Resistivity Behind Casing

Hydrocarbon detection and saturation evaluation have long been a problem in cased holes. After 60 years of dreams and designs, measuring resistivity behind casing is now a reality.

In their quest to improve field productivity, extend field life and increase reserves, oil companies need to be able to identify bypassed hydrocarbons, track changes in saturation and detect movement of reservoir-fluid contacts. Many of the world’s remaining discovered oil and gas reserves are contained in old fields that were discovered from the 1920s to 1950s. In those days, hydrocarbons were commonly detected solely through openhole electrical surveys—often the only logging measurement available. Even today, resistivity logs are still the most widely used measurement for evaluating reservoir saturations and distinguishing hydrocarbon- from water-bearing zones in open holes. However, tracking saturation changes in older reservoirs requires making measurements through steel casing, which had not been possible with earlier resistivity tools.

Now, 60 years after it was first imagined, accurate and reliable measurement of cased-hole formation resistivity is not only possible but available as a standard service. The considerable design and measurement hurdles involved with measuring formation resistivity behind steel casing have been overcome (see “History of Cased-Hole Resistivity Measurement,” page 12). With the aid of innovative electronics, Schlumberger engineers have developed a system that makes an earlier design work.

As with openhole measurements, cased-hole resistivity and nuclear porosity measurements can be combined to provide enhanced saturation evaluation. In addition to reservoir monitoring and identifying bypassed pay, this service provides a resistivity measurement in high-risk wells where openhole logs cannot be run because of borehole conditions or when tool failure prevents successful data acquisition.

This article reveals how the new tool works, how its design overcomes previously insurmountable obstacles to obtaining resistivity behind casing, and limitations of the technique. Field examples demonstrate how well the new measurement matches results from openhole logging tools and how the tool is being used to monitor saturation changes and fluid contacts.
**Principle of Measurement**

The CHFR Cased Hole Formation Resistivity tool is effectively a laterolog, that is, an electrode device that measures voltage differences created when an applied current flows into the rocks around the borehole. The usual way to compute formation resistivity $R_t$ from a laterolog tool requires measuring both emitted current $I$ and tool voltage $V$. To obtain resistivity, the ratio of these two is multiplied by a constant coefficient known as the tool K-factor, which depends on the geometry of the tool itself: $R_t = KV/I$. The CHFR measurement is somewhat more complicated due to the presence of steel casing, but it still comes down to determining $R_t$ from $V$ and $I$.

Openhole laterologs use electrodes to focus the applied current deep into the formation. A significant difference in the physics governing the cased-hole measurement is that the borehole casing itself serves as a giant electrode directing the current away from the wellbore.

Current follows the path of lowest resistance to complete an electrical circuit, and when the option is to pass through low-resistance steel or through the earth, most of the current will flow through the steel. A high-frequency alternating current (AC) will stay almost entirely within the steel, but at low-frequency AC—or with a direct current (DC)—a small part of the current leaks into the formation.

To travel from the source in the tool to the electrical ground located at a surface return electrode, the current passes along the casing and leaks gradually into the surrounding formation, passing through the earth to the electrical ground. The leakage into the earth around the wellbore occurs over the entire length of the casing, so the amount of leakage within each meter is very small. The major challenge to measuring resistivity behind casing is measuring this tiny leakage current.

The way the measurement is made can be understood by following the current from the tool along the paths it takes to the electrical ground. The current electrode is in contact with the inside of the casing. Some of the current travels up the casing, and some travels down. The amount going each direction depends on the position of...
the higher the formation resistivity, the less current enters the formation—at higher formation resistivity.

As the current flows down the casing, a small part goes into the formation. The leakage can be described as a certain fraction of current decrease each meter. When the tool is near the surface, most of the current goes up the casing because it is the shortest—least resistive—path to ground, so there is little leakage into the formation. Through most of the casing length, the leakage is almost constant for low-resistivity formations, until the tool approaches the casing shoe at the bottom of the well. At that point, although the downgoing current decreases, progressively more of it leaks into the formation with each meter, until the last meter where all the downward current goes into that meter of formation, making the leakage quite high. In fact, current leakage is maximum at the casing shoe. This is usually an advantage, since most intervals of logging interest are located near the bottom of the casing string.

The difficulty of measuring resistivity behind casing over the 60-year development period has been with the measurement itself. It is straightforward to measure the current passing down the pipe, because the tool design can include electrodes that contact the casing. It is impossible to directly measure the current flowing in the formation, because there is no access for electrodes there. The formation current must be inferred from the casing current by subtraction. An applied current of one ampere (A) yields leakage currents of a few milliamperes per meter, and even less for formations of higher resistivity. Finding a small quantity by taking the difference of two much larger ones is difficult, particularly when there is noise in the data.

The technical hurdles in measuring resistivity behind casing have been overcome by careful tool design and improved accuracy and precision of measurements. Downhole electronics now are precise and stable enough to determine formation resistivity behind conductive casing.

But how is the measurement made? The first stage of the measurement uses a source in the tool to apply low-frequency alternating current to the casing (next page, left). Four voltage electrodes lie below the injection point with a 2-ft [0.6-m] separation. Three of these are used in each measurement. The voltage drop between pairs of electrodes is a combination of losses due to leakage into the formation plus resistive losses in the casing. A second step, called the calibration step, is needed to determine the resistive losses in the casing.

The circuit in the calibration step starts at the same current-application point, but flows down the casing to a current electrode about 10 m [33 ft] lower on the tool (next page, top right). There is negligible leakage into the formation since the current does not need to flow through the formation to complete the circuit. With the same voltage electrodes as in the measurement step, the casing resistance can be determined. Thus, the formation resistivity can be obtained, essentially by difference of the two measurements. Alternatively, if the steel resistivity is known or assumed, then casing thickness can be derived—as the CPET Corrosion and Protection Evaluation Tool service does now.

The high resistivity contrast between the steel and the formation dictates the direction of current leakage into the formation—perpendicular to the casing—because the casing is essentially an equipotential surface. The tool is most sensitive to the resistivity of the formation near its voltage electrodes because the voltage measurements used to determine it are primarily affected by leakage radially into the formation immediately outside the casing.

