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MR Laboratory Measurements: Requirements to Assure Successful Measurements That Will Enhance MRI Log Interpretation

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ABSTRACT

Low field Magnetic Resonance (MR) laboratory measurements are performed to enhance the interpretation of MR logs. This is best accomplished when the laboratory project starts with a well designed set of objectives based on the desired down-hole tool applications. These objectives are achieved when procedures are listed step-by-step addressing key elements of the laboratory measurements that affect the outcome. The quality of the results is controlled by several factors from the type of sample, it's size, how it was selected and how it was prepared to the instrument settings, such as wait time (T_w), the number of echoes, the interecho spacing (T_e) and the signal-to-noise ratio. Without these preliminary steps required for proper data acquisition, enhancement and/or development of interpretive models becomes elusive. This paper addresses these issues providing guidance and methods to achieve quality measurements. Examples are presented that show how improper instrument settings can mislead interpretations, as well as, how laboratory measurements can be interpreted and used to enhance the interpretation of subsequent MR logs.

INTRODUCTION

Low field MR laboratory instruments operate and gather data in the same manner as their down-hole counterpart. The primary advantage is that direct petrophysical measurements can be performed coincidentally on the same sample analyzed for MR characteristics. This provides an opportunity to make direct comparisons and develop interpretation models that can be directly applied to log data. However, the quality of the data on which the models are based can adversely affect the answers provided. For this reason the laboratory studies need to be well planned to achieve the desired objectives. This paper focuses on guidelines for MR laboratory project planning, starting with a set of objectives, selecting and preparing samples, examples of methodologies to achieve these objectives, effects of improper MR instrument settings, example interpretations of MR results and methods to apply these results to MR log interpretations.

LABORATORY MR MEASUREMENT OBJECTIVES

The first step is to define the objectives of the measurements as they relate to future MR log applications. The objectives can be divided into two categories, optimizing the logging acquisition, and second, enhancing the interpretive models.

ACQUISITION OBJECTIVES: The generally slower logging speeds commonly used for MR logging are of concern in terms of the costs associated with rig time, and the increased time the formation is exposed to potentially damaging drilling fluids. Yet, faster logging speeds can affect the data quality controlled by factors such as full polarization of the hydrogen protons, the number of echoes gathered, and the number of echo trains that can be stacked from a given interval. Compromising these factors with faster logging speeds affects the final application and interpretation of the MR log data. Laboratory MR measurements can be performed to balance these concerns by investigating acquisition parameters, such as wait times (T_w) and the number of echoes required to characterize various fluids in various pore sizes.

MODEL ENHANCEMENT/DEVELOPMENT OBJECTIVES: MR logs provide data in the form of amplitude versus time (echo train). Initially bi-exponential fitting algorithms were used (Miller et al. 1990) to determine movable fluid referred to as free fluid (FFI), and short time data for capillary bound fluid, referred to as bulk volume irreducible (BVI). The sum of these two provided the effective porosity (MPHI). More recently multi-exponential processes have been introduced (Prammer 1994) in which the echo train is inverted to yield a distribution of amplitudes and their associated relaxation times (T_2) which infers pore size distribution in water filled rocks. Echo trains measured by laboratory MR instruments are analyzed using this inversion process with the objectives of 1) verifying formation porosity, 2) evaluating textural effects such as microporosity on MR log responses, 3) determining formation specific models that enhance the accuracy of determining BVI, FFI and permeability, 4) develop models to identify and quantify, hydrocarbons as well as residual hydrocarbons (oil), and 5) developing models to predict changes in pore size.

SAMPLE SELECTION

Three concerns need to be addressed: 1) the sample type and size to be used, 2) the samples are representative of reservoir characteristics, and 3) the sample integrity, i.e., free of defects that render subsequent petrophysical measurements suspect.

SAMPLE REQUIREMENTS: Generally, only plug samples drilled from conventional cores or rotary sidewall cores are suitable for building interpretive models that are based on sound petrophysical measurements. These samples must be of ample size to provide reliable MR measurements. Laboratory MR analyzers are designed to handle two different sizes of samples, 1.0 inch diameter and 1.5 inch diameter. The maximum length of the samples for MR analysis is dictated by the height of the "sweet spot" (the sensitive volume in which the magnetic field is homogeneous). This measurement volume should be characterized for each individual machine. The minimum sample volume is a function of the resolution of the instrument (i.e. the minimum pore volume that can be measured reliably). Percussion sidewalls and cuttings can be analyzed but subsequent application is limited.

REPRESENTATIVE OF THE RESERVOIR: To represent the reservoir characteristics the samples selected should exhibit a dynamic range of porosity and permeability. Each rock type and/or pore type should have a weighted representation based on the percentage of it's occurrence observed in core descriptions.

SAMPLE INTEGRITY: A sample's integrity can be investigated prior to analysis using standard methods such as CT scanning (Gilliland and Coles 1989) or X-Ray fluoroscopy. Eliminate samples that contain features that may have been coring induced (i.e. fractures) or features that on a core sample scale would not represent the reservoir characteristics (i.e. oblique laminations).

SAMPLE PREPARATION

Sample preparation needs to guided by three criteria: 1) the objectives of the study, 2) mineralogy, and 3) sample consolidation. Commonly techniques used in sample preparation are similar to those used in routine and/or special core analysis procedures. It is not the intent of this paper to cover these processes, instead, it is important to point out techniques unique to MR measurements.

