the same measurements of the cement bond amplitude and the same variable density display as the SSLT in standard wellbore sizes. The SCMT Slim Cement Mapping Tool is a through-tubing cement evaluation tool combinable with the PS Platform new-generation production services tool. It is sized so that it may be used to evaluate the cement behind casing in workover operations without having to first pull the tubing.

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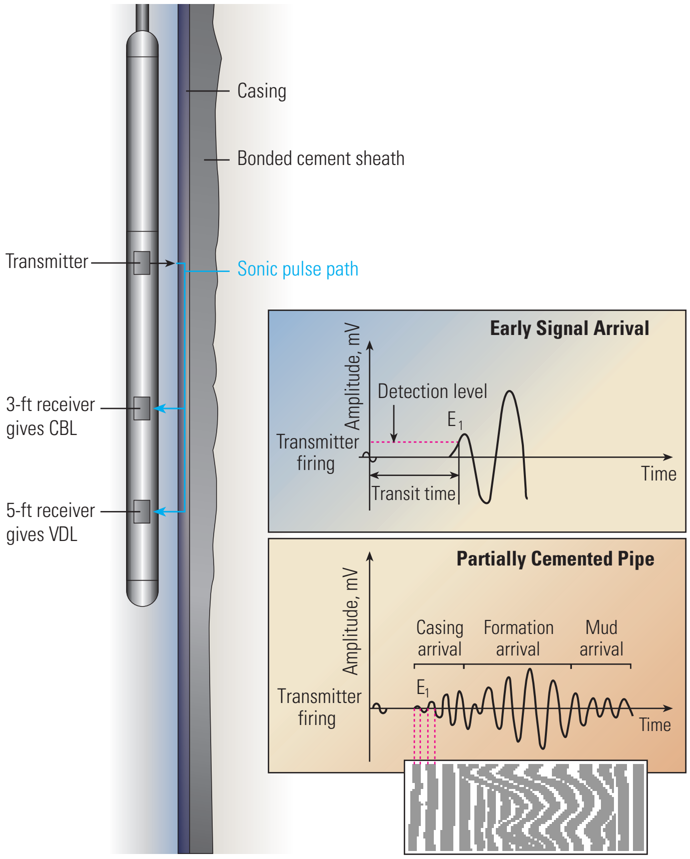

^ Sonic logging tools. Cement bond logs (CBLs) and variable density logs (VDLs) are acquired using a sonic logging tool with a monopole transducer and two monopole receivers placed at 3 and 5 feet [0.9 and 1.5 m] from the transmitter (*left*). The monopole sonic transmitter sends an omnidirectional pulse at relatively low frequency (10 to 20 kHz) that induces a longitudinal vibration of the casing. The recorded amplitude of the first positive peak (E_1) of the sonic waveform received at 3 ft and the full waveform received at 5 ft represent the average values over the circumference of the casing (*top right*). In well-cemented pipe, the sonic signal in the casing is attenuated, and the CBL E_1 amplitude is small. In free pipe, the casing arrivals are strong. The transit time is the time it takes the wave to travel from transmitter to receiver. It is used for quality control of the tool centralization and to set parameters for material detection. In partially cemented pipe (*bottom right*), casing, formation and mud arrivals may be present and can occur in the presence of a microannulus at the casing/cement interface. The VDL (*bottom inset*) provides visualization of arrivals that propagate in the casing as extensional waves and in the formation as refracted waves.

wall. In simple cases, the interpreted log response can provide good information about cement quality (above).

About 25 years ago, engineers developed cased-hole ultrasonic imaging tools that used a high-frequency pulse-echo technique (next page, top left).[10] More recent versions of these ultrasonic imaging tools, such as the Schlumberger USI UltraSonic Imager, use a rotating transducer that emits a broadband ultrasonic wave perpendicular to the casing wall with a frequency that can be adjusted between 250 and 700 kHz (next page, right). The effect is to excite a casing resonance mode at a frequency dependent on casing thickness and with an amplitude decay dependent on the acoustic impedances of the media on either side of the casing. The cement acoustic impedance is then classified as gas, liquid or cement based on the thresholds set for acoustic impedance boundaries between these materials.

Strengths and Weaknesses

These sonic and ultrasonic logging tools have had shortcomings. The traditional sonic CBL-VDL tool does not provide radial or azimuthal information to differentiate among channels, contaminated cement, microannuli and tool eccentricity; this makes confident data interpretation difficult.[11]

Ultrasonic imaging tools that are based on the pulse-echo technique are limited when logging in highly attenuative muds because of low signal-to-noise ratios. Their radial probing power is limited to the cement region adjacent to the casing.[12]

Because of the high acoustic impedance contrast between steel and the surrounding material—mud inside the casing and cement outside—the signal dies away so rapidly that echoes arising from acoustic contrasts outside of the casing are typically undetectable unless they are very close to the casing and strongly reflective surfaces.

Additionally, the pulse-echo technique has difficulty differentiating between a drilling fluid and a lightweight or mud-contaminated cement of similar acoustic impedance. Even under favorable conditions, the acoustic impedance contrast between drilling fluid and cement typically must be larger than 0.5 Mrayl for the pulse-echo technique to distinguish between them.

To overcome tool limitations, and depending on well conditions, an utrasonic and standard CBL-VDL tool may be run together. But even then, experience from various wells around the world has shown that an unambiguous conclusion about the quality of the cement bond may be elusive. This is particularly true in the case of lightweight and contaminated cements.

This issue has become increasingly urgent with the proliferation of lightweight cements in deepwater wells and in sealing across formations with low pore pressure. To deal with this problem, Schlumberger has developed a measurement technique that is the basis of the Isolation Scanner cement evaluation service. The tool combines the classic pulse-echo technique with an ultrasonic imaging technique that provides more effective imaging of the annular fill including reflection echoes at the cement/formation interface.