Another step is required to obtain the casing voltage \( V_0 \). Extremely precise voltage measurements in the range of 10 to 100 mV are required (next page, bottom). They cannot be performed in alternating current like the measurement and calibration steps. In a separate sequence, direct current is sent from the top injector to surface polarization or drift. Since the voltage varies quite slowly with depth, one voltage measurement for 10 depth stations is usually adequate.

The surface reference electrode for the voltage calibration should be located as far as possible from the wellhead. However, this is not always possible or feasible in actual field operations. The inability to obtain sufficient distance for the reference electrode or good electrical contact between the surface electrode and the ground can adversely affect the quality of the
voltage measurement and ultimately, the reliability of the formation-resistivity measurement.

To overcome this difficulty, an empirically derived equation can estimate resistivity without a voltage measurement. When this method is used, the CHFR formation resistivities are apparent rather than absolute. One term of the equation compensates for the casing shoe, and a second term accounts for the geometry of the casing where the measurement is taken. While this formula is not universally applicable, it has provided satisfactory results in many cases. Even where it does not work, the general character of the resistivity curve is preserved but the entire curve is shifted from the actual resistivity curve. This is considered acceptable for the CHFR tool since an openhole reference log will often be available and will permit adjustment of the K-factor.

Calibrating CHFR logs with respect to openhole logs consists of adjusting the gain of the CHFR formation-current measurement (effectively the K-factor) to shift the cased-hole log onto the openhole log. Determining the proper shift requires knowing the resistivity of one layer, such as a shale or unperforated reservoir zone, whose resistivity has not changed since openhole logging.

The first step in the CHFR two-step principle of measurement. In the measurement step, low-frequency alternating current (AC) passes up the pipe to the surface and down the pipe through the formation to a surface return electrode. The tool measures the difference $\Delta I$ in downgoing current between pairs of voltage electrodes. At every station, three measurement electrodes contribute to one resistivity measurement (right side of figure). With four measurement electrodes available, two resistivity measurements can be made at a time. $V_0$ is casing voltage, and $V_1$ and $V_2$ are voltages measured in the formation between two pairs of electrodes. $R_c$ is casing resistance.

The CHFR calibration step with current passing only from the upper current electrode to the lower, yielding $\Delta R_c$, the difference in casing resistance between two measurement points.

<table>
<thead>
<tr>
<th>CHFR Measurement Components</th>
<th>Value (approximate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Differential voltage ($V_1 - V_2$)</td>
<td>5 to 500 nV</td>
</tr>
<tr>
<td>Upper, lower voltage ($V_1, V_2$)</td>
<td>20 to 100 $\mu$V</td>
</tr>
<tr>
<td>Casing voltage ($V_0$)</td>
<td>10 to 100 mV</td>
</tr>
<tr>
<td>Calibration current</td>
<td>0.5 to 3.0 A</td>
</tr>
<tr>
<td>Casing-segment resistance ($R_c$)</td>
<td>20 to 100 $\mu$ohm</td>
</tr>
<tr>
<td>Applied current ($I$)</td>
<td>0.5 to 6.0 A</td>
</tr>
<tr>
<td>Formation current ($\Delta I$)</td>
<td>2 to 20 mA</td>
</tr>
<tr>
<td>Downgoing casing-segment current ($I_{d}$)</td>
<td>0 to 3 A</td>
</tr>
</tbody>
</table>

Typical values detected during CHFR measurements.
Design and Measurement Challenges

The main objective in the design of the CHFR tool was to accurately and reliably measure formation resistivity behind casing, unaffected by casing-contact problems, cement layers and near-wellbore invasion fluids. Additional rigorous objectives were set for thin-bed detection: to determine resistivity boundaries, such as bedding, water-oil or oil-gas contacts, to within 1 ft [0.3 m], and to determine the resistivity-contrast ratio across the boundary to within 5%.

To design such a tool it was first necessary to resolve major technical challenges in three areas: physics, electronics and mechanics. The physical behavior of electrical current in a cased well is different from the openhole situation. Analytical work and modeling provided a good understanding of the physics and the best way to handle inherent sources of error and noise associated with electronic components. This work allowed resistivity logs to be derived from the raw measurements.

Typical formations have resistivities about 1 billion times higher than that of typical steel casing. However, because of the large volume of reservoir rock, the ratio of the formation current to the applied current falls in the range of $10^{-3}$ to $10^{-5}$, rather than $10^{-9}$. Since the wireline cable limits the total current that can be applied to the casing to a few amperes, typical formation currents are in the milliamperes range. Because the formation currents are measured through a drop in the casing resistance of a few tens of ohms, the CHFR measurement is made in the nanovolt range. The main design challenge was to develop tool hardware that could accurately measure nanovolts.

The CHFR Tool

The CHFR tool consists of a newly designed electronics cartridge, a current-injection electrode that also acts as a centralizer, four sets of measurement voltage electrodes, and a current-return electrode that also acts as a centralizer (left). The tool is 43 ft [13 m] long with a diameter of 3 3⁄8 in., which allows it to be run in 4 1⁄2 in. tubing and liners. Although the tool can be run through tubing, it cannot measure formation resistivity through tubing, only through a single string of casing. The tool can be run in holes with up to 70° deviation using an extra centralizer, or even horizontally, using insulating standoffs.

Each set of electrodes consists of three pads spaced 120° apart and connected in parallel. Three arms per set provide improved contact with the casing and redundant measurements in the event of poor contact on any one electrode, or in case an electrode is located at a casing perforation or collar. A typical casing collar is approximately 2 ft long, the same distance that
separates each electrode set, and can affect the CHFR measurement. Collars may appear as spikes on the raw casing-impedance curve. When a CHFR station straddles or overlaps a casing collar, the added steel thickness may affect the resistivity measurement. Relogging using a lower operating frequency has minimized the casing-collar effect in some cases.

Small voltage electrodes on the sonde are designed to push through small amounts of casing scale and corrosion to establish good electrical contact with the casing, essential for the CHFR measurement. The tool moves uphole with electrode arms out to maintain best casing contact. The three-electrode per level design provides built-in redundancy, so few measurements have been lost because of electrode failure.