The objectives of the study dictate the order in which measurements are made. For example, if residual oil saturations are an objective and the sample has been recovered preserving wettability, then an "as received" MR measurement will likely be done first. As observed in special core analysis

preparations, mineralogy plays a role in how to clean and dry the samples. Thus, samples with minerals that are sensitive to standard extraction processes must be prepared using non standard techniques that avoid damage to rock fabric, such as flow through cleaning and miscible saturation. To preserve sample integrity, unconsolidated samples must be encapsulated with specific packaging materials such as Teflon, that lack hydrogen, or have no MR detectable hydrogen and that will not perturb the linearity of the spectrometer's magnetic field. It should be noted that some plastic materials can give a significant MR signal.

SATURATING WITH BRINES: At some point in the protocol the samples are likely to be saturated with brine. As recognized in core testing, using the proper brine composition is a critical step to avoiding damage to the sample. If the composition is unknown and analysis must proceed, KCl brine in concentrations of 2% to 4% generally yields good results. Brines that exceed 10% salts will require a hydrogen index correction to the MR porosity determination. Furthermore, high salinity brines at ambient conditions may precipitate salts causing MR porosity to be too low compared to down hole values.

PREPARATIONS OF RESERVOIR FLUIDS FOR MR ANALYSIS: Crude oils usually cannot be analyzed as received. Produced crudes, especially low gravity types, generally contain fines and water that can alter the MR characteristics. Standard laboratory oil conditioning practices should be employed in order to remove these materials prior to analysis.

Whole muds themselves commonly are not analyzed as they do not affect the MR log measurement except in the case of wash outs or in cases of whole mud invasion. Mud filtrates do however, penetrate the formation. Oil mud filtrates need to be analyzed to determine their relaxation times and diffusion coefficients to aid MR log interpretation. Water filtrates commonly are not characterized unless they are suspected of containing MR doping materials or need to be specifically formulated to alter the MR response (Horkowitz 1995). If only whole mud is available, standard procedures can be employed to extract the filtrate.

TESTING SEQUENCE

There are various testing sequences that can be utilized to address different objectives. Presented here is one that addresses the objective of developing interpretive models to determine BVI, FFI and permeability. This sequence is commonly used for samples that do not contain sensitive mineral assemblages and assumes the reservoir to be of a water wet condition. Most often this process is performed on previously cleaned and dried samples.

The samples are trimmed to achieve the correct length, end face ground to acquire a right cylinder plug, caliper measurements of length and diameter are performed, the samples are dried and weighed (W_d) and standard methods are used to acquire permeability and porosity values. The samples are saturated using the prescribed brine in a vacuum pressure saturation process. After saturation the sample is weighed (W_s) then immersed and weighed (W_i) to determine the bulk volume. Equation 1, summarizes the computation used to determine that the sample is completely saturated. The brine density has been assumed to be constant.

$$\phi_s = \frac{(W_s - W_d)}{(W_s - W_i)} \quad \text{.....(1)}$$

Full saturation (S_w = 100%) has been achieved when the routine core analysis porosity at ambient conditions[1] compares to within +/- 0.5 p.u. of the saturation porosity (ϕ_s).

MR measurements are commonly performed in a homogeneous field at two or more interecho spacings (T_e), from 0.3 (msec.) to 6.0 (msec.) followed by air/brine capillary displacement to achieve BVI. MR measurements of the partially saturated samples are repeated using the same interecho spacings as before. Figure 1 summarizes these steps in a flow diagram.

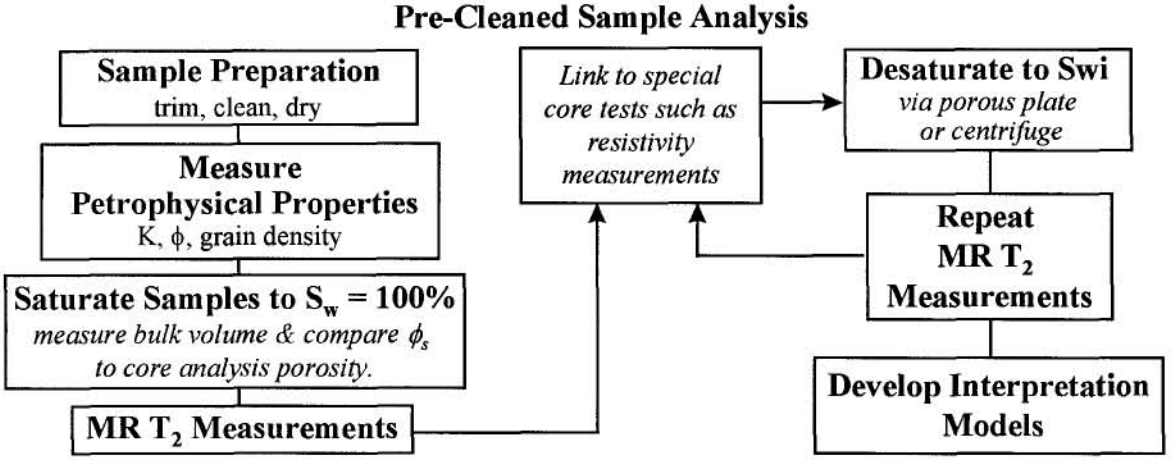

Figure 1: Flow diagram of a common test sequence in which MR laboratory methods can be integrated with special core testing such as resistivity measurements.

