Saturation Monitoring With the RST Reservoir Saturation Tool

The RST Reservoir Saturation Tool combines the logging capabilities of traditional methods for evaluating saturation in a tool slim enough to pass through tubing. Now saturation measurements can be made without killing the well to pull tubing and regardless of the well’s salinity.

Determining hydrocarbon and water saturations behind casing plays a major role in reservoir management. Saturation measurements over time are useful for tracking reservoir depletion, planning workover and enhanced recovery strategies, and diagnosing production problems such as water influx and injection water breakthrough.

Traditional methods of evaluating saturation—thermal decay time logging and carbon-oxygen (C/O) logging—are limited to high-salinity and nontubing wells, respectively. The RST Reservoir Saturation Tool overcomes these limitations by combining both methods in a tool slim enough to fit through tubing. The RST tool eliminates the need for killing the well and pulling tubing. This saves money, avoids reinvasion of perforated intervals, and allows the well to be observed under operating conditions. Moreover, it provides a log of the borehole oil fraction, or oil holdup, even in horizontal wells. To understand the operation and versatility of the RST tool requires an overview of existing saturation measurements and their physics.

The Saturation Blues

In a newly drilled well, openhole resistivity logs are used to determine water and hydrocarbon saturations. But once the hole is cased, saturation monitoring has to rely on tools such as the TDT Dual-Burst Thermal Decay Time tool or, for C/O logging, the GST Induced Gamma Ray Spectrometry Tool, which can “see” through casing.

The Dual-Burst TDT tool looks at the rate of thermal neutron absorption, described by the capture cross section $\Sigma$ of the formation, to infer water saturation (terms in bold are explained in “Gamma Ray Spectrometry at a Glance,” page 38). A high absorption rate indicates saline water, which contains chlorine, a very efficient, abundant thermal-neutron absorber. A low absorption rate indicates fresh water or hydrocarbon.

The TDT technique provides good saturation measurements when formation water salinity is high, constant and known. But oil production from an increasing number of reservoirs is now maintained by water injection. This reduces or alters formation water salinity, posing a problem for the TDT tool.

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In this article, ELAN (Elemental Log Analysis), CNL (Compensated Neutron Log), Gradiomanometer, RST (Reservoir Saturation Tool), GST (Induced Gamma Ray Spectrometry Tool), Dual-Burst and TDT (Thermal Decay Time) are marks of Schlumberger. Macintosh is a mark of Apple Computer, Inc. VAX is a mark of Digital Equipment Corporation.

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In low-salinity water (less than 35,000 parts per million), the tool cannot accurately differentiate between oil and water, which have similar neutron capture cross sections.

When the salinity of the formation water is too low or unknown, C/O logging can be used. C/O logging measures gamma rays emitted from inelastic neutron scattering to determine relative concentrations of carbon and oxygen in the formation. A high C/O ratio indicates oil-bearing formations; a low C/O ratio indicates water- or gas-bearing formations (next page, top).

The major drawback to C/O logging tools has been their large diameters. Producing wells must be killed and production tubing removed to accommodate tools with diameters of nearly 4 in. [10 cm]. In addition, the tools have slow logging speeds and are more sensitive to borehole fluid than formation fluid, which affects the precision of the saturation measurement.

As Easy as RST

The RST tool directly addresses these shortcomings and can perform either C/O or TDT logging (see “Logging the RST Tool in Prudhoe Bay,” page 32). It comes in two diameters—1 11/16 in. (RST-A) and 2 1/2 in. (RST-B)—and can be combined with other production logging tools (next page, bottom). The RST-A tool logs up to four times faster than the GST tool. The RST-B tool—the only C/O tool that can log flowing wells—makes passes at speeds comparable to the GST tool.

Both versions have two gamma ray detectors. In the RST-A tool, both detectors are on the tool axis, separated by neutron and gamma ray shielding. In the RST-B tool, the detectors are offset from the tool axis and shielded to enhance the near detector’s borehole sensitivity and the far detector’s formation sensitivity. This allows the formation oil saturation and borehole oil holdup to be derived from the same RST-B C/O measurement. Because of size constraints, such detector shielding is not possible with the RST-A tool. An independent determination of borehole fluid holdup is then needed, for example from the Gradiometer tool run on the same logging suite or by logging shut-in.