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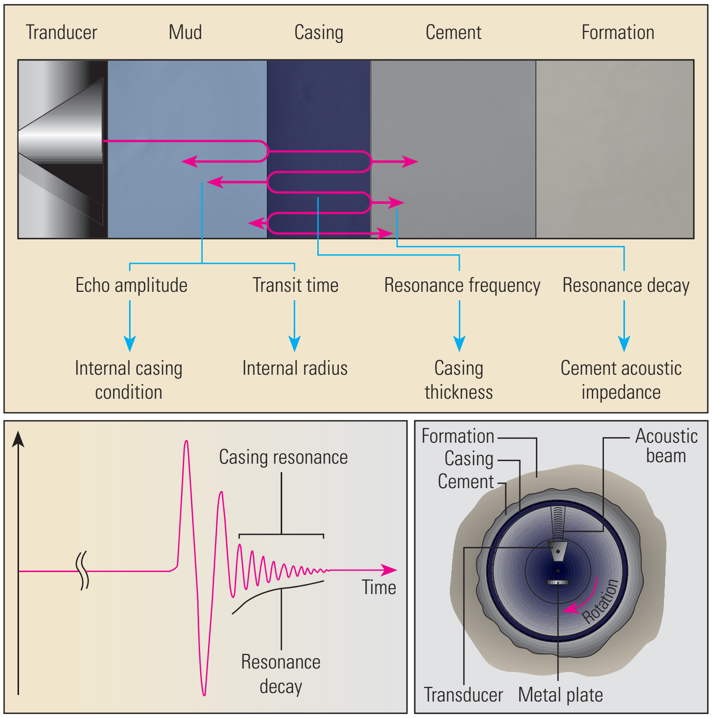
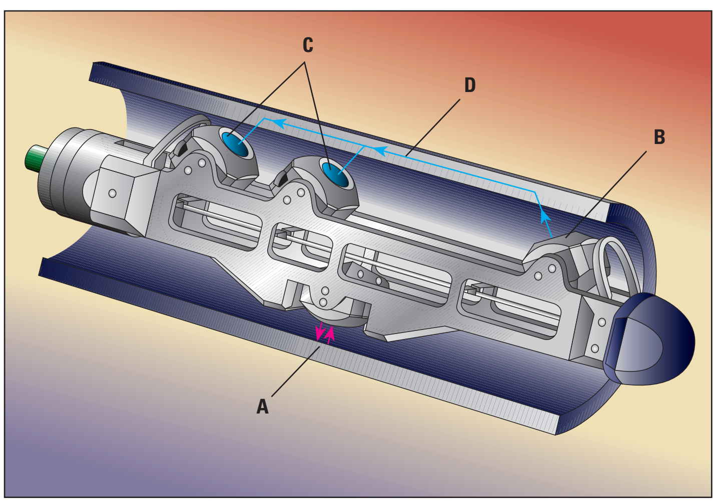
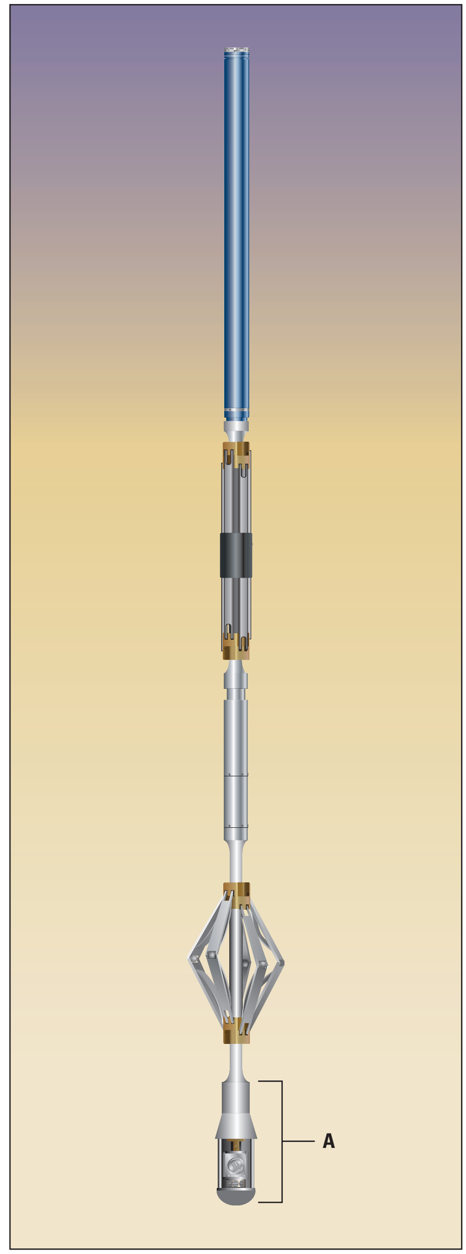


^ Cased-hole ultrasonic tool basics. An ultrasonic tool's transducer sends a slightly divergent beam—an acoustic wave generated by a transducer when electrical power is applied to it—toward the casing to excite the casing into its thickness resonance mode. The USI UltraSonic Imager tool scans the casing at 7½ revolutions per second to render an azimuthal resolution of 5 or 10 degrees. This yields 36 or 72 separate waveforms 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 cement acoustic impedance—from the signal resonance decay (*top*). The acoustic impedance of the cement (essentially the quality of the cement sheath) can be derived from the resonance decay (*bottom*). A good casing-cement bond results in immediate resonance decay, while free pipe rings (generates echoes) for an extended period.



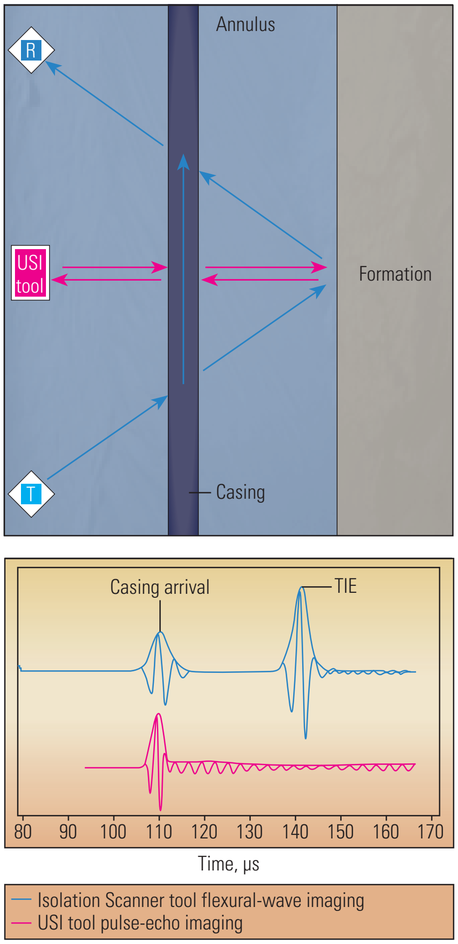
^ Isolation Scanner subassembly. The Isolation Scanner sub combines the traditional pulse-echo technique using an acoustic transmitter and receiver normal to the casing (A), while adding flexural-wave imaging with one transmitter (B) and two receivers (C) aligned obliquely. This configuration excites the casing flexural mode (D). The subassembly, mounted on the same platform as the USI tool and with updated signal generation and acquisition software, is the basis for Isolation Scanner tool.



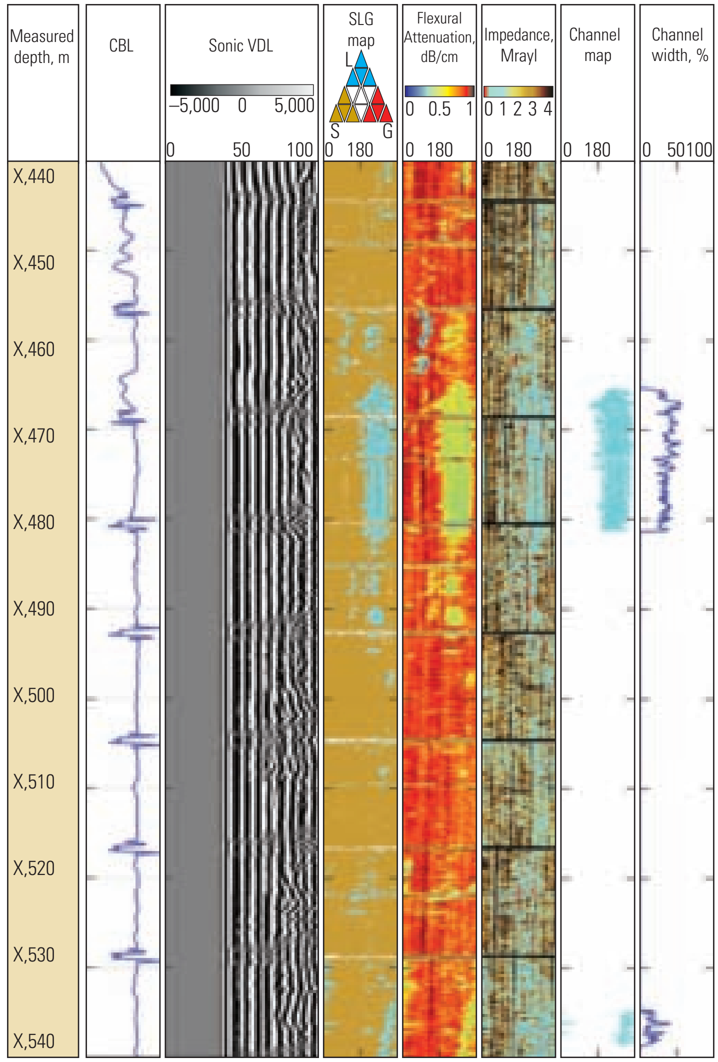
^ USI tool. The Schlumberger USI tool improved on earlier versions of the ultrasonic imaging tool by using a single rotating transducer mounted on the bottom of the tool (A).

