Measuring relative permeability with NMR

Application Note 8

Relative permeability is one of the most important petrophysical parameters assessed in special core analysis experiments. Traditionally, relative permeability is measured via one of two methods: steady state and unsteady state [1-5]. In both measurements, relative permeability is calculated from measurements of fluid saturations, pressure differences and fluid flow rates. In this work we propose using NMR to measure the saturation directly in the rock during an unsteady state measurement.

Typically, the fluid saturations are calculated by material balance, via collection of effluent volumes at the outlet. In this application note, we propose a more elegant technique to measure relative permeability via Nuclear Magnetic Resonance (NMR). NMR can be employed to measure the average saturation in-situ and hence derive the relative permeability of a rock core sample. We have completed an unsteady state relative permeability measurement where the saturation of the core has been tracked as a function of time using NMR T_2 volume measurements. This is a very similar measurement to the conventional unsteady state measurement. However, we believe this measurement should be more accurate than the conventional method because it directly measures the in-situ saturation profiles in the core rather than relying on the material balance method, where factors such as dead volumes and instrument uncertainties can lead to errors in estimating core saturations. In addition, we think that this measurement should outperform other NMR relative permeability measurements [6-8] as it uses the conventional method for determining relative permeability and doesn't rely on less well-established methods involving the measurement of capillary pressure.

Experiments:

The overall experimental setup employed in this study is shown in Figure 1. The core was initially saturated with dodecane and then the sample was confined hydrostatically at a pressure of 4,500 psi in an Oxford Instruments P5 overburden NMR probe [9], using Fluorinert as confining fluid. Fluorinert is chosen as the confining fluid as it produces no NMR signal and thus does not interfere with NMR signals from the core itself. The probe was then inserted into an Oxford Instruments **GeoSpec**2/53 rock core analyser [10]. Once inside the analyser, the confining pressure was kept constant using a Vindum Pump [11].

The success of the relative permeability experiment hinges on accurate measurement of pressure, specifically the pressure difference across the rock core. To ensure this is an accurate measurement, pressure transducers are placed on the inlet and outlet flow lines, as well as on the confining pressure line. A data acquisition system was designed in which an Arduino microcontroller [12] continually logs the pressure from the transducers. This log is crucial in ensuring that pressures can be accurately correlated to the NMR T_2 measurements.

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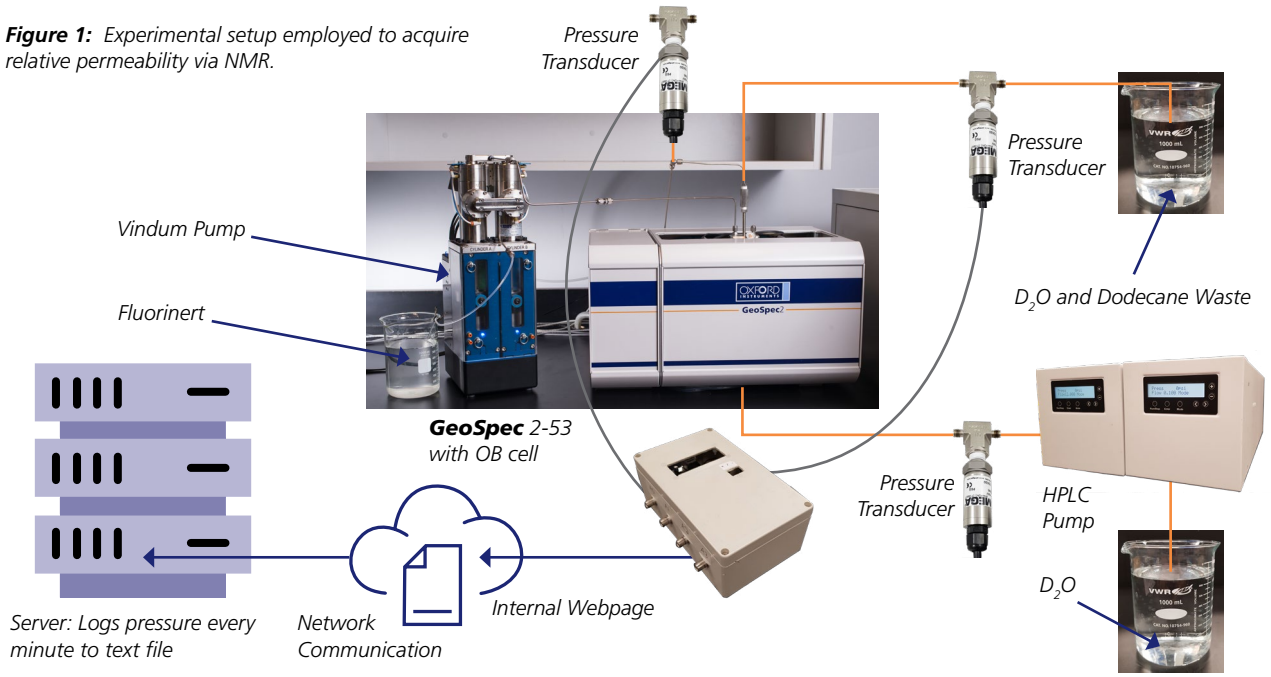
The relative permeability experiment began by flowing 2% KCl in D_2O brine through the rock at 0.1 ml/min using the HPLC pump [13]. The D_2O brine was chosen as a surrogate for H_2O brine as D_2O is NMR invisible. The invisibility of D_2O is important to ensure that any NMR signal observed will only be from dodecane so that the relative saturation levels of D_2O/dodecane can easily be derived from the observed NMR signal and the pore volume of the rock. The NMR measurements were begun simultaneously with the flow of D_2O. T_2 spectra were measured throughout the experiment and were used to monitor the bulk saturation levels in the rock. Data acquisition and analysis of the NMR data were achieved via Green Imaging Technologies software [14]. The software includes a loop function that allows the NMR measurements to be run continuously. The T_2 measurement takes about 3 minutes to complete. As mentioned above, pressure measurements were continually recorded and their time stamps allowed the pressures to be correlated to the corresponding NMR measurements (which also have independent time stamps).

