Green Imaging

OXFORD INSTRUMENTS

Application Note

NMR and Core Analysis

Introduction

Most people involved in core analysis know that NMR (Nuclear Magnetic Resonance) has been part of the available suite of well logging measurements since the mid-90s, and that it is also used for routine laboratory core analysis – in part for calibration of NMR well logs. But how many people really know how NMR works, and the full extent of what it can do for the core analyst? Most core analysts know that NMR can determine porosity and pore size distributions easily and quickly, but what about fluid mobility such as Bound Volume Irreducible (BVI), Free Fluid Index (FFI), Clay Bound Water (CBW), and effective porosity? Furthermore, what about permeability, capillary pressure, and oil/water or gas/water contents? NMR can measure all these parameters quickly and accurately, and current software makes it possible to do so without extensive knowledge of NMR.

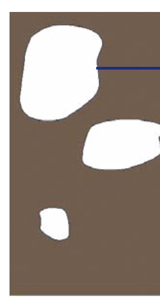
This note is an attempt to introduce NMR and these capabilities to the non-NMR expert petrophysicist and core analyst.

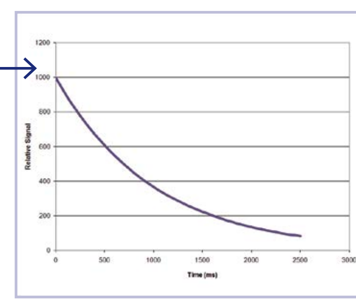
Technical background

Essentially, NMR signals are generated from liquids (oil or brine) when the sample is placed in a magnetic field and then excited with a brief pulse of radio frequency (RF) energy. Immediately after the pulse, an NMR signal appears, which then dies away with a characteristic relaxation time or decay rate known as T_2. The amplitude of the signal immediately after the pulse is an indication of the total amount of fluid present, while the T_2 of the signal gives valuable information about the physical environment of the liquids.

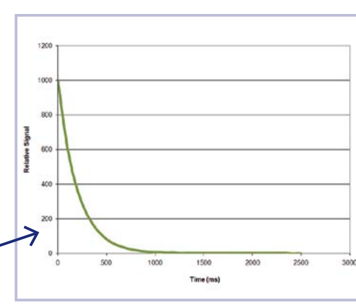
In pores filled with a single fluid, there are two main components to the NMR signal – one coming from the fluid far from the pore walls, and the other from fluid close to the pore walls. Fluids far from the pore walls give NMR signals similar to those from bulk fluids, with relatively long relaxation times, while fluids close to the pore walls undergo a process of adsorption and desorption with the pore walls which has the effect of dramatically reducing their NMR relaxation times.

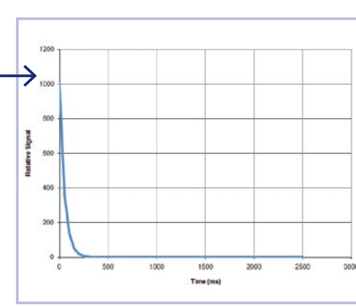
In large pores, the dominant effect is from the bulk fluids, so larger pores tend to have longer NMR relaxation times. In smaller pores, the surface-to-volume ratio is much higher, so the fluids close to the pore walls tend to dominate the NMR signal, and smaller pores show overall shorter NMR relaxation times. This process is illustrated in the figures below.





Fluids in large pores have long T_2 decay times, like bulk fluids





Signals from fluids in smaller pores are modified by surface interactions

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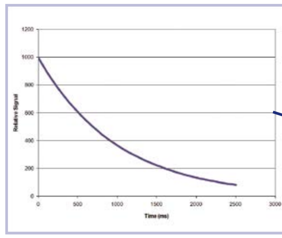
Of course, in a real measurement it is not possible to take NMR measurements from individual pores. The whole core must be measured at once, so the resulting NMR signal is a composite of all the NMR signals from the different pore sizes in the core.