DESATURATING SAMPLES FOR BVI

A primary application of MR logging is the determination of BVI and permeability. Being able to correctly achieve a BVI condition is critical to subsequent development of interpretive models. There are three factors that must be considered: 1) the fluid systems, 2) the displacement technique, and 3) the desaturation pressure that will represent BVI.

The first two factors are relatively simple to determine. Generally air/brine systems are preferred to oil/brine systems as the MR signal is a function of one fluid phase, making quantification simple and direct. Each displacement technique has its advantages and disadvantages in terms of speed, ease of quantification, and pressures that can be achieved. If the time required to complete the displacement process is not an issue, then porous plate is preferable over centrifuge. This eliminates any concerns with regard to capillary end effects. The desaturation process requires that a capillary equilibrium occurs, which when using porous plate requires several weight checks over time until a stable value is achieved. For formations that require air/brine displacements in excess of 150 psi, centrifuge becomes the only practical alternative.

Selection of a pressure for desaturation is more difficult. There are two ways to define BVI. First in terms of fractional flow, BVI represents "non movable water", a saturation maximum (S_{wi}) at which a zero (or low) % fractional flow of water will be produced. Its corresponding ϕS_{wi} represents BVI. The S_{wi} corresponds to a specific capillary pressure (P_c). The second definition is evident given the capillary tube model that relates P_c to pore throat radius (r) for a given interfacial tension and contact angle ($\sigma\cos\theta$),

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[1] Grain volume (V_g) is determined via Boyle's law helium expansion, the bulk volume (V_b) is usually determined by immersion processes or by caliper, ambient porosity = $(V_b-V_g)/V_b$.

$$P_c = 2\sigma\cos\theta / r \quad \text{.....(2)}$$

the ratio $2/r$ is the surface to volume ratio (S/V) of a capillary tube. Equation 3 shows the dependence of relaxation time (T_2) on S/V assuming that the relaxivity (ρ_2) is constant.

$$T_2^{-1} = \rho_2 S/V \quad \text{.....(3)}$$

Substituting $2/r$ for S/V in equ. 3 and comparing equ. 4 to equ. 2 it is clear that P_c is inversely related to radius and is inversely related to T_2.

$$T_2^{-1} = \rho_2 2/r \quad \text{.....(4)}$$

This implies that a *cutoff* T_2 equates to a single capillary pressure. This definition is most commonly employed to separate BVI and FFI components. Determination of a single pressure can be difficult as shown in figure 2, in which reservoir "A's" P_c characteristics are less variable than reservoir "B's". Using a single pressure to characterize reservoir "A" will satisfy both definitions of BVI; however, a single pressure violates the fractional flow definition for reservoir "B". For example selecting a pressure of 100 psi for reservoir B will provide a model that predicts a BVI value, that

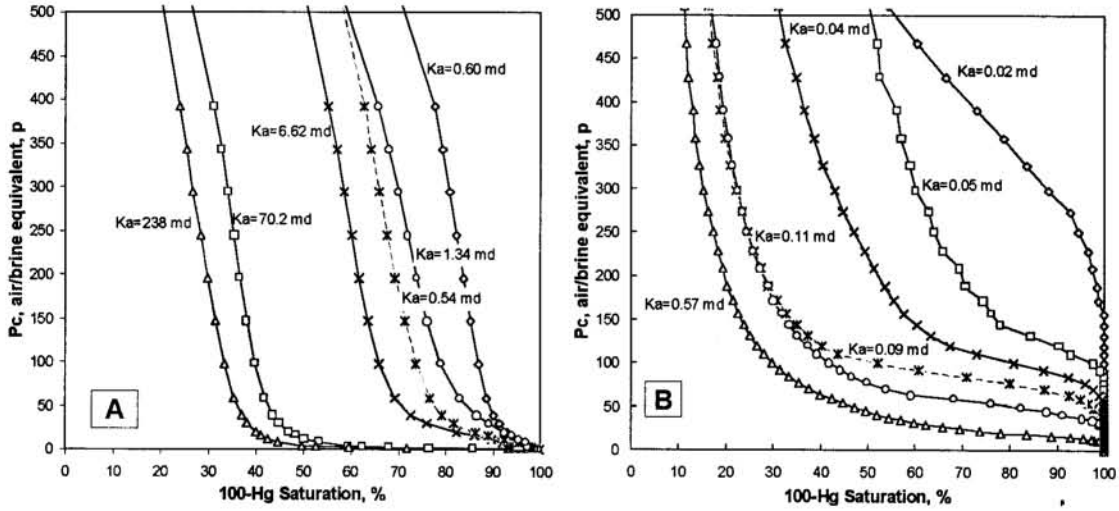

Figure 2: Reservoir "A" exhibits capillary pressure characteristics in which it is possible to select a single pressure to represent "non movable" water for all the rock qualities. This is not the case for reservoir "B". Note: Pc has been converted to an air/brine system from Hg/air, this conversion can very for rock types and is known to be problematic is shaly sands.

exceeds the zero % fractional flow of water, for the three lower permeability samples. Research is needed to develop methods that allow a simple process by which a desaturation pressure can be determined, but for now, it is best to consider the following guidelines. First, determine if a free water level is known in the reservoir; if so, use standard computations to determine the pressure that will represent maximum height above free water. Second, if a free water level is not known, use capillary pressure data to guide the selection of a pressure that best represents "non movable water". Third, when capillary pressure characteristics are variable (fig. 2 "B") determine if, each rock type is considered to be pay and eliminate non pay samples, and/or if variation can not be omitted consider using more than one pressure. Coates, et al 1997, presented a spectral BVI model that can accommodate multiple pressures. Furthermore, Marschall, et al 1995, presented fractional flow techniques that can be used to guide pressure selection.