There is no correlation between contact quality and age of well. To date, only 6 of the 100 wells logged with the CHFR tool have experienced problems with contact quality. In three of the wells, good contact was maintained about half the time, while in the other three wells, good electrical contact was not possible because of scale buildup or casing corrosion. The quality of electrical contact is indicated by the injection-impedance and casing-resistance measurements.

Prior to running the CHFR tool, preliminary casing conditioning is recommended to improve electrical contact, particularly in corroded wells or when scale—resulting from water production—is present. Prejob preparation can include a bit-and-scaper run to remove corrosion or the SCALE BLASTER service to remove scale. Even in fields where these problems are not seen, operators may wish to pull tubing and prepare the casing prior to running the CHFR tool to reduce the risk of electrical contact problems.

The CHFR tool operating frequency can range from 0.25 to 10 Hz but is normally kept to 1 Hz. This low frequency is needed to avoid the polarization and drift that accompany use of DC current and also the casing skin effect that, depending on casing thickness—typically 5 to 15 mm (0.2 to 0.6 in.)—can become a concern even at low AC frequencies. When the operating frequency is too high, the injected current concentrates on the inner part of the casing and will return directly to the surface during the measurement step without going down first. In these circumstances, there will be no formation current and therefore no measurement.

The CHFR two-step measurement requires three levels of electrodes to obtain one resistivity data point. Since the CHFR sonde has four levels, duplication of the main acquisition channel makes it possible to acquire two resistivity measurements, 2 ft apart, at each depth station. The measurement is made with the tool stationary for two reasons. First, the magnitude of the measured quantities is very small and therefore highly sensitive to error. Second, movement of the electrodes along the casing introduces significant noise—as high as 10^4 times greater than the formation signal. At best, this leads to large errors in the formation-resistivity calculation; at worst, it makes reliable measurement impossible. Station times, including downhole calibration, vary from two to five minutes, depending on the estimated formation resistivity, desired accuracy and casing properties. Two-minute stations provide an equivalent logging speed of 120 ft/hr (37 m/hr). A typical logging run, consisting of one 1500-ft [457-m] interval, takes 12 hours. As with nuclear tools, longer CHFR station times improve the accuracy and extend the range of measurable resistivities.

Tool-Response Modeling

For openhole tools, the depth of investigation (DOI) is defined for an infinitely thick formation layer as the point where half the signal comes from the invaded zone and half from the virgin zone. With this definition, the CHFR DOI has a range of 7 to 37 ft [2 to 11 m] depending on formation parameters (previous page, right). Models of the CHFR resistivity response demonstrate that it compares well with the responses from other resistivity tools that have similar characteristics, such as the deep-reading curve from the HRLA High-Resolution Laterolog Array tool and the deep-reading curves from the High-Resolution Azimuthal Laterolog Sonde (HALS) [above].

Similar to openhole laterologs, the CHFR tool measures resistances in series; in contrast, induction response is measured in parallel. Consequently, the measurement of the current leaking out of the casing must pass through and is affected by whatever lies between the casing and the formation (below).

In the CHFR cased-hole measurement, the cement layer plays the same role as the invaded zone in the openhole. Thus, the critical parameters are the contrast between cement and formation resistivities ($R_t/R_{cem}$) and cement thickness. Results of 2D modeling show that the effect of cement on the CHFR measurement is negligible for a conductive cement ($R_t/R_{cem}$ greater than 1), but becomes important for a thick or resistive cement ($R_t/R_{cem}$ less than 1) (next page, top).

Modeling showed that resistive cement or very thick cement can cause CHFR apparent resistivity to read too high in low-resistivity formations (next page, bottom left). This influenced the decision to set the lower limit of the CHFR resistivity range at 1 ohm-m.

In-situ measurement of cement resistivity is not possible, but laboratory studies show that the resistivity of fresh cement typically ranges from 1 to 10 ohm-m.\(^3\) In addition, cement has a microporosity of around 35% that allows cement water to exchange ions with formation water. High-salinity formation water can lower the cement resistivity and minimize its impact.

Modeling results have been used to develop cement sensitivity charts for 4.5-in., 7-in. and 9\(\frac{5}{8}\)-in. OD casings (next page, bottom right). For typical values of cement thickness (0.75 in., for example) and cement resistivity (between 1 and 5 ohm-m) within the CHFR resistivity measurement range (1 to 100 ohm-m), the error due to cement is less than 10%. A cement correction has not been required in more than 95% of the CHFR logging jobs.

There are two additional cement-related factors whose effects on CHFR apparent formation resistivity are uncertain. One factor is the possible change of cement resistivity with time. This cannot be determined because measurement of cement resistivity in situ is not currently possible. The second factor is the effect of cement job quality. In this case, it is recommended that

Models showing the effect of cement resistivity, or other material between casing and formation, on the CHFR apparent resistivity response. Low-resistivity cement (left) has almost no effect on the measurement in a high-resistivity formation. The resistive bed is 500 ft [152 m] above the shoe of a 10,000-ft [3048-m] length of 5½-in. diameter casing. In the reverse situation (right), resistivity measurement is significantly affected where high-resistivity cement is present in a low-resistivity formation.

Relative error in formation resistivity measurement due to cement resistivity. For a 7-in. OD casing, 0.75-ohm-m cement layer and formation resistivities less than 1 ohm-m, the effect of cement becomes increasingly greater. For this reason, the CHFR applications are recommended for formation resistivities higher than 1.0 ohm-m.

CHFR cement sensitivity chart for 7-in. OD casing. Similar to openhole laterolog borehole-correction charts, this plot shows the correction coefficient as a function of the apparent resistivity contrast $R_{	ext{CHFR}}/R_{	ext{cem}}$, for typical values of cement thickness.
CHFR log in poor cement. Although the USI cement map (far right) shows poor quality (pale blue) in places, the agreement between the two CHFR passes (Track 2) and the openhole log in the Schlumberger test well in Villejust, France, is very good. A groove worn into the casing by wireline is also visible in the cement map.
cement quality be evaluated using CBT Cement Bond Tool, CET Cement Evaluation Tool or USI UltraSonic Imager services. Cement thickness can be approximated from the openhole caliper and casing size. An example from the Schlumberger test well in Villejust, France, compares two CHFR passes made two years apart with the original openhole laterolog log, made 30 years earlier (previous page). Field results in both old (30 years) and new (9 days) wells did not show any noticeable cement effect.