Sounds of Success

The Isolation Scanner tool includes a rotating subassembly supporting four transducers (left). A normally aligned transducer for generating and detecting the pulse echo is positioned on one side of the tool. The other three transducers are on the opposite side of the tool and are aligned obliquely. One of these transducers transmits a high-frequency pulsed beam of about 250 kHz to excite a flexural mode in the casing.



^ Geometrical interpretation of USI measurements and Isolation Scanner flexural-wave imaging. Shown here is a geometrical ray interpretation of the propagation of the signal for the pulse-echo (*top*, red) and from the transmitter (T) to a receiver (R) for the flexural-wave pitch-catch techniques (*top*, blue). A typical waveform from the latter technique comprises an early echo, called casing arrival, and third-interface echoes (TIEs) (*bottom*, blue). The attenuation of the casing arrival amplitude is used to complement the pulse-echo measurement (*bottom*, red) in distinguishing unambiguously between fluid and solid behind the casing. The properties of the TIE provide an enhanced characterization of the cased-hole environment, indicating the acoustic properties of the material filling the annulus, the position of the casing within the hole and the geometrical shape of the hole.

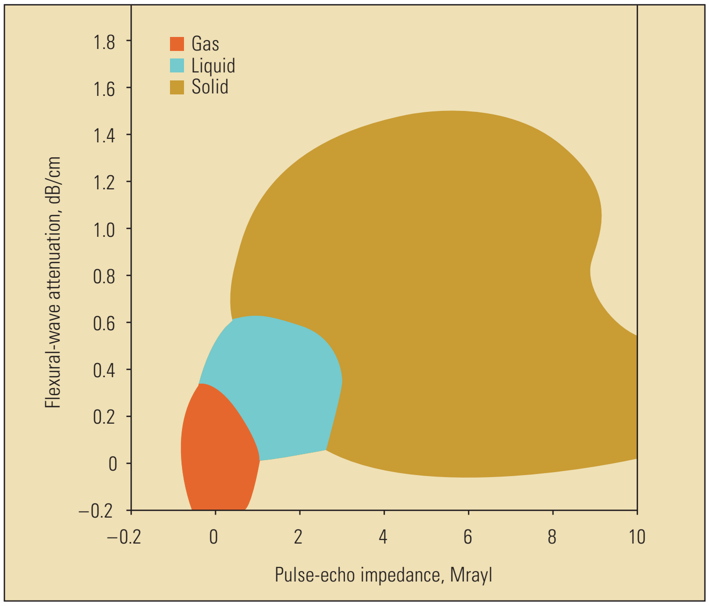


^ Isolation Scanner and CBL-VDL measurements. In 2003, the Isolation Scanner prototype was tested in an In-Salah Gas vertical well. The 9⅝-in. casing was cemented in a 12¼-in. hole using the low-density (low-impedance) LiteCRETE slurry system. The CBL (Track 1) and VDL (Track 2) show a nearly free-pipe response with strong casing arrivals in the VDL. The pulse-echo impedance map (Track 5) shows fluid with patches of solid. Obtaining an adequate interpretation from both measurements was made difficult by the low-impedance LiteCRETE cement. The flexural-wave attenuation map (Track 4), on the other hand, provides a correct diagnosis of the solid behind casing. It also reveals the existence of a fluid-filled channel between X,465 and X,485 m. The solid-liquid-gas (SLG) map (Track 3) supports and simplifies this information. The azimuthal and axial extent of the channel is reported automatically in Tracks 6 and 7.

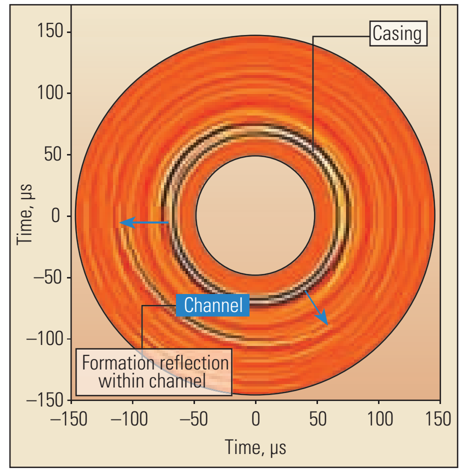
As it propogates, this mode radiates acoustic energy into the annulus; this energy reflects at interfaces that present an acoustic contrast, such as the cement/formation interface, and propagates back through the casing predominantly as a flexural wave to reradiate energy into the casing fluid. The two receiving transducers are placed to allow optimal acquisition of these signals (above left).

This new technique is termed pitch-catch. Processing of the resulting signals provides information about the nature and acoustic velocity of the material filling the annulus, the position of the casing in the hole and the geometrical shape of the hole.

The first aim of processing Isolation Scanner logs is to obtain a robust interpretation of the material immediately behind the casing. The inputs to this processing sequence are the



^ Solid-liquid-gas mapping of the measurement plane for a Class G cement. Once the expected impedance values are defined for the cement, liquid and gas through a laboratory-measured database and the material selection is converted into acoustic properties, the next step is to predict the measurements from the expected acoustic material properties. Then, multiple realizations of the measurement noise are added to generate three clouds of points (solid, liquid and gas) in the bidimensional measurements plane.



^ Waveform polar plot across the fluid-filled channel at a depth of X,477 m on the Isolation Scanner log (*previous page, top right*). The curvature of the annulus-formation echo reveals that the casing is slightly eccentered in the borehole and that the channel is located on the narrow side (direction of blue arrows). The absence of a third-interface echo across the cement azimuth may be due to a low acoustic contrast between the cement and formation.

cement impedance, as delivered by the pulse-echo measurement, and the flexural-wave attenuation computed from the amplitude of the casing arrivals on the obliquely aligned receivers.

These two inputs are independent measurements linked through an invertible relation to the properties of the fluids inside both the casing and annular fill. The inputs are first combined to eliminate the effect of the inside fluid, thus obviating the need for specific hardware for fluid-property measurements required by the USI tool.