DATA ACQUISITION

For this discussion it will be assumed that the MR instrument has been properly tuned and calibrated. There are a number of parameters that affect the quality of MR experimental results. Four major ones will be discussed. The first two are the choice of Interecho Spacing (T_e) and the Wait Time (T_w). Depending on the sample characteristics, these two can have a major impact on the signal amplitude, with some corresponding shifting of the relaxation time components. The timing between successive echoes or interecho spacing mainly impacts the fast decaying components of the relaxation time spectrum. If possible, it is best to have an interecho spacing that is half the fastest decaying T_2 component. Wait time, which is the time between echo trains necessary to realign the protons with the static magnetic field, primarily affects the slow decaying components of the relaxation time spectrum. If possible, it is best to have a wait time that is five times the slowest decaying T_1 component, but certainly no less than three times (95% recovery).

The second two parameters are the choice of Pulsing Time (T_p) and the Signal-to-Noise Ratio (SNR). These two can have a major impact on the distribution of the relaxation time spectrum and the ability to resolve components in that spectrum. Pulsing time, which is the time span over which echoes are measured, is best set to at least twice the slowest decaying T_2 component. Failure to do so can seriously distort the spectrum. Signal-to-noise affects mainly the ability to resolve components in the relaxation time spectrum. Other more subtle effects can be observed but are beyond the scope of this paper. The SNR, determined by the number of stacked echo trains required to adequately resolve the relaxation time components depends on the liquid volume in the sample and the proximity of adjacent relaxation time components. In general, the less the liquid volume and/or closer the components, the higher the SNR required to resolve them.

Figures 3 to 8 will demonstrate the effects of the above four parameters on a core sample of average T_2 relaxation time characteristics. These parameters are presented in sequence from the initial acquisition (fig. 3) where all four parameters were incorrectly set (i.e. T_p too short, T_e too long, T_w too short, and SNR too low), changing each parameter successively, to the final result (fig. 8) where all parameters are correctly set. It must be recognized that the effects of these parameters are interdependent and if the sequence were changed the details of the individual steps would change, however, the final result would be the same.

The above four parameters are the major ones to be considered in running experiments. They can vary considerably from sample to sample. It is recommended that a test run or series of test runs be performed on each sample to determine the optimal settings of these parameters. This assures the acquisition of quality data and saves time by optimizing wait time and the number of echo train stacks for the desired SNR. It is clear from these examples that the failure to run experiments with the proper parameter settings will lead to the misinterpretation of the true MR characteristics. Subsequent interpretation model development may produce unfavorable results when applied to MR log data.

INTERPRETATION OF RELAXATION TIME DISTRIBUTIONS

Two points should be considered prior to making interpretations. First, the relaxation time distributions should all have been processed using the same algorithm, and second, it is important to have some knowledge of the fluids inhabiting the interstices of the rock. For example, a brine saturated sample has different MR characteristics than when it has both oil and water. Knowing the bulk relaxation time of the oil is helpful in providing interpretations (assuming water wet conditions).

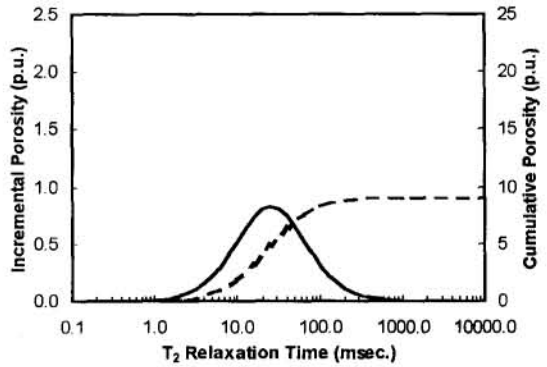

Figure 3: *Initial Acquisition* results showing an apparent uni-modal result. For fig. 3 - 7 bold solid = incremental T_2, bold dashed = cumulative T_2, light solid = previous incremental T_2 and light dash = previous cumulative T_2.

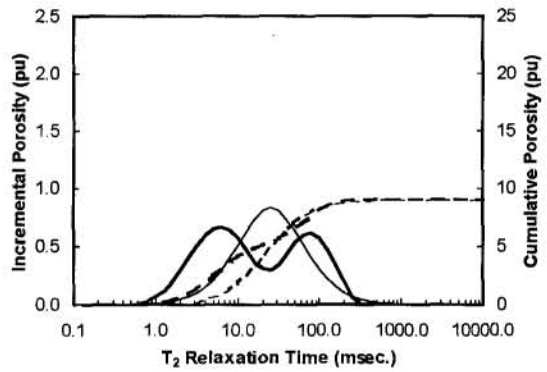

Figure 4: *Increasing The Pulsing Time* shows that this sample is in fact bi-modal. There is a significant change in the distribution but little change in the cumulative porosity.

