Evaluating and Monitoring Reservoirs Behind Casing

Advanced formation-evaluation services help accurately determine porosity, resistivity, lithology, shale content, fluid saturations and pressure, and recover formation-fluid samples in cased wells. Innovative tool designs and processing software make formation evaluation behind casing a viable option to evaluate bypassed zones and intervals that must be cased before openhole logs are run. Cased hole data reveal the effects of time on producing zones. Exploration and production companies now are able to obtain cost-effective, useful data in difficult operating environments.

Imagine trying to read a newspaper in a dark room, or to sense with your hands the temperature of a baked potato or the texture of a rock while wearing insulated gloves. Measuring rock properties using logging tools is equally difficult when the formation is on the other side of steel casing and cement. Significant software and tool developments now make possible rigorous evaluation of formations behind casing.

Advanced formation-evaluation services help exploration and production (E&P) companies search for additional or initially unrecognized zones and identify bypassed hydrocarbons after casing is set. These innovative, cased hole wireline services facilitate determining porosity, lithology, shale content, fluid saturations and pressure. A state-of-the-art testing tool recovers formation-fluid samples from cased holes. The ABC Analysis Behind Casing suite of services offers a robust, cost-effective method for E&P companies to analyze or monitor formations in wells that are already cased.

Whether dealing with aging fields or new discoveries, cased hole services bolster effective decision-making. For example, ABC services provide backup logs when openhole logging is too risky. The tools also offer valuable data when looking for bypassed pay in older wells or when monitoring saturation, depletion and pressure to optimally manage oil and gas fields.

In this article, we review cased hole formation-evaluation tools and examine their effectiveness in operations in Canada, Ecuador and the Norwegian North Sea.

Evaluation Between a Rock and a Hard Place

Given the choice, many operators prefer evaluating formations that are not yet cased. There are many instances, however, when the risk of openhole logging is too great, or when it makes economic sense to conduct logging operations after drilling operations have ceased and the drilling rig has been released. For example, in a multiwell drilling campaign, some operators prefer
to case all the wells and evaluate them afterwards. There also are existing wells and fields in which the potential rewards behind casing are too rich to bypass.

In mature fields, commonly known as brownfields, operators reevaluate zones that might have been logged decades ago using only gamma ray, spontaneous potential and resistivity devices. In other situations, wellbores might penetrate formations that were not logged at all. New measurements facilitate formation evaluation no matter how old the well is. Typically, the cost of acquiring data from these cased holes is far less than that of drilling a new well solely to gather data. The risk of cased hole logging operations is also substantially less than that of drilling operations.

When drilling new wells, operators occasionally encounter formations in which openhole-logging conditions are difficult. Rather than risk losing tools due to sticking in these formations, operators may opt for cased hole formation evaluation, or they may acquire cased hole logs to complement logs acquired while drilling. In areas where openhole logging is difficult, operators save time and money and optimize their formation-evaluation programs by planning cased hole logging operations ahead of time.

Cased hole logging also helps operators evaluate the effects of production, such as the movement of fluid contacts, changes in saturation and pressure, and depletion and injection profiles. An integrated suite of new and not-so-new tools makes these types of evaluations possible and cost-effective.

Formation Evaluation Behind Casing
Several key elements contribute to effective formation evaluation behind casing. A thorough understanding of the condition of the casing and cement is a prerequisite for successful evaluation. A cement-evaluation log, ideally a combination of USI UltraSonic Imager and CBT Cement Bond Tool data, reveals any anomalies in the cement sheath that might affect results from through-casing formation-evaluation tools. Of course, the diameter of the wellbore and completion configuration influence logging-tool selection.
Skilled log interpreters incorporate completion details—wellbore geometry, tubulars, inclination angle and any downhole restrictions—and the well-log data into production estimates and recommendations for perforating or other procedures, such as stimulation treatments. These recommendations stem from a detailed description of the formation—porosity, lithology and fluid saturation—derived from density, gamma ray, neutron, resistivity, sonic and spectroscopy data. Fluid-mobility data from cased hole testers complement the petrophysical analysis. Time-lapse evaluations require two sets of these data.