The output of the Isolation Scanner service is a solid-liquid-gas (SLG) map displaying the most likely material state behind the casing. The state is obtained for each azimuth by locating the two measurements, corrected for the effects due to the inside fluid, on a crossplot of attentuation and acoustic impedance, giving the area encompassed by each state (above left). The measurement plane can be mapped out in different regions with three colors corresponding to the different states (previous page, top right). The white-colored areas in the SLG map correspond to locations with nonsolvable inconsistencies between measurements, such as might appear at the casing collars.

In addition to evaluating the material behind the casing, a second objective of processing is to extract relevant information from the annulus-formation reflection echo or echoes and further characterize the annulus between the casing and formation.

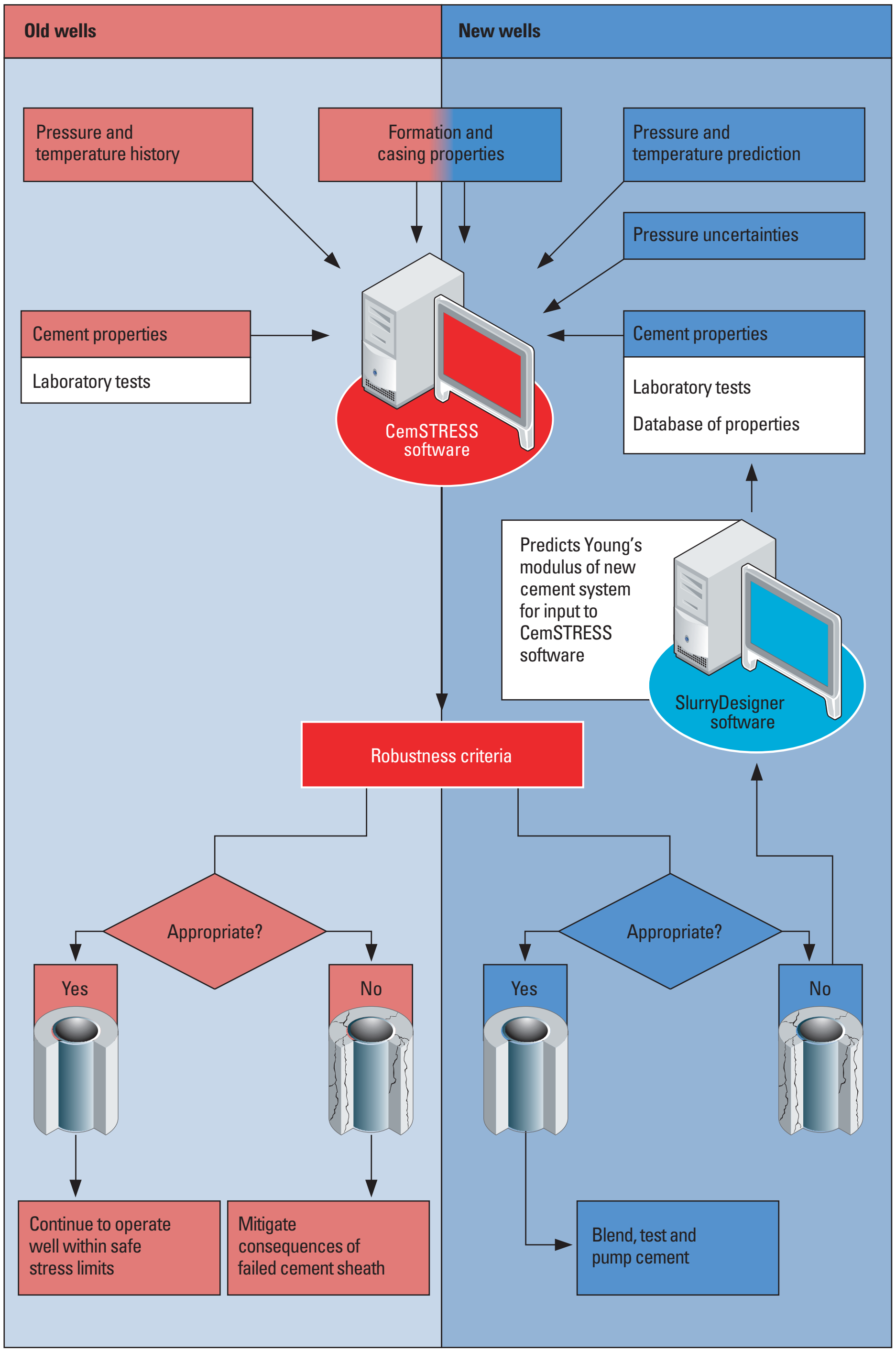
First, the software detects the echoes on the waveform envelope following the casing arrival and then measures their time of arrival and amplitude. From the time differences between the reflection echoes and the casing arrival—provided enough echo azimuthal presence is available in the data—it is straightforward to determine how well the casing is centered within the borehole. This is presented as a percentage in which 100% represents perfect centering, and 0% is casing in contact with the formation wall. Additionally, if the borehole diameter is known, the time-difference processing can be further converted into a material-wave velocity and displayed as an annulus-velocity map or cement azimuthal thickness.

A polar plot of the flexural waveforms from the variable density log provides a picture of the geometry of the casing within the borehole (above right).

New Cements

Even the most sophisticated logs present only a snapshot of the cement condition and its ability to provide zonal isolation. Over the long life span of a well, changing downhole conditions remain the enemy of cement sheaths and may cause even well-placed sheaths to fail over time.

Throughout the industry's long history of using cement in well construction, addressing these failures first focused on placement of the slurry and later on its chemical makeup. During the 1980s, engineers and scientists began to consider ways to deliver specific set-cement properties with the aim of increasing the



^ Designing cement systems. Cementing experts can use the CemSTRESS cement sheath stress analysis software to analyze the radial and tangential stresses imposed on each casing string during events such as treating and pressure testing. In addition to indicating cement sheath performance in compression, tension, or both, the software has the ability to establish parameters, including set-cement flexibility, support and standoff. It can also be used to identify both inner and outer microannuli and show their size and development over time. CemSTRESS software uses a three-stage methodology to aid in selecting and designing a cement system that can extend well life. In the first stage of the method, a cement expert determines whether the well requires a conventional cement system or a specialized system. This provides direction for the next two stages. The second stage of the methodology analyzes scenarios to design a cement system whose Young's modulus is below the stress level that the software predicted would induce failure. In the third stage, Schlumberger cementing engineers use proprietary software, such as SlurryDesigner cement blend and slurry design software, to optimize the cement slurry design.

likelihood of attaining good zonal isolation. From this strategy came the idea of reducing cement density through the injection of nitrogen into the slurry while pumping, and of introducing ceramic microspheres into the cement blend. The latter design was the precursor to the Schlumberger CemCRETE concrete-based oilwell cementing technology, including the LiteCRETE slurry system, and CemSTONE advanced cement technology. These innovations allowed engineers to increase or decrease slurry density without significantly affecting the permeability of the set cement.

The new cement systems were accompanied by development and deployment of software to analyze and improve fluid displacement behind casing and simulate stresses on the cement over the life of the well (left). Beginning in 2000, continual improvements to cementing software provided engineers with a tool to tailor slurries based on gas-migration risks and wellbore stresses.

