Although well logging has made major advances over the last 70 years, several important reservoir properties are still not measured in a continuous log. Among these are producibility, irreducible water saturation and residual oil saturation. Nuclear magnetic resonance (NMR) logging has long promised to measure these, yet it is only recently that technological developments backed up by sound research into the physics behind the measurements show signs of fulfilling that promise.

**Nuclear Magnetic Resonance Imaging—Technology for the 21st Century**

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In this article, CMR (Combinable Magnetic Resonance tool), ELAN (Elemental Log Analysis), Litho-Density (photoelectric density log) and NML (Nuclear Magnetism Logging tool) are marks of Schlumberger. MRIL (Magnetic Resonance Imager Log) is a mark of NUMAR Corporation.

For nearly 70 years, the oil industry has relied on logging tools to reveal the properties of the subsurface. The arsenal of wireline measurements has grown to allow unprecedented understanding of hydrocarbon reservoirs, but problems persist: a continuous log of permeability remains elusive, pay zones are bypassed and oil is left in the ground. A reliable nuclear magnetic resonance (NMR) measurement may change all that. This article reviews the physics and interpretation of NMR techniques, and examines field examples where NMR logging has been successful.

**Some Basics**

Nuclear magnetic resonance refers to a physical principle—response of nuclei to a magnetic field. Many nuclei have a magnetic moment—they behave like spinning bar magnets (next page, left). These spinning magnetic nuclei can interact with externally applied magnetic fields, producing measurable signals.
For most elements the detected signals are small. However, hydrogen has a relatively large magnetic moment and is abundant in both water and hydrocarbon in the pore space of rock. By tuning NMR logging tools to the magnetic resonant frequency of hydrogen, the signal is maximized and can be measured.

The quantities measured are signal amplitude and decay (see “All in a Spin—NMR Measurements,” below). NMR signal amplitude is proportional to the number of hydrogen nuclei present and is calibrated to give porosity, free from radioactive sources and free from lithology effects. However, the decay of the NMR signal during each measurement cycle—called the relaxation time—generates the most excitement among the petrophysical community.

Relaxation times depend on pore sizes (right). For example, small pores shorten relaxation times—the shortest times corresponding to clay-bound and capillary-bound water. Large pores allow long relaxation times and contain the most readily producible fluids. Therefore the distribution of relaxation times is a measure of the distribution of pore sizes—a new petrophysical parameter. Relaxation times and their distributions may be interpreted to give other petrophysical parameters such as permeability, producible porosity and irreducible water saturation. Other possible applications include capillary pressure curves, hydrocarbon identification and as an aid to facies analysis.

Two relaxation times and their distributions can be measured during an NMR experiment. Laboratory instruments usually measure longitudinal relaxation time, $T_1$, and $T_2$ distribution, while borehole instruments make the faster measurements of transverse relaxation time, $T_1$ and $T_2$ distribution.

In the rest of this article, $T_2$ will mean transverse relaxation time.

\[ \text{Relaxation curves. Water in a test tube has a long } T_2 \text{ relaxation time of } 3700 \text{ msec at } 40^\circ \text{C (upper curve). Relaxation times of a vuggy carbonate might approach this value. However, water in rock pore space has shorter relaxation times. For example, relaxation times for a sandstone typically range from } 10 \text{ msec for small pores to } 500 \text{ msec for large pores. The initial amplitude of the relaxation curve gives CMR porosity.} \]

2. For examples of laboratory $T_2$ core measurements enabling direct comparison to log measurements and to laboratory $T_1$ core measurements:

\[ \text{Precessing protons. Hydrogen nuclei—protons—behave like spinning bar magnets. Once disturbed from equilibrium, they precess about the static magnetic field (left) in the same way that a child’s spinning top precesses in the Earth’s gravitational field (right).} \]
NMR Applications and Examples

The $T_2$ distribution measured by the Schlumberger CMR Combinable Magnetic Resonance tool, described later, summarizes all the NMR measurements and has several petrophysical applications:

- $T_2$ distribution mimics pore size distribution in water-saturated rock
- the area under the distribution curve equals CMR porosity
- permeability is estimated from logarithmic-mean $T_2$ and CMR porosity
- empirically derived cutoffs separate the $T_2$ distribution into areas equal to free-fluid porosity and irreducible water porosity.