The next step is to use a mathematical procedure known as an inversion to process the composite NMR signal and separate it out into its component parts. In theory, there is one T_2 component for each different pore size in the core. But in practice, the analysis is usually restricted to a maximum of about 256 individual T_2 components, which is more than adequate for most practical purposes.



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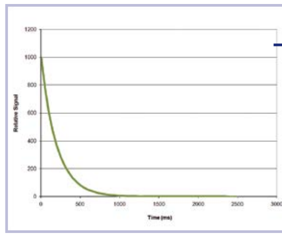

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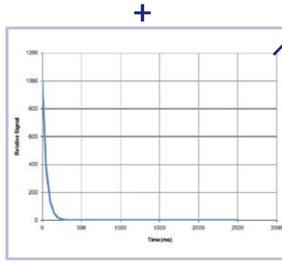
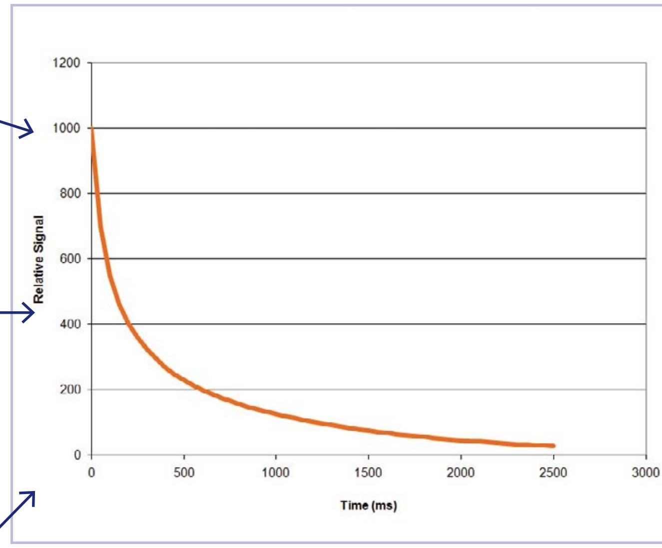
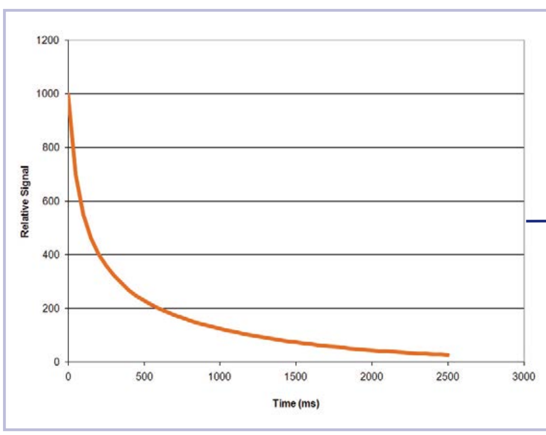
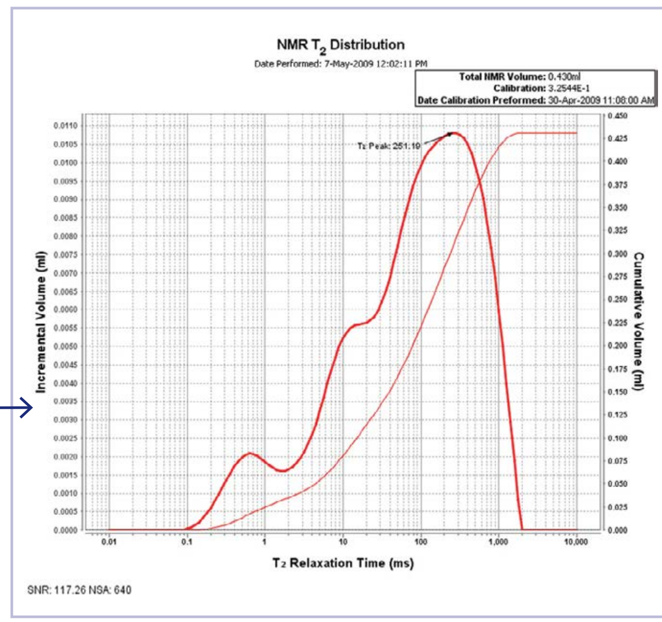