For both tools, the detector crystal is cerium-doped gadolinium oxyorthosilicate (GSO), one of a new generation of scintillation crystals that outperforms the sodium-

(continued on page 34)
Combining the diagnostic capabilities of C/O logging and TDT logging with the RST-B tool in a Middle East observation well. From left to right: Track 1 shows openhole fluid analysis. Track 2 shows C/O logs from the near and far detectors and oil holdup. Track 3 shows the fluid analysis based on C/O logging. Track 4 shows the log of $\Sigma$. Track 5 shows a combined C/O and $\Sigma$ fluid analysis.

The observation well contained water in the borehole over the entire interval, so the oil holdup value was set to 0. The C/O fluid analysis, used to distinguish between oil and water, shows only a small oil depletion from X190 ft to X250 ft and a large oil depletion from X140 ft to X170 ft. By itself, however, C/O logging cannot differentiate between injection and connate water. To accomplish this, a log of $\Sigma$ is used in conjunction with the C/O logs. The $\Sigma$ log can differentiate between oil and salt water but not oil and fresh water. The revised interpretation indicates formation water from X170 to X210 ft and a water injection breakthrough from X140 to X170 ft. Interpretation based on $\Sigma$ alone would have identified the water injection breakthrough as oil.

The dual-detector RST-A and RST-B tools.
Prudhoe Bay, the largest oil field in North America, contained 20 billion stock tank barrels when it was discovered in 1968.¹ Most of the hydrocarbons are in the Ivishak Sandstone. The main recovery methods used in Prudhoe Bay are gravity drainage, gas injection, aquifer influx, waterflooding and miscible gas flooding. Over time, the expansion of gas above and water below the oil column has produced mobile oil lenses that are elusive to tap. The salinity of injected water is low, creating conditions suited to C/O logging with the RST tool.²

As the Prudhoe Bay field matures, increasing gas and water production is exceeding the capacity of surface handling facilities, thus limiting oil production. No pipeline exists for the gas, so it must be reinjected. Wells with declining oil production and increasing gas and water production are typically worked over or produced intermittently. Extending the life and economic viability of these marginal wells relies on reducing gas and water production and maximizing oil production by producing bypassed oil zones.

RST data were used to reduce water cut in a BP well with a 250-ft [76-m] oil-bearing sandstone interval (right). Openhole logs from 1983 (not shown) marked the original oil-water contact (OWC) at X1250 ft and the original gas-oil contact (GOC) at X1050 ft.

By 1992, production rates fell, indicating severe reservoir depletion. The well was producing 3750 B/D of fluids with a 94% water cut. Production was 220 BOPD and the gas/oil ratio (GOR) was 1115 ft³ of gas per barrel of oil. The RST tool was run to evaluate hydrocarbon distribution and locate fluid contacts.

C/O data measured with the well flowing were combined with CNL Compensated Neutron Log data as input to the ELAN Elemental Log Analysis program (right track). The resulting fluid analysis confirmed oil depletion over both perforated intervals and identified the current GOC at X1110 ft. The borehole oil holdup log showed oil production from perforations above X1170 ft and was used to identify the present OWC at that depth. The lower perforations were not producing any oil. After these were plugged, the well produced 300 BOPD of oil with negligible water cut.

Locating Bypassed Oil

In early 1992, ARCO drilled and perforated a sidetrack well in an area of Prudhoe Bay undergoing waterflooding. Less than six months later, production was 90% water with less than 200 BOPD, as expected. The original perforations extended from X415 to X440 ft (next page). C/O logging measurements were made in the shut-in well with three different tools—the RST tool and two sondes from other service companies.

The RST results confirmed depletion over the perforated interval (Tracks 2 and 3). Effects of the miscible gas flood sweep are apparent throughout the reservoir. The total inelastic count rate ratio of the near and far detectors indicates qualitatively the presence of gas in the reservoir. In


addition, differences between the openhole fluid analysis and the RST fluid analysis were assumed to be gas.