Application and interpretation of NMR measurement rely on understanding the rock and fluid properties that cause relaxation (see “NMR Relaxation Mechanisms,” page 26). With this foundation of the mechanisms of relaxation, the interpretation of $T_2$ distribution becomes straightforward.

$T_2$ Distribution—In porous media, $T_2$ relaxation time is proportional to pore size. At any depth in the well the CMR tool probes a rock sample that has a range of pore sizes. The observed $T_2$ decay is the sum of $T_2$ signals from hydrogen protons, in many individual pores, relaxing independently. The $T_2$ distribution graphically shows the volume of pore fluid associated with each value of $T_2$, and therefore the volume associated with each pore.

Signal processing techniques are used to transform NMR signals into $T_2$ distributions (right). Processing details are beyond the scope of this article.

Proton alignment—Hydrogen protons are aligned by application of a large constant magnetic field, $B_0$. Alignment take a few seconds and the protons will remain aligned unless disturbed. The latest logging tools use elongated permanent magnets, of about 550 gauss in the measurement region—about 1000 times larger than the Earth’s magnetic field. These are applied to the formation during the entire measurement cycle (right).

Spin tipping—The next step is to tip the aligned protons by transmitting an oscillating external magnetic field. The net magnetization along the $z$-axis is precessing about an axis parallel to the $B_0$ direction—the net precessing magnetic moments being the sum of all the pro cessing protons. In logging applications $B_0$ is perpendicular to the borehole axis.

1. This article uses hydrogen proton when discussing NMR measurements. However, other texts use proton, nucleus, moment and spin interchangeably. For the purposes of NMR theory they are all considered synonyms.
2. For a detailed description of NMR measurements:
3. The SI unit of magnetic flux density is the Tesla—equal to 1000 gauss.
In an example taken from a carbonate reservoir, T2 distributions from X340 ft to X405 ft are biased towards the high end of the distribution spectrum indicating large pores (left). Below X405 ft, the bias is towards the low end of the spectrum, indicating small pores. This not only provides a qualitative feel for which zones are likely to produce, but also helps geologists with facies analysis.

Lithology-independent porosity—Traditional calculations of porosity rely on borehole measurements of density and neutron porosity. Both measurements require environmental corrections and are influenced by lithology and formation fluid. The porosity derived is total porosity, which consists of

magnetic field, B1, perpendicular to the direction of B0 (right). For effective spin tipping:

\[ f = \gamma B_0 \]

where f is the frequency of B1—called Larmor frequency—and \( \gamma \) is a constant called the gyromagnetic ratio of the nucleus. For example, the Larmor frequency for hydrogen nuclei in a field of 550 gauss is about 2.3 MHz.

The angle through which spins are tipped is controlled by the strength of B1 and the length of time it is switched on. For example, to tip spins by 90°—as in most logging applications—a B1 field of 4 gauss is switched on for 16 microseconds (\( \mu \)sec).

Precession and dephasing—When protons are tipped 90° from the B0 direction, they precess in the plane perpendicular to B0. In this respect they act like gyroscopes in a gravitation field (page 20, left).

At first all the protons precess in unison. While doing so they generate a small magnetic field at the Larmor frequency which is detected by the antenna and forms the basis of the NMR measurements. However, the magnetic field, Bp, is not perfectly homogeneous, causing the protons to precess at slightly different frequencies. Gradually, they lose synchronization—they dephase—causing the antenna signal to decay (next page). The decaying signal is called free induction decay (FID) and the decay time is called

Pore-size distribution and free-fluid index—carbonate example. In this well, the oil company was concerned about water coning during production. The interval below X405 ft showed nearly 100% water saturation by conventional log interpretation (track 3). However, the CMR log showed low T2 distribution values over this interval (track 4) indicating small pores. Larger pores are indicated above X405 ft by higher T2 distributions. Applying a free-fluid index cutoff of 100 msec to the distributions showed that most of the water was irreducible. This result gave the oil company confidence to add the interval X380 ft to X395 ft to its perforating program.

Spin tipping. Aligned protons are tipped 90° by a magnetic pulse oscillating at the resonance, or Larmor frequency.
Pulse sequence and refocusing. Each NMR measurement comprises a sequence of transverse magnetic pulses transmitted by an antenna—a CPMG sequence. Each CPMG sequence starts with a pulse that tips hydrogen protons 90° and is followed by several hundred pulses that refocus the protons by tipping them 180° (top). After each pulse the antenna becomes a receiver that records the signal amplitude (middle). The fast decay of each echo—called free induction decay—is caused by variations in the static magnetic field, $B_0$. The decay of each echo amplitude is caused by molecular interactions and has a characteristic time constant of $T_2$—transverse relaxation time. The circled numbers correspond to steps numbered in the race analogy (below).

