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STATE-OF-THE-ART REPORT SUMMARIZING TECHNIQUES TO DETERMINE RESIDUAL OIL SATURATION AND RECOMMENDATIONS ON THE REQUIREMENTS FOR RESIDUAL OIL SATURATION RESEARCH AND DEVELOPMENT — TOPICAL REPORT

By
M. M. Chang
N. L. Maerefat

May 1986

Performed Under Contract No. DE-FC22-83FE60149

National Institute for Petroleum and Energy Research
A Division of IIT Research Institute
Bartlesville, Oklahoma

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U. S. DEPARTMENT OF ENERGY
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Printed in the United States of America. Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Paper copy: A03
Microfiche copy: A01

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NIPER—64
Distribution Category UC-92A

NIPER--64

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Prepared for
U. S. Department of Energy
Assistant Secretary for Fossil Energy

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ABSTRACT

An investigation was conducted on the residual oil saturation measurement techniques developed during the last fifteen years. Knowledge of precise ROS measurements is required for EOR project planning. The advantages, limitations, and problems of each one of the techniques are presented in tabulated form. Also, some of the possible improvements in the measurement techniques for the residual oil saturation are summarized. The following residual oil saturation techniques are discussed: core analyses, well logging, backflow tracer tests, material balance and well testing, newly developed gravity log methods, and interwell residual oil saturation measurements. Several aspects left to be improved in both instrumentations and data interpretation on pressure coring, back-flow tracer tests, well logging, material balance calculations, well testing, and interwell ROS measurements are presented. A nuclear magnetism log-inject-log method is proposed in which the need for porosity measurement for determining residual oil saturation is eliminated.

INTRODUCTION

Declining domestic reserves and development of improved methods for oil recovery have increased the need to know the remaining oil reserve or residual oil saturation (ROS) in reservoirs. Residual oil saturation, by strict definition, is the remaining oil saturation after waterflooding. The amount of the residual oil left behind is one of the most important parameters critical to the selection of an enhanced oil recovery process.

There are a variety of engineering methods to estimate ROS. Each one has some uncertainties and limitations. Because there is a high precision requirement and typical complexity of formation properties, a single method can not handle all the requirements for ROS determination. The ROS methods were evaluated by the IOCC (1) up to 1978. In the present literature review, the ROS techniques were evaluated up to date to facilitate field designs and measurements. A total of fifty-seven new references are presented in this paper. Three methods have been developed to measure the ROS between wells: resistivity method (5), well-to-well tracer test (7), and chemical displacement method (8). Other methods used in the past to measure ROS from one well (1-4) include: core analyses, well logging, backflow tracer tests, material balance calculations, well testing, and newly developed gravity logging method. Some of these ROS techniques (e.g. core analyses, conventional well logging) can also be used to measure the initial and remaining oil saturation at any production stage.

In this report, a state-of-the-art review of residual oil saturation measurement methods is presented first. This is followed by a study of systematic and random errors involved in different ROS methods. At the end of the report, potential improvements of methods for determining ROS are discussed.

SINGLE-WELL ROS MEASUREMENTS

Single-well ROS methods including core analyses, backflow tracer tests, well logs, newly developed gravity logging, material balance calculations, and well testing are described below.

CORE ANALYSIS

The routine core analysis that defines oil saturation measurements is performed on cores obtained from: conventional coring (9). Methods commonly used for core ROS determination (1,9) include (i) vacuum distillation to recover oil and water under moderate vacuum and 450° F, (ii) distillation-extraction, in which water is distilled and oil is extracted, (iii) high temperature (1200° F) retorting at atmospheric pressure, (iv) a combination of techniques for formations containing hydratable clays (10), and (v) special techniques for analyzing cores recovered in pressure-coring (11).

The residual oil saturations measured from conventional coring are substantially less than its in situ values obtained from logging methods. The most severe change in oil saturation is caused by the expulsion (bleeding) and associated shrinkage of oil as pressure decreases during lifting of the core to the surface. Attempts have been made to correct the oil saturation measurements in conventional coring but the resulting values are still unreliable. Luffel and Randall (12) showed that for oil with formation volume factor of 1.10 to 1.25, oil saturation reductions varied from 20 to 56 percent. Rathmell, et al. (13), recommended for the oil adjustment to multiply the surface oil saturations $(So)_{core}$ by B_oE, where B_o is the oil formation volume factor and E is the adjustment for bleeding. The suggested value for E is 1.11. Kazemi (14) modified Rathmell's oil saturation value by dividing the surface oil saturation by an additional factor, the conformance factor $(1 - V^2)/M$, to calculate the average waterflood residual oil saturation $(So)_{res}$. So the resulting equation becomes:

$$(S_o)_{res} = (S_o)_{core} \; B_oE \; \frac{M}{1 - V^2} \qquad \text{Eq. 1}$$

where M = mobility ratio $= \frac{\mu_o k_w}{\mu_w k_o} = \frac{\text{(oil viscosity) (water permeability)}}{\text{(water viscosity) (oil permeability)}}$

V = permeability variation (Dykstra - Parsons (14) coefficient)

Hensel (15) corrected the measured oil saturation from conventional cores by a depletion ratio which is defined as: total oil/(total oil - oil lost by pressure depletion). The depletion ratio was found to be 1.28 in Hensel's case and was not a function of rock property (porosity, permeability).