Many ABC services are available to meet diverse customer requirements (below). To evaluate saturation, the CHFR Cased Hole Formation Resistivity tool applies groundbreaking technologies for deep-reading resistivity measurements beyond steel casing. The new CHFR-Plus Cased Hole Formation Resistivity tool offers enhanced hardware and measurement techniques that improve the operational efficiency of cased hole resistivity measurements. Both tools operate in a similar way, by introducing current into the casing. A voltage drop occurs as a small amount of the current escapes into the formation. The voltage drop is proportional to formation conductivity, allowing calculation of formation resistivity.

Commercially available since 2000, the original CHFR device has proved its value worldwide for applications such as evaluation of bypassed pay, reevaluation of old fields, reservoir and saturation monitoring and primary evaluation of wellsbores cased before complete formation evaluation. The CHFR-Plus tool, introduced in 2002, offers similar measurement capabilities, but at twice the speed of the CHFR device, because of a new measurement technique. To date, the CHFR and CHFR-Plus tools have performed more than 800 logging jobs.

The RSTPro Reservoir Saturation Tool for the PS Platform string also helps determine saturation. Formation sigma measurements are most effective in high-salinity formation fluids for water-saturation answers. As part of the RSTPro service, SpectroLith lithology processing of spectra from neutron-induced gamma ray spectroscopy tools quantifies lithology interpretations. Carbon/oxygen logging, commonly known as C/O logging, can give saturation results in fresh water and in waters of unknown salinity, for example in zones where there is ongoing water injection and the salinity of the injected water differs from that of the original water in place. When made more than once on a given reservoir, saturation measurements from the CHFR and RSTPro devices are key elements of time-lapse monitoring for reservoir management.

To complement saturation analyses, the CHFP Cased Hole Formation Porosity tool measures formation porosity and sigma. This tool has an electronic neutron source, also known as a minitron, eliminating the need for a chemical source. Borehole shielding and focusing allow petrophysicists to perform environmental corrections. The CNL Compensated Neutron Log device also may be run in cased holes, but requires more extensive environmental corrections because it lacks the borehole shielding and focusing of the CHFP device.

The CHFP Cased Hole Formation Density tool uses a new characterization of the three-detector density device incorporated in the Platform Express tool specifically for cased hole operations.

The DSI Dipole Shear Sonic Imager tool provides accurate measurements of formation compressional transit times—used to establish porosity and as a gas indicator. The tool also measures shear slowness—key for evaluating mechanical properties such as wellbore or perforation stability, hydraulic fracture-height prediction or sanding analysis. DSI results can also be used to determine stress anisotropy, a key component for oriented fracturing. The data also contribute to geophysical interpretations using synthetic seismograms, vertical seismic profiles and amplitude variation with offset analysis. Fully combinable with other cased hole logging tools, the DSI device operates at logging speeds up to 3600 ft/hr (1100 m/hr). Prior to running the DSI tool, it is crucial to evaluate cement integrity because a high-quality cement sheath improves the quality of DSI results.

The CHDT Cased Hole Dynamics Tester tool is a unique tool that measures multiple pressures and collects fluid samples behind casing. The tool drills a small hole through casing and cement and into the formation. After measuring pressure and collecting fluid samples, the tool plugs the hole drilled through the casing. The device has been used to drill more than 300 holes and has a success rate of more than 91% when the operator has chosen to plug the test hole. CHDT operations
offer a cost-effective method to optimize recompletion plans, enhance old or incomplete log data, assess pay zones and evaluate wells for their economic potential. The tool also can be used to monitor flood fronts and measure their effectiveness in secondary-recovery operations.

Customized software, known as the ABC Composer, helps log interpreters prepare meaningful composite log presentations. The software can incorporate PDS and ASCII files.  

Thorough prejob planning is essential for successful ABC services. Job preparation includes a bit and scraper run to clear debris from the wellbore. Wellbore conditions affect certain tools more than others. For example, in the presence of corrosion, the CHFR tool is susceptible to poor electrical contact with the casing. USI and CBT logs identify potential casing corrosion, so running these tools before deploying the CHFR device is recommended practice.