Imagine runners lined up at the start of a race (bottom). They are started by a 90° pulse (1). After several laps, the runners are spread around the track (2, 3). Then the starter fires a second pulse of 180° (4, 5) and the runners turn round and head back to the starting line. The fastest runners have the farthest distance to travel and all of them will arrive at the same time if they return at the same rate (6a). With any variation in speed, the runners arrive back at slightly different times (6b). Like the example of the runners, the process of spin reversal is repeated hundreds of times during an NMR measurement. Each time the echo amplitude is less and the decay rate gives $T_2$ relaxation time.

$T_2^*$—the asterisk indicates that the decay is not a property of the formation. For logging tools $T_2^*$ is comparable to the span of the tipping pulse—a few tens of microseconds.

Refocusing: spin echoes—The dephasing caused by the inhomogeneity of $B_0$ is reversible. Imagine a race started by a starting gun, analogous to a 90° tipping pulse. The runners start off in unison, but after several laps they become dispersed around the track—due to their slightly different speeds. Now the starter gives another signal by firing a 180° pulse. The runners turn around and race in the opposite direction. The fastest runners have the greatest distance to travel back to the start. However, if the conditions remain the same—which is never the case—all the runners arrive back at the same time (above).

Similarly, the hydrogen protons—precessing at slightly different Larmor frequencies—can be refocused when a 180° pulse is transmitted. The 180° pulse is the same strength as a 90° pulse, but switched on for twice as long. As the protons rephase, they generate a signal in the antenna—a spin echo.

Of course, the spin echo quickly decays again. However, the 180° pulses can be applied repeatedly—typically several hundred times in a single NMR measurement. The usual procedure is to apply 180° pulses in an evenly spaced train, as
close together as possible. The entire pulse sequence, a 90° pulse followed by a long series of 180° pulses, is called a CPMG sequence after its inventors, Carr, Purcell, Meiboom and Gill. The echo spacing is 320 μsec for the Schlumberger CMR tool and 1200 μsec for NUMAR’s MRIL tool.

Transverse relaxation, T₂ — The CPMG pulse sequence compensates for dephasing caused by B₀ field imperfections. However, molecular processes also cause dephasing, but this is irreversible. These processes are related to petro-

CMR porosity. Hydrogen in rock matrix and in clay-bound water has short relaxation times that are lost in the dead time of the CMR tool. CMR porosity includes only capillary-bound water and producible fluids and is not influenced by lithology. Total porosity—as measured by conventional logs—also includes clay-bound water. The dotted line indicates that CMR porosity does not include microporosity associated with hard shales.

CMR porosity is not influenced by lithology and includes only producible fluids and capillary-bound water. This is because hydrogen in rock matrix and in clay-bound water has sufficiently short T₂ relaxation times that the signal is lost during the dead time of the tool.

An example in a clean carbonate formation compares CMR porosity with that derived from the density tool to show lithology independence (next page, top). The lower half of the interval is predominantly limestone, and density porosity, assuming a limestone matrix, overlays CMR porosity. At X935 ft, the reservoir changes to dolomite at XX41 m to XX49 m the porosity varied little. However, permeability varied considerably from a low of 0.07 md at XX48 m to a high of 10 md at XX43 m. CMR permeability also showed excellent vertical resolution and compared well to that of core values. The value of C used for this well will be applied to subsequent CMR logs in this formation enabling the oil company to reduce coring costs.

Free-fluid index — The value of free-fluid index is determined by applying a cutoff to the T₂ relaxation curve. Values above the cutoff indicate large pores potentially capable of producing, and values below indicate small pores containing fluid that is trapped by capillary pressure, incapable of producing.

Irreversible dephasing is monitored by measuring the decaying amplitude of the spin echoes in the CPMG echo train (left). The characteristic echo amplitude decay time is called the transverse relaxation time, T₂, because dephasing occurs in the plane transverse to the static field B₀. Longitudinal relaxation, T₁ — After a period of several times T₂, the protons completely lose coherence, and no further refocusing is possible. After the CPMG pulse sequence is delivered the protons return to their equilibrium direction parallel to B₀.
Lithology-independent porosity. Below X935 ft, the lithology is limestone with some dolomitization (track 1), while above is dolomite. Two porosity curves (track 2) are derived from density measurements—one assumes a limestone lithology and the other dolomite. CMR porosity overlays the density limestone porosity in limestone regions and overlays dolomite porosity in dolomite regions—demonstrating that CMR porosity is independent of lithology.