In 2002, Schlumberger introduced FlexSTONE advanced flexible cement technology to handle changing stresses imposed on cement sheaths over time. Expected stress changes from drilling, production and abandonment activities are predicted by numerical modeling. The system's mechanical properties are customized using FlexSTONE trimodal particle-size distribution technology. The resulting mechanical flexibility allows these cement systems to resist failure through a variety of changes that may occur during the drilling, production and abandonment cycles of a well.[13]

While such methods increase the resistance of the cement matrix to physical stresses, they are ineffectual once the cement sheath fails. Even if the sheath is intact during the well's lifetime, the increased emphasis on environmental responsibility dictates that hydrocarbon-bearing formations remain sealed for many years after the asset has been plugged and abandoned. This extended period of service significantly increases the chances that even the most appropriate and resilient cement sheath may fail.

In response to these concerns, Schlumberger engineers have taken another step in the evolution of zonal isolation systems with the introduction of self-healing cement (SHC). As the name implies, when cracks or microannuli occur at the interface between the cement sheath and the casing or formation, self-healing components within the set-cement matrix swell to close the gaps without any outside intervention. This FUTUR active set-cement technology reacts specifically to the presence of hydrocarbons. When the integrity of the cement sheath is compromised and zonal isolation is breached, the cement reacts to the presence of hydrocarbons by swelling. This effectively closes the gap and shuts off formation fluid movement.

Except for its self-healing abilities, FUTUR cement is similar to traditional cement. Successful placement requires adherence to the same best practices as any oilfield cementing operation, and the cement itself requires no special mixing or pumping equipment. FUTUR slurries are compatible with all standard additives and spacers. Standard mixing and slurry tests of rheological properties, free fluid, sedimentation, fluid-loss control, thickening time and development of compressive strength all apply.

Once placed in the well, FUTUR cement behaves in the same way as classic cements when not in the presence of hydrocarbon, and its set-cement properties are equivalent to those of traditional cements (right).

Laboratory Work

FUTUR cement technology is designed to provide well integrity for the very long term. Therefore, laboratory testing to replicate downhole sheath failure was critical in proving that the cement would indeed heal itself and that it would continue do so for years after placement. The cement also had to be checked for any problems its self-healing characteristic might create.

To test swelling properties, the cement was placed in an annular expansion mold. These tests simulate normal setting of the cement matrix in the well, followed by an invasion of hydrocarbon such as would be expected when cracks or creation of a microannulus causes a loss of zonal isolation. The FUTUR cement was cured in water for seven days prior to immersion in oil, and identical temperatures and pressures were used in water and oil. Results showed that the linear swelling increased with temperature at constant pressure.

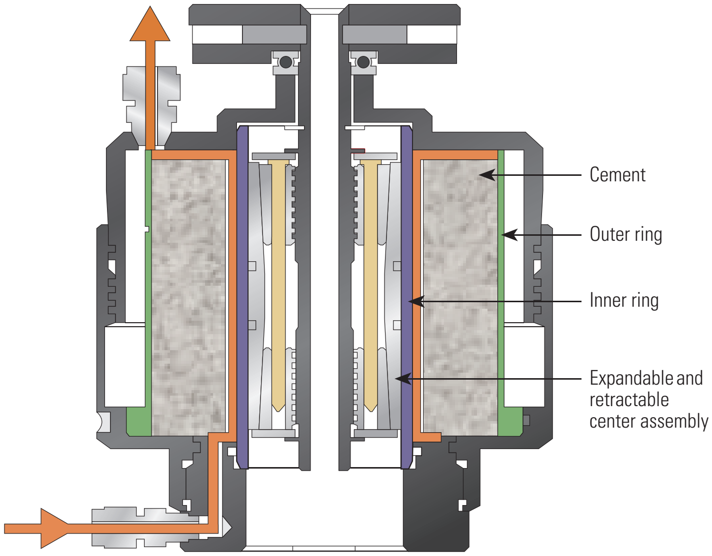
To evaluate the FUTUR system's self-healing properties, engineers at the Schlumberger Riboud Product Center in Clamart, France, developed a flow loop to simulate downhole conditions and installed an SHC cell designed to

13. For more on new cements: Abbas et al, reference 6.

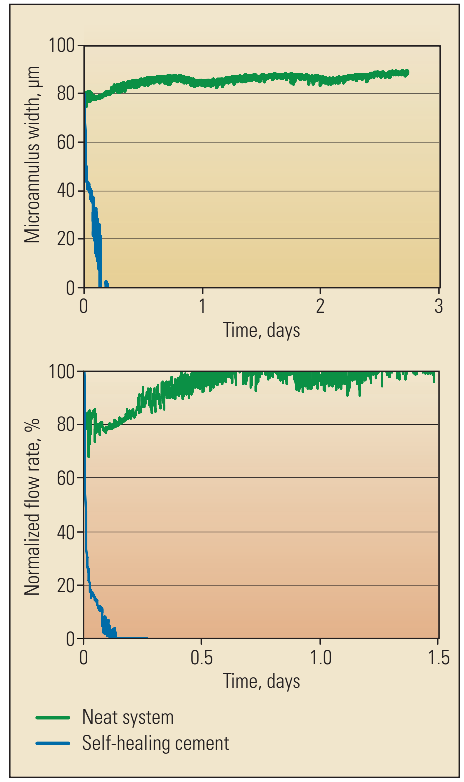
Formulation and Properties	Design 1	Design 2	Design 3
BHCT, °C [°F]	60 [140]	25 [77]	60 [140]
Density, kg/m^3 [lbm/galUS]	1,870 [15.8]	1,700 [14.2]	1,400 [11.7]
Antifoam, L/t [gal/sk]*	2.66 [0.03]	0.2% BWOB	4.2 [0.05]
Dispersant, L/t [gal/sk]	6.22 [0.07]	4.2 [0.05]	
Retarder, L/t [gal/sk]	2.66 [0.03]		0.5% BWOB
Gas-migration control additive, %BWOC***		0.77	
Fluid-loss control agent, %BWOB**			0.7
Gelling control agent, %BWOB			0.5
Mixing Rheology			
Ty, Pa [lbf/ft^2]	1.9 [4.0]	11.4 [23.9]	5.9 [12.3]
PV, MPa [thousand psi]	237 [34.3]	202.7 [29.4]	55 [8.0]
API Rheology			
Ty, Pa [lbf/ft^2]	5.7 [11.8]	9.0 [11.9]	7.8 [16.3]
PV, MPa [thousand psi]	151 [21.9]	148.7 [21.6]	60 [8.7]
10-s gel, Pa [lbf/100 ft^2]	5.1 [10.7]	18.2 [38]	7.4 [15.4]
10-min gel, Pa [lbf/100 ft^2]	13.7 [28.5]	10.8 [22.6]	10.2 [21.4]
1-min stirring gel, Pa [lbf/100 ft^2]		11.4 [23.7]	
API free fluid at 60°C [140°F], mL	Traces		58
API free fluid at 25°C [77°F], mL		0.5	
API fluid loss at 25°C [77°F], mL		30	
API sedimentation test, lbm/galUS	0.2	–0.2	–0.15
Thickening Time			
At BHCT, h:min	6:16	8:05	6:33
Time 30 to 100 Bc****, h:min	0:54	1:09	4:13
Compressive Strength Development			
Time to reach 50 psi at BHST, h:min		9:23	6:00
Time to reach 500 psi at BHST, h:min		35:44	11:16
24-h compressive strength, MPa [psi]		2.5 [363]	4 [637]
Mechanical Properties of SHC Matrix After 7 Days Curing in Water at Atmospheric Pressure			
Temperature, °C [°F]	60 [140]	25 [75]	25 [75]
Compressive strength, MPa [thousand psi]	20 ± 5 [2.9 ± 0.7]	10 ± 0.8 [1.5 ± 0.1]	4.5 ± 0.5 [0.65 ± 0.07]
Young's modulus, MPa [thousand psi]	6,500 ± 500 [940 ± 73]	2,800 ± 400 [400 ± 60]	1,300 ± 300 [190 ± 44]