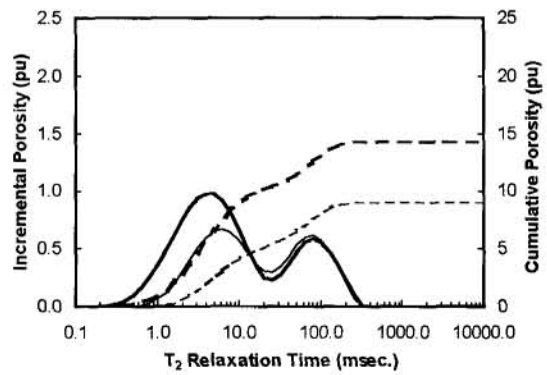

Figure 5: *Decreasing The Echo Spacing* shows that there are fast components in this sample that were masked by too long a T_e. There is a significant change in the cumulative porosity with a characteristic downward shift of the fastest components in the distribution.

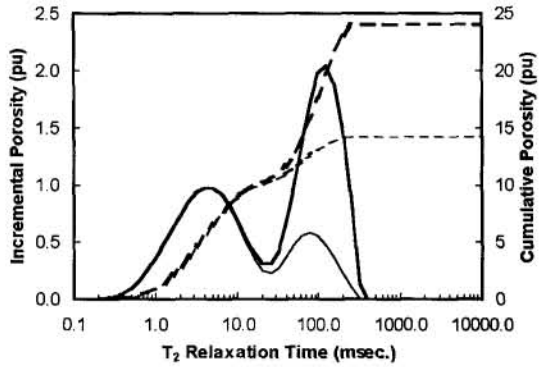

Figure 6: *Increasing The Wait Time* has significantly increased cumulative porosity. After correction for a T_w that is too short there is a characteristic upward shift in slow T_2 components.

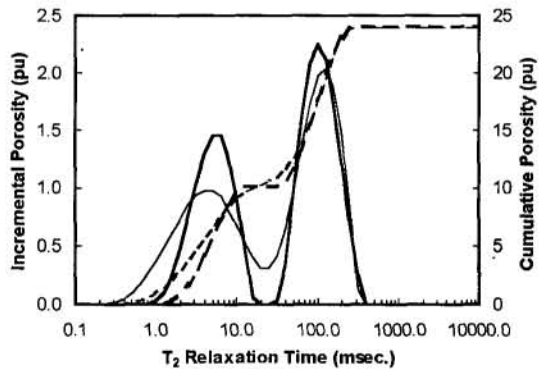

Figure 7: *Increasing The SNR* allows a sharper resolution of the two major components. While each one becomes more well defined in the distribution, little change is noted in the cumulative porosity.

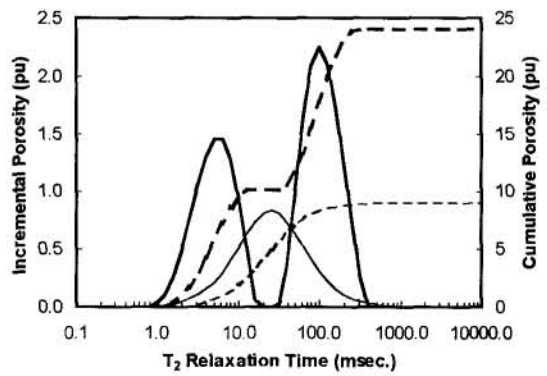

Figure 8: *Final Result*, in which all acquisition parameter defects have been corrected, is compared with the initial result. Bold solid = incremental T_2, Bold dash = cumulative T_2, light solid = initial incremental T_2 (fig. 3) and light dashed = initial cumulative T_2 (fig. 3).

SAMPLES SATURATED WITH A SINGLE WETTING PHASE. Relaxation time distributions from samples that have been saturated with a single wetting phase (brine), mimic their pore size distributions as shown by several authors (Straley et al 1994, Chang et al 1994, and Marschall et al 1995). Comparisons of shorter to longer interecho spacing measurements can yield information regarding the abundance of very small pores that can be associated with water in micropores and/or clay bound water (fig. 9). From an MR log perspective, verification of abundant fast components below the interecho spacing measured can verify that the apparent low effective porosity was due to micropores and/or clay bound water and not due to low hydrogen index fluids.

Brine saturated samples analyzed in a homogenous magnetic field can show shifts in T_2 distributions that are caused by internal gradients. Internal gradients can be formed when paramagnetic minerals (minerals containing iron or manganese) are present in the pore wall area. For low field MR measurements (1 - 2 MHz) the porosity value is not affected (Straley et al 1994); however, comparison of two different interecho spacing T_2 distributions show the evidence and effect of internal gradients (G) on low field MR measurements (fig. 10). The shift exhibited in T_2 is governed by the factors shown in equations 5 and 6, in which the relaxation rate R_2 is the sum of the intrinsic relaxation rate R_{2i} and the apparent relaxation rate R_{2D} due to gradients (G), diffusion (D), etc.

$$R_2 = R_{2i} + R_{2D} \quad \text{.....(5)}$$

$$R_{2D} = \gamma^2 G^2 D T_e^2 / 12 \quad \text{.....(6)}$$

where: γ is the gyromagnetic ratio of ^1H

In equation 6 if R_{2D} is non zero (i.e. internal gradients are present), then R_{2D} increases as T_e increases. This will cause an increase in R_2 as in equation 5 or a decrease in T_2 since $T_2 = 1/R_2$. The sample shown in figure 10 was analyzed petrographically and found to contain Fe-dolomite and iron rich authigenic chlorite.