Longitudinal relaxation, $T_1$. When the CPMG pulse sequence ends, the protons gradually relax back towards the static magnetic field. They do so with characteristic time constant $T_1$, longitudinal relaxation.

$T_1$ and $T_2$ both arise from molecular processes. In many laboratory measurements on water-saturated rocks, it has been found that $T_1$ is frequently equal to 1.5 $T_2$. However, this ratio varies when oil and gas are present in rock samples.

5. Transverse relaxation is sometimes called spin-spin relaxation in early NMR literature. Similarly, longitudinal relaxation is sometimes called spin-lattice relaxation.

Kleinberg et al, reference 2 main text.
Many experiments have been made on rock samples to verify this assumption. T2 distributions were measured on water-saturated cores before and after they had been centrifuged in air to expel the producible water. The samples were centrifuged under 100 psi to simulate reservoir capillary pressure. Before centrifuging, the relaxation distribution corresponds to all pore sizes. It seems logical to assume that during centrifuging the large pore spaces empty first. Not surprisingly, the long relaxation times disappeared from the T2 measurement (next page, top).

Observations of many sandstone samples showed that a cutoff time of 33 msec for T2 distributions would distinguish between free-fluid porosity and capillary-bound water. For carbonates, relaxation times tend to be three times longer and a cutoff of 100 msec is used. However, both these values will vary if reservoir capillary pressure differs from the 100 psi used on the centrifuged samples. If this is the case, the experiments may be repeated to find cutoff times appropriate to the reservoir.

In a fine-grained sandstone reservoir example, interpretation of conventional log data showed 70 to 80% water saturation. Comparison of log and core data. CMR porosity shows a good match with core porosity measurements. Computed CMR permeability has been fine-tuned to match core permeability enabling CMR logs to replace conventional coring on subsequent wells.

NMR Relaxation Mechanisms

There are three NMR relaxation mechanisms that influence T1 or T2 relaxation times: grain surface relaxation, relaxation by molecular diffusion in magnetic field gradients and relaxation by bulk fluid processes.1

Grain surface relaxation—Molecules in fluids are in constant motion—Brownian motion—and diffuse about a pore space, hitting the grain surface several times during one NMR measurement. When this happens, two interactions may occur. First, hydrogen protons can transfer nuclear spin energy to the grain surface allowing realignment with the static magnetic field, B0—this contributes to longitudinal relaxation, T1. Second, protons may be irreversibly dephased—contributing to transverse relaxation, T2. Researchers have shown that in most rocks, grain-surface relaxation is the most important influence on T1 and T2. The ability of grain surfaces to relax protons is called surface relaxivity, r.2

Surfaces are not equally effective in relaxing hydrogen protons. For example, sandstones are about three times more efficient in relaxing pore water than carbonates. Also rocks with a high content of iron or other magnetic minerals have larger than usual values of r and, hence, shorter NMR relaxation times. Pore size also plays an important role in surface relaxation. The speed of relaxation depends on how frequently protons can collide with the surface and this depends on the surface-to-volume ratio (S/V) (next page, bottom). Collisions

Grain surface relaxation. Precessing protons move about pore space colliding with other protons and with grain surfaces (left). Every time a proton collides with a grain surface there is a possibility of a relaxation interaction occurring. Grain surface relaxation is the most important process affecting $T_1$ and $T_2$ relaxation times. Experiments have shown that when the probability of colliding with a grain surface is high—small pores (center)—relaxation is rapid and when the probability of colliding with a grain surface is low—large pores (right)—relaxation is slower.

Free-fluid porosity. Free-fluid porosity is determined by applying a cutoff to the $T_2$ distribution curve. The area underneath the curve above the cutoff gives free-fluid porosity (top). This zone relates to the large producible pores of a rock sample. The value for the cutoff was determined in the laboratory from a large number of water-saturated core samples. First, $T_2$ distributions were measured. Then the cores were centrifuged under 100 psi pressure to simulate draining down to typical reservoir capillary pressures. The amount of fluid drained equals the free-fluid porosity, which is converted into an equivalent area on the $T_2$ distribution curve. The area—shaded from the right—determines cutoff values. A comparison of $T_2$ distributions taken before and after centrifuging shows the validity of this technique (top). Free-fluid porosity measured in sandstone formations in two wells using the cutoff value of 33 msec obtained above shows good correlation when plotted versus centrifuge porosity (bottom).