One potential bypassed zone, A, was identified from X280 to X290 ft. A second zone, B, based on the openhole logs and a C/O log from another service company, was proposed from X220 to X230 ft. The RST log shows Zone B to contain more gas and water than Zone A.

After assessing the openhole logs and the three C/O logs, ARCO decided to perforate Zone B. The initial production was 1000 BOPD with a 75% water cut. Production declined to 200 BOPD with more than 95% water cut in a matter of weeks. The decline prompted ARCO to perforate Zone A, commingling production from earlier perforations. Production increased to an average of 600 BOPD with the water cut decreased to 90%. Subsequent production logs confirm that Zone A is producing oil and gas and Zone B is producing all of the water with some oil.
iodide [NaI] crystal conventionally used for gamma ray detection (see “New Scintillation Detectors,” page 35). Several properties of GSO allow for a smaller diameter detector crystal than if NaI were used, and hence a smaller diameter tool.

**Modes of Operation**

Flexibility is a key advantage of the RST tool. It operates in three modes that can be changed in real time while logging:

- inelastic-capture mode
- capture-sigma mode
- sigma mode.

**Inelastic-capture mode**: The inelastic-capture mode offers C/O measurements for determining saturations when the formation water salinity is unknown, varying or too low for TDT logging. In addition to C/O logging, thermal neutron capture gamma-ray spectra are recorded after the neutron burst. Elemental yields from these spectra provide lithology, porosity and apparent water salinity information.

In the inelastic-capture mode, each measurement cycle contains one neutron burst and three timing gates for collecting spectra (right). The first gate measures the total gamma ray spectrum during the neutron burst, which contains both inelastic and capture spectra. The second gate measures an early capture spectrum following the neutron burst, which is used to subtract the capture background from the previous inelastic spectrum, yielding the net inelastic spectrum. The C/O ratio from the net inelastic spectrum is used to determine saturation. The third gate measures a capture spectrum after the neutron burst, which is used to determine formation lithology. For example, the ratio of silicon to calcium is used to distinguish silicates from carbonates. Logging passes are made at 60 to 100 ft/hr [18 to 30 m/hr].

**Capture-sigma mode**: The capture-sigma mode is used to determine lithology and the capture cross section $\Sigma$ in the same logging pass. It simultaneously records capture gamma ray spectra and total capture gamma ray count rates. Elemental yields from the capture spectra can provide lithology, porosity and apparent water salinity information as in the inelastic-capture mode. Total count rate measurements are used to determine $\Sigma$ for the formation and the borehole. Unlike the inelastic-capture mode, each measurement cycle in the capture-sigma mode contains two neutron pulses—a short one and a long one. Total count rates collected during and after the short burst are used to determine the borehole fluid $\Sigma$; total count rates collected after the longer burst are used to determine the formation $\Sigma$. Logging is usually performed at 600 ft/hr [180 m/hr].

**Sigma mode**: The sigma mode is used when the salinity of the formation water is high enough for TDT logging. It provides capture cross-section data in a fast pass—up to 1800 ft/hr [550 m/hr]. Although the timing sequence mimics the capture-sigma mode, only decay-time data and a pulse height spectrum, for calibrating the tool gain, are recorded.

**Interpretation**

The conversion of C/O ratios to saturations relies on an extensive data base designed to measure RST tool response to a variety of borehole environments. The RST-A and RST-B tools have been logged in a wide variety of conditions at Schlumberger’s Environmental Effects Calibration Facility in Houston, Texas, USA. For each combination of lithology, casing and cement at the facility, four C/O ratio measurements were made to cover the four combinations of oil and water in the borehole and formation: water-water, water-oil, oil-water and oil-oil. The resulting measurements represent the largest C/O characterization data base for any nuclear tool in the oil field today. Similarly, the largest data base of capture-sigma measurements was also acquired. Different
What Makes a Great Crystal?

Scintillation detectors are so named because they generate flashes of light when struck by gamma rays (for details on how scintillator crystals work, see “Gamma Ray Spectrometry at a Glance,” page 38). Most of the properties that make a crystal desirable for logging are those that maximize the intensity of these flashes and the number of counts. In addition, crystals should be rugged, not cracking on impact, and unaffected by moisture.