SAMPLES WITH MORE THAN ONE PHASE PRESENT. As other non miscible and non wetting fluids are added to brine saturated samples the MR distribution no longer mimics pore size. A common displacement for determining a cutoff T_2 is air/brine displacement. Since air provides no MR signal the missing components after air/brine displacement is the FFI fluid (fig. 11). It is also important to note that a layer of capillary bound water remains in the larger free fluid pores and has a short T_2 signal due to the volume reduction for the same surface area. This causes the capillary bound spectrum to change, in this case, appearing to shift downward. As oil is added to a brine saturated sample (fig. 12) the oil, being non wetting, maintains its bulk liquid T_2, and as in the air/brine case the capillary bound spectrum changes. A cutoff T_2 value is readily apparent in figure 12 after oil/brine displacement; however, as oils become more viscous, their bulk liquid T_2 decreases (T_2 is inversely related to viscosity). High viscosity crude oils can interfere with the cutoff T_2 determination causing BVI to be overestimated.

DETECTING CHANGES IN WETTING PREFERENCE. Howard (1994) presented chalk core samples with different wetting characteristics and in effect provided a model from which to gauge if a wetting change has occurred. As oil wets the pore walls its T_2 spectrum originally only a function of one relaxation mechanism (bulk liquid), now includes, the effects of surface relaxation causing a

reduction in the T_2 of the oil. At the same time, water that was originally in contact with the pore wall, is now only in partial contact or not in contact at all. Thus the BVI components move to longer time. The sample shown in figure 13 was analyzed for MR characteristics after crude oil was used to displace brine. It was then flushed with a simulated mud filtrate (mixture of a base oil + surfactants). The surfactants allowed the filtrate phase to wet the rock surface removing BVI as evidenced by the lack of short time components. Further evidence of a wetting change is given by the downward shift in the T_2 spectrum of the filtrate from it's bulk liquid T_2 value.

APPLICATION MODEL DEVELOPMENT (LAB to LOGS)

Concentrating on two major applications, BVI and permeability, obtaining the first is of most importance. A cutoff T_2 model is commonly used to predict BVI. The cutoff T_2 can be measured directly by comparing brine saturated MR T_2 distributions to the desaturated T_2 distributions. An optimal cutoff T_2 is obtained when the error between predicted S_{wi} and Core S_{wi} has been minimized. Figure 14 is a cross plot showing how well the model predicts S_{wi}. In this case, one cutoff T_2 value does not appear to accurately represent the range of rock quality found in this data set. In these cases, multiple cutoff values or other BVI models, such as the spectral BVI model presented by Coates et al 1997 should be considered.

While there are several permeability models that are available, they can be categorized into two groups, those that utilize an average T_2 value, and those that utilize a FFI/BVI ratio. Straley, et al, 1994, presented a model to determine permeability (k) using a geometric average of T_2 in equation 7, in which C is a variable adjusted for specific reservoirs.

$$k = CT_2^2\phi^4 \quad \text{.....(7)}$$

The variable C can be determined through comparisons of predicted versus core permeabilities until a value for C is found that minimizes the error. Coates and Denoo (1981) presented a free fluid model (equ. 8), now commonly used in MR log applications. The value for C in equation 8 is also a variable, and is dependent on the formation encountered. The value of ϕ is often substituted with MPHI.

$$k = \left(\left(\frac{\phi}{C}\right)^2\left(\frac{FFI}{BVI}\right)\right)^2 \quad \text{.....(8)}$$

Solving equation 8 in a y = mx + b form yields,

$$\sqrt{\frac{FFI}{BVI}} = m\left(\frac{\sqrt[4]{k}}{\phi}\right) + b \quad \text{.....(9)}$$

Assuming b is zero in equation 8, core permeability is substituted for k. The slope of the line m (C value in equ. 8) is determined using a least squares regression. A cross plot example is shown in figure 15.

Once each model has been calibrated to core a cross plot of predicted permeability versus core permeability should be used to determine which model performs best over the range of permeabilities observed in the reservoir. Each model has its own strengths and weaknesses based on the fluids encountered in the logging operations (Table 1). Final model selection should be governed by the fluid types and conditions.

SUMMARY

An MR laboratory project should begin by examining the potential applications and developing a set of objectives. Core samples selected should have the same range of permeability and porosity

exhibited by the reservoir. Considering the objectives and the samples available a protocol listing the step-by-step process is needed. Core sample preparation generally is similar to special core processes in which the mineralogy must be considered. Unconsolidated samples need to encapsulated in materials that will not interfere with the MR measurements. Generally samples are analyzed using two or more interecho spacings at different saturation conditions, usually brine saturated and at a partial saturated condition representing BVI. The selection of a desaturation pressure is critical and should be based on petrophysical information such as free water level, maximum height in the reservoir above free water level as well as capillary pressure measurements. Acquisition parameters significantly affect the relaxation time distributions, and if not properly set can cause misleading interpretations. Laboratory MR distributions can be used to interpret pore size distributions, the presence of fluids in micropores and/or clay bound water, internal gradients caused by paramagnetic minerals, cutoff T_2 values, effects on the T_2 distribution when more than one phase is present and changes in wetting characteristics. Laboratory MR data can be used to develop interpretive models to determine BVI and permeability on MR logs.