Grain surface relaxation. Precessing protons move about pore space colliding with other protons and with grain surfaces (left). Every time a proton collides with a grain surface there is a possibility of a relaxation interaction occurring. Grain surface relaxation is the most important process affecting $T_1$ and $T_2$ relaxation times. Experimenters have shown that when the probability of colliding with a grain surface is high—small pores (center)—relaxation is rapid and when the probability of colliding with a grain surface is low—large pores (right)—relaxation is slower.
are less frequent in large pores and they have a small S/V—relaxation times are, therefore, relatively long. Similarly, small pores have large a S/V and short relaxation times.\(^3\)

For a single pore, the nuclear spin magnetization decays exponentially, so the signal amplitude as a function of time in a \(T_2\) experiment decays with characteristic time constant, \([\rho_2(S/V)]^{-1}\). Therefore,
\[
1/T_2 = \rho_2 S/V.
\]

Similarly,
\[
1/T_1 = \rho_1 S/V.
\]

Rocks have a distribution of pore sizes, each with its own value of S/V. The total magnetization is the sum of the signal coming from each pore. The sum of the volumes of all the pores is equal to the fluid volume of the rock—the porosity. So the total signal is proportional to porosity and the overall decay is the sum of the individual decays, which reflects pore size distribution. NMR measurements of porosity and pore size distribution are the key elements of NMR interpretation.

Relaxation by molecular diffusion in magnetic field gradients—When there are gradients in the static magnetic field, molecular motion can cause dephasing and hence \(T_2\) relaxation. \(T_1\) relaxation is not affected. In the absence of such gradients, molecular diffusion does not cause NMR relaxation.

A \(B_0\) gradient has two possible sources: the magnet configuration of the logging tool, and the magnetic susceptibility contrast between grain materials and pore fluids in porous rocks.

Keeping the CPMG echo spacing to a minimum, and keeping the applied magnetic field small reduce the contribution of diffusion to \(T_2\) relaxation to a negligible level.

\(\square\)Free-fluid index—sandstone example. In this predominantly shaly-sandstone (track 1), \(T_2\) distributions (track 5) fall mainly below the 33-msec cutoff line, indicating capillary-bound water. However, the ELAN interpretation (track 3)—made without CMR data—shows high water saturation, implying water production. The ELAN interpretation with CMR data (track 4) clearly shows that most of the water is irreducible. This well produced at 30% water cut, validating the CMR results.
across a shaly sandstone formation. However, on the CMR log most of the T2 distribution falls below the 33-msec cutoff indicating capillary-bound water. Interpretation including CMR data showed that most of the water was irreducible. The well has since been completed producing economic quantities of gas and oil with a low water cut (previous page). The water cut may be estimated from the difference between residual water saturation and water saturation from resistivity logs.

In another example, but this time in a complex carbonate reservoir, the oil company was concerned about water coning during production. CMR log data showed low T2 values below X405 ft indicating small pore sizes. Applying the carbonate cutoff of 100 msec showed that nearly all the water was irreducible, which allowed additional perforation (see page 22, top). To date no water coning has occurred.

Values for cutoffs can also be tailored to particular reservoirs and help with facies analysis, as in the case of the Thamama group of formations in Abu Dhabi Oil Company's Mubarraz field offshore Abu Dhabi, UAE. In this field, classical log interpretation showed water saturation of 10 to 60%. However, some zones produced no water, making completion decisions difficult. Permeability also varied widely even though porosity remained almost constant. Laboratory measurements were performed on cores to determine whether NMR logging would improve log evaluation.

Cores showed a good deal of microporosity holding a large volume of capillary-bound water. Free-fluid porosity was found in the traditional way by centrifuging the water-saturated cores. For this reservoir, however, capillary pressure was known to be 25 psi, so the core samples were centrifuged accordingly. This showed that NMR measurements could provide a good estimate of nonproducing micro pores using a T2 cutoff of 190 msec. In addition, permeable grainstone facies could be distinguished from lower-permeability packstones and mudstones with a cutoff of 225 msec.