Contingency Logging in Norway  
To develop the Snorre field, located in the Tampen area offshore Norway in the North Sea, Statoil and its partners are drilling development wells from two platforms (right). In the Norwegian sector, this field is second in size only to the Ekofisk field. Thanks in part to continual application of new technology, the Snorre field has been producing oil and gas for more than a decade. Horizontal production wells drain several complex reservoirs by water-alternating-gas (WAG) injection. WAG injection creates distinct pressure regimes in separate reservoir compartments. Understanding these pressure regimes is critical to effective reservoir management.

In a Snorre injection well with deviation of 63° from vertical, logging-while-drilling (LWD) measurements were acquired from 4070 to 6300 ft with a 100-ft vertical resolution. The reservoir is a cratonic, low-relief structure consisting of sandstones, siltstones, and marls, with minor carbonate. The reservoir pressure is 10,000 psi, and the temperature is 120°F. The Snorre reservoir is a gas cap on top of a mini oil column. The oil column is overlain by a gas cap topped by a large marine shaliness that is impermeable to oil. The top of the reservoir is a fault block that is sealing and confining the oil and gas volumes. The reservoir pressure is maintained by continuous gas injection from the Grampian High. The reservoir is drained by a horizontal production well that has produced more than 300 MMBOE. The Snorre field has been producing oil and gas for more than a decade. Horizontal production wells drain several complex reservoirs by water-alternating-gas (WAG) injection. WAG injection creates distinct pressure regimes in separate reservoir compartments. Understanding these pressure regimes is critical to effective reservoir management.

2. The CHFR-Plus device introduces current on the side of the casing opposite where current is flowing to reduce the sensitivity of the measurement to the resistance of the casing. Also, the calibration step for this device occurs at the same time as the formation-resistivity measurement, saving additional time.
3. Sigma is the macroscopic cross section for the absorption of thermal neutrons, or capture cross section, of a volume of matter, measured in capture units (c.u.). Sigma also refers to a log of this quantity. Sigma is the principal output of the pulsed neutron capture log, which is mainly used to determine water saturation behind casing. Sigma typically increases as water saturation increases, or as oil saturation decreases. For more on pulsed neutron cased hole logging: Albertin I, Darling H, Mahdavi M, Plasek R, Cedeño I, Hemingway J, Richter P, Markley M, Olesen J-R, Roscoe B and Zeng W: “The Many Facets of Pulsed Neutron Cased Hole Logging,” Oilfield Review 8, no. 2 (Summer 1998): 29–41.
7. Picture Description Script (PDS) is a proprietary Schlumberger graphics format for displaying log data. American Standard Code for Information Interchange (ASCII) is another industry standard for computer data formats.
Additional measurements from the DSI, MDT Modular Formation Dynamics Tester and Platform Express tools using the TLC Tough Logging Conditions system were originally planned for the entire openhole section. The Platform Express integrated wireline logging tool, the DSI device and the MDT tool were run in combination to acquire openhole data and three formation pressures. The MDT pressure measurements were sufficient to characterize the pressure regime in the upper reservoir section. This Snorre well was not considered high risk, but the logging tools reached a depth of just 4440 m [14,568 ft] because of hole problems, measuring only 50 m [164 ft] of the reservoir interval and leaving a critical 380-m [1247-ft] interval through the remaining reservoir section without porosity logs of any type.

The operator decided to set casing and deploy an ABC tool suite to obtain the required data. This ABC logging program, which was the first use of the ABC suite, included the USI, CBT and GPIT General Purpose Inclinometry Tool devices to evaluate cement quality across the interval (left). The CHFD, CHFP, DSI and GPIT devices were run for formation evaluation. The operation was planned and executed without problems, and the data were transmitted using the InterACT real-time monitoring and data delivery system for processing by Schlumberger Data & Consulting Services in Stavanger, Norway, and New Orleans, Louisiana, USA, and the Schlumberger-Doll Research Center in Ridgefield, Connecticut, USA. The cased hole logs closely match the openhole logs in overlapping intervals.