*gal/sk = gallon of additive per sack of cement **%BWOB = by weight of blend
***%BWOC = by weight of cement ****Bc = Bearden's unit of consistency

^ Slurry designs. Laboratory tests determined the properties of three FUTUR slurry designs. Designs 1 and 3 were tested at 60°C, and Design 2 was tested at 25°C. All designs used Class G cement and were prepared with fresh water. The slurry rheologies were measured with a Fann 35 viscometer after mixing at ambient conditions and after 20 minutes of conditioning at the bottomhole circulating temperature (BHCT). The plastic viscosity (PV) and the yield value (Ty) were calculated using the Bingham plastic model. Thickening times of these systems were controllable, and no free water was observed. For all three designs, a compressive strength of 3.44 MPa [500 psi] was achieved in less than 48 hours, as measured using an ultrasonic cement analyzer. The compressive strengths of the designs ranged from 4.5 to 20 MPa.



^ Healing check. An SHC cell with two concentric cylinders simulates an annular volume. The outer cylinder, or ring, is a thin, steel sleeve (green). The inner cylinder (purple) is made of a deformable elastic material into which a radially expandable core assembly (gray) is inserted, allowing expansion of the inner sleeve in a controlled manner. Top and bottom plugs sealing the annular volume are equipped with fittings that allow fluid to enter and to escape the cell. With the inner cylinder expanded by a core assembly, the cement is injected into the annular space. Once the cement has set, the inner-cylinder expansion is released. The inner cylinder shrinks back to its original shape, generating a microannulus of a controlled size. Radial cracks within the cement are created by expanding the inner core assembly after the cement has set.



^ Test cell results. The SHC cell was installed in a flow loop to investigate FUTUR self-healing efficiency. Oil was injected through samples in the SHC cell at pressures up to 0.4 MPa [58 psi], corresponding to a differential pressure of 5.3 MPa/m [234 psi/ft] across the sample. In one test, a microannulus of 100 microns was created between the casing and the cement inside the SHC cell. The neat cement system (green) allowed oil to flow through the sample, whereas the SHC system (blue) responded to oil invasion with an efficient closure of the microannulus in less than 6 hours.

evaluate self-healing capability in an annular configuration (above). Oil was injected through samples to test both cracks and microannuli. In one test, a microannulus of 100 microns was created between the casing and cement inside the SHC cell. While a conventional cement system tested in this apparatus allowed oil to flow through the sample, the FUTUR system reacted to oil invasion with an efficient closure of the microannulus in less than six hours (above right).

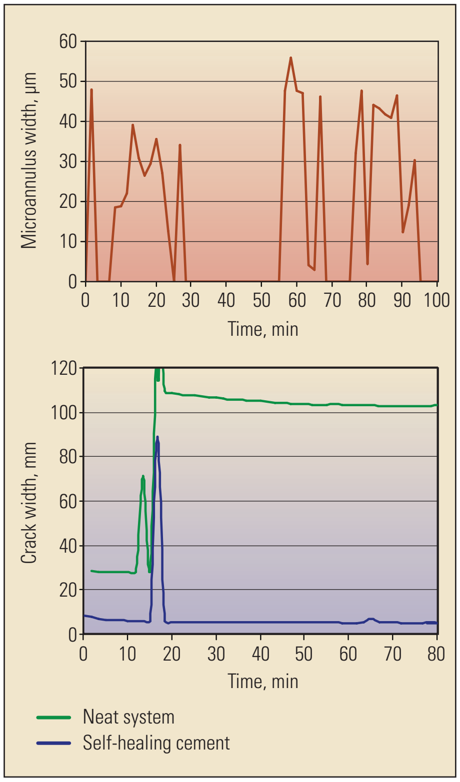
The self-healing system has also been tested in a cyclic failure scenario. Successive microannuli were created and repaired with the SHC at a differential pressure of 1.4 MPa/m [62 psi/ft]. Using the same flow loop, the flow of oil through successively generated cracks was repeatedly shut off by the SHC. The same test using a conventional neat cement system did not show any decrease in flow (next page, top left).

FUTUR cement also can handle oil flows at higher pressure. A pressure increase to 3 MPa/m [133 psi/ft] did not diminish the self-healing capabilities of the system, which maintained integrity and continued to block the flow of oil at high pressure. The tests were repeated with differential pressures up to 5.3 MPa/m, and the cement's self-healing property was confirmed in every test.

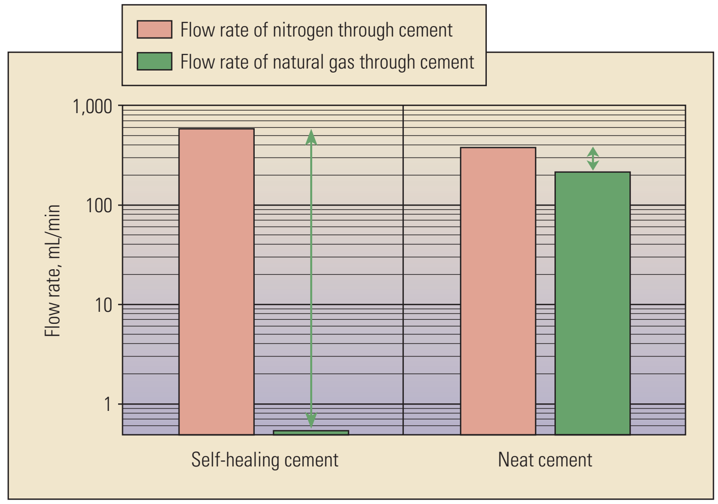
A specialized testing system was devised to study self-healing properties in dynamic conditions with dry gas under realistic reservoir conditions. Test results highlighted the efficiency of the FUTUR system when exposed to natural gas under dynamic conditions. In less than one hour, the self-healing cement caused a significant decrease of flow rate from 425 mL/min [26 in.^{3}/min] to 0.52 mL/min [0.03 in.^{3}/min] (next page, top right).

Finally, researchers investigated the durability of the self-healing cement. The durability—or aging—test consisted of two parts. The first part, using a swelling test, was to check that the self-healing property is maintained over time. The second was to evaluate whether matrix integrity is maintained when the cement is immersed in oil for a long period of time.