Measurement Repeatability, Reliability and Limits
CHFR field logs have demonstrated that the measurement is repeatable and directly comparable to openhole formation resistivity recorded at drilling time. CHFR data have clearly identified virgin, depleted and unswept zones.

Because of hole problems, an openhole resistivity log could not be obtained in an intermediate section of an Austrian gas well drilled by Rohoel-Aufsuchungs AG (RAG), prior to setting 7-in. casing. Drilling continued in the lower zone, and after openhole resistivity logs were run, 4.5-in. liner was set. The CHFR tool was then run in both sections (above). The agreement between the Platform Express deep laterolog and CHFR resistivity in the lower section provided a high degree of confidence in the CHFR measurement, which allowed RAG to evaluate the intermediate section without further testing. A second pass made over

(continued on page 14)
History of Cased-Hole Resistivity Measurement

Measuring resistivity behind casing has long been a dream in the oil field. In the 1930s, soon after Conrad and Marcel Schlumberger introduced the first openhole electric logs, the industry recognized the need for an equivalent cased-hole measurement to evaluate bypassed pay and monitor production in the thousands of wells completed prior to the advent of logging. To obtain resistivity behind casing, the current leaking through the steel casing into the adjacent formation must be measured. Although relatively simple in theory, this is extremely difficult in practice because of the enormous contrast in electromagnetic properties of steel and earth formations. Steel casing is $10^{2}$ to $10^{10}$ times more conductive than the formations being measured and has a magnetic permeability that is 10 to 200 times greater. The net effect of this wide dynamic range is that the tiny formation signal is masked by the overwhelming casing signal.

During the past 60 years, numerous patents have been issued for theories, methods and apparatus designed to measure and acquire cased-hole formation resistivity. These patents have included proposals for both galvanic—electrode orlaterolog methods—as well as induction methods.1 Many of the proposed methods fail to recognize and compensate for a number of factors affecting the measurement. These include optimal electrode spacing, variations in electrode contact resistance, and variations in casing thickness, resistance and skin effect—the amount of current actually leaking into the formation is a small fraction of the current introduced into the casing. Variations in casing resistance may result from differences in manufacturing tolerances, chemical composition, corrosion and fractures. In theory, some of the proposed methods could produce valid data. However, the extremely low signal-to-noise ratio and the limited technology available at the time these patents were granted made it virtually impossible to accurately measure the tiny, nanovolt formation signal.

To date, only the electrode methods have been demonstrated as feasible. The basic principles of measurement were proposed independently in a USSR patent issued to Alpin, in 1939, and a USA patent to Stewart, in 1949.2 In 1972, a French patent proposed a six-electrode design and used a two-step measurement that is close to the one used by the first demonstration tool, developed by Vail, almost 20 years later.3 It was not until the early 1990s that advances in electronics technology enabled development of this wireline device. Beginning in the late 1980s, ParaMagnetic Logging (PML) laid out the design and acquisition methods that resulted in its first demonstration tool.4 During the same period, Alexander Kaufman independently arrived at a solution similar to Vail’s.5 Initial feasibility studies, tool development and cement evaluation were supported and funded by a diverse group that included operating companies, service companies, the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency and the Gas Research Institute (GRI, now the Gas Technology Institute, GTI).6

The first experimental logging of the PML tool in 1992 proved the measurement concept and demonstrated several important points.7 First, the measurements confirmed the theory of operation, and the acquired data generally reproduced features of the openhole laterolog. Second, measurements were repeatable and worked in the range of 7 to 100 ohm-m. Third, casing cement did not appear to affect the measurement. Finally, vertical resolution was within an interval of several electrode spacings. The first successful oilfield test took place in the DOE MWX-2 research gas well in Rifle, Colorado, USA, in 1994, using an improved PML tool design.8 In 1995, Western Atlas began development of a commercial instrument, in conjunction with GRI, and two years later acquired PML and its technology.9 The Baker Atlas TCRT (Through Casing Resistivity Tool) is currently a prototype device in field testing.10

1. Examples of proposed galvanic methods include the following:
   - Examples of proposed induction methods include the following:


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Schlumberger interest in cased-hole resistivity logging was a natural outgrowth of the development of the CPET Corrosion and Protection Evaluation Tool method. This tool already applied four levels of electrodes to the casing to measure its resistance and current. Research began in the late 1980s at Schlumberger-Doll Research (SDR), Ridgefield, Connecticut, USA, and in 1992, a cased-hole formation-resistivity project was established at the Schlumberger Riboud Product Centre (SRPC) in Clamart, France. In 1995, the SRPC project team evaluated the PML technology in relation to their own design efforts and elected to continue the development of Schlumberger CHFR Cased Hole Formation Resistivity technology. An intensive research and engineering effort developed new downhole electronics and signal processing as well as methods for supplying power downhole and maintaining electrode contact. A single-channel experimental tool obtained the first log in 1996. In 1998, a second-generation experimental tool, using a two-channel design, was introduced to the field. The subsequent engineering prototypes and commercial tools employ this two-channel design. More than 100 wells around the world have been successfully logged with the CHFR service, and tool production is gearing up to meet increasing worldwide demand.

The CHFR tool delivers a measurement that reads deeper, approximately 2 m (6.6 ft), than conventional cased-hole saturation monitoring from nuclear tools, approximately 25 cm (10 in.). Unlike nuclear measurements, the CHFR resistivity measurement can work at low formation porosity or salinity and allows easy and direct comparison with openhole resistivity logs.


Klein et al, reference 3, main text.

Klein and Martin, reference 3, main text.


the interval 1220 to 1250 m illustrates the excellent repeatability of the measurement (above).

Due to the physics of measurement and depth of investigation, the CHFR resistivity is not affected by borehole washout. An example from the Middle East shows how the CHFR tool reliably reads resistivities even in enlarged boreholes (next page).

