Nuclear Magnetic Resonance Imaging—Technology for the 21st Century

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.

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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
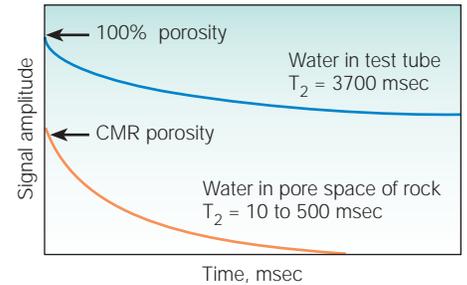
□*Relaxation curves. Water in a test tube has a long T_2 relaxation time of 3700 msec at 40°C (upper curve). Relaxation times of a vuggy carbonate might approach this value. However, water in rock pore space has shorter relaxation times. For example, relaxation times for a sandstone typically range from 10 msec for small pores to 500 msec for large pores. The initial amplitude of the relaxation curve gives CMR porosity.*
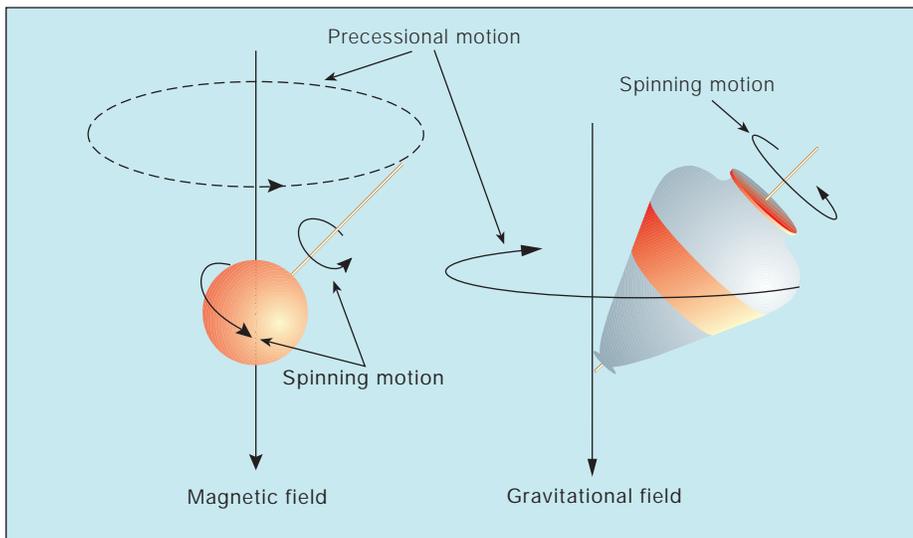
petrophysical parameters such as permeability, producible porosity and irreducible water saturation. Other possible applications include capillary pressure curves, hydrocarbon identification and as an aid to facies analysis.[1]

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_2 and T_2 distribution.[2] In the rest of this article T_2 will mean transverse relaxation time.

□*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).*

All in a Spin— NMR Measurements

NMR measurements consist of a series of manipulations of hydrogen protons in fluid molecules.[1] Protons have a magnetic moment and behave like small bar magnets, so that their orientations may be controlled by magnetic fields. They also spin, which makes them act like gyroscopes.

A measurement sequence starts with proton alignment followed by spin tipping, precession, and repeated dephasing and refocusing. Transverse relaxation and longitudinal relaxation limit how long a measurement must last. Only after completion of all these steps—which takes a few seconds—can the measurement be repeated.[2]

1. Murphy DP: "NMR Logging and Core Analysis—Simplified," *World Oil* 216, no. 4 (April 1995): 65-70.

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

   Straley C, Rossini D, Vinegar H, Tutunjian P and Morriss C: "Core Analysis by Low Field NMR," *Proceedings of the 1994 International Symposium of the Society of Core Analysts*, Stavanger, Norway, September 12-14, 1994, paper SCA-9404.

   Kleinberg RL, Straley C, Kenyon WE, Akkurt R and Farooqui SA: "Nuclear Magnetic Resonance of Rocks: T_1 versus T_2," paper SPE 26470, presented at the 68th SPE Annual Technical Conference and Exhibition, Houston, Texas, USA, October 3-6, 1993.

3. Kenyon WE: "Nuclear Magnetic Resonance as a Petrophysical Measurement," *Nuclear Geophysics* 6, no. 2 (1992): 153-171.

4. Kenyon WE, Howard JJ, Sezinger A, Straley C, Matteson A, Horkowitz K and Ehrlich R: "Pore-Size Distribution and NMR in Microporous Cherty Sandstones," *Transactions of the SPWLA 30th Annual Logging Symposium,* Denver, Colorado, USA, June 11-14, 1989, paper LL.

   Howard JJ, Kenyon WE and Straley C: "Proton Magnetic Resonance and Pore Size Variations in Reservoir Sandstones," paper SPE 20600, presented at the 65th SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 23-26, 1990.

   Gallegos DP and Smith DM: "A NMR Technique for the Analysis of Pore Structure: Determination of Continuous Pore Size Distributions," *Journal of Colloid and Interface Science* 122, no. 1 (1988): 143-153.

   Loren JD and Robinson JD: "Relations Between Pore Size Fluid and Matrix Properties, and NML Measurements," *SPE Journal* 10 (September 1970): 268-278.

5. Freedman R and Morriss CE: "Processing of Data From an NMR Logging Tool," paper SPE 30560, to be presented at the 70th SPE Annual Technical Conference and Exhibition, Dallas, Texas, USA, October 22-25, 1995.

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.[3]

