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Status Report

EVALUATION OF NUCLEAR MAGNETIC RESONANCE IMAGING FOR THREE-PHASE RELATIVE PERMEABILITY MEASUREMENTS

Project BE9, Task 2 in FY86 Annual Plan

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SUMMARY

The ultimate objective of project BE9 is to identify the mechanisms and improve the understanding of multiphase flow in porous media. Task 2 will help in achieving this ultimate goal by studying the feasibility of using nuclear magnetic resonance imaging (NMRI) as a technique for measuring fluid saturations in core samples.

In this preliminary work, the recovery curves obtained from perturbing fluid saturated core samples in a NMRI machine with an inversion recovery sequence were analyzed. A difference of 100 msec between inversion time (TI) at the null points for 100 percent oil saturated and 100 percent water saturated Cleveland cores was determined. The inversion time at the null point in the recovery curve corresponds to the point at which magnetization crossed the null intensity point. This result suggests that water signal can be differentiated from oil signal by setting up different inversion time in the inversion recovery sequence. The potentiality of this technique to estimate the amount of oil and water present at different locations in core samples should be further investigated. Future work should study the effect of pore size distribution present in a core on the TI at the null points in the recovery curve. The effect of different water (or oil) saturation levels on TI at the null point should also be investigated.

If pore size distribution and/or fluid saturation level change the determined TI at null points by this investigation, there will be a range of TI's for which magnetization is zero instead of a single value. Therefore, the inversion recovery technique would not be able to be used to differentiate between oil and water in rock samples.

INTRODUCTION

Reservoir engineering designs, oil recovery predictions, and evaluation of enhanced oil recovery (EOR) processes require knowledge about relative permeability data. These data are used in reservoir simulators to evaluate and predict the potential for success of an EOR project. Some EOR processes create three-phase flow in reservoirs, so knowledge of three-phase relative permeability is required.

In generating relative permeability data, accurate measurement of fluid saturations is required. For three-phase flow (gas, oil, and water), two of these three saturations must be determined experimentally. The most common methods for obtaining fluid saturation measurements are volumetric, gravimetric, and electrical resistivity. More sophisticated methods, however, such as x-ray absorption, microwave attenuation, nuclear magnetic resonance imaging, and computer tomography (CT), are gradually being adopted for saturation measurement. These techniques also provide saturation profile information which can be used in evaluating EOR projects. The evaluation of NMRI for three-phase relative permeability measurement was the objective of task 2 in project BE9.

The NMRI technique relates fluid saturation to magnetic resonance relaxation. The image produced is essentially a density map or pixel value (NMRI signal proportional to magnetization) which is related to the number of protons (principal isotope of hydrogen) contained in the core sample and their NMR relaxation times. The total number of protons is proportional to the amount of oil and water present in a core sample saturated with an oil-brine-nitrogen system.

The inversion recovery (IR) sequence was suggested in this work for distinguishing oil-filled pores in NMR images from water-filled pores so that oil-saturation and water-saturation values could be determined. Three nearly identical rock samples were saturated--one with oil, another with water, and the third with oil and water. Recovering magnetization for these three samples was measured for different inversion times. Magnetization values versus TI for each rock were ploted on millimeter charts, so that TI at zero magnetization could be determined.

Preliminary results from these experiments are presented and discussed in the Results and Discussion section of this report. This report also contains sections on NMRI Technology and Apparatus and Experimental Procedure. The last section presents significant observations obtained during this work along with some recommendations.

NMRI TECHNOLOGY AND APPARATUS

NMRI is the application of a controlled sequence of radio frequency (RF) pulses and magnetic field gradients in three dimensions to the standard pulsed NMR experiment to develop a "map" of the NMR spin density as a function of position within the sample. Thus, information about the physical location within the sample of selected nuclei (for example, protons) possessing certain characteristic chemical shifts, or relaxation times, is attainable and can be related to the properties of the sample.

NMRI technology is well established in the field of medicine. The technique provides physicians with an unprecedented ability to discriminate between various tissues and their pathology. Applications of NMRI in the petroleum engineering field have just begun.

The attractiveness of the NMR method for investigating the nature of rock-fluid interactions and monitoring changes in these interactions arises from the number of different NMR parameters available for investigation, such as variations in chemical shift between fluid types, changes in spin-lattice (T_1) and spin-spin (T_2) relaxation times, and from the nondestructive nature of the experiment, permitting successive experiments on the same sample. Instrument parameters which influence the quality of images significantly are (1) RF pulse sequence, (2) RF pulse timing parameters, (3) RF gain setting, (4) field strength of the magnet, (5) type of RF probe (coil) used, and (6) imaging techniques.