The ROS measured from pressure coring of a new drilled well is highly preferred to the one measured from conventional coring because of its good (≤±4%) to excellent (≤±2%) accuracy (2). Pressure coring solves expulsion and shrinkage problems by maintaining the core specimen at bottom hole pressure until the core fluids can be immobilized by freezing. Pressures from several hundred psi to in excess of 6000 psi have been processed. Core recovery varying from 51 percent of very soft to soft formations, to 70 percent for consolidated formations was reported (16).

Carefully designed mud and core handling are essential to the success of pressure coring analyses. The mud should be designed to have low mud weight (6), low water loss, and no chemicals which enhance oil movement. Added tracer (e.g. nitrate) in the mud can be used to monitor the filtrate invasion to the core (15). Hensel (17) discussed the coring method and the invasion and flushing of the core pore spaces by the filtrates of coring fluids. During a pressure coring operation, a foam mud system was successfully used to maintain pressure balance and subsequently helped to minimize flushing of ROS of the underpressured reservoirs (6).

Successful pressure coring of tight gas sand for gas and water saturation determination has recently been reported in the literature (18). Experience has shown excellent accuracy in ROS profile from pressure coring. However, ROS measurement using pressure core in developed fields requires expensive new drilled wells.

BACKFLOW TRACER TESTS

By looking at the residual oil away (about 10 to 40 feet) from the wellbore, the backflow tracer (or single-well tracer) test is able to measure the residual oil saturation of a relatively large volume of formation. The single-well tracer test can be run in cased wells.

Exxon has developed a single-well tracer technique (19). The technique consists of injecting primary tracer (e.g. ethyl acetate) bank into the test well. Then, the well is shut-in to permit the tracer to hydrolyze to form the second tracer (ethanol). Finally the well is produced and the concentration profiles of the two tracers are monitored. Because of the different partition coefficients in water-oil system, the two tracers will be back produced at a different velocity. The difference in arrival times is used to determine the ROS through specialized computer program (19) that simulate the tracer test. A ±2 to ±3 pore volume percent accuracy in ROS using the tracer method is confirmed by both laboratory results from pressure cores and mathematical model.

In this test procedure fluid dilution in the tested formation is a problem. The dilution happens when water from some zones in the formation that does not accept tracer injection becomes available for production. The dilution effect of produced tracer fluid has been studied in the computer model to successfully interpret the tracer test results (20). The single-well tracer test is unique in its large depth of investigation from the well-bore and the ability to control the depth of investigation. A multiple-tracer system (methyl acetate, ethyl acetate, and isopropyl acetate) was developed to measure average oil saturation over the different pore volume contacted by each of the acetate tracers (21).

Antunez and Brigham (22) developed a computer program to interpret the tracer test by using semi-analytic solutions and presented the results in a set of charts. In the program, a back calculating technique was implemented which allows fluids to continue moving, dispersing, adsorbing, and reacting during production. It was found that oil saturation and tracer partition coefficient have the greatest effect, dispersion and shut-in time have less effect, while flow rate and tracer reaction constant have no effect on the results. The program does not consider drift effects, formation stratification, dilution corrections, and any other mobility ratio but unity.

To help the design and analysis of tracer tests, experiments were conducted to determine how reservoir parameters (i.e. temperature, brine salinity, gas-oil ratio, tracer concentration and crude oil characteristics) affect tracer partition coefficients (23). A survey of 59 single-well tracer tests in 30 reservoirs was reported (24). The tracer design, injection profile, shut-in time, and limits on test conditions were examined to improve future tests.

WELL LOGGING

Logging procedures are the most widely used methods for obtaining reliable profiles of residual oil saturation for EOR field evaluation (25-33). During the last decade a special attention has been given to increase the degree of accuracy that usually involved injection of a fluid, as discussed later. Each logging technique has its own advantages and limitations. Since each log has its own limited investigation depth into the tested formation, a small mud filtrate invasion around the wellbore needs to be maintained to measure the real formation properties. Based on the wellbore conditions, two major groups of logs are employed in ROS measurements: open hole logs and cased hole logs.

Open Hole Logs

The resistivity log, nuclear magnetism log (NML), dielectric constant log, and electromagnetic propagation log are logs that need to be run in open holes. The resistivity log is widely available, relatively inexpensive, and it can be used for relatively deep investigation. The resistivity measured oil saturation (S_o) is determined based on the Archie's equation (34) as following:

$$S_o = 1 - {\frac{R_w \phi^{-m}}{R_t}}^{1/n} \qquad \text{Eq. 2}$$

where R_w = formation water resistivity
R_t = true formation resistivity
ϕ = fractional porosity
m = lithology exponent
n = saturation exponent

The dependence of oil saturation measurements on many formation parameters (ϕ, n, m) makes the uncertainty (± 10%) of conventional resistivity logs unacceptable for ROS determination. One way to reduce uncertainties in resistivity logging was suggested by Murphy, et al. (35), in 1973. After logging the formation (R_1 is measured), the oil could be removed by injecting chemicals. The formation could then be reinjected with formation brine and again logged for resistivity (R_2). With knowledge of the saturation exponent (n), ROS (S_{or}) could be calculated from

$$S_{or} = 1 - (R_2/R_1)^{1/n} \qquad \text{Eq. 3}$$

This technique is called log-inject-log (LIL) technique which could improve ROS measurements of resistivity log to an accuracy of ±2 to ±5 percent.