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.[4] 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.[5]
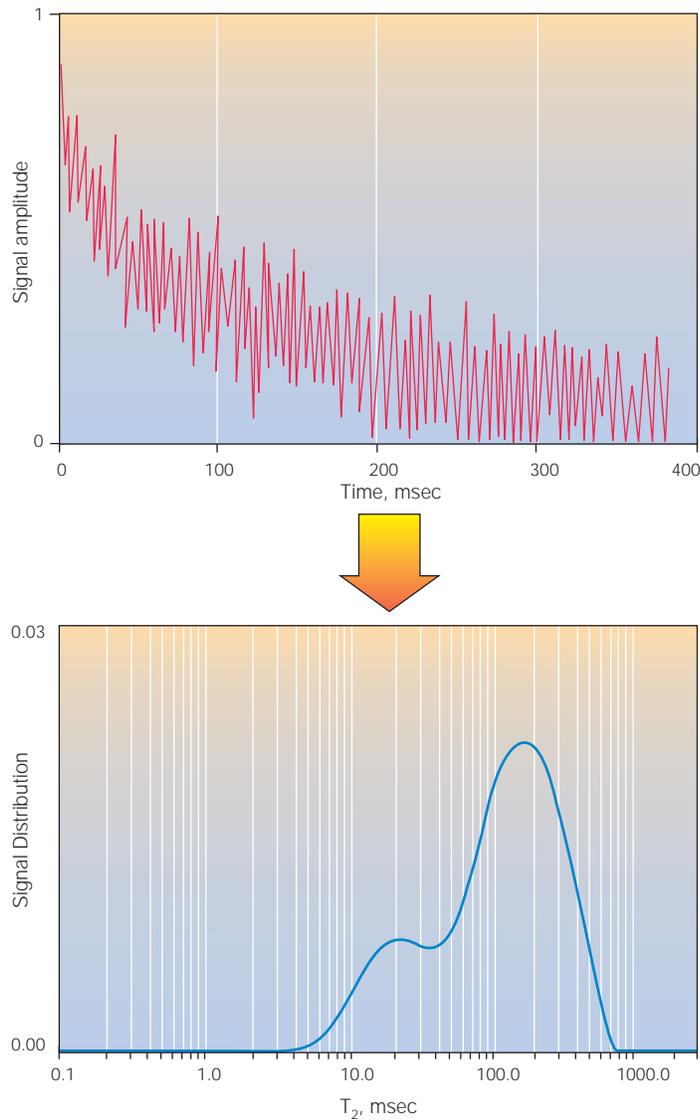
□Signal amplitude processed to give T_2 distribution. The CMR tool measures decaying NMR signal amplitude (top), which is the sum of all the decaying T_2 signals generated by hydrogen protons in the measurement volume. Separating out ranges of T_2 values by a mathematical inversion process produces the T_2 distribution (bottom). The curve represents the distribution of pore sizes, and the area under the curve is CMR porosity. Interpretation of pore size distribution and logarithmic mean T_2 are used to calculate such parameters as permeability and free-fluid porosity.
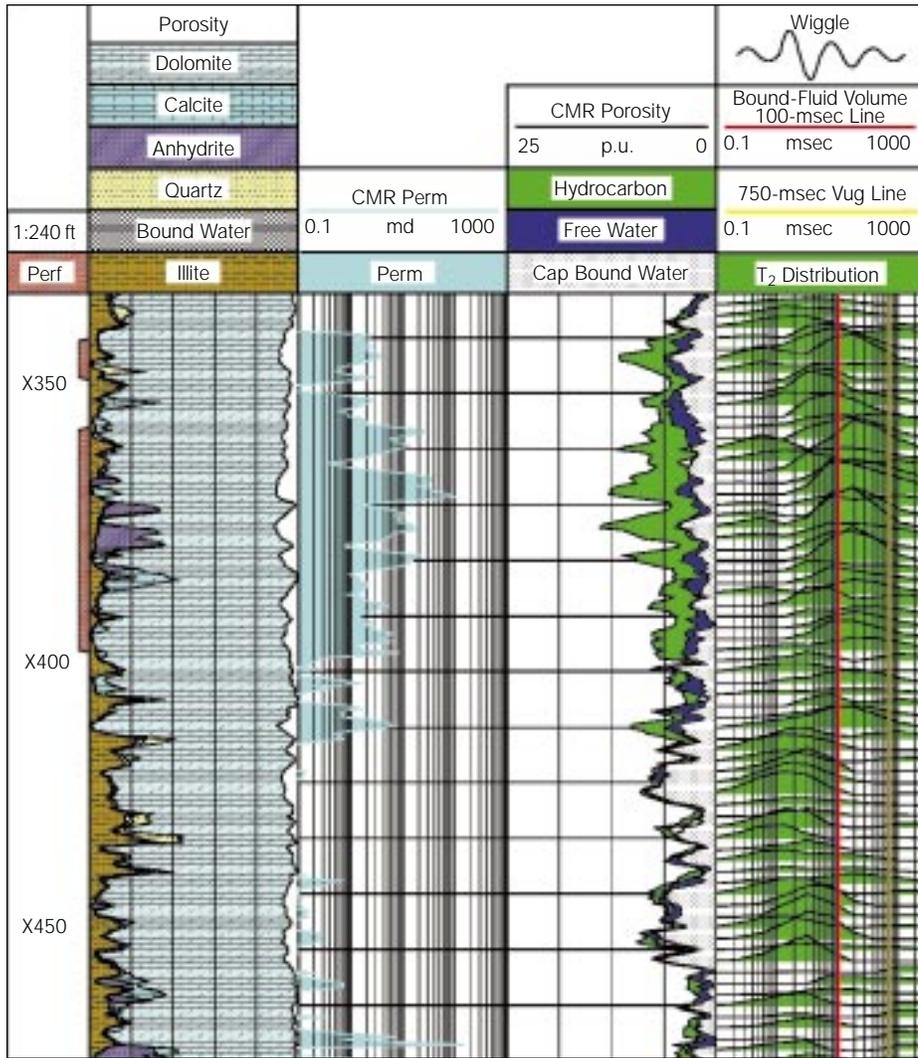
Proton alignment—Hydrogen protons are aligned by application of a large constant magnetic field, B_0. Alignment take a few seconds and the protons will remain aligned unless disturbed. The latest logging tools use elongated permanent magnets, of about 550 gauss in the measurement region—about 1000 times larger than the Earth's magnetic field. These are applied to the formation during the entire measurement cycle (right).[3]

Spin tipping—The next step is to tip the aligned protons by transmitting an oscillating
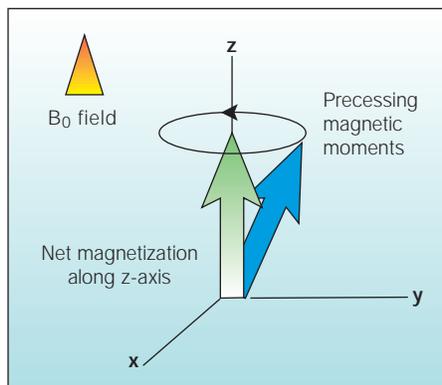
□Proton alignment. The first step in an NMR measurement is to align the spinning protons using powerful permanent magnets. The protons precess about an axis parallel to the B_0 direction—the net magnetization being the sum of all the precessing protons. In logging applications B_0 is perpendicular to 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:
Fukushima E and Roeder SBW: *Experimental Pulse NMR: A Nuts and Bolts Approach.* Reading, Massachusetts, USA: Addison-Wesley, 1981.

Farrar TC and Becker ED: *Pulse and Fourier Transform NMR: Introduction to Theory and Methods.* New York, New York USA: Academic Press, 1971.

3. The SI unit of magnetic flux density is the Tesla—equal to 1000 gauss.

Porosity
Dolomite
Calcite
Anhydrite
Quartz
Bound Water
Illite

1:240 ft
Perf

CMR Perm
0.1   md   1000
Perm

CMR Porosity
25   p.u.   0
Hydrocarbon
Free Water
Cap Bound Water

Wiggle

Bound-Fluid Volume 100-msec Line
0.1   msec   1000

750-msec Vug Line
0.1   msec   1000

T₂ Distribution

X350
X400
X450

□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 T_2 distribution values over this interval (track 4) indicating small pores. Larger pores are indicated above X405 ft by higher T_2 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.

In an example taken from a carbonate reservoir, T_2 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

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magnetic field, B_1, perpendicular to the direction of B_0 (right). For effective spin tipping:

$$f = \gamma\,B_0$$

where f is the frequency of B_1—called Larmor frequency—and γ 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.
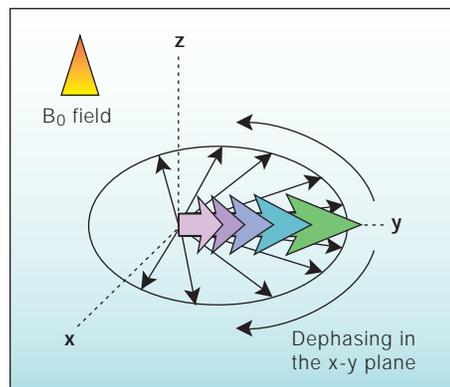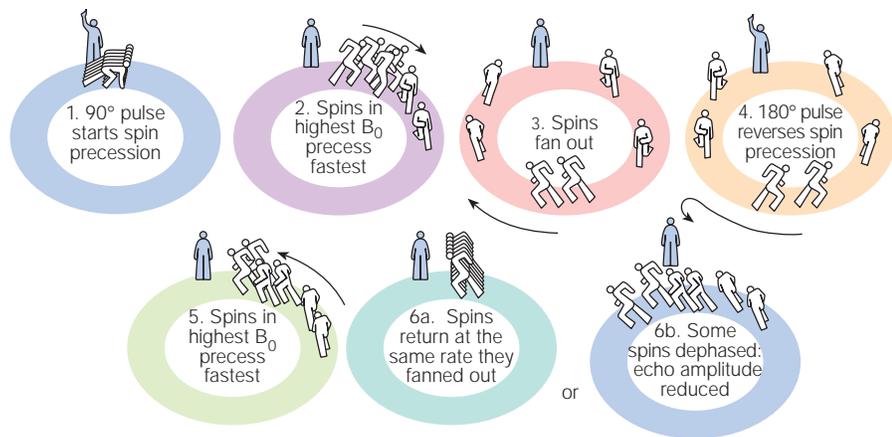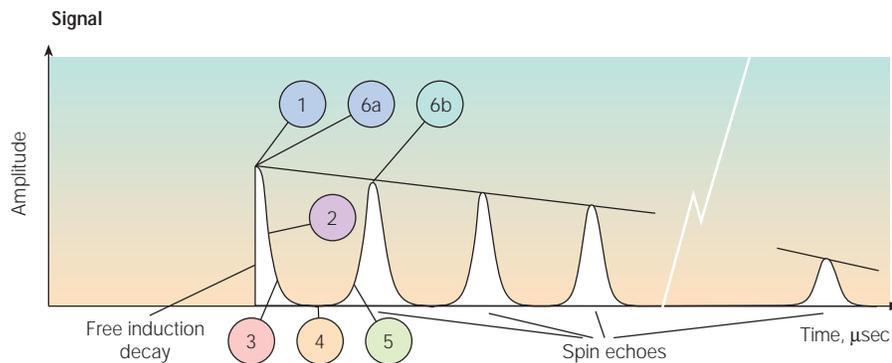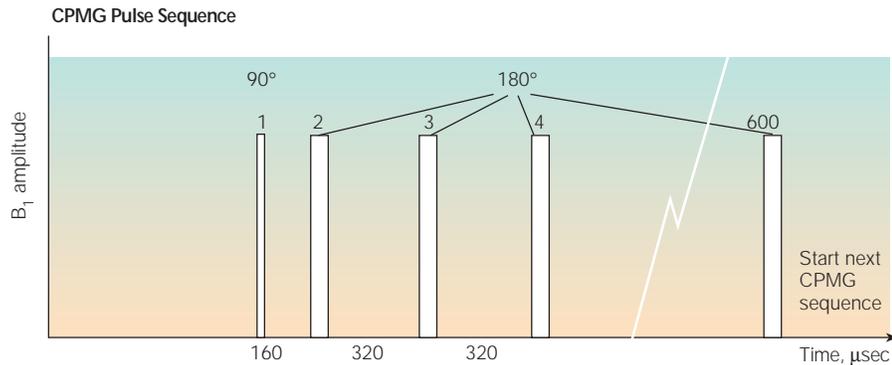
The angle through which spins are tipped is controlled by the strength of B_1 and the length of time it is switched on. For example, to tip spins by 90°—as in most logging applications—a B_1 field of 4 gauss is switched on for 16 microseconds (μsec).
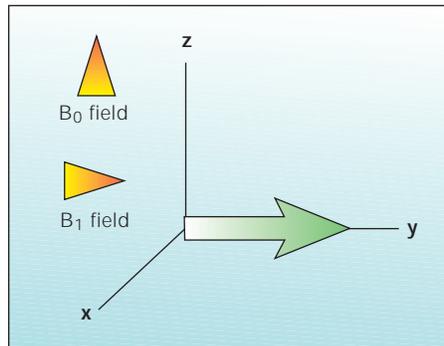
□Spin tipping. Aligned protons are tipped 90° by a magnetic pulse oscillating at the resonance, or Larmor frequency.

Precession and dephasing—When protons are tipped 90° from the B_0 direction, they precess in the plane perpendicular to B_0. 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, B_0, is not perfectly homogeneous, causing the protons to process 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

CPMG Pulse Sequence

Signal

□Pulse sequence and refocusing. Each NMR measurement comprises a sequence of transverse magnetic pulses transmitted by an antenna—called 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.

□Transverse decay. As the protons precess about the static field, they gradually lose synchronization. This causes the magnetic field in the transverse plane to decay. Dephasing is caused by inhomogeneities in the static magnetic field and by molecular interactions.

$T_2{}^*$—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

producible fluids, capillary-bound water and clay-bound water (*below*).

However, 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 T_2 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 and density porosity has to be adjusted to a

dolomite matrix to overlay the CMR porosity. If the lithology is not known or if it is complex, CMR porosity gives the best solution. Also, no radioactive sources are used for the measurement, so there are no environmental concerns when logging in bad boreholes.

Permeability—Perhaps the most important feature of NMR logging is the ability to record a real-time permeability log. The potential benefits to oil companies are enormous. Log permeability measurements enable production rates to be predicted, allowing optimization of completion and stimulation programs while decreasing the cost of coring and testing.

Permeability is derived from empirical relationships between NMR porosity and mean values of T_2 relaxation times. These

relationships were developed from brine permeability measurements and NMR measurements made in the laboratory on hundreds of different core samples. The following formula is commonly used:

$$k_{NMR} = C (\phi_{NMR})^4 (T_{2, log})^2$$

where k_{NMR} is the estimated permeability, ϕ_{NMR} is CMR porosity, $T_{2, log}$ is the logarithmic mean of the T_2 distribution and C is a constant, typically 4 for sandstones and 0.1 for carbonates.

A cored interval of a well was logged using the CMR tool. The value of C in the CMR permeability model was calculated from core permeability at several depths. After calibration CMR permeability was found to overlay all core permeability points over the whole interval (*page 26*). Over the zone 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 T_2 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.
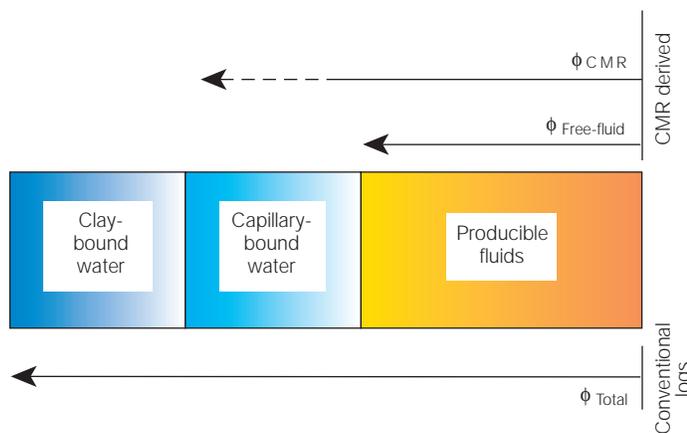
□CMR porosity. Hydrogen in rock matrix and in clay-bound water has short relaxation times that are lost in the dead time of the CMR tool. CMR porosity includes only capillary-bound water and producible fluids and is not influenced by lithology. Total porosity—as measured by conventional logs—also includes clay-bound water. The dotted line indicates that CMR porosity does not include microporosity associated with hard shales.

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.[4] The echo spacing is 320 μsec for the Schlumberger CMR tool and 1200 μsec for NUMAR's MRIL tool.

Transverse relaxation, T_2—The CPMG pulse sequence compensates for dephasing caused by B_0 field imperfections. However, molecular processes also cause dephasing, but this is irreversible. These processes are related to petro-

CPMG Decay for a Rock
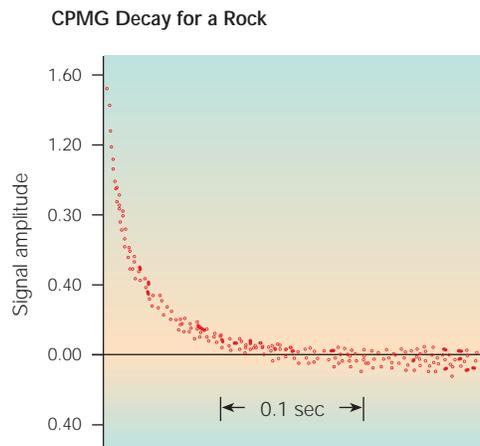
□Typical decaying spin echo amplitude plot for a rock. Each dot represents the amplitude of a spin echo. In this example recorded time is less than 0.3 sec.

physical properties such as movable fluid porosity, pore size distribution and permeability.