ACKNOWLEGEMENTS

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REFERENCES

Chang, D, Vinegar, H., Morriss, C., and Straley, C., 1994, "Effective Porosity, Producible Fluid and Permeability in Carbonates from NMR Logging", SPWLA 35th Annual Logging Symposium, June, paper A.

Coates, G. R. and Denoo, S., 1981, "The Producibility Answer Product", *Schlumberger Technical Review*, **29** (2), pp. 55.

Coates, G. R. Marschall D., Mardon, D., Galford, J., 1997, "A New Characterization of Bulk-Volume Irreducible Using Magnetic Resonance", SPWLA 38th Annual Logging Symposium, Houston, Texas, June 15-18.

Gilliland, R.E., Coles, M. E., 1989, "Use of CT Scanning in the Investigation of Damage to Unconsolidated Cores", Society of Core Analysts Conference, New Orleans, paper 8902.

Horkowitz, J.P., Harman D.E., Clearke, E.A., 1995, "Residual Oil Saturation Measurements in Carbonates with Pulsed NMR Logs", SPWLA 36th Annual Logging Symposium, June 26-29, paper Q.

Howard, J. J., 1994, "Wetting and Fluid Saturations Determined from NMR T1 Distributions", Magnetic Resonance Imaging, Vol. 12 No. 2 pp. 197-200.

Miller, M.N., Paltiel, Z., Gillen, M.E., Granot, J. and Bouton, J.C., 1990, "Spin Echo Magnetic Resonance Logging: Porosity and Free Fluid Index Determination", SPE 20561, presented at the 65th Annual Technical Conference and Exhibition, New Orleans, Sept. 23 - 26.

Marschall, D., Gardner, J. S., Mardon, D, and Coates, G. R., 1995, "Method for Correlating NMR Relaxometry and Mercury Injection Data", Society of Core Analysts Conference, San Francisco, paper 9511.

Prammer, M. G., 1994, "NMR Pore Size Distributions and Permeability at the Well Site", SPE 69th Annual Technical Conference and Exhibition, September 25-28, SPE 28368.

Straley, C., Rossini, D., Vinegar, H., Tutunjian, P., Morriss, C., 1994, "Core Analysis By Low Field NMR", Society of Core Analysts Conference, Stavanger, paper 9406.

The NMR Sandstone Rock Catalogue, Applied Reservoir Technology, Ltd./Sintef Unimed, 1996.

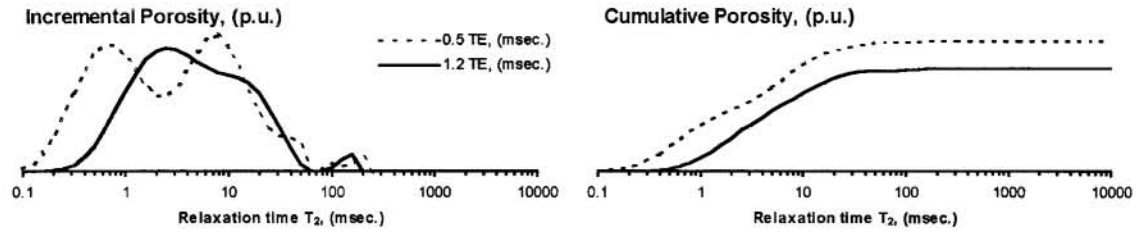

Figure 9: Abundant clay fractions show short time components in the 0.5 T_e measurement not shown in the 1.2 T_e.

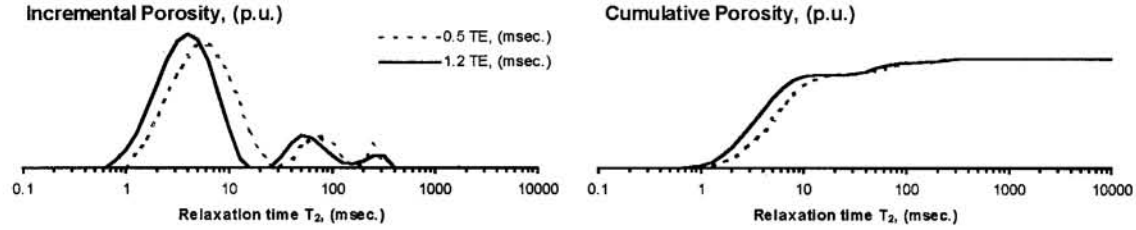

Figure 10: The 0.5 T_e has T_2's longer than the 1.2 T_e. For a homogeneous magnetic field the two should be equal. Internal gradients cause T_2 components to shift to shorter time with longer T_e.

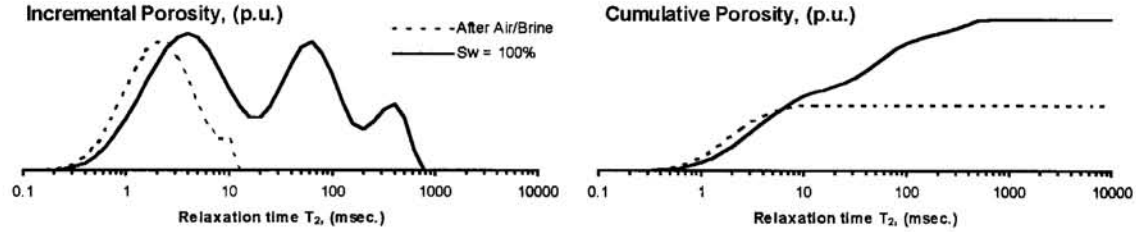

Figure 11: After air/brine displacement FFI components associated with larger pores, are removed, a smaller water volume for the same surface area in the larger FFI desaturated pores has altered the fast component spectrum (dashed).