Figure 1: *Experimental setup employed to acquire relative permeability via NMR.*



Results

Figure 2 shows three T_2 measurements taken at three different times throughout the experiment. The y-axis is the NMR signal in units of equivalent water volume. The NMR spectrometer is calibrated in units of equivalent water volume. The black measurement was taken prior to the initiation of D_2O flow. This spectrum is from the 100% dodecane saturated sample. The red spectrum was taken after D_2O had entered the core but prior to breakthrough of D_2O from the outlet face of the core. The blue spectrum was taken towards the end of the experiment after breakthrough of D_2O from the outlet face. The area under any of these spectra is the amount of dodecane in the core at the time of the measurement. Plotting the area under these T_2 spectra as a function of time allows us to calculate the relative permeability of the core.

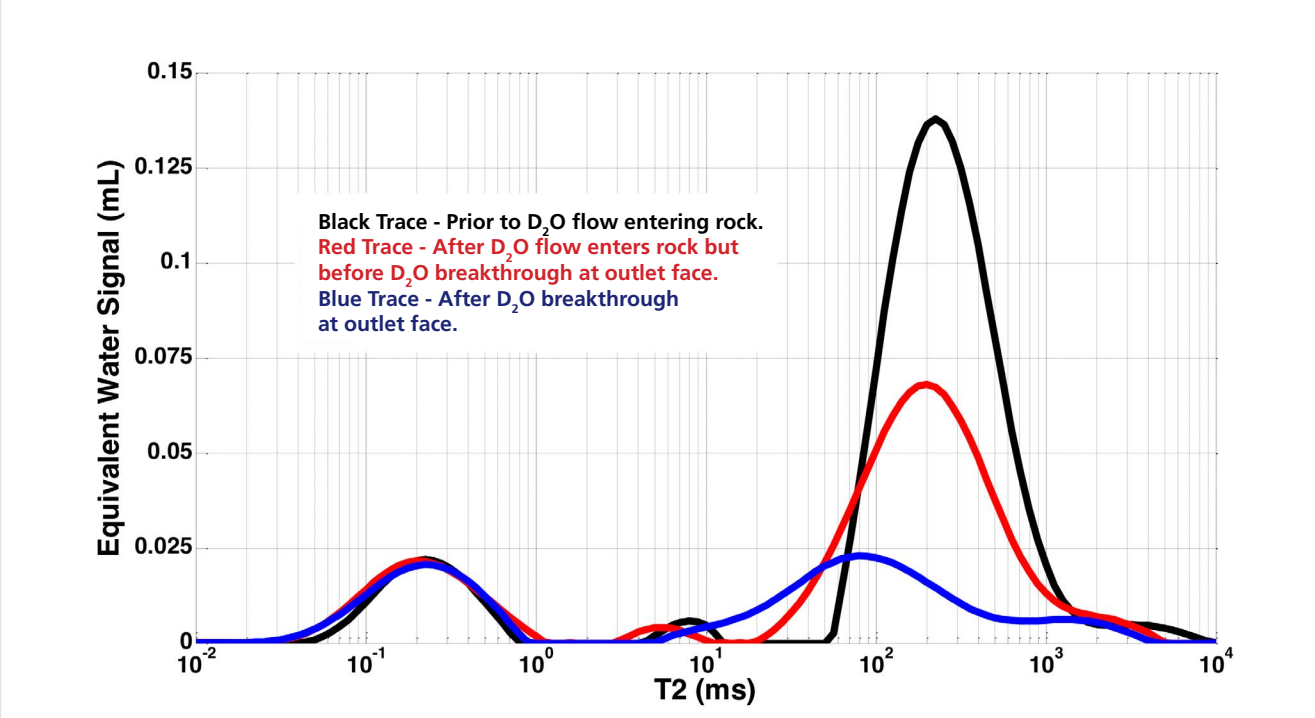


Figure 2: *Typical T_2 spectra recorded at various times during D_2O flooding in the relative permeability experiment.*

The upper panel of Figure 3 shows the NMR signal plotted as a function of time, as well as the pressure difference across the rock plotted as a function of time. This data was recorded as D_2O was being injected through the core sample at 0.1 ml/min. Therefore, the NMR signal observed is proportional to the amount of dodecane in the rock as any D_2O in the rock will be NMR invisible. During the first approximately 50 mins (Figure 3 - black lines) both the pressure across the core and the amount of dodecane in the core remain constant. This is because it takes about 50 minutes for the D_2O to reach the core. After 50 minutes, the NMR signal observed from the rock begins to decrease. This corresponds to D_2O beginning to replace dodecane in the plug (Figure 3 - red lines). The decrease in the NMR signal is proportional to the amount of D_2O entering the rock and dodecane leaving the rock. During this same period, the pressure increases because the two immiscible fluids are being pushed through the rock simultaneously. The pressure increases until approximately the 80 minutes mark when a peak pressure of 1,400 PSI is reached. This peak corresponds to breakthrough of D_2O through the outlet face of the rock. The pressure slowly decreases after this as the rate of dodecane being evacuated by the D_2O decreases. This is reflected in a reduction in the rate of change of the NMR signal observed. Eventually very little dodecane is produced from the core (Figure 3 – blue lines) and only D_2O is moving through the core (i.e. S_{or} is reached).

To derive relative permeability from this data, the NMR signal observed as a function of time must be converted to oil produced as a function of time. To do this, the NMR signal in units of volume of water is converted to oil produced by subtracting each measurement from the pore volume of the rock. It should be noted that dodecane and water have a similar hydrogen index so there is no need to convert NMR signal in ml of water to ml of dodecane prior to doing the subtractions.

Black Trace - Prior to D_2O flow entering rock.
Red Trace - After D_2O flow enters rock but before D_2O breakthrough at outlet face.
Blue Trace - After D_2O breakthrough at outlet face.