**Additional Applications**

Borehole NMR instruments are shallow-reading devices. In most cases, they measure formation properties in the flushed zone. This has some advantages as mud filtrate properties are well-known and can be measured at the wellsite on surface. When fluid loss during drilling is low, as in the case of low-permeability formations, hydrocarbons may also be present in the flushed zone (see "The Lowdown on Low-Resistivity Pay," page 4). In these cases NMR tools may measure fluid properties such as viscosity and so distinguish oil from water.

A published example of the effects of hydrocarbon viscosity comes from Shell’s North Belridge diatomite and Brown shale formations, Bakersfield, California, USA, 10. Both CMR logs and laboratory measurements on cores show two distinct peaks on the T2 distribution curves. The shorter peak, at about 10 msec, originates from water in contact with the diatom surface. The longer peak, at about 150 msec, originates from light oil. The position of the oil peak correlates roughly with oil viscosity. The area under this peak provides an estimation of oil saturation.

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History of Nuclear Magnetic Resonance Logging

As far back as 1946, nuclear magnetic resonance (NMR) signals from hydrogen atom nuclei—protons—were first observed independently by Purcell and Bloch, and have since been used extensively to characterize materials.¹ Magnetic resonance imaging instruments are commonly used as diagnostic tools in medicine today.

Oil industry interest followed in the 1950s with several patents for NMR logging tools filed by companies such as California Research Corporation, Schlumberger Well Surveying Corporation, Texaco Incorporated and Socony Mobil Oil Company.

The first NMR log was run in 1960. Developed by Brown and Gamson of Chevron Research Company, the tool used the Earth’s magnetic field for proton alignment—the principle underlying NMR logging tools for the next 30 years.² Schlumberger ran two versions of this tool in the 1960s and early 1970s under license from Chevron and later developed a third-generation tool—NML-C—commercialized at the end of the 1970s.³

During this time, continuing research into NMR interpretation produced some outstanding contributions. Seevers developed a relationship between relaxation time and permeability of sandstones in 1965, and Timur developed the concept of free-fluid index and new methods to measure permeability using NMR principles in 1968.⁴ The relationship between pore size, fluid and matrix properties was presented by Loren and Robinson of Shell Oil Company in 1969.⁵

The 1970s and 1980s saw continuation of this work by many oil companies in parallel with laboratory NMR techniques developed to characterize core samples. Schlumberger also has a long tradition of research into NMR techniques and produced important work on relaxation mechanisms and pore-size distributions in the late 1980s.⁶ Much of this work continues today.

In the late 1980s the first experimental pulsed-NMR logging tools were developed. A major disadvantage of early logging tools was having to dope the mud system with magnetite to eliminate the NMR signal from the borehole. To make the technique more widely acceptable meant a radical design change to profit from advances in pulsed-NMR technology—more commonly used in the laboratory for core measurements.

A patent for a pulse-echo NMR logging tool was filed by Jackson in 1978. This was followed

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**Table:**

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<thead>
<tr>
<th>Borehole Fields</th>
<th>Magnetization</th>
<th>NML Signal</th>
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- Principle of early NMR tools. The Schlumberger NML Nuclear Magnetism Logging tool measured transverse relaxation, $T_2$. Protons in the formation are aligned to the Earth’s magnetic field—considered to be homogeneous on these scales. A horizontally-mounted coil tips the protons 90° (Borehole). They then start to precess about the Earth’s field and gradually relax back towards it (Magnetization). The same coil measures the decaying horizontal magnetization as protons relax. The envelope of the decaying signal gives $T_2$ (NML Signal). $T_2$ amplitude was extrapolated back to the start of the measurement to give NML porosity, assumed equal to free-fluid index. One big drawback with this type of tool was that the borehole signal had to be eliminated by doping the mud system with magnetite—not very popular with drillers.
Permanent magnet

Static magnetic field lines

Radio frequency coil

Radio frequency field lines

Sensitive zones

**Borehole NMR tool designs.** Earth-field tool proposed by Brown and Gamson in 1960 (top left) was the principle behind three generations of Schlumberger NML tools. Inside-out NMR uses permanent magnets and pulsed NMR technology (top right). This configuration was first proposed by Jackson in 1984. The MRIL Magnetic Resonance Imager Log built by NUMAR Corporation in 1990 (bottom left) was the first commercial pulsed NMR tool. A side-looking inside-out configuration invented by Schlumberger is the basis for the QMR tool commercialized this year (bottom right). The top two figures are side views of the borehole and the bottom two figures are cross sections.