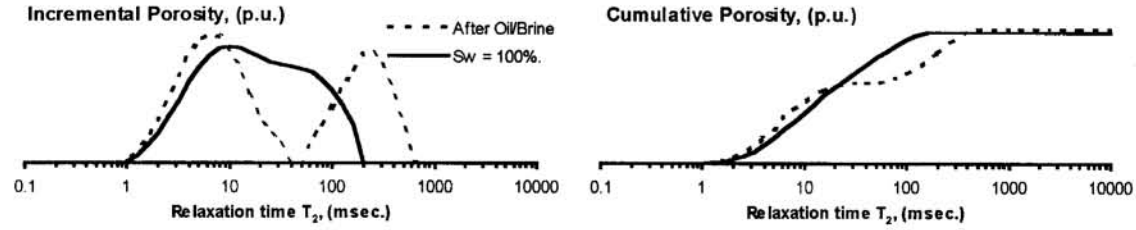

Figure 12: After oil/brine displacement the T_2 distribution is not a function of pore size as the non wetting phase (oil) has a bulk T_2 independent of pore size. The fast relaxing spectrum has changed as in fig. 11.

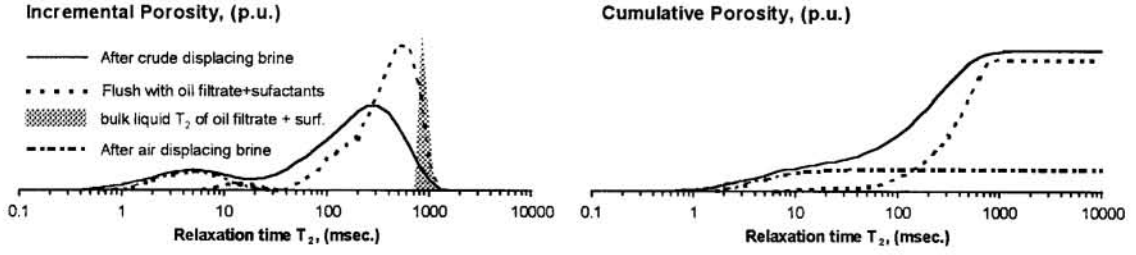

Figure 13: A change in wetting is evident after flushing the sample with a filtrate oil + surfactants. Key to this interpretation is the lack of fast time components compared to the oil/brine and air/brine displacements. Furthermore the peak at approx. 500 (msec.), associated with the filtrate + surfactants, is low to its bulk liquid T_2 at 770 (msec.).

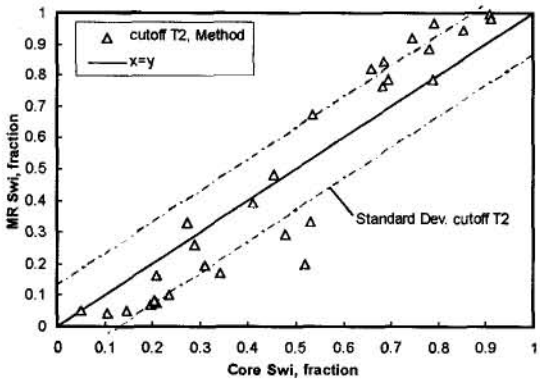

Figure 14: Cross plot comparing the predicted MR Swi (using an optimal cutoff T_2) to the Core measured values. Two groups are apparent, high versus low Swi. More than one cutoff T_2 value would be required in order to more accurately represent BVI.

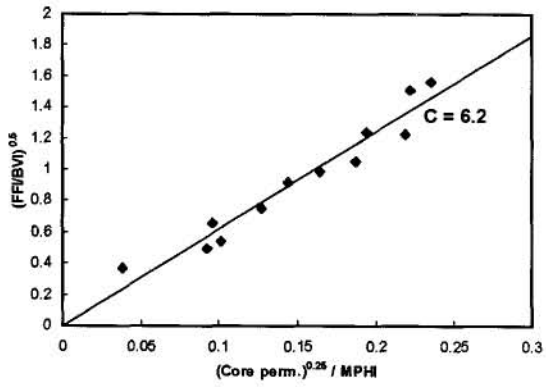

Figure 15: Free fluid permeability model in which a slope of 6.2 was determined using MR laboratory data.

Table 1

Permeability Model	Summary of Strengths and Weaknesses
Average T_2 models	• Perform best in zones containing a single phase only. • If oils or oil filtrates are present the average T_2 is skewed toward the oils bulk liquid T_2 value and permeability is erroneous. • Unflushed gas zones yield average T_2 values that are too low, underestimating permeability. • Multiplier "C" is variable for different formations (NMR Sandstone Rock Catalog)
FFI/BVI models	• More flexible, as it is not affected by an additional liquid phase such as oil or oil filtrates (assuming no wetting change has occurred). • In unflushed gas zones MPHI can be too low and must be hydrogen index corrected or an alternative porosity source should be used. Also if a long wait time acquisition is used that fully polarizes all hydrogen protons, BVI using a cutoff T_2 method can be too high (gas effected) underestimating permeability. • Heavier oils can be counted as BVI causing permeability to be underestimated. • Coefficient "C" is variable for different formations.