The nuclear magnetism log is the most accurate field technique for measuring ROS (3). This tool measures the residual oil directly after eliminating the water signals with paramagnetic ions. The accuracy of NML depends largely on the porosity estimate and the signal-to-noise ratio. Since NML measures oil saturation directly, this enables random errors to be minimized. Therefore, systematic errors can be determined and the ROS measurement can be corrected. Systematic errors in other techniques will never be eliminated because they cannot be measured. Systematic and random errors involved in determining ROS using different techniques will be discussed in detail later in this report. Very viscous oil does not contribute to the NML logged signal, therefore, the heavy oil saturation can be estimated by measuring the water NML signal (36). Accuracy and confidence in NML interpretation can be enhanced by processing the data to distinguish low level signals from noise. NML has 30 inches investigation depth into the formation (37). A low frequency NML was studied to improve the certainty for measuring ROS (38).

Dielectric constant (39) log is valuable to distinguish oil from water that is fresh or of unknown salinity. A fair to poor accuracy, ±6 percent and ±9 percent, of dielectric constant log measurement of ROS in the field was reported (40). In general, the depth of investigation of dielectric logging is 1.3 to 1.7 ft, thus the deeper invaded zone will impose a great effect on the measurement.

The electromagnetic propagation tool (EPT) (41,42) estimates ROS by measuring the travel time and the attenuation rate of an electromagnetic wave propagated through the formation at a frequency of 1.1 GHz. The EPT log is much less sensitive to salinity change than the resistivity log, making it valuable for use in mixed salinity environments, such as reservoirs under waterflood. The EPT log was reported (43) to have considerable success in evaluating ROS where conventional resistivity logs failed to provide consistent water saturation calculations with a shallow formation investigation depth of about 4 cm (4). The EPT log responses are strongly water saturation dependent, and the quantitative value of fluid mixtures and their effect in different rock matrices are not fully understood yet.

Cased Hole Logs

Cased hole logs, such as pulsed neutron capture log (PNC), carbon/oxygen log (C/O), and gamma ray log, are particularly valuable to measure ROS through metal casing (44).

Capture cross section (Σ) is a measure of the absorption of emitted thermal neutrons. PNC log measures the total capture cross section (Σ_t) of the formation which is the sum of the component cross sections of the rock matrix (Σ_{ma}) and the fluids (Σ_w water, and Σ_h hydrocarbon) within the pores of the rock. This may be expressed as (34).

$$\Sigma_t = \Sigma_{ma} (1 - \phi) + \Sigma_w (1 - S_o) \cdot \phi + \Sigma_h S_o \phi \qquad \text{Eq. 4}$$

To obtain the oil saturation (S_o) value, we need to measure the other variables including Σ_{ma}, which is the most difficult value to ascertain.

Because of its uncertainty in determining θ_{ma}, conventional PNC log has limited application in ROS measurement.

The log-inject-log waterflood technique (45) enhances the ROS measurement by injecting a contrasting-salinity water to eliminate the capture cross-section measurements of rock matrix and residual oil. Since this technique were developed, a series of studies were pursued to improve the capability of the tool measurements (46-50) and an extensive application in field ROS evaluations was performed with successful results (51-55). The log-inject-log with chemical strip techniques in PNC can further eliminate the uncertainty of porosity estimation, but this method is further complicated by additional required injection procedures and associated uncertainties of measurements (56) . The main advantage of the PNC method is its good to excellent accuracy of ROS obtained behind casing.

Carbon/Oxygen log determines ROS by measuring the relative amounts of certain elements, such as C/O and Ca/Si (59-62). Extensive improvements in tool designs (57,58) and interpretation methods in the last few years have made C/O log a practical alternative way of measuring ROS (63-66). Since the C/O ratio is insensitive to the chlorine content of borehole and/or formation water, for which PNC log was primarily measuring to yield formation water amount, the C/O log can be used in areas where PNC is not applicable. The C/O log has an investigation depth of approximately 8.5 inches into the formation, accordingly, the mud invasion effects need to be known and corrections made (64). To compute ROS from the C/O log, a simple linear equation was proposed (83) for homogenous formations of constant lithology and porosity as:

$$\mathrm{ROS} = \frac{(C/O)_{log} - (C/O)_w}{(C/O)_{oil} - (C/O)_w} \qquad \text{Eq. 5}$$

where $(C/O)_{log}$ = log measured carbon/oxygen ratio
$(C/O)_w$ = carbon/oxygen ratio of water saturated rock
$(C/O)_{oil}$ = carbon/oxygen ratio of oil saturated rock

An empirical cross-plotting approach was reported (60) to obtain better accuracy in interpreting C/O response. But this approach is limited to the application to sandstone reservoirs of good porosity. Log-inject-log technique has been used with the C/O log to measure ROS in several field applications in U.S. with good to excellent accuracy (44).