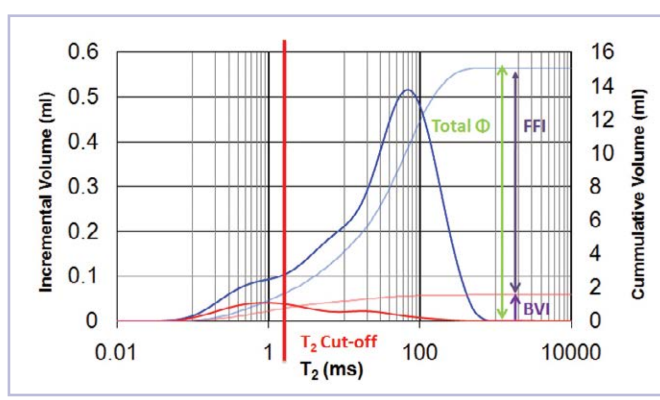




Inversion



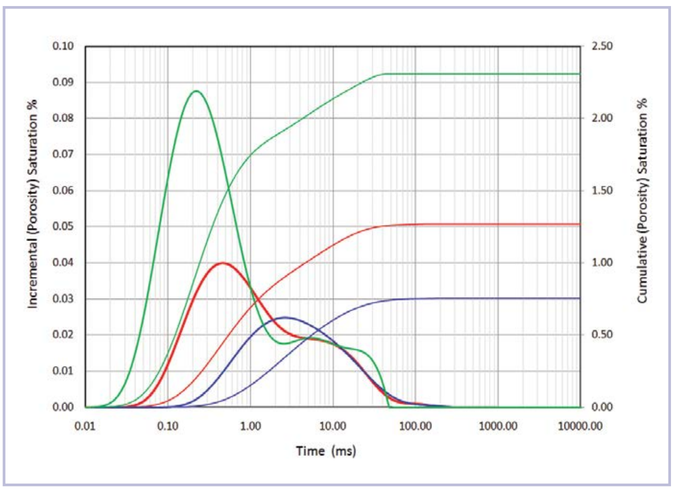
The result of the inversion process is a T_2 distribution showing the relative population of the individual T_2 decay times that make up the composite NMR signal from the core. Because long T_2s come from large pores, and short T_2s from small pores, this T_2 distribution is in effect a model of the pore size distribution in the core.



Beyond the T_2/pore size distribution – porosity, BVI, FFI, CBW and permeability

Once we have the basic pore size distribution from the NMR data, a number of useful petrophysical parameters can be quickly and easily inferred. The integral of all the T_2s (area under the curve) gives us the total porosity when compared to the signal from a known reference. If we centrifuge the core and then repeat the NMR measurement, the integral of the second data set is the irreducible fluid (Bound Volume Irreducible, or BVI), while the difference between the two is the Free Fluid Index (FFI).

It is very important to note that the area under the saturated T_2 distribution curve (which gives us a measure of total porosity) is of course influenced by the shape of the curve. If the T_2 curve does not represent all the T_2s present in the sample, then signal from some pores will be missing and porosity will be under-reported. This situation can occur, for example, if the instrument being used is not capable of detecting short T_2 signals from small pores, in which case porosity due to small pores will not be accounted for. Technically, this means that the instrument being used must be able to perform sustained measurements using short Time-to-Echo (TE) values. This effect is illustrated in the following figure, which shows three T_2 distributions obtained on the same core sample with TE=100µs (green), 200µs (red) and 600µs (blue).



It is clear that the green (TE=100 µs) and the red (TE=200 µs) distributions show more detail at the shorter T_2 values (smaller pores) than does the blue distribution (TE=600 µs). The green distribution also records a much higher total integral signal, corresponding to a higher porosity value. The results are summarised in the following table:

Sample	TE (µs)	Acquisition Time (min)	Number of Scans	Signal to Noise Ratio	NMR Porosity (ml)
	100	2	80	220.18	4.248
1-4R	200	5.5	224	203.06	2.175
	600	21.5	864	200.16	1.151

It is standard practice nowadays to assume that all T_2s of 2.5 ms or less come from clay bound water (CBW), so these can be integrated separately to report CBW, and thence Effective Porosity.