A crystal of high density and high atomic number provides more opportunity for interaction with incident gamma rays, maximizing count rates. Crystal volume also affects performance. A bigger crystal intercepts more gamma rays, thereby increasing count rates. It also decreases the probability that a gamma ray will escape the crystal after one or two scatterings.

A high light-flash intensity produces large voltages that are easily measured, improving energy resolution, and makes the detector more sensitive to low-energy gamma rays. If at all possible, the light-flash intensity and duration should be relatively unaffected by temperature change. This eliminates the need for temperature control hardware downhole.

C/O logging and thermal decay time logging expose the crystal to high instantaneous gamma ray fluxes during or immediately after the neutron burst. The light flashes must have a short enough duration to avoid “piling up” on one another, which produces false pulse amplitudes and counting rates.

Once a light flash has been generated, the goal is to get as much light as possible to the photomultiplier tube (PMT). To prevent internal absorption of light, the crystal should be transparent to the light it generates. Because light generated by the crystal must eventually pass through the window of the photomultiplier tube, the index of refraction of the crystal and window should be similar to maximize light transmission. The photocathode of the PMT must be highly responsive to the wavelength of the crystal light to maximize the number of photoelectrons it ejects.

The New Detectors

For nearly 45 years, thallium-doped sodium iodide (NaI) has been the gamma ray detector of choice for nuclear logging. It is widely used to determine formation density and chemical composition, salinity through casing, and mineralogy. NaI excels in intensity of light flash and temperature stability. Although new crystals literally do not outshine NaI, they do bring increased detection efficiency, greater ruggedness, reduced sensitivity to humidity, and the ability to handle much higher counting rates without pileup (see “Comparison of Scintillation Crystals,” above).

Bismuth germanate (BGO) was first manufactured commercially in the early 1970s, providing higher counting rates than NaI that result in better spectral resolution. Sharply defined spectral peaks indicate good energy resolution.

Running the RST tool through tubing would not be possible without a scintillation crystal called cerium-doped gadolinium oxyorthosilicate (GSO), one of several new crystals finding its way to the oil patch. Developing these crystals for borehole detectors requires coupling a knowledge of nuclear physics with sophisticated crystal-growing techniques.

### Comparison of Scintillation Crystals

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Density g/cm³</th>
<th>Effective Atomic Number Z</th>
<th>Refractive Index</th>
<th>Relative Light Flash Intensity</th>
<th>Energy Resolution @662keV, %</th>
<th>Light Flash Decay Time² ns</th>
<th>Rugged</th>
<th>Unaffected By Moisture</th>
<th>Dewar System Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>51</td>
<td>1.85</td>
<td>100</td>
<td>6.5</td>
<td>230</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BGO</td>
<td>7.13</td>
<td>75</td>
<td>2.15</td>
<td>15</td>
<td>9.3</td>
<td>300</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>GSO</td>
<td>6.71</td>
<td>59</td>
<td>1.85</td>
<td>20</td>
<td>8.0</td>
<td>56 and 600</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>LSO</td>
<td>7.40</td>
<td>66</td>
<td>1.82</td>
<td>75</td>
<td>10</td>
<td>40</td>
<td>Yes</td>
<td>Yes</td>
<td>Depends on application</td>
</tr>
</tbody>
</table>

1. Energy resolution refers to the commonly used relative “full width at half maximum” for the 137Cesium gamma ray peak at 662 keV. Sharply defined spectral peaks indicate good energy resolution.

2. Decay time is the time constant for the exponential decay of the light flash. Faster decay times are preferred.

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1. For a discussion of scintillation spectrometry:

Quantifying BGO’s statistical advantage.

The high density and high atomic number by the Hitachi Chemical Co., Ltd. in the early 1980s.4 The high density also improves the crystal’s ability to detect gamma rays, particularly high-energy ones. GSO has a detection efficiency nearly as high as BGO’s but can operate at higher temperatures without a bulky Dewar flask. It produces significantly less pulse pileup during the neutron burst. Because the light output from GSO is lower than for NaI, the RST tool employs a newly designed, sensitive PMT.