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, T_2, because dephasing occurs in the plane transverse to the static field B_0.[5]

Longitudinal relaxation, T_1—After a period of several times T_2, 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 paral-

1:240 ft	Combined Model			Density Porosity, Limestone		
	0 % 100			30	p.u.	−10
	Illite			Density Porosity, Dolomite		
	Bound Water			30	p.u.	−10
	Quartz			CMR Porosity		
	Calcite			30	p.u.	−10
	Dolomite				Zero Porosity	
	Oil				0 p.u. −10	
	Water					
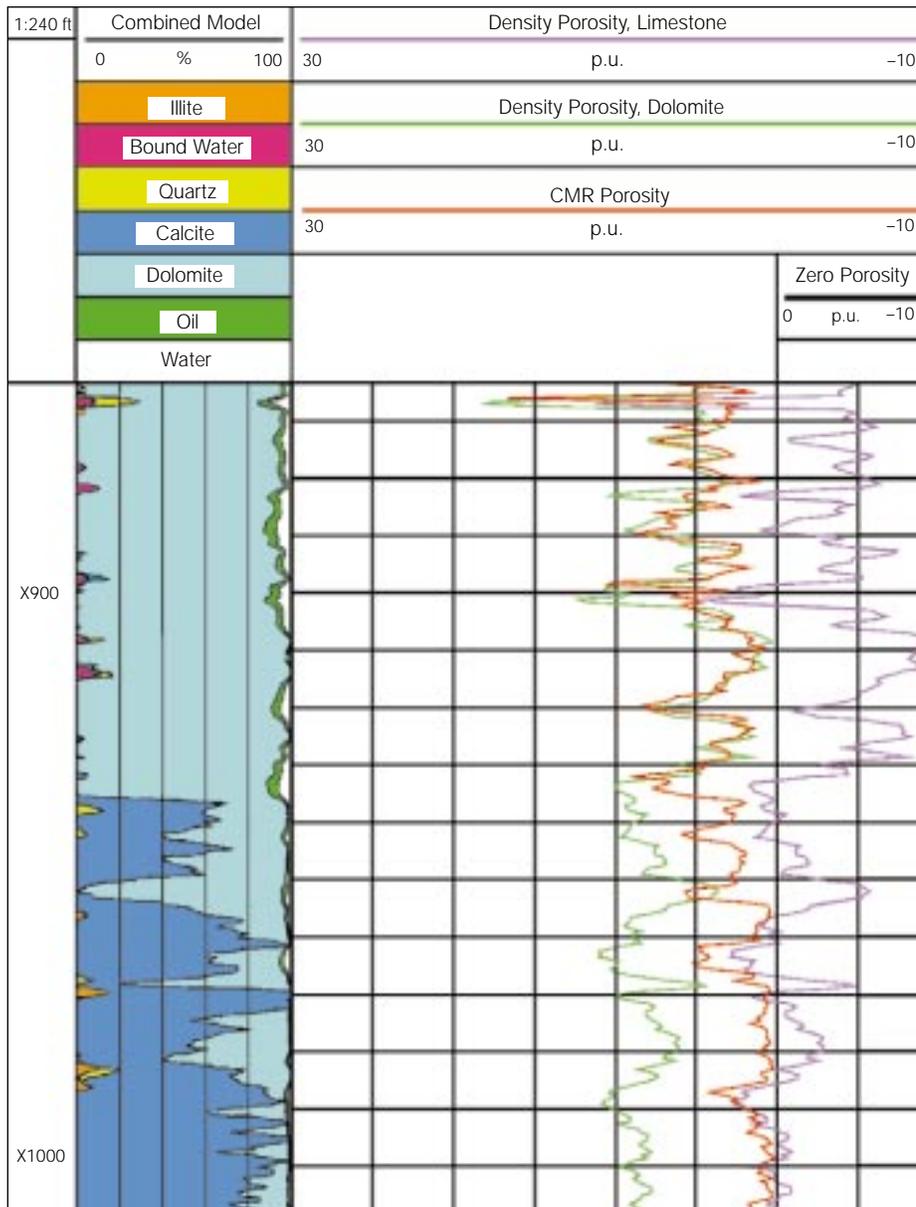
☐ Lithology-independent porosity. Below X935 ft, the lithology is limestone with some dolomitization (track 1), while above is dolomite. Two porosity curves (track 2) are derived from density measurements—one assumes a limestone lithology and the other dolomite. CMR porosity overlays the density limestone porosity in limestone regions and overlays dolomite porosity in dolomite regions—demonstrating that CMR porosity is independent of lithology.
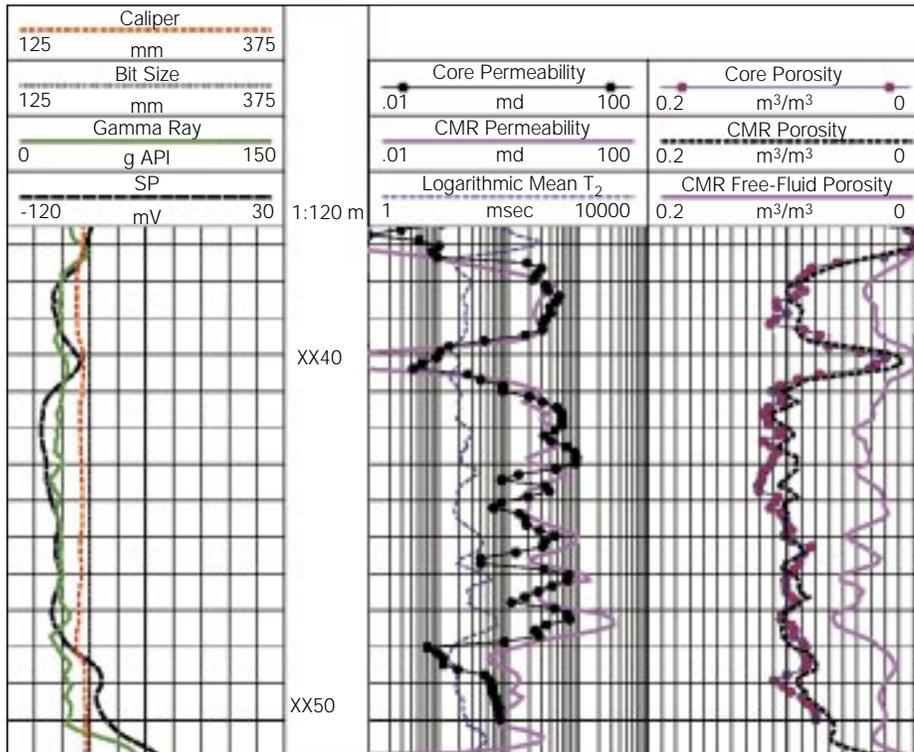

☐ Longitudinal relaxation, T_1. When the CPMG pulse sequence ends, the protons gradually relax back towards the static magnetic field. They do so with characteristic time constant T_1, longitudinal relaxation.
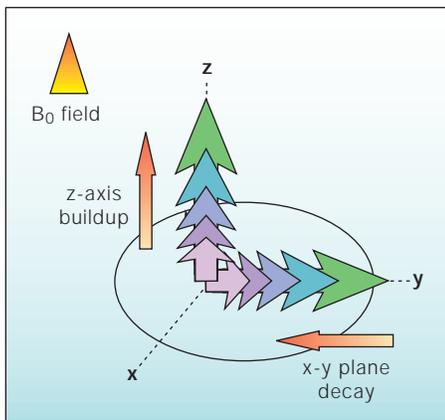
lel to B_0 (left). This process occurs with a different time constant—longitudinal relaxation, T_1. The next spin-tipping measurement is not started until the protons have returned to their equilibrium position in the constant B_0 field.