Finally, using either the Coates or the Schlumberger model, permeability can be estimated from the relaxation data. All of these calculations are carried out and reported automatically by the LithoMetrix software incorporated in every **GeoSpec** instrument – and the NMR measurement is non-destructive and much faster than conventional methods of obtaining the same parameters.

There's more – Capillary Pressure, Pore Throat Distribution, Wettability and Fluid Typing

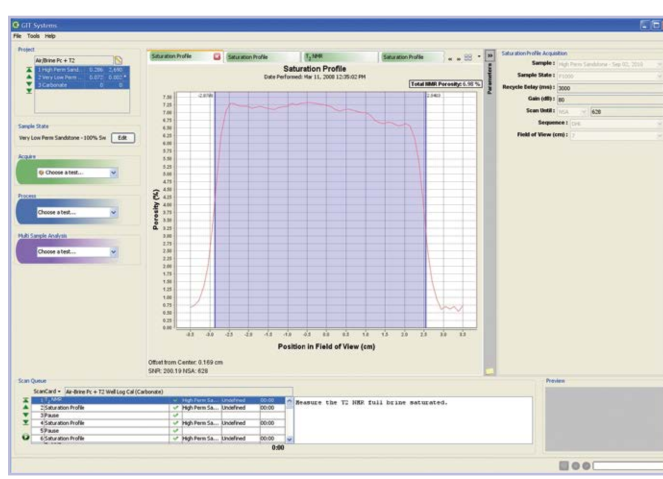
By adding an accessory called Pulsed Field Gradients (pfg) to the NMR instrument, it becomes possible to carry out measurements dependent on the diffusion, flow, or distribution of the fluids within the core sample. As with the standard measurements discussed above, integrated **GIT Systems** software controls the NMR instrument to deliver pfg-based measurements without expert knowledge of the NMR theory behind the measurements.

Capillary Pressure

One of the more exciting recent developments in the use of NMR for core analysis is the ability to measure Capillary Pressure. Measurements that took weeks or months by special centrifuge or porous plate can now be done by NMR in hours or days – and with many times more data points.

The patented GIT-CAP technique is available in Green Imaging Technologies software offerings, which are available exclusively on Oxford Instruments' **GeoSpec** instrument range. GIT-CAP uses a combination of conventional centrifuge and a technique called 1-D Profiling, which is a simple version of MRI (Magnetic Resonance Imaging) that records NMR signals in one dimension only – along the axis of the core.

Here's how it works. After saturating a core, a 1-D profile measurement is acquired via the NMR instrument. The result is usually a more-or-less uniform distribution of fluid along the length of the core, as seen in the figure below.



The 1-D profile records fluid saturation at between 30 and 40 points along the length of the core

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The core is then spun in a standard centrifuge, which has the effect of shifting the fluid distribution towards the outer end of the core, and another 1-D profile with 30 – 40 points is obtained.

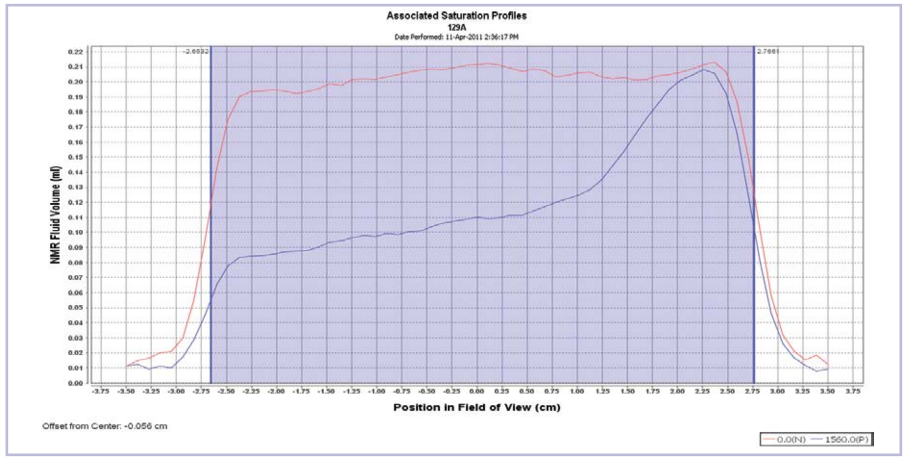
This process is repeated at one more centrifuge spin speed, then the data is analysed. Capillary pressure is calculated from knowledge of the centrifuge spin speeds and the changes in the saturation profile.