A new member of the scintillation detector family was developed two years ago by scientists at Schlumberger-Doll Research, Ridgefield, Connecticut, USA. They found that cerium-doped lutetium oxyorthosilicate (LSO), a cousin of GSO, promises to be the best scintillator for many applications.6 Although still in development, this scintillator combines high counting efficiency with a light-flash intensity nearly that of NaI and five times that of BGO. It is unaffected by moisture, is rugged and can handle higher counting rates free of pileup than other scintillators under consideration for borehole use. The light generated by an LSO crystal, similar in wavelength to that of NaI, works well with existing photocathode materials.

Competing crystals are breaking the near monopoly held by NaI for over four decades, though the price is high. The pair of GSO scintillators in the RST tool costs about $10,000 at present. But an expanding market is likely to result in improved production methods and reduced prices. These new scintillators are sure to make further inroads on NaI’s territory. Crystal research and development are continuing and new crystals with special properties may be added to this expanding list of exotic detectors.—JT, TAL

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>BGO</th>
<th>NaI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th</td>
<td>2.82 ppm</td>
<td>4.63 ppm</td>
</tr>
<tr>
<td>U</td>
<td>1.51 ppm</td>
<td>2.61 ppm</td>
</tr>
<tr>
<td>K</td>
<td>0.51%</td>
<td>0.74%</td>
</tr>
</tbody>
</table>

\[ \text{Th} = 12 \, \text{ppm}, \text{U} = 6 \, \text{ppm}, K = 2\% \]

Comparison of a GSO crystal used in the RST tool and the larger NaI crystal used in the GST tool. GSO’s higher density and higher atomic number allow it to function in the small diameter RST tool.


sured under known conditions. Ideally, the windows-based C/O tool would be logged first in a known water-bearing zone to determine a zero carbon value, then logged in a zone of known oil saturation to obtain a second calibration point.

Alpha processing for the RST tool combines the accuracy of the yields ratio with the precision of the windows ratio to obtain saturation results in the minimum time. It calculates the volume of oil (the product of porosity and oil saturation) from the C/O windows method—the windows oil volume, and the volume of oil from the C/O yields method—the yields oil volume. The difference between these volumes is tracked and used to adjust the windows oil volume. Alpha processing is applied over a specified number of levels, known as the alpha filter length.

Planning the RST Job

With nuclear tools like the RST tool, careful job planning can significantly affect the precision—and the cost—of the final answer. To facilitate planning an RST job, a software program called RST Job Planner is used to determine the logging speed and number of passes needed to produce results according to clients' specifications. Versions of RST Job Planner can run on VAX computers at the field logging interpretation center (FLIC) or on a Macintosh computer. The Macintosh version is available to clients.

RST Job Planner requires a variety of input parameters, including tool type, lithology, porosity, oil gravity (referred to as carbon density value—CDV), casing size and weight, borehole diameter, number of levels for alpha processing and number of levels of vertical averaging. In addition, clients specify the precision, or standard deviation of the answer, in terms of a percent saturation. The output consists of station times and logging speeds in a table showing two levels of confidence, 68% and 95%. The use of alpha processing increases logging speeds by improving measurement statistics.

Future of the RST Tool

With the RST tool's accuracy, precision and versatility for saturation monitoring unmatched in the oil field, applications for the tool continue to grow. The RST tool has recently provided holdup measurements in horizontal and through-tubing wells. A porosity measurement determined from a ratio of the count rates in the near and far detectors will soon be added to the sigma mode. Software is being developed that will convert between RST and TDT logs, enhancing the value of RST logs in Σ monitoring programs. In addition, the RST tool's response to gas is being studied. These ongoing projects, plus experimental use of the RST tool in uncharacterized environments by innovative field engineers and clients, promise an exciting future for this newest saturation monitoring device. —TAL

5. Oil volume is the volume of formation taken up by oil. It can be expressed as porosity times oil saturation.

6. Accuracy refers to how close the mean value of a measurement is to the true value. Consider a speedometer that always registers 10 miles per hour (mph). It is inaccurate when the car is traveling 60 mph but accurate when the car travels 10 mph. Precision refers to the spread of individual measurements from the mean. A precise system produces results with very little spread. The broken speedometer is very precise, since it always gives the same measurement of 10 mph.