The CHFR tool measures a resistivity range of 1 to 100 ohm-m with ±10% accuracy. The lower limit of 1 ohm-m is set by the influence of cement. The upper limit of 100 ohm-m is set by the signal-to-noise ratio and the acceptable time per station. Depending on casing diameter, thickness and weight, and distance to the casing shoe, the actual upper limit may be higher than 100 ohm-m. Prejob planning can determine whether reservoir properties are suited to the CHFR service as well as the relationship between the maximum formation resistivity that may be measured and the station acquisition time required to achieve the desired accuracy and precision.

Results from a TOTAL ABK monitoring well offshore Abu Dhabi, UAE, show the importance of complete data acquisition and cement correction for extending the specified operating limits

<table>
<thead>
<tr>
<th>EOC-100</th>
<th>Repeat Casing-Segment Resistance</th>
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<tr>
<td>0</td>
<td>1.638E-01 ohm</td>
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<table>
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<tr>
<th>Depth, m</th>
<th>Repeat CHFR Apparent Resistivity</th>
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<tr>
<td>0</td>
<td>0 ohm-m</td>
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<tr>
<td>1200</td>
<td>100 ohm-m</td>
</tr>
<tr>
<td>1250</td>
<td>1000 ohm-m</td>
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</tbody>
</table>

^ Excellent repeatability of the CHFR measurement (Track 2) in a shallower section of the same Austrian well.
Comparing the effects of extreme borehole enlargement (washout) on nuclear and CHFR measurements. In this Middle East well, at depth X600 ft, the caliper (Track 1) indicates a washout with a borehole diameter of nearly 16 in. [41 cm]. In Track 2, the CHFR resistivity (black dashed/open circles) overlays the Platform Express openhole deep laterolog (red) and appears to be unaffected by the hole washout. In contrast, at the same depth, the openhole porosity logs presented in Track 3 (blue, neutron porosity; green, sonic slowness) are significantly affected.
of the CHFR tool (above). Review of other field data indicated that the distribution of the applied casing current in this well varied significantly from the CHFR model: the downward component of the applied current was much greater than the upward component. This situation can be explained by poor electrical contact between the 4½-in. liner and the 7-in. casing above the injection point, which prevented the current from flowing in the path expected for homogeneous casing. Poor electrical contact between casing strings can result in significant error in the CHFR resistivity calculation, particularly when the voltage is estimated, rather than measured.

In this case, a DC voltage measurement had been acquired on the same run and could be included in a recomputation of CHFR resistivity. The recomputed results are closer to the openhole data but still high.

In the aquifer zone from XX45 to XX70 m, openhole resistivity is in the range of 0.2 to 0.3 ohm-m, well below the normal operating range of the CHFR tool. Cement resistivity is known to be within the acceptable range. However, at these low formation resistivities, the influence of cement on CHFR measurements cannot be ignored. A cement correction (5-ohm-m cement resistivity and 0.75-in. thickness) was calculated and applied to the recomputed CHFR data. The resulting CHFR resistivities now closely match the openhole data over this interval that was initially thought to be outside the CHFR operating range.

In addition to cement and formation-resistivity restrictions, CHFR vertical resolution has some limitations. Vertical resolution is a function of the voltage electrode spacing. The 4-ft [1.2-m] value represents the minimum bed thickness for which the reading is correct in the middle of the bed. An oil-water contact (OWC) can be localized to ±1 ft, even with a 2-ft station spacing acquisition. The depth of investigation is 7 to 37 ft [2 to 11 m]—nearly unlimited by most wireline logging standards. It varies slightly with the contrast between the cement and formation resistivity.

Applications

The basic applications for cased-hole resistivity measurements were recognized in the 1930s; these consist of primary logging, contingency logging, identifying bypassed pay and reservoir monitoring. Primary logging is a planned decision to replace all or most openhole services with cased-hole measurements. This decision comes from a desire to reduce risks associated with borehole instability or poor logging conditions, or perhaps for improved economics. For example, in a producing field where the geology is already well-characterized through existing wells, a combination of CHFR log and cased-hole nuclear measurements, such as TDT Thermal Decay Time or RST Reservoir Saturation Tool logs for porosity, can provide complete formation saturation analysis.

Contingency logging—This type of logging is appropriate for unplanned situations in which openhole conditions such as borehole instability
or tool failure prevent successful logging. Now, with the CHFR service, cased-hole devices can provide the needed data. In one recent North Sea well, logging-while-drilling (LWD) tools failed and no other openhole logs were available. Without the evaluation provided by the CHFR log, the operator might have abandoned the well. In another case, hole conditions prevented acquisition of openhole logs; without the cased-hole evaluation provided by the CHFR tool, the operator would have had to drill another well for proper evaluation of the reservoir. Field experience now indicates that contingency logging comprises a substantial portion of the total market for behind-casing resistivity.

**Identifying bypassed pay**—Bypassed pay constitutes a significant percentage of potential reserves in many old fields. This category includes not only zones that were inadvertently missed or misidentified, but also those that were deliberately bypassed and others that experienced resaturation after years of production. In these cases, wells may have been drilled prior to the availability of well logging or of modern tools. Cased-hole evaluation facilitates identification of these zones and allows estimation of additional reserves.

Deep invasion sometimes masks producible zones. The openhole laterolog in one Indonesian well was highly affected by invasion and underestimated the resistivity (right, top). Since curve separation from X725 to X950 ft suggested a wet zone, it was not perforated. Soon after the well was completed, it produced nearly 100% water from deeper zones and was shut in. A few months later, after the mud filtrate had time to disperse, a CHFR log indicated that this zone was actually hydrocarbon-bearing. The zone was completed on the basis of the CHFR log interpretation and is producing at the rate of 200 BOPD [32 m3/d].

**Reservoir monitoring**—Reservoir monitoring consists of time-lapse logging—logging at different times—to track changes in saturation and monitor the position of fluid contacts during production and flooding projects. This technique has been successful in another Indonesian well, where the CHFR log showed an unexpected oil-water contact 12 ft [3.5 m] below the original OWC determined from the openhole logs (right). This lower zone was perforated and three weeks later was producing 2150 BOPD [342 m3/d] with no water cut, confirming the CHFR results. The most likely explanation is that
the waterflood project in the field had swept a
bank of oil to the vicinity of this well, but the oil
could not be produced through the higher perfo-
rations because of a vertical-permeability barrier.