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.[6] However, this ratio varies when oil and gas are present in rock samples.

4. Carr HY and Purcell EM: "Effects of Diffusion on Free Precession in Nuclear Magnetic Resonance Experiments," *Physical Review* 94, no. 3 (1954): 630-638.

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

6. Kleinberg RL, Farooqui SA and Horsfield MA: "T_1/T_2 Ratio and Frequency Dependence of NMR Relaxation in Porous Sedimentary Rocks," *Journal of Colloid and Interface Science* 158, no. 1 (1993): 195-198.

Kleinberg et al, reference 2 main text.

Caliper		
125	mm	375
Bit Size		
125	mm	375
Gamma Ray		
0	g API	150
SP		
-120	mV	30

Core Permeability		
.01	md	100
CMR Permeability		
.01	md	100
Logarithmic Mean T_2		
1	msec	10000

Core Porosity		
0.2	m³/m³	0
CMR Porosity		
0.2	m³/m³	0
CMR Free-Fluid Porosity		
0.2	m³/m³	0

1:120 m

XX40

XX50

□ *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.*

Many experiments have been made on rock samples to verify this assumption.[6] T_2 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 T_2 measurement (*next page, top).*

Observations of many sandstone samples showed that a cutoff time of 33 msec for T_2 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.[7] 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

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6. Straley C, Morriss CE, Kenyon WE and Howard JJ: "NMR in Partially Saturated Rocks: Laboratory Insights on Free Fluid Index and Comparison with Borehole Logs," *Transactions of the SPWLA 32nd Annual Logging Symposium*, Midland, Texas, USA, June 16-19, 1991, paper CC.

7. Akbar M, Petricola M, Watfa M, Badri M, Charara M, Boyd A, Cassell B, Nurmi R, Delhomme JP, Grace M, Kenyon B and Roestenberg J: "Classic Interpretation Problems: Evaluating Carbonates," *Oilfield Review* 7, no. 1 (January 1995): 38-57.

Chang D, Vinegar H, Morriss C and Straley C: "Effective Porosity, Producible Fluid and Permeability in Carbonates from NMR Logging," *Transactions of the SPWLA 35th Annual Logging Symposium*, Tulsa, Oklahoma, USA, June 19-22, 1994, paper A.

NMR Relaxation Mechanisms

There are three NMR relaxation mechanisms that influence T_1 or T_2 relaxation times: grain surface relaxation, relaxation by molecular diffusion in magnetic field gradients and relaxation by bulk fluid processes.[1]

1. Kleinberg RL, Kenyon WE and Mitra PP: "On the Mechanism of NMR Relaxation of Fluids in Rocks," *Journal of Magnetic Resonance* 108A, no. 2 (1994): 206-214.

2. Kleinberg RL and Horsfield MA: "Transverse Relaxation Processes in Porous Sedimentary Rock," *Journal of Magnetic Resonance* 88, no. 1 (1990): 9-19.

Sezginer A, Kleinberg RL, Fukuhara M and Latour LL: "Very Rapid Simultaneous Measurement of Nuclear Magnetic Resonance Spin-Lattice Relaxation Time and Spin-Spin Relaxation Time," *Journal of Magnetic Resonance* 92, no. 3 (1991): 504-527.