In the gamma-inject logging method (67), the natural gamma background is first logged, radioactive tracer solution is injected, and then, the well is logged again. A study (68) was reported to identify the associated errors of this method. It was found that the incomplete replacement of formation water by radioactive brine is the greatest single source of error. Since the gamma ray log has better vertical resolution than induction (resistivity) and PNC log to detect the formation thin layers, a better vertical ROS profile can be provided by gamma ray log (69).

GRAVITY LOGGING

A new method (70) was developed for determining ROS using wellbore gravity measurements in conjunction with the procedures followed in the log-inject-log operation. A first borehole gravity log survey is made after the formation has been flushed with a fluid having density greater than the formation water density. The formation is then flushed with a fluid having a density greater than that of the formation water and differing from the density of the first fluid injections. A second borehole gravity survey is then done, and the formation porosity is also measured. From the density, borehole gravity and porosity factors, the water and oil saturation are determined. An U.S. patent was granted for this method (70). No field tests have been reported to date to evaluate the accuracy in ROS using this LIL gravity logging method.

Another new gravimetric logging method (71) has been developed to measure ROS. In this method, a gravimetric logging tool is traversed in the borehole to measure the earth's gravity over a radius of 50 feet at spaced locations. The gravitational gradient of the formation then is determined by comparison of the measurements of the earth's gravity at successive locations. The formation bulk density is calculated from the variations in the gravitational gradient at these locations. From measurements of the matrix density, water density, oil density, fractional porosity of the formation, the bulk density is calculated and then the ROS is determined. By using a combination of gravity log and resistivity log (91), a simultaneous solution of the bulk density and Archie's equation (34) can provide water saturation and porosity of the tested formation. The ROS is then obtained by subtracting the water solution from unity.

MATERIAL BALANCE AND WELL TESTING METHODS

Material balance calculations are an average estimation of the remaining oil content in the field after subtracting produced oil volume from the initial estimates of the reservoir. The volumetric or material balance equations are used to estimate initial oil in place. The ultimate recoverable oil can be predicted before a residual oil saturation is reached by (i) production decline plots (72,73), (ii) material balance equation (74), or (iii) computer reservoir simulations (75). Then, ROS can be calculated. To predict the recoverable oil amount, a substantial amount of production history is necessary. The principal problem with the use of material balance calculations is in determining the proper reservoir data, which determine the initial oil in place, reservoir performance and the accuracy of ROS. In general, the material balance methods can lead to inaccuracies because of two important respects: (i) errors in basic volumetric data of the reservoir are compounded in the final calculated value of ROS, and (ii) it yields one average value of ROS. Theoretically equivalent to material balance methods, computer simulation is found useful to provide areal distribution of ROS.

Well testing methods require the estimated effective permeability from the transient test and a relative permeability curve of the reservoir core from the laboratory. Since the oil/water relative permeability is a function of water (or oil) saturation, the oil saturation or ROS can then be estimated from the effective permeabilities using well testing methods (33,76). In addition, oil saturation (including ROS) can be estimated by using the total compressibility computed from multiple-well testing methods (76-78): interference or pulse testing. This compressibility method is not acceptable if there is free gas saturation in the formation. The oil saturation accuracy of this method is considered poor because of the difficulty to get an accurate pore-volume compressibility. Another method for estimating oil saturation based on the relative permeability values is the water-oil production ratio method (76,79). In this method, a trial-and-error graphical procedure (80) is used to determine oil saturation within a reasonable accuracy based on the fractional flow equation and production data. The estimated oil, water, and gas saturation from each well can then be mapped to obtain the saturation distribution in the field. Because of the characteristics of pressure transient tests, the reservoir oil amount (or saturation) can also be estimated from pressure changes in well tests, e.g. pressure build-up test (81,82). Similar to the material balance methods, only one average oil saturation value can be obtained from one particular well transient test.

INTERWELL ROS MEASUREMENTS

A method was developed in 1981 to measure directly the multiple-well oil saturation distribution (5). This method measures the formation resistivity by generating electrical current and measuring potentials among pairs of open hole wells geometrically distributed throughout the oil field. Poisson's equation is used to develop fluid saturation distributions from the electrical current and potential measurements. A patent (5) was granted to U. S. Department of Energy for this interwell ROS method but no field tests have been reported.

Cooke, Jr. (7) developed a well-to-well tracer test to measure the interwell ROS in 1971. In Cooke's method, two or more tracers having different partition coefficients between oil and water phases are injected. As the tracer fluid moves through the reservoir, one tracer is retarded more than the other. The average interwell ROS can be determined by monitoring the degree of separation of the tracers at the observation well. Another method developed by Jones and Parson (8) in 1974 can be used to measure the average oil saturation (including residual and mobil oil) between two wells. This method determines oil saturation by injecting into the reservoir a displacing fluid to displace both water and oil toward the observation well, and measuring the arrival time of the oil-water bank by detecting a change of bottom hole pressure. No field tests of the above two methods have been reported, probably because of the long time required to move the injected fluid from one well to another well.

Advantages and disadvantages of each ROS determination technique are summarized in table 1.