Several points are important to notein this process:

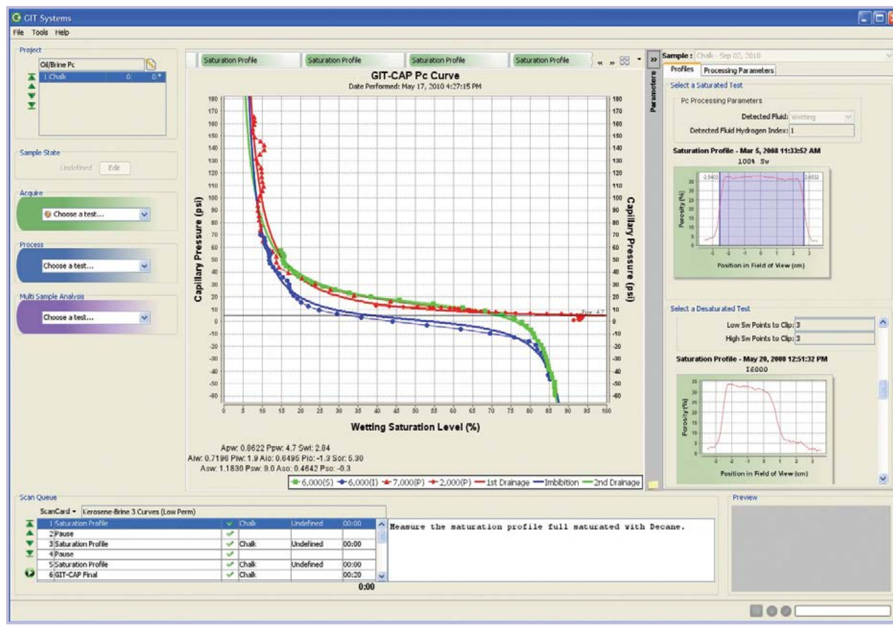
1. Only two centrifuge speeds are required, compared to eight in a traditional centrifuge Pc measurement, so four times more samples can be measured in a given time.
2. Each saturation profile yields 30 – 40 data points along the core sample instead of just one per spin speed in the traditional method. So typically 10 times more data points are collected in the NMR method.
3. The NMR method uses a standard centrifuge without stroboscope or fluid collection measurement, so the centrifuge itself is likely to be less expensive.