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, B_0— this contributes to longitudinal relaxation, T_1. Second, protons may be irreversibly dephased—contributing to transverse relaxation, T_2. Researchers have shown that in most rocks, grain-surface relaxation is the most important influence on T_1 and T_2. The ability of grain surfaces to relax protons is called surface relaxivity, ρ.[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 ρ and, hence, shorter NMR relaxation times.
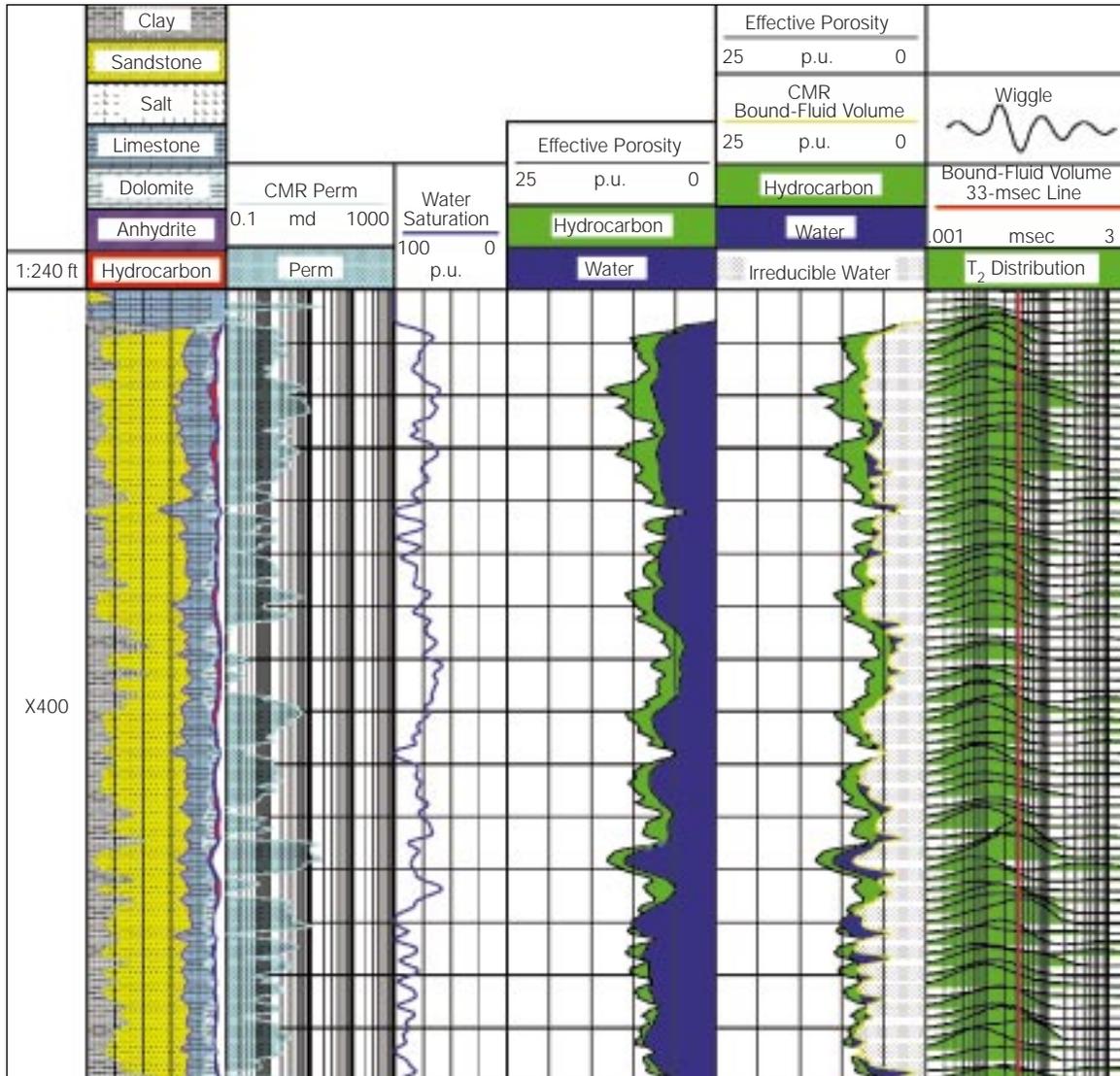
Pore size also plays an important role in surface relaxation. The speed of relaxation depends on how frequently protons can collide with the surface and this depends on the surface-to-volume ratio (S/V) (next page, bottom). **Collisions**
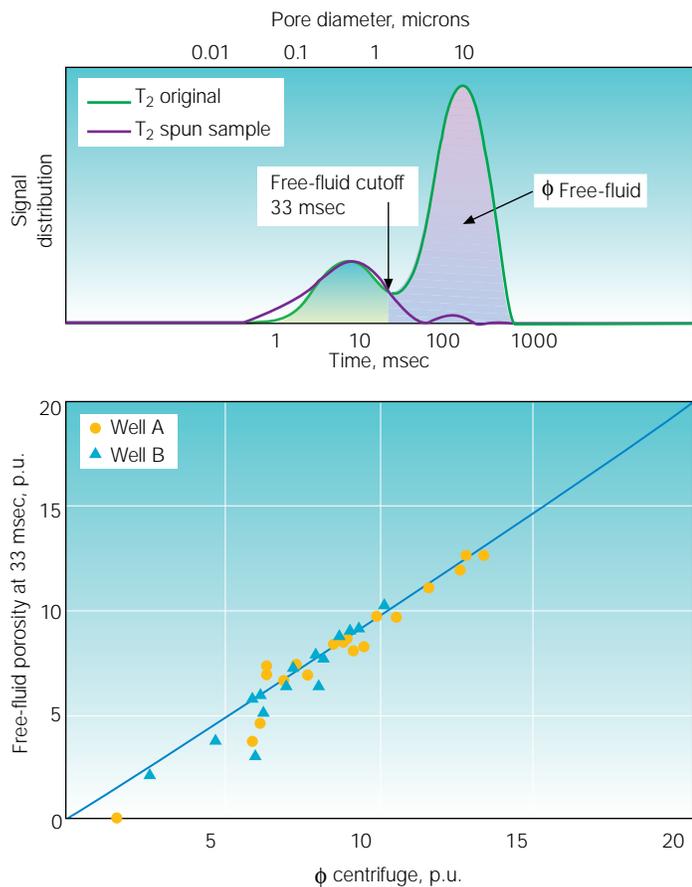
□*Free-fluid porosity. Free-fluid porosity is determined by applying a cutoff to the T_2 distribution curve. The area underneath the curve above the cutoff gives free-fluid porosity (top). This zone relates to the large producible pores of a rock sample. The value for the cutoff was determined in the 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).*
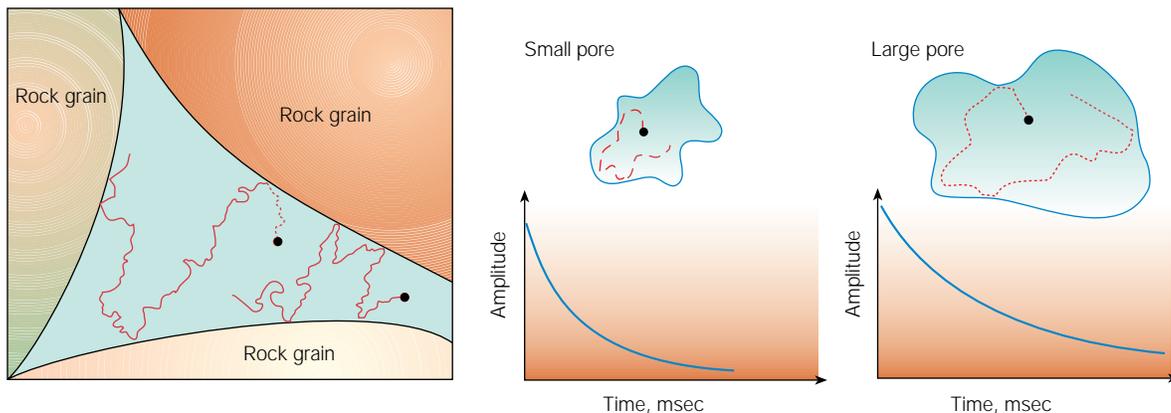
□Grain surface relaxation. Precessing protons move about pore space colliding with other protons and with grain surfaces *(left)*. Every time a proton collides with a grain surface there is a possibility of a relaxation interaction occurring. Grain surface relaxation is the most important process affecting 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.

Clay					Effective Porosity		
Sandstone					25 p.u. 0		
Salt					CMR Bound-Fluid Volume		Wiggle
Limestone			Effective Porosity		25 p.u. 0		
Dolomite	CMR Perm	Water	25 p.u. 0		Hydrocarbon		Bound-Fluid Volume 33-msec Line
Anhydrite	0.1 md 1000	Saturation 100 0	Hydrocarbon		Water		.001 msec 3
1:240 ft Hydrocarbon	Perm	p.u.	Water		Irreducible Water		T$_2$ Distribution

X400

□*Free-fluid index—sandstone example. In this predominantly shaly-sand-stone (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.*

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.

across a shaly sandstone formation. However, on the CMR log most of the T_2 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 T_2 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.[8] 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 micropores using a T_2 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.[9] This has some advantages as mud fil-trate 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 T_2 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.

8. Kenyon WE, Takezaki H, Straley C, Sen PN, Herron M, Matteson A and Petricola MJ: "A Laboratory Study of Nuclear Magnetic Resonance Relaxation and Its Relation to Depositional Texture and Petrophysical Properties—Carbonate Thamama Group, Mubarraz Field, Abu Dhabi," paper SPE 29886, presented at the SPE Middle East Oil Show, Bahrain, March 11-14, 1995.

9. For research into the effects of particulate invasion on NMR measurements:

Fordham E, Sezginer A and Hall LD: "Imaging Multiexponential Relaxation in the (y, $\log_e$ (T_1) Plane with Application to Clay Filtration in Rock Cores," *Journal of Magnetic Resonance* A113, no. 2 (April 1995): 139-150.

Fordham EJ, Roberts TPL, Carpenter TA, Hall LD and Hall C: "Dynamic NMR Imaging of Rapid Depth Filtration of Clay in Porous Media," *American Institute of Chemical Engineering Journal* 37, no. 12 (1991): 1900-1903.

10. Morriss CE, Freedman R, Straley C, Johnston M, Vinegar HJ and Tutunjian PN: "Hydrocarbon Saturation and Viscosity Estimation from NMR Logging in the Belridge Diatomite," *Transactions of the SPWLA 35th Annual Logging Symposium*, Tulsa, Oklahoma, USA, June 19-22, 1994, paper C.

Bulk fluid relaxation—Even if grain surfaces and internal field gradients are absent, relaxation occurs in the bulk fluid. Bulk fluid relaxation can often be neglected, but is important when water is in very large pores—such as in vuggy carbonates—and, therefore, hydrogen protons rarely contact a surface. Bulk relaxation is also important when hydrocarbons are present. The nonwetting phase does not contact the pore surface, and so it cannot be relaxed by the surface relaxation mechanism. Also, increasing fluid viscosity shortens bulk relaxation times.[4] A bulk relaxation correction must be made when the mud filtrate contains ions of chromium, manganese, iron, nickel or other paramagnetic ions. A sample of mud filtrate can be measured at the wellsite to calculate the correction.

Relaxation processes summary—Relaxation processes act in parallel—their rates are additive:

$$(1/T_2)_{total} = (1/T_2)_S + (1/T_2)_D + (1/T_2)_B$$

where $(1/T_2)_S$ is the surface contribution, $(1/T_2)_D$ is the diffusion in field gradient contribution, and $(1/T_2)_B$ is the bulk contribution. The corresponding equation for T_1 is

$$(1/T_1)_{total} = (1/T_1)_S + (1/T_1)_B.$$

There is no diffusion contribution to T_1, because that process results in a dephasing mechanism. For the CMR tool, the surface relaxation mechanism will usually be dominant for the wetting phase, and the bulk relaxation mechanism will dominate for the nonwetting phase.