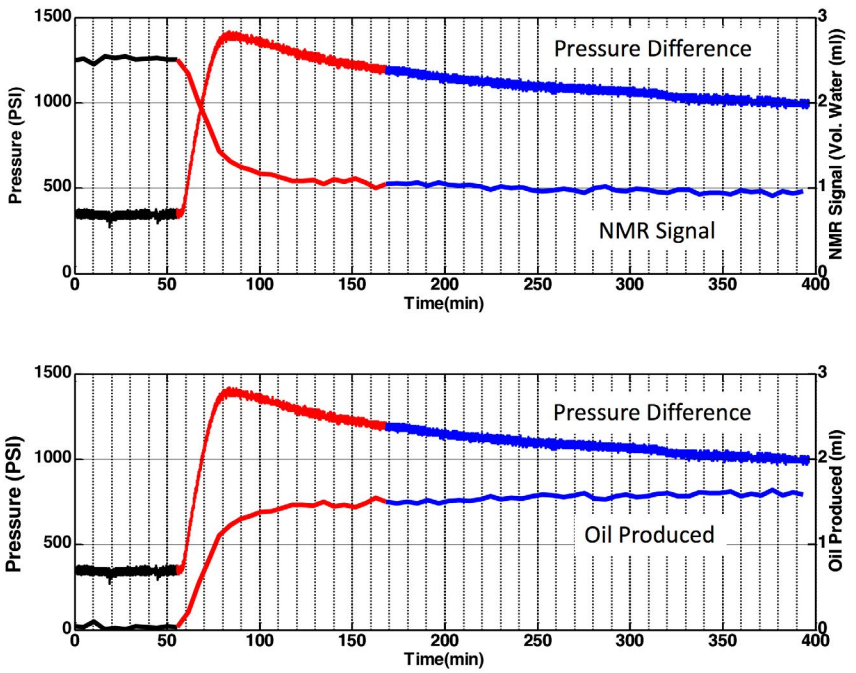


Figure 3: *NMR signal and pressure across the rock core as a function of time (Upper Panel). Oil produced and pressure across the rock core as a function of time (Lower Panel).*

The dodecane produced as a function of time is plotted in the lower panel of Figure 3.

To derive the relative permeability from the experimental data, only those measurements taken after D_2O breakthrough at the outlet face occurs are to be considered. Figure 4 shows both the oil produced (red plot) and pressure across the rock (blue plot) after breakthrough. The figure also includes least-square fits of the reduced data set to polynomial equations (black plots) of time. Once the expressions for oil produced and pressure difference as a function of time are known, the derivation of relative permeability follows the Johnson-Bossler-Naumann relative permeability calculation [2-5]. Figure 5 shows the relative permeability curves for oil (red plot) and water (blue plot) derived for this rock via the NMR measurement.