The operator characterizes certain wells as high-risk because the time between drilling and achieving zonal isolation of the reservoir units is critical. Time spent running openhole logs—primarily the MDT device for pressure data—allows borehole conditions to deteriorate, sometimes to the degree that the casing cannot be run successfully or cement quality is suboptimal and zonal isolation cannot be achieved. To eliminate this problem, the operator selected the CHDT service to obtain formation pressures through casing and cement.

4820 m [13,353 to 15,814 ft].
To date, three CHDT jobs have been completed in the Snorre field; additional jobs are planned. These have been some of the most challenging tractor-conveyed CHDT wells in the world.\(^9\) The first Snorre well in which the tool was run was highly deviated—approximately 83°—and, therefore, the first ever tractor-conveyed CHDT operation. It also was the first commercial use of the CHDT tool in the Snorre field. The second well was the first CHDT job in a horizontal well—in this case, a well with a 95° deviation. At 1460 kg [3219 lbm], the tool string for that job, which included both pressure and sampling modules, remains the heaviest conveyed by tractor to date. Recently, the first dual-probe CHDT tool string was run in a Snorre well to maximize the number of test points in a single trip. Valuable formation-pressure data have been obtained from these three CHDT operations. The main lesson learned is that good cement quality is crucial for a proper and reliable CHDT formation-pressure interpretation.

For high-risk Snorre production wells, formation-pressure data help establish uniform pressure zones in the completion design and optimize the completion-fluid weight. Without pressure data, completion-fluid weight is based on the maximum pore-pressure prognosis for well control. If the reservoir pressure is considerably lower than this prognosis, the well will not flow, which delays production. In addition, the well will require an intervention for stimulation operations, which cost more than USD 1 million in rig time alone.

Pressure data in the high-risk injection wells are vital for confirming communication between injection wells and production wells located in the same fault block. If the reservoir pressure in a newly drilled injector is at initial pore pressure, then the injector is not in communication with producing wells and will not increase oil recovery. A new injector is required—at a cost of approximately USD 10 million—to sweep hydrocarbons from the producing reservoir.

**Formation Evaluation Behind Casing in Canada**

In the Caroline field of Alberta, Canada, Big Horn Resources, Ltd. (now part of Enterra Energy Corp.), drilled the 11-26-34-7 well to test two potential hydrocarbon zones (previous page, top). A downhole bridge prevented openhole logging tools from accessing the bottom 50 m of the well, which was the location of the primary objective. The secondary objective was evaluated using openhole resistivity and porosity logs.

Big Horn Resources wanted to evaluate gas-detection indications from mud logging, but had to run casing because of poor wellbore conditions for openhole logging. The company planned to gather additional reservoir information by logging behind casing, deploying the USI and CBT tool combination to assess cement quality, the DSI and CNL tools to determine porosity, the CHFR tool to evaluate fluid saturations and the CHDT device to acquire formation-fluid samples and pressure measurements.

The primary and deeper objective—the Elkton carbonate formation in the bottom zone at XX00 m—proved to be nonproductive on the basis of ABC results (above). The CHFR resistivities, combined with porosity measurements

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10. A tractor is a device used to convey equipment in wells beyond the point where gravity alone would help the equipment reach the bottom of the hole.
from the sonic and neutron tools, indicated high water saturation, and since there was no gas indication from the neutron and sonic combination, this zone was abandoned.

The secondary, upper zone at XX75 m, a Cretaceous sandstone of the Mannville Group, the Rock Creek formation, was expected to be gas-bearing; its productivity was evaluated with a CHDT sample (above). The CHDT fluid sampling confirmed the presence of hydrocarbon in this zone. On the basis of fluid-mobility estimates (the ratio of permeability to viscosity in units of mD/cp), however, the potential mobility of the fluid was uncertain, but considered likely to be low. Big Horn Resources elected to perforate this zone using tubing-conveyed perforating technology. Pressure-transient measurements from a flow test confirmed the low mobility estimate from the CHDT device, so the company abandoned the upper zone. (next page, top).