7. A precision of ± one standard deviation corresponds to 68% confidence; ± two standard deviations correspond to 95% confidence and ± three standard deviations correspond to 99.9% confidence.
The starting point for induced gamma ray spectrometry is the generation of neutrons. Like its predecessors, the RST tool uses a downhole accelerator to emit pulses of high-energy neutrons into the formation. This device creates 14-million electron volt (MeV) neutrons by accelerating deuterium ions into a tritium target. The neutrons primarily interact with formation nuclei in three ways:

1. In elastic neutron-scattering, the neutron bounces off the bombarded nucleus without exciting or destabilizing it. With each elastic interaction, the neutron loses energy. Hydrogen, with the mass of its nucleus equal to that of a neutron, is very good at slowing down neutrons. Hence, how efficiently a formation slows down neutrons generally indicates the abundance of hydrogen. Because hydrogen is most abundant in pore fluids, neutron slowdown indicates porosity.

2. Inelastic neutron scattering, the neutron bounces off the nucleus, but excites it into quickly giving off what are called inelastic gamma rays. The measurement of gamma ray energies from inelastic neutron scattering yields the relative concentrations of carbon and oxygen, which are then used to determine water saturation.

3. In neutron absorption, the nucleus absorbs the neutron and becomes excited, typically emitting capture gamma rays. Neutron absorption, or neutron capture, is most common after a neutron has been slowed by elastic and inelastic interactions to thermal energies of about 0.025 eV. The measurement of capture gamma ray energies is used to estimate the abundances of elements most likely to capture a neutron—silicon, calcium, chlorine, hydrogen, sulfur, iron, titanium and gadolinium.

The interactions and measurements associated with gamma ray spectrometry may be confusing to nonexperts in nuclear logging. Simply put, gamma ray spectrometry measures gamma rays (counts) in time and gamma ray energies. Some elements emit gamma rays naturally; others can be bombarded with neutrons to induce gamma ray emissions. Each element produces characteristic gamma rays of specific energies. Moreover, the number of characteristic gamma rays produced is proportional to the abundance of the element. Naturally occurring and induced gamma rays may be counted and sorted according to energy. This produces a gamma ray spectrum that can be processed, or decoded, to identify the elements and their concentrations.
A decrease in the production rate of capture gamma rays over time, as measured with the TDT tool, is proportional to the absorption rate of thermal neutrons. This decay is basically exponential and accounts for both the absorption and diffusion of neutrons in the formation. The slope of a semilog plot of gamma ray counts versus time yields the capture cross section $\Sigma$ of the formation. Expressed in capture units, the capture cross section expresses the probability that a neutron passing through a cross-sectional area of a material will be captured.

A gamma ray is detected when its interactions with the detector crystal create electrons and holes that excite the crystal into generating flashes of light (scintillations). The intensity of these scintillations is related to the energy of the bombarding gamma ray. Most gamma rays lose some of their energy on the way to the detector because they scatter randomly, create new particles or disappear.

The light flashes pass through a window at one end of the crystal and fall on the photocathode surface of a photomultiplier tube, liberating electrons via the photoelectric effect. The tube amplifies the electronic charges about 200,000 times and provides a current signal large enough to be analyzed by downhole electronics.

As with any other nuclear logging tool, the gamma ray spectra collected by the RST tool must be processed to identify the elements that contributed to the spectra and their abundances. This is possible because each element produces a characteristic set of gamma ray peaks.

A library of standard elemental spectra is used to determine the individual elemental contributions. Each standard elemental spectrum represents the response of a tool to a particular element. A computer determines the linear combination of these elemental standards that best fits the measured spectrum and calculates the elemental yields. A yield is the fractional contribution of an element to the total observed spectrum, after subtracting off the capture background. It is proportional to the abundance of the element.