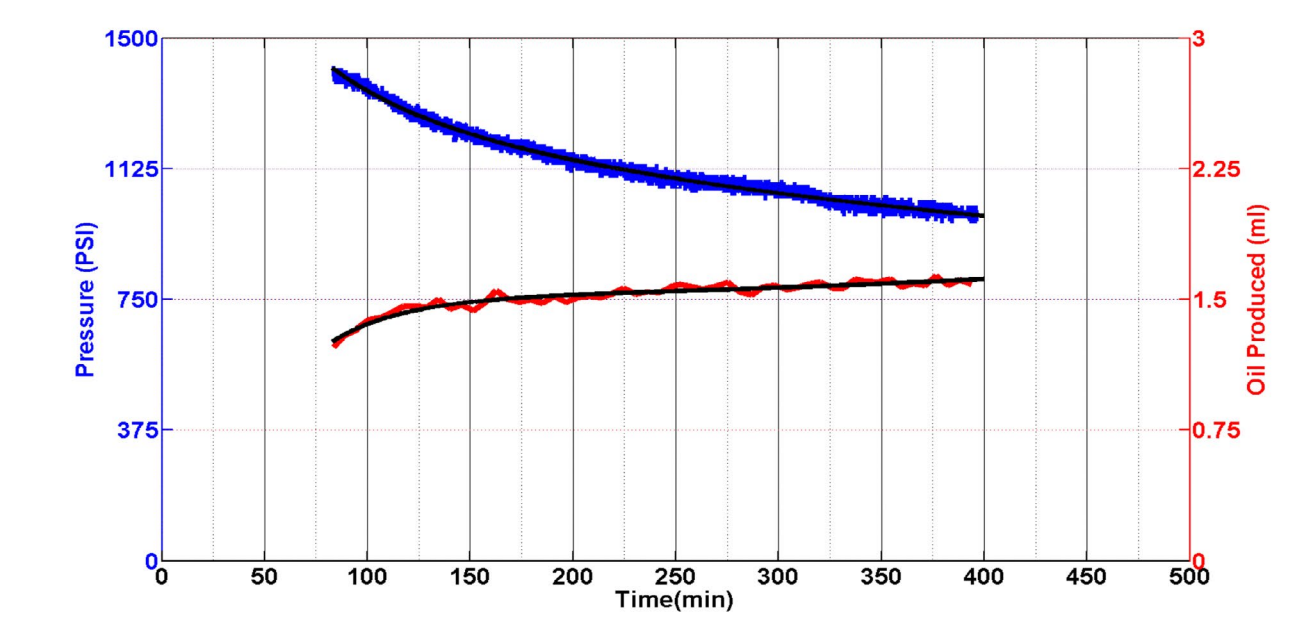


Figure 4: *The pressure across the core (blue trace) and oil produced from the core (red trace) after breakthrough of D_2O from the outlet face of core.*

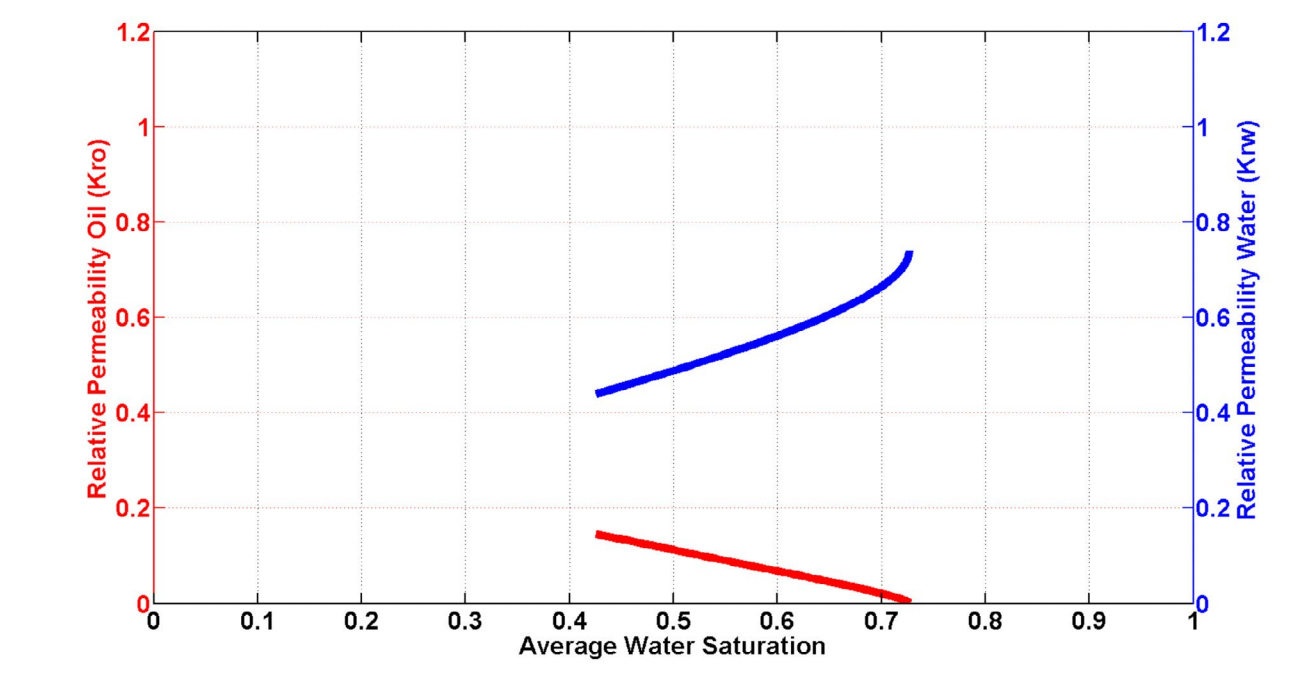


Figure 5: *The relative permeability curves generated from NMR data. The relative permeability to water is shown in blue while the relative permeability to dodecane is shown in red.*

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Conclusion:

This application note summarises a conventional relative permeability measurement done with NMR. This method couples fluid saturation determination via NMR T_2 distributions with measurement of the pressure drop across the rock. Using this method, we have successfully determined the relative permeability for a carbonate sample. This new relative permeability measurement should be more accurate than the conventional method because it directly measures the in-situ saturation profiles in the core rather than relying on the material balance method, where factors such as dead volumes and instrument uncertainties can lead to errors in estimating core saturations.

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