While the CHFR tool can provide resistivity
measurements behind casing, more can be
learned by combining these with nuclear mea-
surements. The CHFR resistivity tool provides
saturation measurements from a depth of inves-
tigation significantly beyond that of the nuclear
logging tools currently used for behind-casing
evaluation. The dynamic range of the CHFR mea-
surement is such that evaluation also is possible
in reservoirs with low porosity and low forma-
tion salinity, conditions that are generally unfavorable
for accurate evaluation by nuclear tools. Where
borehole and conditions are unfavorable for the
CHFR measurement, nuclear logs can provide the
necessary data (above).

<table>
<thead>
<tr>
<th>Formation</th>
<th>Carbon/Oxygen Ratio</th>
<th>Sigma</th>
<th>CHFR Tool</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low porosity (&lt;15 p.u.)</td>
<td></td>
<td></td>
<td></td>
<td>Limitation on maximum measurable $R_t$</td>
</tr>
<tr>
<td>Moderate porosity and low salinity (&lt;20 ppk)</td>
<td></td>
<td></td>
<td></td>
<td>Limitation on maximum measurable $R_t$</td>
</tr>
<tr>
<td>Moderate porosity and moderate salinity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High porosity (&gt;30 p.u.) and high salinity (Gulf of Mexico)</td>
<td></td>
<td></td>
<td></td>
<td>CHFR tool could work but cement effect becomes important at low $R_t/R_{cem}$</td>
</tr>
<tr>
<td>Variable (flood)</td>
<td></td>
<td></td>
<td></td>
<td>CHFR tool can identify change from original reservoir saturation but not quantitatively.</td>
</tr>
<tr>
<td>Very low water saturation</td>
<td></td>
<td></td>
<td></td>
<td>Limitation on maximum measurable $R_t$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Completion</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casing collars</td>
<td>CHFR tool may lose data over 4 to 6 ft. RST tool C/O mode will give good answers after SpectroLith processing quantifies the iron content.</td>
</tr>
<tr>
<td>Run-in through small tubing</td>
<td></td>
</tr>
<tr>
<td>Log inside tubing</td>
<td>RST tool will give answer as long as the fluid effect between tubing and casing can be corrected.</td>
</tr>
<tr>
<td>Heavy casing</td>
<td>48 lbm/ft limit for CHFR signal-to-noise</td>
</tr>
<tr>
<td>Dual casing</td>
<td>RST tool will give answer as long as the fluid/formation/cement effect between tubing and casing can be corrected. In C/O mode, characterization may be needed.</td>
</tr>
<tr>
<td>Alloy or chrome casing</td>
<td>Electrode scratching may induce corrosion.</td>
</tr>
<tr>
<td>Fiberglass casing</td>
<td>Induction logging is another option.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry microannulus</td>
<td></td>
</tr>
<tr>
<td>Gas-cut cement</td>
<td></td>
</tr>
<tr>
<td>Washed-out holes</td>
<td>Sigma can stand washout size roughly twice as large as in C/O mode. If washout is comparable to depth of investigation, then sigma also will be affected.</td>
</tr>
<tr>
<td>Flowing wells</td>
<td></td>
</tr>
<tr>
<td>Fluid contacts in hole</td>
<td></td>
</tr>
<tr>
<td>Near-wellbore effects</td>
<td>Sigma is robust compared to C/O mode due to depth of investigation.</td>
</tr>
<tr>
<td>Deviated wells</td>
<td></td>
</tr>
<tr>
<td>Acid effect</td>
<td></td>
</tr>
<tr>
<td>Perforations</td>
<td></td>
</tr>
<tr>
<td>Lithology</td>
<td></td>
</tr>
<tr>
<td>Scale</td>
<td>CHFR tool relies on good electrical contact between electrodes and casing. Casing must be clean.</td>
</tr>
</tbody>
</table>

Chart comparing the applicability of CHFR resistivity and RST carbon/oxygen and sigma measurements to different formation conditions. In many borehole and reservoir conditions, the tool measurements are complementary.
To better understand reservoir behavior, CHFR resistivity and porosity measurements from nuclear devices, such as the RST tool, can be combined to provide a quantitative saturation evaluation that is equivalent to an openhole interpretation. The RST tool provides two important measurements for determining hydrocarbon saturation and porosity. The ratio of the relative abundance of carbon and oxygen in a formation can predict hydrocarbon and water saturations independent of water salinity. The thermal-decay measurement, sigma, is used to estimate porosity and hydrocarbon saturation in salty formations.4

A combined interpretation of cased-hole resistivity and nuclear measurements can be seen in a monitoring well from a Middle East carbonate oil reservoir (above). After openhole logging, casing was set in this monitor well and several cased-hole devices, including the CHFR and RST tools, logged at intervals over the next 15 months. During this period, and before an injector well was active in this area, the series of log runs showed a progressive increase in CHFR apparent resistivity indicating hydrocarbon resaturation in the primary oil zone between X0950 to X1085 ft. Subsequent to the second run, water injection began in a well approximately 100 m away. At the time of the third cased-hole logging run, the flood front was approaching the monitor well and influencing the deep-reading CHFR measurement, thereby enabling the effects of water injection to be detected and quantified. In contrast to the

CHFR data, analyses based on the shallow-reading RST tool showed no change from the openhole data during this period [below].

The difference between resistivity and nuclear evaluations indicates that a damaged zone has been created around the borehole in which filtrate invaded at least as far as the RST depth of investigation. A combined interpretation from the CHFR and RST tools provided a complete understanding of the resaturation, flood progress and formation damage around the borehole.