3. Sen PN, Straley C, Kenyon WE and Whittingham MS: "Surface-to-Volume Ratio, Charge Density, Nuclear Magnetic Relaxation and Permeability in Clay-Bearing Sandstones," *Geophysics* 55, no. 1 (1990): 61-69.

4. Morriss et al, reference 10 main text.

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 (below).[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]

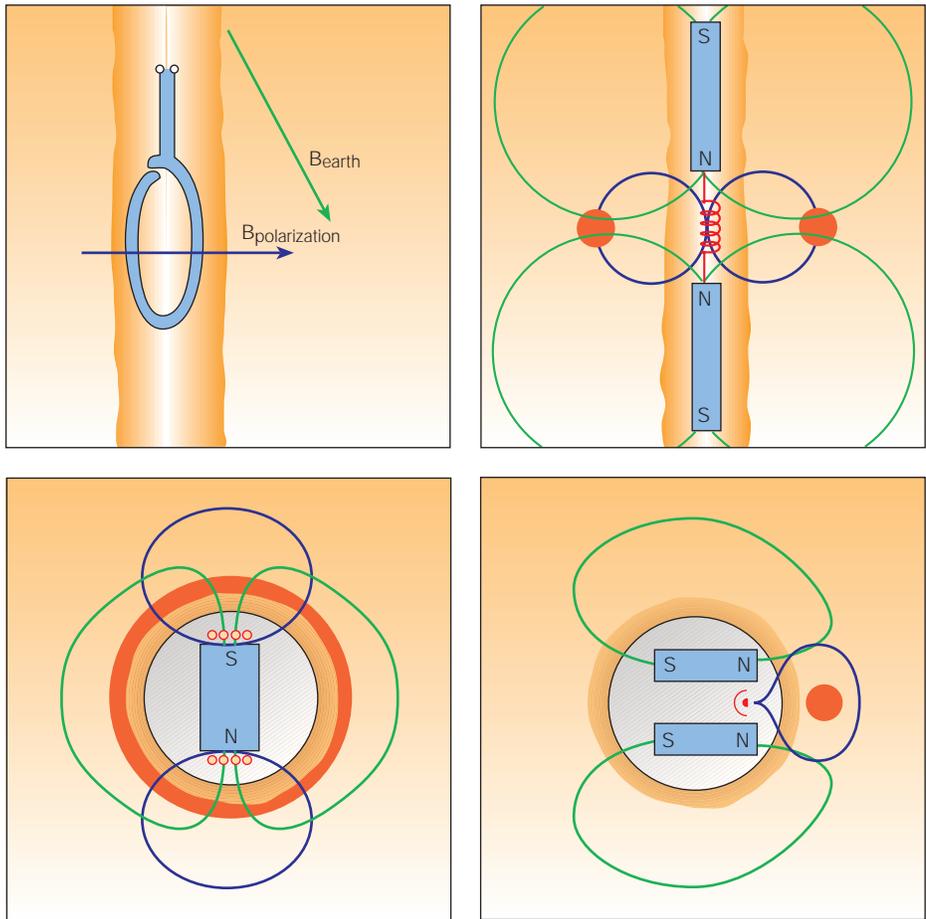The 1970s and 1980s saw continuation of this work by many oil companies in parallel with laboratory NMR techniques developed to characterize core samples. Schlumberger also has a long tradition of research into NMR techniques and produced important work on relaxation mechanisms and pore-size distributions 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
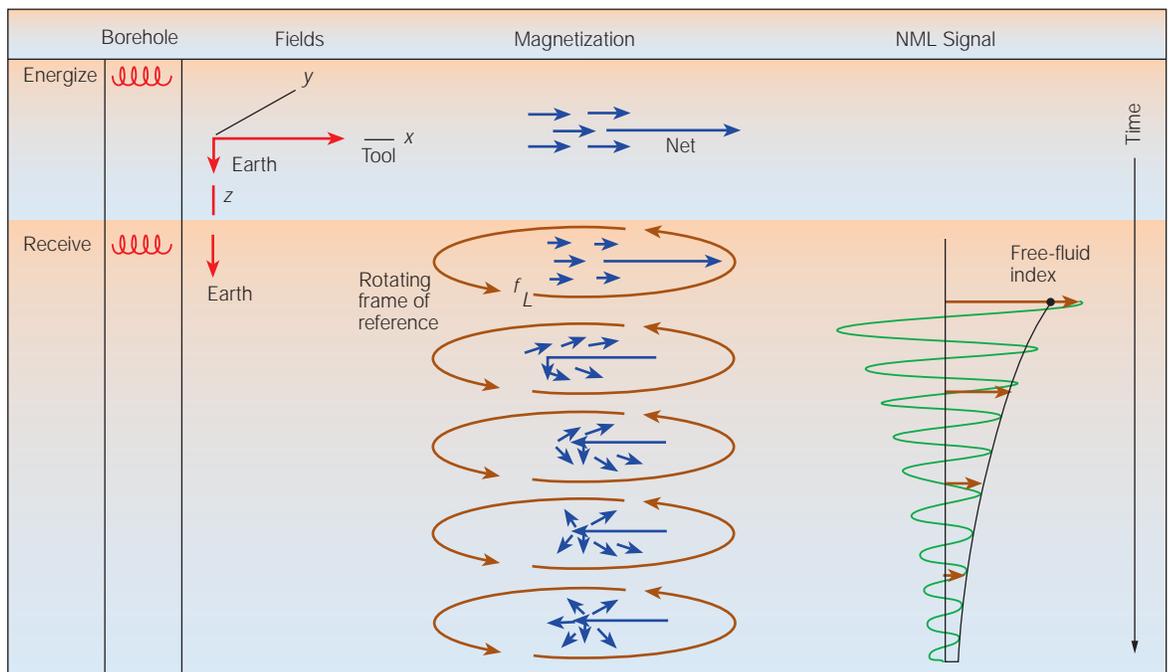
□Principle of early NMR tools. The Schlumberger NML Nuclear Magnetism Logging tool measured transverse relaxation, T_2. Protons in the formation are aligned to the Earth's magnetic field—considered to be homogeneous on these scales. A horizontally-mounted coil tips the protons 90° (Borehole). They then 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.

in the late 1980s and 1990s by designs from NUMAR and Schlumberger (left).[7]

The two tools currently available are the Schlumberger second generation, pulse-echo NMR tool—the CMR tool—and NUMAR's MRIL Magnetic Resonance Imager Log.[8] Both use permanent magnets, instead of the Earth's magnetic field, to align protons, and a system providing controllable radio-frequency (rf) magnetic pulses allowing T_2 measurements. The use of permanent magnets means that the position of the measurement volume can be controlled by tool design—eliminating borehole doping.

Permanent magnet	S N
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 CMR tool commercialized this year *(bottom right)*. The top two figures are side views of the borehole and the bottom two figures are cross sections.
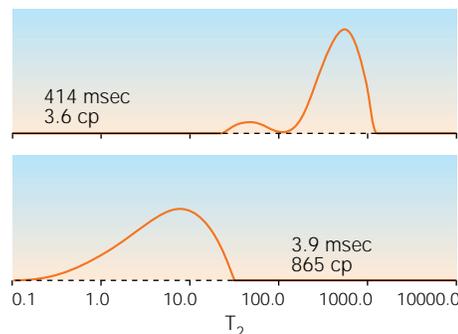
1. Bloch F, Hansen W and Packard ME: "The Nuclear Induction Experiment," *Physical Review* 70 (1946): 474-485.