**T**₂ distribution measurements were also made on crude oil samples having viscosities of 2.7 cp to 4300 cp (below). Highly viscous oils have less mobile hydrogen protons and tend to relax quickly. The CMR log showed the **T**₂ oil peak and correctly predicted oil viscosity. It also showed that the upper 150 ft of the diatomite formation undergoes a transition to heavier oil.

Capillary pressure curves, used by reservoir engineers to estimate the percentage of connate water, may also be predicted from **T**₂ distributions. Typically these curves—plots of mercury volume versus pressure—are produced by injecting mercury into core samples. Under low pressure the mercury fills the largest pores and, as pressure increases, progressively smaller pores are filled. The derivative of the capillary pressure curve approximates the **T**₂ distribution. Some differences in shape are expected as mercury injection measures pore throat sizes, whereas NMR measurements respond to the size of pore bodies.¹¹

Other applications and techniques are likely to follow with more complex operations that might involve comparing logs run under different borehole conditions. For example, fluid may be injected into the formation that is designed to kill the water NMR signal so that residual oil saturation may be measured. This type of technique, called log-inject-log, has been used with other borehole logs to monitor injectivity or to monitor acid treatments.

**T**₂ distributions for two oils of different viscosities. When bulk fluid relaxation dominates, as in the case of fluid samples, viscosity influences relaxation time. Hydrogen protons in highly viscous fluids are less mobile and tend to relax quickly.

Function of a Pulsed Magnetic Resonance Tool
The CMR tool is the latest generation Schlumberger NMR tool (see “History of Nuclear Magnetic Resonance Logging,” page 30). The measurement takes place entirely within the formation, eliminating the need to dope mud systems with magnetite to kill the borehole signal—a big drawback with the old earth-field tools. It uses pulsed-NMR technology, which eliminates the effects of nonuniform static magnetic fields and also increases signal strength. This technology, along with the sidewall design, makes the tool only 14 ft [4.3 m] long and readily combinable with other logging tools (above).¹²

The skid-type sensor package, mounted on the side of the tool, contains two permanent magnets and a transmitter-receiver antenna. A bowspring eccentricizing arm or powered caliper arm—if run in combination with other logging tools—forces the skid against the borehole wall, effectively removing any upper limit to borehole size.

An important advantage of the sidewall design is that the effect of conductive mud, which shorts out the antenna on mandrel-type tools, is greatly reduced. What little effect remains is fully corrected by an internal calibration signal. Another advantage is that calibration of NMR porosity is simplified and consists of placing a bottle of water against the skid to simulate 100% porosity. **T**₂ properties of mud filtrate samples—required for interpretation corrections—may also be measured at the wellsite in a similar fashion. Finally, the design enables high-res-
olution logging—a 6-in. [15-cm] long measurement aperture is provided by a focused magnetic field and antenna.

Two permanent magnets generate the focused magnetic field, which is about 1000 times stronger than the Earth's magnetic field. The magnets are arranged so that the field converges to form a zone of constant strength about one inch inside the formation. NMR measurements take place in this region.

By design, the area between the skid and the measurement volume does not contribute to the NMR signal. Coupled with skid geometry, this provides sufficient immunity to the effects of mudcake and hole rugosity. The rugose hole effect is similar to that of other skid-type tools such as the Litho-Density tool.

The measurement sequence starts with a wait time of about 1.3 sec to allow for complete polarization of the hydrogen protons in the formation along the length of the skid (for measurement principles, see “All in a Spin—NMR Measurements,” page 20). Then the antenna typically transmits a train of 600 magnetic pulses into the formation at 320-msec intervals. Each pulse induces an NMR signal—spin echo—from the aligned hydrogen protons. The antenna also acts as a receiver and records each spin echo amplitude. T₂ distribution is derived from the decaying spin echo curve, sometimes called the relaxation curve.

Logs for the Future?
The prospects have always looked bright for nuclear magnetic resonance logging. Research has shown that interpretation of NMR relaxation times provides a wealth of petrophysical data. The latest generation logging tools—using pulsed NMR techniques—are building on that research and are providing powerful wellsite answers that shed new insight into the basic question, “What will the well produce?” —AM