RF pulse sequences refer to the difference in how 90-degree and 180-degree or other types of pulses, are sequenced. Some of the frequently used sequences are saturation recovery (SR), inversion recovery (IR), and spin echo (SE) sequences. The spin echo is further subdivided into Hahn single echo and Carr-Purcell-Meiboom-Gill multiple echo sequences.[1]

RF pulse timing parameters refer to the sequence repetition time (TR), the time interval between the 180-degree and the 90-degree pulse in the IR sequence, inversion time (TI), and the time interval between the 90-degree pulse and the spin echo in the SE sequence, or echo time (TE).

Figure 1 shows the NMRI signal (magnetization) when the IR sequence is applied. As it is observed, the magnetization goes from negative to positive passing through a null point (where the magnetization is zero.) The dotted line in figure 1 is the response obtained from the instrument used since negative magnetization is converted to positive magnetization. In this work, we intend to determine the existence of different null points for water- and oil-saturated core samples.

The NMR scanner used in this study was used in conjunction with a laboratory-built solenoid receiving coil.[2] We used a Picker MR VISTA - 2055 scanner, operated at 0.5 Tesla with a proton resonance frequency of 21.3 MHz. Other components of the scanner include a RF pulse synthesizer; a wide band RF linear amplifier (2kW); x, y, and z gradient drive and amplifier; active magnetic field shimming drive; a magnet power supply (used only once for initial power up of the superconducting magnet), cryogen level detectors for liquid nitrogen and liquid helium, and a digital computer. The current software employed is Picker MR4/TABF which includes 2 dimensional Fourier transform imaging with multiple slice capability. The slice thickness was 10 mm; spatial resolution was 1 mm.

EXPERIMENTAL PROCEDURE

Three Cleveland sandstone cores, 1.5-inch diameter and 1-inch long, were cut and dried. The first and second cores were fully saturated with 1 percent NaCl and Soltrol-220, respectively. The third core was saturated to 50 percent with 1 percent NaCl and to 50 percent with Soltrol-220.

The inversion recovery frequency sequence followed by a short spin echo sequence was selected for all NMRI experiments to try to distinguish water from oil. The inversion time was varied from 200 to 600 msec in intervals of 100 msec. TR (sequence repetition time) was selected as 2,000 msec because it gave the best image. Cross sectional images were obtained at the center of each core (10 mm slice thickness). The pixel intensity for a circular element (about the size of the core cross section) was obtained from these cross sectional images. Experiments were repeated taking two more cross sectional images, one at either side of the center of each core.

RESULTS AND DISCUSSION

The NMRI signals obtained for each core sample at different TI are presented in figure 2. The positive sign in pixel densities for TI less than TI at the null point was changed to a negative sign so that the TI at the null point could be estimated by interpolation. The results showed that the null point for Soltrol-220 occurs at a TI equal to 240 msec, whereas the null point for water occurs at a TI equal to 340 msec. This indicates that the inversion recovery technique may be used to estimate the amount of oil and water present at different locations in a core because of the 100-msec difference in TI at the null point between the oil and the water.

The TI at the null point for the core 50 percent saturated with oil and 50 percent saturated with brine was 260 msec. This value, as expected, is between the TI at the null point for oil (240 msec) and the TI at the null point for water (340 msec). This result shows the magnetization to be a function of the amount of proton present in the rock sample as well as a function of the type of element to which the proton is attached (proton in the water behaves differently than proton in the oil). If this technique for distinguishing oil and water is to be considered feasible, it is necessary to show that different water (or oil) saturation levels do not affect the TI values found in this investigation.

It is also necessary to show that TI at the null point does not vary significantly with pore size distribution. If it does vary, there will not be a single TI at the null point for either water or oil (see figure 1.) If ranges rather than single values exist at the null points, the range of TI's at the null point along the core sample for oil may overlap the range of TI's at null point for water, making it impossible to distinguish water from oil by this technique.

Results from cross sectional images at either side of the center of the cores show that the pixel intensities deviate a maximum of 13 percent, 8 percent, and 12 percent for 100 percent water, 100 percent oil and 50 percent water - 50 percent oil-saturated cores -- respectively, from the pixel intensity measured at the center of core. Assuming a linear relationship between pixel intensity and TI in the area of interest, a maximum of 13 percent deviation is expected for the TI at the null point because of differences in the pore size of the Cleveland core samples. The effect of this deviation on ability to distinguish between water and oil has not been satisfactorally determined because of the limited amount of data available at this time. Further studies are required to verify these findings.