Another way to detect changes in hydrocarbon saturation over time is with the quick-look depleted hydrocarbon index. This index is based on the Archie water-saturation equation, \( S_w = \frac{1}{\phi} \left( \frac{R_w}{R_t} \right)^{1/2} \), and relates cased-hole resistivity and saturation derived from CHFR data to the reference openhole values through the ratio:

\[ \left( \frac{R_{CHFR}}{R_{OH}} \right)^{1/2} = \frac{S_{WOH}}{S_{CHFR}} \]

where \( R_{CHFR} \) is CHFR apparent formation resistivity; \( R_{OH} \) is reference openhole formation resistivity; \( S_{WOH} \) is Archie openhole water saturation calculated using \( R_{OH} \); and \( S_{CHFR} \) is Archie cased-hole water saturation calculated using \( R_{CHFR} \).

The advantages of this approach are that it is relatively immune to the CHFR geometrical-factor, does not require knowledge of the formation water resistivity—although it is assumed that it has remained unchanged between the openhole and cased-hole logs—and does not require knowledge of the porosity. If an incorrect K-factor is used, the curve baseline, which should be 1.0 in clean, water-bearing formations, will be shifted. Even in this case, however, it should still be possible to identify the baseline position and to detect depleted zones by deflection of the curve toward the left of this baseline. At the same time, this approach retains the limitations inherent in the Archie approach, such as the assumption of a clean sand formation.

The depletion index provided a quantitative measure of the extent of reservoir depletion in a 27-year old North Slope, Alaska, USA, production well (next page, top). The casing-resistance curves for each measurement channel for two separate runs overlay, indicating good electrode contact. The reduced CHFR resistivity relative to the openhole clearly indicates depletion in the two squeezed-off oil zones, X720 to X740 ft and X820 to X955 ft.
Another monitoring example comes from a mature field in Indonesia. The reservoir is made up of a series of channel sands with a wide range of permeability. Production from these sands is often commingled and, because of low formation pressures, requires downhole pumps. Typically, the high-permeability zones are the major contributors to production; they deplete first, then produce significant amounts of water. Nuclear carbon/oxygen (C/O) logs are routinely used to monitor reservoir production and depletion.

Interpretation of C/O logs is complicated by two factors. First, because of low reservoir pressure, once the pumps are stopped to work over the well, borehole fluid reinvents the reservoir. This newly created invaded zone causes the shallow-reading C/O logs to underestimate the oil saturation. Also, pressure differences between zones can result in crossflow.

One solution is to squeeze off all the perforations and leave the well idle for two to three weeks to allow the near-borehole region to return to reservoir conditions before running the C/O log and perforating new intervals. This approach, however, is expensive and results in significant lost production.

Furthermore, the squeeze process itself, during which a large volume of water is injected into the formation at high pressure prior to cementing, may actually result in a long-term change in the formation saturation near the wellbore. The C/O logs often show oil saturations below the residual oil saturation; this finding could be due to the permanent flushing of residual oil away from the near-borehole region by the high-pressure squeeze. These practices, combined with variable cement quality in old wells, make accurate interpretation of C/O logs a challenge.

The CHFR service suffers from none of these drawbacks and gives the operator a more accurate and cost-effective alternative to C/O logging for identifying depleted zones (left). Prior to executing a squeeze job in an Indonesian well, a CHFR run was performed, followed weeks later by two more CHFR runs and a C/O log acquisition. The deep CHFR depth of investigation allowed the first log to be run immediately after...
pulling the completion, prior to squeezing and waiting for the invaded zone to return to residual conditions (above).

The first CHFR job was the most accurate run because it occurred before the cement squeeze job, which injected a large amount of water into the formation. The second and third CHFR runs showed reduced resistivities because of the large amount of injected water. The C/O log run at the same time as the third CHFR run greatly underestimates the saturation of remaining oil due to its inability to see past the invaded zone. The first CHFR run shows that beyond the invasion this interval has preserved nearly the original oil saturation. Compared to the C/O log, the CHFR tool provided a more accurate, deep-reading log, as well as considerable savings in production time and expense.

Many oil fields in the Middle East use enhanced methods to improve oil recovery in their carbonate reservoirs. Flood projects use injected water, gas or both, to sweep oil to the producing wells. Logs in monitor wells generally indicate good drainage in the high-permeability, grain-supported carbonates but frequently indicate inconsistent drainage in the lower- and mixed-permeability mud-supported carbonate zones. Individual flow units within these lower permeability zones are often capped by thin, high-permeability layers that allow water or gas fingering during the floods and prevent good recovery.

Historically, the progress of these floods has been evaluated through dedicated monitor wells using thermal-decay sigma or C/O nuclear measurements in steel casing, or induction logs in fiberglass casing. Each of these methods has limitations. Nuclear tools work best in steel casing and in medium- to high-porosity formations. The nuclear sigma measurement requires saline formation water. Mud filtrate and acids used to stimulate the reservoir may damage the near-borehole region, often lingering for months or years. Nuclear devices, which have a shallow depth of investigation—less than 12 in. [30 cm]—may not see beyond the filtrate-invaded zone. fiberglass casing deteriorates with time and develops leaks; induction logs run in such circumstances may be unreliable. Typically, when leakage occurs, fiberglass is replaced by steel casing. Under these conditions, CHFR logging may be more suitable and may provide better answers than traditional nuclear measurements.

The CHFR depth of investigation allows it not only to monitor the uninvaded zone but, under some conditions, to provide early indication of approaching flood fronts. In one Middle East monitor well, two CHFR logs were acquired in a four-month period (next page, left). No change was detected in the reservoir between runs. In addition, except for one zone, the overall match between openhole LWD deep resistivity and CHFR apparent resistivity is excellent at both low and high resistivities. Modeling has shown that the higher CHFR resistivity in the interval X850 to X890 ft is due to an event far from the borehole, possibly an oil leg or the gas-flood front, perhaps 50 to 100 ft [15 to 30 m] beyond the borehole. The LWD resistivity is responding to the near-borehole water-flooded zone.

ELAN Elemental Log Analysis interpretation of CHFR and RST reservoir monitoring logs. In this Indonesian well, the C/O log results are affected by near-wellbore effects, in this case underestimating the remaining oil due to invasion. The deeper CHFR depth of investigation helps to better estimate the remaining oil.