Swelling tests performed after prolonged immersion of FUTUR cement in water confirmed that the self-healing properties were maintained. In this test, cement placed in an expansion cell was cured in water for several months, then immersed in oil at 60°C. Results showed that the reactivity of the self-healing matrix remained effective even after resting dormant for a year. Testing of the matrix integrity, after one year of exposure in oil, also showed no indication that the integrity of the matrix was deteriorating. The mechanical properties remained within the same range even after immersion in oil for a year.



^ Repeated healing. The self-healing systems were also tested in a cyclic failure scenario. Successive microannuli were created and repaired with the SHC system (*top*). At a differential pressure of 1.4 MPa/m, the flow of oil through successively generated cracks was repeatedly shut off by the SHC system, while the same test using a conventional system did not show any decrease in flow. At increased pressure, the FUTUR slurry design reacted to stop the invasion of oil through a 100-micron crack in less than 20 minutes (*bottom*).



^ Testing SHC with gas flow. SHC seals in the same way for hydrocarbon gas as it does for oil. A test cell containing cement was cured in such a way that a microannulus of an arbitrary size was present. With SHC in the holder, the flow rate through the cement drops significantly in less than one hour from the time the fluid was switched from inert nitrogen to natural gas (*left*). Traditional cement tested in the same fashion experienced almost no loss of flow rate in that time (*right*). The specialized testing system is based on a Hassler sleeve-type core holder to prevent gas passing around the outside of the core.

Surface Solutions

The self-healing nature of FUTUR cement over time, as demonstrated in the laboratory, makes it particularly well-suited for long-term zonal isolation. That same ability also means SHC is a good solution for immediate or chronic gas-migration problems.

For instance, because of highly varied geology and several shallow, gas-bearing coal seams, wells in the foothills of the Rocky Mountains of Alberta, Canada, present a particular set of cementing challenges. The coal seams may emit gas that eventually migrates through the casing annulus and manifests as surface casing vent flows (SCVF). Depending on the extent of the leak, operators may be required to shut in, repair or even abandon their afflicted wells. Remediation of SCVF on these wells costs from US $250,000 to $1 million per well—a figure that does not include the loss in production or potential loss of the well.[14]

To address the problem, the operator of a deep gas field in the west-central Alberta Grande Cache area turned to FUTUR cement technology for zonal isolation in two new wells. The self-healing system was chosen to complement cementing practices implemented to reduce the risk of SCVF, which occurs in approximately 10% of Grande Cache area wells.

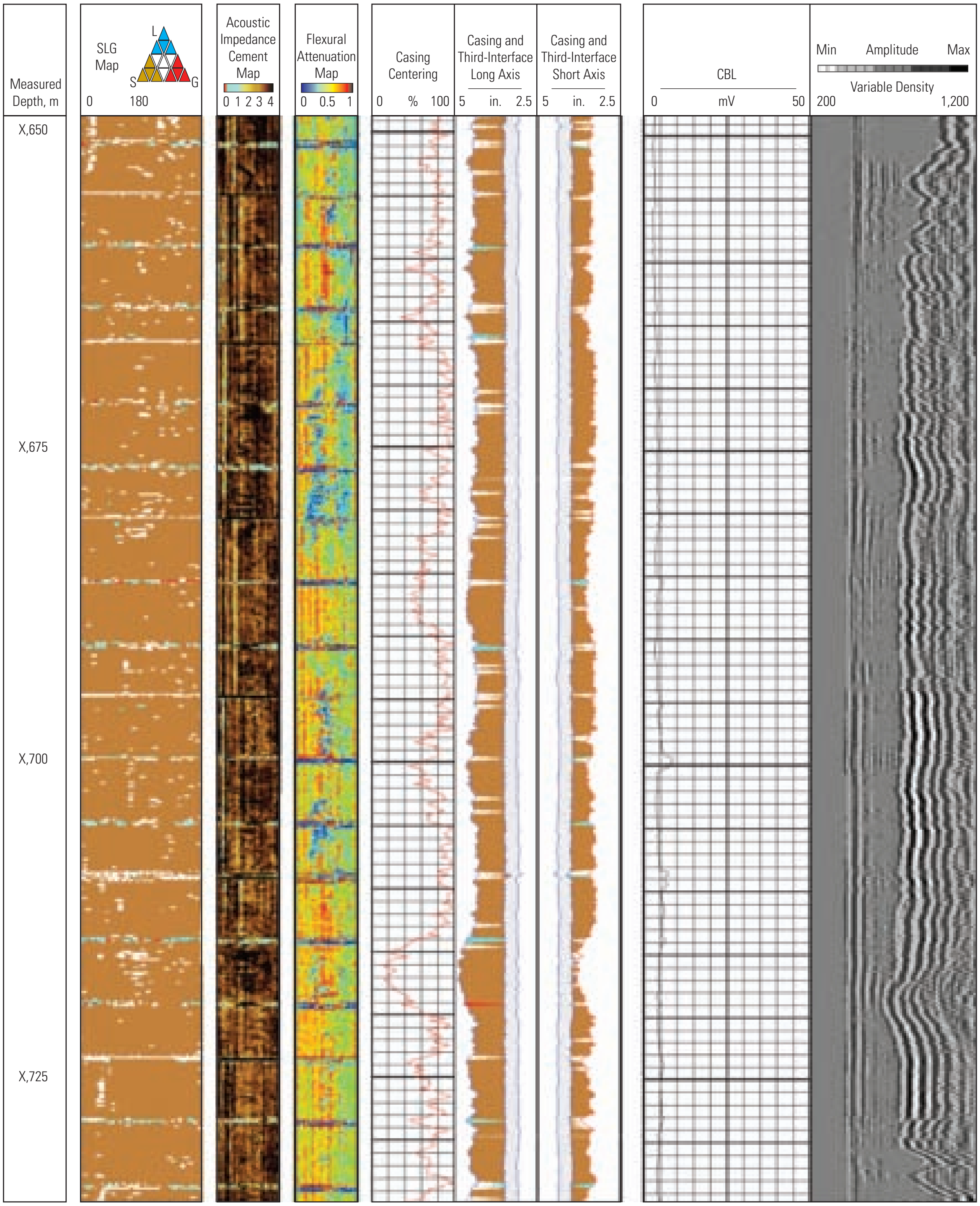
Both Well 1 and Well 2 required cement to the surface. The operator had a particular concern about Well 1; a similar well located about 500 m [1,640 ft] away had experienced SCVF. Losses encountered while drilling Well 2 required the use of a stage tool to ensure cement placement to the surface across known nuisance gas zones.[15] The SHC slurries were mixed and pumped using standard oilfield equipment, easily achieving continuous mixing rates of up to 0.95 m^3/min [6 bbl/min].

Immediately after cementing of Well 1, some gas pressure was observed in the intermediate casing annulus. However, gas pressure was not evident after the well's completion, suggesting that the SHC had activated to contain a leak. Well 2 displayed no leaks in the 12 months following cementing operations. While that may seem a short observation period, SCVF in this area typically occurs within days or weeks of the cementing operation.

During completion and production, the two wells were subjected to various downhole stresses, including downhole pressure of 64 MPa [9,282 psi] applied to test the completion and stresses related to cyclical temperature changes caused by a heater string in the top 600 m [1,968 ft] of the well. Throughout and after these events, no surface casing vent flows were detected.