TABLE 1. - Advantages and disadvantages of ROS methods

	Advantages	**Disadvantages**
Coring		
Conventional	widely available	difficult to get in situ ROS
Pressure	excellent accuracy	(1) new well required (2) poor to fair core recovery
Tracer Test	(1) fair to excellent accuracy (2) large reservoir vol. measured (3) measured vol can be controlled	(1) computer program required for good ROS interpretation (2) for relatively homogenous formation only (3) one average ROS value only
Logging		
Resistivity		
Conventional	widely available, large investigation radius	poor accuracy
LIL*	excellent accuracy	
NML		
Conventional		poor accuracy
Inject-log	direct ROS measurement, excellent accuracy	
Dielectric Const.		
Conventional	can be run under various formation salinity	poor accuracy
EPT		
Conventional	can be run under various formation salinity	(1) poor accuracy (2) short investigation depth
PNC		
Conventional		poor accuracy
LIL (water)	excellent accuracy	
LIL (chemical)	porosity not required	3 injections required
LIL (chlorin. oil)	movable oil saturation can be measured	4 injections required

TABLE 1. - Advantages and disadvantages of ROS methods (continued)

C/O		
Conventional	can be run under various formation salinity	questionable accuracy
LIL (water)	can be run under various formation salinity, excellent accuracy	
LIL (chemical)	can be run under various formation salinity, porosity not required	3 injections required
Gamma Ray log		
Conventional	good vertical resolution, wide available	questionable accuracy
LIL (water/chem.)		hard to eliminate wellbore radioactivity before 2nd log run
Gravity		
Conventional	large investigation radius	questionable accuracy
LIL	large investigation radius	questionable accuracy
Material Balance	simple calculation	(1) required accurate reservoir/production data (2) poor accuracy
Well Test Methods		
Effective Permeability		poor accuracy
Total Compressibility		poor accuracy
Water-Oil Ratio	simple calculation	poor accuracy
Production Simulation	provide areal ROS	poor accuracy
Interwell ROS		
Resistivity	interwell ROS	field test and improvement required
Well-to-Well Tracer	interwell ROS	long time required
Oil Displacement	interwell ROS	long time required

* Log-inject-log

SYSTEMATIC AND RANDOM ERRORS

The measured errors of ROS determinations are composed of two parts: systematic errors and random errors. The general problems and analysis methods involved in ROS determinations are studied here.

SYSTEMATIC ERRORS

Systematic errors are unidirectional in magnitude and caused by poor measurement conditions. Systematic errors in ROS can be caused by problems of contamination, heterogeneity, miscalibration, duplication, and wellbore interference. The way these factors affect the ROS measurement is described below:

(i) Contamination (9) is a change of the reservoir fluid content or wellbore fluid distribution due to drilling fluids or production of fluids from the reservoir. Contamination can change oil saturation, alter rock wettability, cause chemical reaction with the rock, and deposit suspended mud solid. Therefore, contamination needs to be avoided to obtain reliable ROS measurement. As an example, the oil saturation estimated from material balance method must account for water influx or loss during oil production.

(ii) The estimated ROS assuming a homogenous reservoir model or wellbore model will deviate from the real ROS value which exists in a real heterogeneous formation. Some heterogeneity problems is caused by: a) injection procedures (e.g. in tracer tests or log-inject-log techniques) may not be able to completely displace reservoir fluid around the wellbore as desired (32), b) presence of surrounding beds especially for thin zone formation that effect log responses, c) biased sample selection that may occur in cores d) the fact that complex reservoir models are not available to correct the formation heterogeneity as in tracer test interpretations, e) a pseudo-scientific method, used to average the rock and fluid properties. These problems make measured ROS values deviate substantially from actual ROS values.

(iii) Miscalibration (34) occurs when the interpretation model used is different from the real condition of the reservoir or wellbore. The assumptions involved in the interpretation model must be known to avoid serious errors of extrapolation.

(iv) Duplication of reservoir processes in the laboratory (9) is difficult, because *in situ* conditions are not known with certainty. Wrong assumptions about reservoir conditions can produce systematic errors in laboratory measurements or data interpretation.

(v) Wellbore interference (34,49,57) is caused by the presence of the wellbore, casing, cement, or formation damage which can affect logging values. Logging tool correction factors are often empirically derived and may not fit specific conditions.

Systematic errors can contribute to erroneous ROS calculation no matter how carefully the measurements are obtained. Therefore, a ROS technique which has minimum systematic errors should be selected.

RANDOM ERRORS

Random errors are deviations from the best estimate measurement which can quantify the confidence in a particular result. The causes of random errors are: (i) round-off errors after a significant digit, (ii) averaging empirical data to develop general relationship, (iii) averaging raw data for calculations, and (iv) repeatability of measurements.