   Bloembergen RM, Purcell EM and Pound RV: "Relaxation Effects in Nuclear Magnetic Resonance Absorption," *Physical Review* 73 (1948): 679.

   Jackson J and Mathews M: "Nuclear Magnetic Resonance Bibliography," *The Log Analyst* 34, no. 4 (May-June 1993): 35-69.

2. Brown RJS and Gamson BW: "Nuclear Magnetism Logging," *Journal of Petroleum Technology* 12 (August 1960): 199-207.

3. Herrick RC, Couturie SH and Best DL: "An Improved Nuclear Magnetism Logging System and its Application to Formation Evaluation," paper SPE 8361, presented at the 54th SPE Annual Technical Conference and Exhibition, Las Vegas, Nevada, USA, September 23-26, 1979.

   Chandler RN, Kenyon WE and Morriss CE: "Reliable Nuclear Magnetism Logging: With Examples in Effective Porosity and Residual Oil Saturation," *Transactions of the SPWLA 28th Annual Logging Symposium*, London, England, June 29-July 2, 1987, paper C.

4. Seevers DO: "A Nuclear Magnetic Method for Determining the Permeability of Sandstones," *Transactions of the SPWLA 7th Annual Logging Symposium*, Tulsa, Oklahoma, USA, May 8-11, 1966.

   Timur A: "Effective Porosity and Permeability of Sandstones Investigated Through Nuclear Magnetic Resonance Principles," *Transactions of the SPWLA 9th Annual Logging Symposium*, New Orleans, Louisiana, USA, June 23-26, 1968, paper K.

5. Loren JD and Robinson JD: "Relations Between Pore Size Fluid and Matrix Properties, and NML Measurements," paper SPE 2529, presented at the 44th SPE Annual Fall Meeting, Denver, Colorado, USA, September 28-October 1, 1969.

   Loren JD: "Permeability Estimates from NML Measurements," *Journal of Petroleum Technology* 24 (August 1972): 923-928.

6. Kenyon WE, Day PI, Straley C and Willemsen JF: "Compact and Consistent Representation of Rock NMR Data for Permeability Estimation," paper SPE 15643, presented at the 61st SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, October 5-8, 1986.

   Kenyon WE, Day PI, Straley C and Willemsen JF: "A Three-Part Study of NMR Longitudinal Relaxation Properties of Water-Saturated Sandstones," *SPE Formation Evaluation* 3, no. 3 (1988): 622-636.

   Kenyon et al, reference 4 main text.

7. Jackson JA and Cooper RK: "Magnetic Resonance Apparatus," US Patent No. 4,350,955, August 1980.

   Jackson JA: "Nuclear Magnetic Resonance Well Logging," *The Log Analyst* 25 (September-October 1984): 16-30.

   Kleinberg RL, Griffin DD, Fukuhara M, Sezginer A and Chew WC: "Borehole Measurement of NMR Characteristics of Earth Formations," US Patent No. 5,055,787, October 1991.

8. Kleinberg et al, reference 12 main text.

   Miller MN, Paltiel Z, Gillen ME, Granot J and Bouton JC: "Spin Echo Magnetic Resonance Logging: Porosity and Free Fluid Index Determination," paper SPE 20561, presented at the 65th SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, September 23-26, 1990.

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.
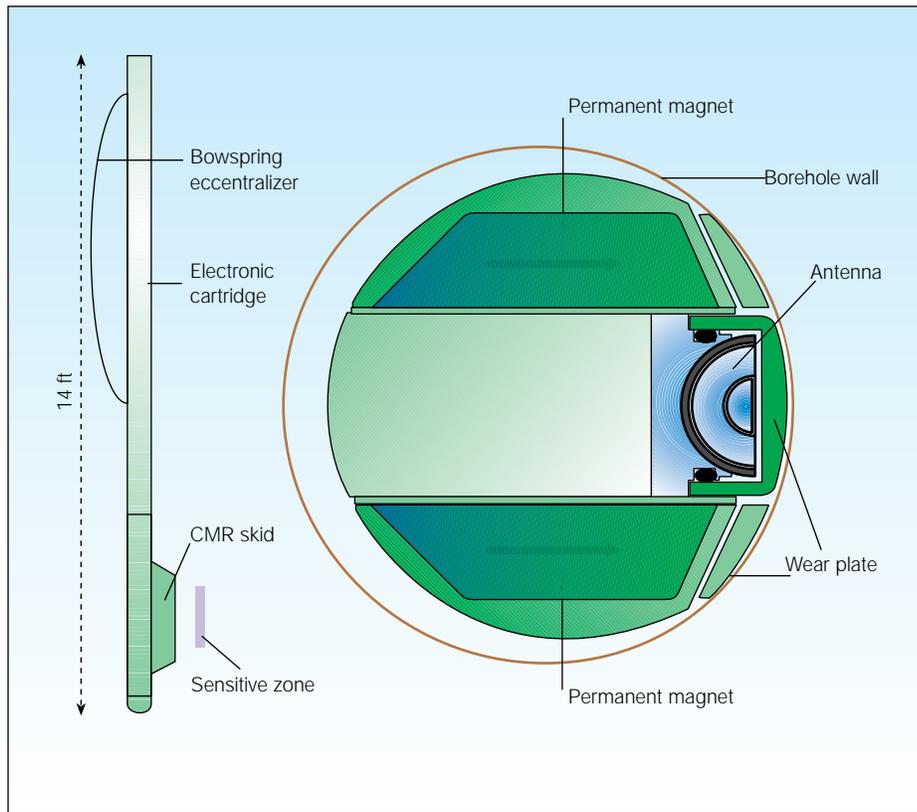
Capillary pressure curves, used by reservoir engineers to estimate the percentage of connate water, may also be predicted from T_2 distributions. Typically these curves—plots of mercury volume versus pressure—are produced by injecting mercury into core samples. Under low pressure the mercury fills the 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 opera-

□ CMR tool. The CMR tool (left) is only 14 ft [4.3 m] long and is combinable with many other Schlumberger logging tools. The sensor is skid-mounted to cut through mud cake and have good contact with the formation over most hole sizes. Contact is provided by an eccentralizing arm or by powered calipers of other logging tools. Two powerful permanent magnets provide a static magnetic field (right). By design the tool measurement volume is a region of about 0.5 in. to 1.25 in. [1.3 cm to 3.2 cm] into the formation and stretches the length of the antenna— about 6 in. [15 cm], providing the tool with excellent vertical resolution. The area in front of the antenna does not contribute to the signal, which allows the tool to operate in holes with a certain amount of rugosity, similar to density tools. The antenna acts as both transmitter and receiver—transmitting the CPMG magnetic pulse sequence and receiving the pulse echoes from the formation.

□ 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.

tions 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.

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 borehole 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 eccentralizing 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. T_2 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

11. Morriss et al, reference 10.

12. Kleinberg RL, Sezginer A, Griffin DD and Fukuhara M: "Novel NMR Apparatus for Investigating an External Sample," *Journal of Magnetic Resonance* 97, no. 3 (1992): 466-485.

   Sezginer A, Griffin DD, Kleinberg RL, Fukuhara M and Dudley DG: "RF Sensor of a Novel NMR Apparatus," *Journal of Electromagnetic Waves and Applications* 7, no. 1 (1993): 13-30.

   Morriss CE, MacInnis J, Freedman R, Smaardyk J, Straley C, Kenyon WE, Vinegar H and Tutunjian PN: "Field Test of an Experimental Pulsed Nuclear Magnetism Tool," *Transactions of the SPWLA 34th Annual Logging Symposium*, Calgary, Alberta, Canada, June 13-16, 1993, paper GGG.