Pore Throat Distribution and Wettability

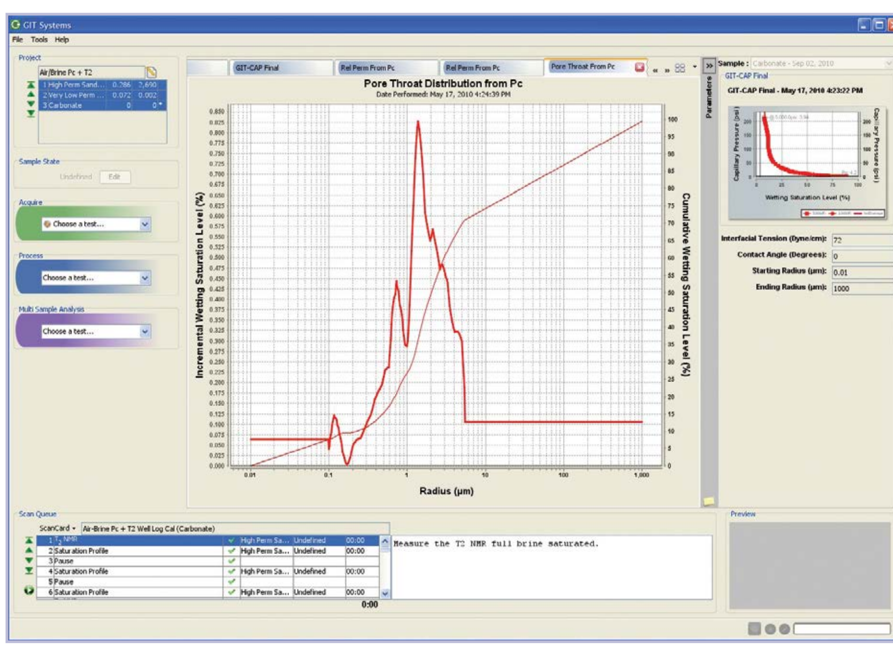
Having obtained a Pc curve, pore throat distributions can now be calculated using the Washburn equations. The imbibition and secondary drainage curves generated by the NMR Pc measurement also allow USBM wettability to be predicted. Both of these calculations are integrated into the software, and follow as a natural consequence of the NMR Pc data. A further added advantage is that the NMR measurement is non-destructive and can use reservoir fluids and reservoir wettability.



Saturation profiles before and after the first centifugation



Primary drainage, imbibition, and secondary drainage capillary pressure curve



Pore throat distribution obtained from Pc data

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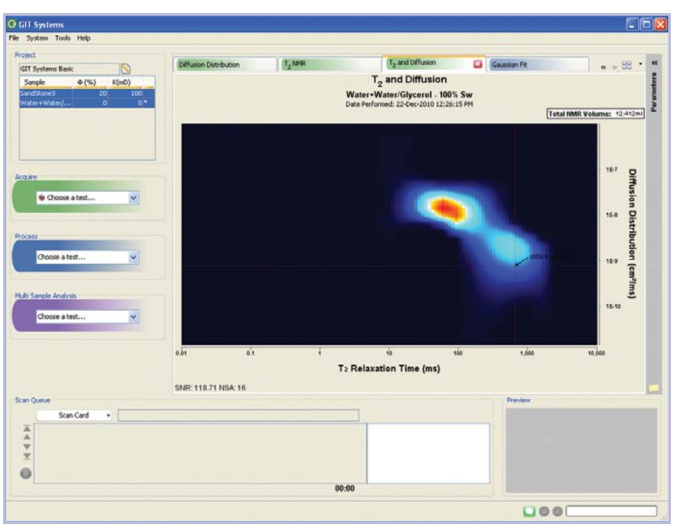
Fluid Typing

It was mentioned earlier that **GeoSpec** instruments fitted with Pulsed Field Gradients (pfg) are able to carry out measurements dependent on the diffusion, flow, or distribution of the fluids within the core sample. One application of this is for fluid typing.

It is possible that different fluids, such as heavy oils and partially bound water, may exhibit similar T_2 values, which makes it difficult to identify which fluid is which using a standard T_2 distribution. However, even if they have similar T_2 values they are unlikely also to have similar diffusion characteristics, so a measurement that collects both T_2 and diffusion data should in principle be able to separate the fluid types. **GIT Systems** software, together with a pfg accessory on a **GeoSpec**2+ NMR instrument, enables such measurements to be done. The result is a two-dimensional data map illustrating the relative proportions of the different fluid types in the sample.

Conclusions

NMR is now a well established core analysis tool, capable of making a wide range of core measurements, from pore size distributions to capillary pressure, on a single instrument. The partnership between Oxford Instruments and Green Imaging Technologies allows an integrated hardware and software solution to be offered to core analysts so that this wide range of applications can be covered by technicians with no specialised knowledge of NMR technology.



Diffusion T_2 map

For more information visit: **nmr.oxinst.com/geospec**

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