To evaluate the random errors of ROS, Monte Carlo analysis (53) and an error equation (84) are generally used. The error equation has an advantage due to its simplicity to use, as illustrated by the following example. Assume that ROS and porosity (ϕ), as well as their standard deviations (ΔROS and $\Delta\phi$) are known. The random error, or uncertainty of (ROS . ϕ) product is given by:

$$\Delta(ROS\ .\ \phi) = \left[\left(\frac{\partial(ROS\ .\ \phi)}{\partial\phi}\right)^2 .\ \Delta\phi^2 + \left(\frac{\partial(ROS\ .\phi)}{\partial\ ROS}\right)^2 .\ \Delta\ ROS^2\right)^{\frac{1}{2}}$$

$$= (ROS^2\ .\ \Delta\phi^2 + \phi^2\ .\ \Delta ROS^2)^{\frac{1}{2}} \qquad \text{Eq. 6}$$

As shown in the above example, the more complex (more parameters) the ROS equation becomes, the higher random error of ROS value is expected. Therefore, the ROS random errors of direct measurements (e.g. Nuclear Magnetic log (NML), which measures oil saturation directly) tend to be small, but indirect ROS measurements can produce significant uncertainties which happen to most ROS logging methods. Among the components of ROS uncertainties, the uncertainty of porosity measurement (1) is a major contributor to the random error. So, the most accurate method for porosity should be considered to get an accurate ROS value. Another source of random errors is the introduction of an empirical relationship, such as a rock property to log response relation. The log-inject-log procedures (35) benefit because the number of parameters in the ROS determination equation is reduced.

Monte Carlo simulation studies can be used to investigate the uncertainty (random error) of ROS values (53). A mathematical model is developed in a Monte Carlo simulation technique to describe the measuring operation. The model is then used to perform a number of repeated trials. The uncertainty derived in such log-derived ROS values will increase with a decrease in porosity and oil saturation.

ERRORS AND UNCERTAINTIES OF ROS METHODS

Both random and systematic errors depend on the technique used, fluid and rock properties, and mechanical conditions under which ROS is determined. Some of these conditions produce systematic errors which can make the calculated ROS erroneous. Others might affect the uncertainty in the ROS obtained. An analysis of errors and uncertainties for determining ROS involved in single-well and interwell methods are discussed as follows:

SINGLE-WELL ROS METHODS

Core Analysis

The ROS obtained from core analysis is the only direct measurement of *in situ* formation oil saturation. The standard laboratory analysis procedures for saturation determination are well documented (9). Often, the economics of a particular well program determines the degree of sophistication in analysis technique utilized. However, the core-derived ROS suffers from the systematic errors of coring and handling operations. Although the random errors in core analysis for ROS are small, the systematic errors are large and cannot be entirely eliminated.

The ROS measured from the conventional coring is much less than its *in situ* value (9) because: (i) flushing of the core by mud filtrate during coring operations, (ii) oil displacement by gas expansion when pressure is released, (iii) oil shrinkage by the gas evolution and the temperature reduction. Hence the core analysis data obtained are "minimum" residual oil saturations. Various correction factors have been obtained for the ROS from conventional coring, but the correction factors can only be considered as qualitative guides.

Pressure coring (16) avoids the gas expansion and oil shrinkage problem in ROS determinations. The average ROS obtained from pressure coring rarely exceeds the ROS measured by logging techniques. It is apparent that flushing of oil from the cores by drilling mud filtrate is a significant problem. Non-invading drilling fluids such as foam (15) appear to be an ideal alternative drilling fluid for ROS determination in the pressure coring.

Backflow Tracer Test

The ROS measurement determined by the backflow tracer test (19) is about equal to or less than the ROS measurement determined by other methods (1,4). This is due to the biased measurement of the oil saturation in the more permeable part of the formation so yields a permeability-weighted average value of ROS. If this ROS value is close to the values determined by other methods, it indicates that the tested formation is relatively homogenous. If tracer-derived ROS is much less than the values determined by other methods, more information is necessary for proper interpretation.

Heterogeneous formations are suitable for backflow tracer test only when reservoir heterogeneities are taken into account in the ROS interpretation program. The potential heterogeneities include drift effects, stratification, dilution, multiple-phase flow, mobility ratio different than one, fractures, and rock properties, etc. (22).

The tracer partition coefficient has a great effect in the ROS determination. However, the tracer partition coefficient varies with formation temperature, brine salinity, gas-oil ratio, tracer concentration and crude oil characteristics (23). The control or understanding of these reservoir parameters is then important to derive ROS values. Effects on the injection of brine on the dissolved gas content of residual oil are also important. When a brine solution is injected, it will generally strip the residual oil of part of its dissolved gas. Then, the volume of the oil and the partition coefficient are going to be altered. To obtain an accurate ROS measurement from tracer test, additional equations to describe gas stripping need to be incorporated in the test interpretation.Because of the large investigation depth of backflow tracer test, it is the best method to determine ROS of a washed out or disturbed zone around the borehole. Tracer test can be run in cased hole but fails to provide vertical ROS profile.