The experience of Big Horn Resources demonstrates that formation evaluation behind casing can be a viable alternative to openhole logging when wellbore conditions make openhole logging difficult and increase the risk of sticking logging tools in the hole while performing these operations. For operators deciding whether to perform expensive operations, such as well completions, stimulation or testing operations, on the basis of incomplete formation evaluations, ABC services are a cost-effective alternative.

Formation Evaluation in Ecuador
Openhole logging operations in the Dorine field, Oriente basin, Ecuador, are risky and often expensive because of borehole-stability issues. The field is in development, so the operator, AEC Ecuador Ltd. (now Encana Corporation), is emphasizing rig efficiency and minimizing capital and operating expenses. AEC decided to acquire cased hole logs for a well in which openhole logs had been acquired several months earlier. By comparing openhole and cased hole logs, the operator sought to gain confidence in an evaluation technique that would help reduce field-development costs. Rather than spending time and money acquiring suboptimal openhole data from difficult wells, the operator was considering acquiring only cased hole logs in future wells. Cased hole density, porosity and sonic data closely matched openhole data (next page, bottom).

Several conditions led to the high quality of the cased hole data. The operator and Schlumberger performed extensive prejob planning to ensure that the well was a suitable candidate for ABC services. Specifically, engineers checked the condition of the cement sheath to ensure that the well was an appropriate candidate for using the CHFP, DSI and CHFD devices. The USI and CBT tool used in combination indicated the cement quality was generally good. Corrosion can be a particular concern when using the CHFR device in older wells, but the casing in this well was new.

As operations began, the wellsite crew ran scrapers in the wellbore to remove cement stringers or scale that might interfere with cased hole data acquisition. Data were transmitted to

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Schlumberger Data & Consulting Services in Quito in real time using the InterACT service. This example from the Dorine field demonstrates that logging after setting casing is a cost-effective method of formation evaluation when borehole stability presents unacceptable risks.

ABC services have been used elsewhere in Ecuador. For example, an operator selected the CHFR device to reevaluate saturation in a zone of interest in which openhole logs indicated a relatively high water saturation; the CHFR results indicated a lower water saturation. The ABC services also have proved to be a critical part of the candidate-recognition process to evaluate wells for PowerSTIM well optimization services. ABC results helped determine Young's modulus, Poisson's ratio and the formation-fracture gradient, which are crucial inputs for optimizing the design of the hydraulic fracturing operations.

ABC services also have been used in wells that had to be cased before openhole logs were acquired.

Staying Ahead Behind Casing

As more E&P companies emphasize brownfield activity, formation evaluation behind casing will become more essential as a cost-effective method to optimize production. ABC services, including interpretation support, allow companies to acquire and interpret data and then make informed decisions, such as sidetrack drilling, offset drilling, well interventions, wellbore or field monitoring, and other operations.

ABC services make it possible for E&P companies to obtain well logs in situations that previously would have impeded or prevented data acquisition. In adverse wellbore conditions, such as wells experiencing borehole-stability problems, operators now can decide to run casing and conduct logging operations afterwards using the ABC services. For older fields, operators may use these services to evaluate potential pay behind pipe rather than drill a new well simply to acquire data. Producing wells and fields are easily monitored using ABC tools. In many situations, planning these operations ahead of time minimizes rig-time costs. Perhaps the only obstacles to successful data acquisition with these tools are well accessibility and the condition of the casing, cement and well-completion hardware. As service companies and E&P companies gain familiarity with comprehensive formation evaluation through casing, they will continue to seek first-class answers to questions about ever-changing reservoirs. —GMG

^ CHDT results from Caroline field, Canada. This plot of CHDT pressure versus time shows a complete test cycle, beginning with the casing-seal test, drilling into the casing, performing multiple formation pretests and plugging the casing. The pressure changed as soon as the tool drilled through the casing, which is typical for this region. The USI log in this well revealed the existence of cement channels in the zone, which might have influenced the pressure response. The test required more than four hours to complete because of the low permeability of the zone. An openhole formation test of similar duration would present a higher risk of sticking the tool. In this case, the logging tools were run from a service rig, which cost much less than a drilling rig.

^ Comparison of openhole and cased hole density, porosity and sonic data. Openhole and cased hole data (Tracks 2 and 3) match closely.