Elsewhere in central Alberta, another field was also plagued by SCVF from zones above the target formation. To complement other cementing technologies already in use, the operator selected FUTUR self-healing cement for use in two wells. In the first, cement density was constrained to a maximum 1,380 kg/m^3 [11.5 lbm/galUS] because fluid losses had been observed during drilling. With a nearly opposite problem on the second well—nuisance gas detected by mud loggers during drilling—drilling fluid density was increased to 1,470 kg/m^3

14. Roth J, Reeves C, Johnson CR, De Bruijn G, Bellabarba M, Le Roy-Delage S and Bulte-Loyer H: "Innovative Hydraulic Isolation Material Preserves Well Integrity," paper IADC/SPE 112715, presented at the IADC/SPE Drilling Conference, Orlando, Florida, March 4–6, 2008.
15. Cementing stage tools allow slurry to be placed at specific depths along the casing through sliding sleeves. They are used when the hydrostatic pressure of the full column of cement threatens to overcome the wellbore fracture gradient beneath the stage tool.



^ Analysis of cement evaluation logs in the Cortemaggiore 155dir underground gas-storage (UGS) well. The brown color of the SLG map (Track 1) of the ultrasonic flexural attenuation logging tool indicates solid (cement), resulting from a measured acoustic impedance (Track 2) of about 5 Mrayl (close to the expected cement value) and high flexural attenuation. The CBL (Track 7) is in agreement, showing 100% casing to cement bonding (average CBL value of 5 mV) and strong formation arrivals on the VDL (Track 8), which is an indication of excellent cement-to-formation bonding. The optimal cement bonding is also related to the fact that the liner is fairly well-centralized, as shown by casing centering (Track 4) and third interface short- and long-axis outputs (Tracks 5 and 6). The casing centering curve is above 80% for most of the interval shown except near a depth of X,720 m, where the casing nearly touches the formation. This is also indicated in the vanishingly small cement thickness along the short axis. The horizontal features visible on the SLG map, cement map and flexural attenuation map (Track 3) are the casing joints about every 14 m [45 ft] and two casing centralizers per joint. Together the logs show optimal cement bonding to the casing and to the formation, providing assurance of effective hydraulic isolation across the permeable injection zones of the UGS well.

[12.25 lbm/galUS]. This meant cement density for that well had to be increased to 1,550 kg/m^3 [12.9 lbm/galUS] to meet the requirements of the mud-removal plan.[16]

Zonal isolation was achieved with the new cementing system in both wells despite difficult conditions—a low-pore-pressure zone in Well A, and a narrow pore-pressure-fracture window across a gas-influx zone in Well B. Cement returns to the surface in Well A also demonstrated that SHC can be applied in a single-stage cement job in wells prone to lost circulation. During and after subsequent drilling, stimulation and completion operations, there was no indication of annular gas flow.

Gas Storage

Sustaining self-healing characteristics over time holds special attraction for engineers charged with sealing underground gas-storage (UGS) wells. Because these wells are used to both inject and produce, the wellbores are repeatedly subjected to considerable temperature and pressure changes—often in short cycles—that can induce stress-load changes on the casing and cement.

Additionally, in contrast to producing wells that have a life expectancy of perhaps 20 years, UGS well plans are likely to include a production-injection life span of 80 years or more. As a consequence, zonal isolation failure in underground gas storage wells is a significant and ongoing operator concern (see "Intelligent Well Technology in Underground Gas Storage," *page 4*). In many UGS facilities, poor hydraulic isolation is caused by drilling fluid channeling as a result of eccentric casing or through the development of a dry microannulus.[17]

A combination of these factors had historically resulted in poor zonal isolation in UGS wells in an Eni S.p.A.-operated, depleted gas field in northern Italy. The challenges facing Eni and Schlumberger engineers included obtaining seals across gas-injection zones and gas-tight cement sheaths across deviated (49°), washed-out sections.

For a new well in this field, Eni subsidiary Stogit chose to cement the production casing with FUTUR self-healing cement. The plan also included proper placement of centralizers, a gas-migration analysis software package and Isolation Scanner logging tools to evaluate the cement bond.

The solution to persistent problems of sustained casing pressure in UGS wells drilled in this area involved a multipronged approach:

- more centralizers to improve standoff
- a liner across the zone of interest to facilitate casing rotation during cementing
- use of a software advisor tool for gas-migration prediction and prevention during cement hydration
- software to tailor the cement system to associated risk
- use of FUTUR SHC
- a full suite of postcementing logging tools that included all ultrasonic and flexural-wave measurements.

In 2007, the SHC cementing operation was performed on the Cortemaggiore 155dir UGS well. The team used a computer-aided design and evaluation software program that optimized mud removal and standoff, and fine-tuned the spacer and slurry characteristics. A separate software program was used to evaluate the risk of the severity of gas migration based on the pressure-decay limit—a measurement of how far the hydrostatic pressure of the slurry will fall during hydration before it is below the pore pressure and might allow gas migration into the annulus.

Finally, a mechanical-stress modeling software tool that simulated pressure and temperature variations during the life of the well was used to evaluate cement sheath integrity over time. The software modeled the three mechanisms of cement sheath failure—traction, compressional failure and both internal and external microannulus development.

Once the cement was placed, CBL-VDL and Isolation Scanner tool analyses all indicated optimal cement bonding at the casing and formation interfaces (previous page). The ultimate success of the SHC system is being monitored over time as gas is cyclically injected into and produced from the well.

In another recent FUTUR cement application, the technology was applied in environmentally sensitive areas of the Canadian Rocky Mountains. Following the suspension of drilling because of surface casing leaks and resulting environmental concerns, one US operator reevaluated its well construction procedures in the area and then resumed operations. Despite the revised strategy, three of seven wells drilled had obvious gas leaks while the other four were suspect; possible leaks were masked by heavy cement poured around the casing at the surface. The company then added FUTUR cement to its drilling and completion program. Of the 13 area wells drilled and completed since then, only two wells had detectable leaks; one was due to an operational failure unrelated to the SHC and a second was barely detectable.

Time Will Tell

Long-term performance of its self-healing characteristics is key to the success of FUTUR cement. Laboratory work shows that this SHC will continue to close the pathways through which gas migrates without intervention throughout the life of the well and beyond. In time, operators pressured by environmental regulators—internal and external—will insist that the cement sheaths in their wells prevent hydrocarbons from escaping formations long after the well has been plugged and abandoned. The ability of FUTUR cement to react to and repair the channels through which formation fluids travel to the surface makes it an ideal answer to such demands.

Operators, especially those in gas-migration prone areas, will also come to expect an improved view behind casing to eliminate other costly zonal isolation tests in the face of conflicting or ambiguous CBL-VDL logs. In drilling environments with proximate pore pressures and fracture gradients, lightweight cements that pose a significant challenge to traditional sonic logging tools are required. The Isolation Scanner tool offers a clear solution to these and other current zonal isolation challenges. —RvF

16. Cavanagh et al, reference 2.

17. Moroni N, Panciera N, Zanchi A, Johnson CR, LeRoy-Delage S, Bulte-Loyer H, Cantini S, Belleggia E and Illuminati R: "Overcoming the Weak Link in Cemented Hydraulic Isolation," paper SPE 110523, presented at the SPE Annual Technical Conference and Exhibition, Anaheim, California, USA, November 11–14, 2007.