CONCLUSIONS AND RECOMMENDATIONS

- The inversion recovery technique may be used to estimate the amount of oil and water present at the different locations in core samples since a 100-msec difference in TI at the null point was found. Further studies are recommended to verify whether findings are applicable to different rock types.

- A maximum of 13 percent deviation in the TI at the null point is expected in Cleveland cores because of differences in pore size along the length of the core. Further studies to determine the effect of this deviation on water and oil saturation measurements are recommended.

- Software improvement to the NMR scanner is needed to permit selection of any TI instead of only 100 to 600 msec in intervals of 100 msec. This improvement is necessary for the success of the inversion recovery technique for this application.

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(EEH) SR-BE9Tk2

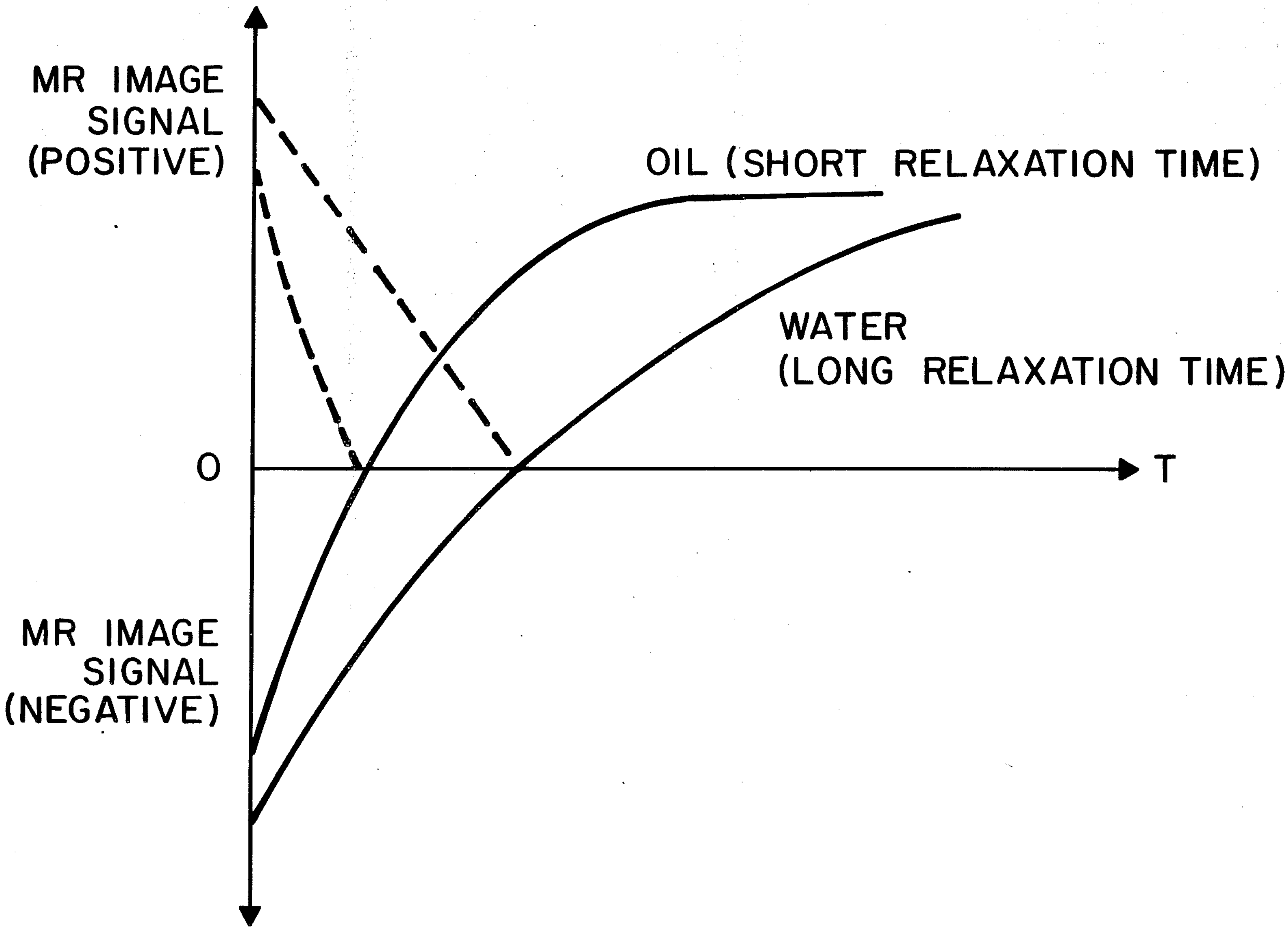

FIGURE 1. - Inversion recovery scheme for distinguishing oil-filled pores in image from water-filled pores.