Well Logging

Conventional Logging

None of the conventional logging methods provide "accepted" accuracy in ROS determinations as shown in table 2, due to systematic and random errors. These methods cannot measure directly the amount of oil in place. They determine ROS indirectly by measuring secondary properties. For example, lithology exponent (m) and saturation exponent (n) need to be determined in resistivity log (1,34) technique before an accurate ROS value can be derived. Unfortunately, estimated m and n values are usually not accurate enough for ROS measurements. In conventional Pulse Neutron Capture log (1,34), the capture cross section value of formation matrix ($^{\Sigma}$ma) is required to derive the ROS value. Furthermore, $^{\Sigma}$ma must be estimated from knowledge of lithology which is the most difficult value to ascertain. For conventional NML, the free fluid indices of both oil and water need to be known to determine ROS. In carbon/oxygen log, ROS is determined by the radiations from oil, water, and rock. The poor accuracy (±10 percent or more) (1) makes the conventional logging methods to have limited applications in ROS determinations.

Gravity log method (70,71) is a new technique to measure *in situ* ROS, but no field measurements have been reported. Field tests are important to evaluate the accuracy of measured ROS or improve the hidden problems.

Log-Inject-Log Technique

Log-inject-log techniques (35) are designed to reduce the uncertainties of ROS measurements in conventional logging methods. For instance, m value in resistivity log, $^{\Sigma}$ma in PNC log, and free fluid index of water in NML, are not required to estimate ROS using log-inject-log techniques. The ROS accuracy is improved from poor, in conventional loggings, to good to excellent (±2%) (1), in log-inject-log techniques. Comparing all logging methods, the NML inject-log (36,37) appears to have the best ROS accuracy since it measures directly the oil amount in pore space around the wellbore. The disadvantage of this technique is that it has to be run in open holes. Log-inject-log techniques are also

TABLE 2. - Limitations and accuracies of ROS methods

	Cased Well	Vertical ROS Profile	Field Tested	Accuracy*	Investigation Depth
Coring					
Conventional	cut while drilling hole	Yes	Yes	poor	< 10"
Pressure	cut while drilling hole	Yes	Yes	good to excellent	< 10"
Tracer Test	Yes	No	Yes	fair to excellent	15-40 ft
Logging					
Resistivity					
Conventional	No	Yes	Yes	poor	2'-20'
LIL**	No	Yes	Yes	good to excellent	2'-20'
NML					
Conventional	No	Yes	Yes	poor	2.5'
Inject-log	No	Yes	Yes	excellent	2.5'
Dielectric Const					
Conventional	No	Yes	Yes	poor to fair	1.3-1.7'
EPT					
Conventional	No	Yes	Yes	limited exp.	2"
PNC					
Conventional	Yes	Yes	Yes	fair	7-24"
LIL (water)	Yes	Yes	Yes	good/excellent	7-24"
LIL (chemical)	Yes	Yes	limited exp.	limited exp.	7-24"
LIL (chlorin. oil)	Yes	Yes	limited exp.	limited exp.	7-24"

TABLE 2. - Limitations and accuracies of ROS methods (continued)

C/O					
Conventional	Yes	Yes	limited exp.	fair/good	8.5"
LIL (water)	Yes	Yes	limited exp.	good/excellent	8.5"
LIL (chemical)	Yes	Yes	limited exp.	limited exp.	8.5"
Gamma Ray Log					
Conventional	Yes	Yes	limited exp.	could be excell.	2-4"
LIL (water/chem)	Yes	Yes	No	could be excell.	2-4"
Gravity					
Conventional	Yes	Yes	No	-	50'
LIL	Yes	Yes	No	-	50'
Material Balance	Yes	No	Yes	poor	Whole reservoir
Well Test Methods					
Effective Permeability	Yes	No	Yes	poor to fair	Well drainage area
Total Compressibility	Yes	No	Yes	poor	Well-to-well distance
Water-Oil Ratio	Yes	No	Yes	poor to fair	Well drainage area
Production Simulation	Yes	No	Yes	poor	Whole reservoir
Interwell ROS					
Resistivity	No	No	No	-	well to well distance
Well-to-well Tracer	Yes	No	limited exp.	-	well to well distance
Oil Displacement	Yes	No	No	-	well to well distance

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* Expected accuracy (one standard deviation fractional pore volume) for rocks that have porosities greater than 0.25. If rock porosity is lower than 0.25, the expected accuracy will be poorer than it is shown in the table.

Excellent - less than 2%; Good - 2% to 4%; Fair - 4% to 6%; Poor - greater than 6%

** Log-inject-log

successful in the application to resistivity log (1,44), PNC log (44,85), and C/O log (44). No tests have been reported for LIL applied to Gamma ray log, dielectric constant log, and electromagnetic propagation log. Gamma ray-LIL appears to have some difficulties accounting for or eliminating the radioactivity from the borehole. A summary of the limitations and accuracies of these ROS determination techniques are presented on table 2.

The LIL technique is straightforward in theory, but complex in practice. Accurate ROS measurements require accurate porosity, brine analysis, good controls of wellbore condition and injection procedures. The general problems associated with LIL processes are described below:

(i) The injected solution might not be able to displace all the in-place formation brine causing incomplete displacement. A modification to the conventional LIL procedure was reported to allow corrections for incomplete brine displacement (86). In this modified LIL procedure, formation brine is injected both before and after the injection of the alternate brine. PNC logs are run before and after each injection. The first injection of formation brine is used to determine the fraction (if any) of removable oil. The injection of the alternate brine is used as in the conventional LIL to determine ROS. Log readings after the initial and final injections of formation brine are compared to establish the brine displacement efficiency *in situ*. ROS values are adjusted to account for the incomplete displacement.