In another well, the CHFR tool was run three different times: three, six and eight months after the well was cased to monitor fluid movement during a waterflood (above right). All three runs repeat and match the openhole deep laterolog except between X0970 and X1020 ft, where CHFR apparent resistivity is progressively increasing with time. The increase in cased-hole resistivity between the first and second runs validated the reservoir-simulation model that predicted that water injection into this high-permeability zone would push a bank of oil past this well. This example demonstrates CHFR repeatability and the ability of the deep-reading CHFR tool to detect remote changes long before near-borehole nuclear methods could detect changes in reservoir fluids.

Reservoir monitoring log examples in an Abu Dhabi carbonate oil reservoir. Track 2 presents three CHFR runs and the reference openhole deep laterolog. Run 1 (red) was logged three months after casing was set, Run 2 (blue), six months after casing, and Run 3 (green), eight months after casing. The CHFR measurement repeats except from X0970 to X1020 ft, where resistivity is clearly increasing with time. The increased resistivity between Runs 1 and 2 supports a simulation model that predicts that water injected in a nearby well would push a bank of oil past this wellbore.

Enhancing Production Efficiency
Elk Hills oil field, near Bakersfield, California, USA, is one of the largest in the United States, with cumulative production exceeding 1.2 billion BOE [190 million m³] and remaining reserves of 250 million BOE [39 million m³]. Prior to privatization in 1998, Elk Hills was part of the United States Naval Petroleum Reserves. Now operated by Occidental Oil and Gas (OXY), the field has
recently served as a testing ground for cased-hole resistivity services. OXY is seeking to develop confidence in the measurement and is testing its potential applications. More than 25 wells in the field have been logged with the Schlumberger CHFR tool and the Baker Atlas TCRT tool. The primary applications are reservoir monitoring and enhancement of reservoir production efficiency, primarily through reduction of unwanted water or gas—known as conformance control. Location of bypassed pay, including zones of resaturation, is a secondary application.

Many of the 900 production wells in this field, discovered in 1911, date back to the 1940s. The field consists of stacked siliceous shales and thin, interbedded turbidite reservoirs primarily within the Miocene Monterey formation. Openhole resistivity logs frequently are old normal or laterologs whose response must be modeled to modern equivalents before they can serve as reference logs for cased-hole resistivity. The logging and producing environments present challenges for conventional cased-hole formation evaluation. The sands contain fresh pore water and frequently have low porosities. Pulsed neutron and C/O logs are rarely run because of the existing wellbore completions. A shallow depth of investigation causes the cased-hole nuclear tools to detect the kill fluid that has invaded the perforated intervals.

For running of cased-hole resistivity tools here, standard operating practices include pulling the completion and preparing the casing using a scraper and brush to ensure good electrical contact. To build confidence in the cased-hole measurement, the CHFR tool was logged at 1-ft [0.3-m] high-density sample spacing. This reduced the statistical uncertainty in the measurement by increasing the signal-to-noise ratio and improved vertical resolution.

The average CHFR log in this field covers a 1000-ft [300-m] interval, including a short unperforated interval used to verify the CHFR calibration with the openhole logs. Although a 1-ft sample interval is used, because the CHFR tool makes two measurements per station, the time required for logging an average well was only 12 hr.
In 1978, a peripheral water-injection project was implemented in the Main Body “B” (MBB) Stevens sand on the 31S structure. The 31S structure is the largest and most prolific of the Elk Hills Stevens structures and contains the 26R and MBB turbidite reservoirs.

Water has steadily advanced up the structure during the past 20 years of injection (previous page, top). The 315A-34S well was drilled in 1982 as a vertical producer in the MBB and was producing more than 300 BWPD [48 m³/d]. A logging program consisting of cased-hole gamma ray and CHFR measurements was proposed to identify water and the location of water entry. In the upper, permeable interval, differences between the openhole and cased-hole gamma ray are attributed to barium scale and used to identify water entry (right).

Before the CHFR tool was run, the casing was cleaned. In oil zones depleted through production and swept by the waterflood, CHFR resistivity is less than openhole resistivity. The dark blue flag indicates intervals where both the gamma ray and the CHFR resistivity indicate water breakthrough. The tighter lower intervals show fewer breakthrough effects. A casing patch was set over the original perforations (yellow flags), and then the well was reperforated in the lower interval. However, as a result of operational difficulties, an attempt to test this section was mechanically unsuccessful.

Occidental’s experience with cased-hole resistivity and the CHFR tool has been extremely positive. OXY engineers and petrophysicists now prefer cased-hole resistivity to traditional nuclear measurements because they find resistivity interpretation is simpler, more straightforward, and less uncertain than interpretation of thermal-decay sigma or C/O measurements. With cased-hole resistivity, high resistivity indicates pay, and lower resistivity relative to openhole logs indicates produced or swept zones. High-density sampling at a 1-ft sample interval is recommended in laminated beds. Finally, Occidental’s petrophysicists now have sufficient confidence in the measurement to recommend it in problem wells, instead of nuclear logs.

The Future of Cased-Hole Formation Evaluation

With the enormous base of existing wells in old and producing fields, as well as the huge potential for future wells, the need for cased-hole formation evaluation is clear. Cased-hole logging not only provides information on bypassed pay and changing fluid contacts, but also reduces risk by allowing formation evaluation when openhole resistivity logs are not practical. The benefits are also clear: more revenue, lower costs and earlier production of reserves. Cased-hole resistivity enables operators to better optimize their operations, while still acquiring the data for evaluation and planning.

Over the past 10 years, the suite of cased-hole devices providing behind-casing formation evaluation has expanded to meet growing demand.

As an addition to the traditional nuclear and acoustic measurements, the new CHFR tool provides a familiar measurement that solves important industry formation-evaluation needs in both new and old wells. Cased-hole resistivity allows reservoir monitoring in conditions unfavorable for traditional nuclear logs and enhanced evaluation when combined with nuclear measurements in favorable conditions.

No one can predict what advances will be made in the next 60 years, but the near future is easy to foresee. As more operators gain experience with the CHFR tool and push the limits of current technology, innovative applications will be established and more cased-hole formation-evaluation hurdles will be overcome. The rewards will be finding more oil and gas. —SP, LS