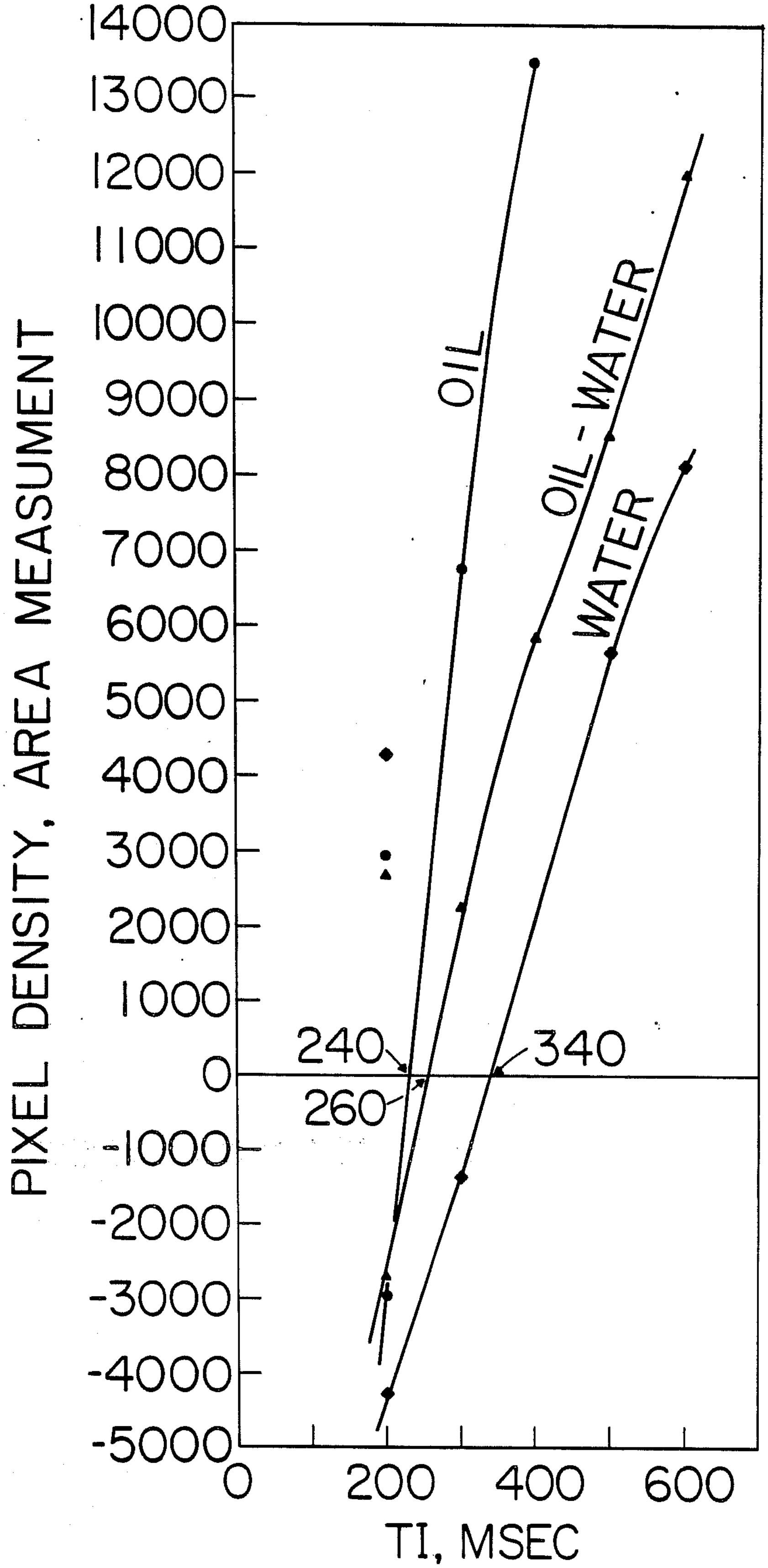

FIGURE 2. - Inversion recovery for oil-filled, oil-water-filled and water-filled pores in Cleveland core.