(ii) In water-wet reservoirs, the injected fluid appears to displace the formation brine in two separate regions distinguishable by different rates of displacement.

(iii) Paramagnetic metal ions injected before NML measurement might be adsorbed by the rock. Injecting less adsorbed metal ions, or metal ions in a chelated form appears to be a good alternative.

(iv) In LIL-chemical techniques, chemicals are injected to strip the residual oil away from the borehole. Then the formation is reinjected with formation brine or other fluids before being logged the second time. It appears that the injected formation brine or other fluids does not fill the void space left by the displaced oil.

(v) In LIL gamma ray log techniques, injection could be made with radioactive water instead of a contrast of water salinity. This method hasn't been field tested because of the difficulty to account for, or eliminate, radioactivity from the borehole.

The required conditions of reservoir, logging devices, well conditions, and injection have been studied for LIL in ROS determinations (44). Ideal reservoir for LIL is a uniform reservoir with high porosity, high ROS, zero gas saturation, and good permeability. Fractured reservoirs need to be avoided because the fracture is detrimental to sweep efficiency of injection. Logging devices should be properly functioning and calibrated instruments. Logging devices which has multiple repeat runs (6 to 10) at proper logging speed should be selected to reduce random errors. To facilitate control of proper injection procedures, a short single zone rather than a long zone should be evaluated by LIL. Newly perforated intervals are preferred to zones with old perforations to avoid formation slumping, sand production, and resulting drastic porosity changes. To obtain a successful injection, proper control of injection rates and pressure (versus fracture gradient) are important.

Material Balance Calculation

In this technique, the ROS is determined by using the material balance equation (74). This equation has four unknowns: (i) oil-in-place, (ii) gas cap size, (iii) rock compressibility, and (iv) aquifer geometry. In most cases, it is unlikely to provide an accurate estimate of oil-in-place initially. Therefore, the obtained oil saturation after subtraction of cumulative oil production is not accurate enough. A big difficulty presented when using the material balance equation is to accurately segregate the expansion effects of oil and gas from the expansion effects of rock and water in the aquifer. These effects are associated with pressure changes. Hence, the ROS accuracy of material balance method is considered to be low (1). Also, material balance method derives an average value of ROS for an entire oil field and not value for site of specific interest.

The ROS estimated from history matching reservoir production by computer simulation, suffers from the uncertainties of initial reservoir parameters required in the computer model. Although the calculated ROS is not accurate, it provides a good prediction of areal ROS distribution of the formation.

Well Testing

Data from single-well transient tests, such as pressure buildup and drawdown tests, can be used with core-analysis relative permeability curve to estimate oil saturation *in situ*. Multiple-well (interference or pulse) transient tests also can be used to estimate oil saturations. Multiple-well tests provide two independent oil saturation measurements, one from the permeability and one from the compressibility computed from the test. The oil saturation estimated from pressure transient test is an overall average for the influence region of the tested well. These techniques are based on the assumption (87) that the entire tested interval is homogenous, isotropic, and uniform in fluid saturation distribution. Theoretically equivalent to well transient tests, oil, water, and gas production data also can be used with relative permeability curves to estimate oil saturation around a well. The uncertainties of different well testing methods for determining oil saturation are discussed below:

(i) Effective Permeability Method: it has much greater uncertainty in ROS estimation than the LIL tests or other direct measurements. The uncertainties relate primary interpretation of the pressure transient tests (88) and how to average the core data to an average effective permeability of the whole formation.

(ii) Total Compressibility Method (1,88): the variation of compressibility with ROS changes is not sensitive enough to provide accurate ROS values. Also, the variation in calculated compressibilities may be due to large reservoir heterogeneity, rather than to variation in ROS. In general, the method based on compressibility is less accurate than the method based on relative permeability.

(iii) Water-Oil Ratio: this method is more commonly used than the previous two methods because in many cases, the estimation of oil saturations are easier to make. This is a useful tool to evaluate the reservoir performance (72). However, this method does not provide information about wellbore damage and fluid permeabilities that can be obtained from transient-test data.

INTERWELL ROS METHOD

The success of a resistivity method (5) in measuring interwell ROS depends on how well the apparent resistivity can be measured between two wells. The electrical current generated between two wells must be large enough for the resistivity measurement. Therefore, a sensitive amperemeter and a strong generated current are important to obtain an accurate interwell ROS. In the resistivity method, a ROS distribution can be calculated through a mathematical model.

To measure interwell ROS, both well-to-well tracer method (6) and oil displacement method (7) require a long time to move a tracer or chemical fluid from one well to another well, in most cases. In addition, only an average interwell ROS between two tested wells can be measured, not a ROS distribution in the field.

The accuracy of all these methods (5-7) to measure interwell ROS is questionable, because no field tests have been reported. Improvements in instrumentation and interpretation technique appear to be important.

SUGGESTED PROCEDURES

A general guide to decide the best ROS technique under certain wellbore or reservoir conditions is presented by Wyman (2). This guide is extended in this study by incorporating carbon/oxygen log as shown in table 3. The techniques chosen to determine ROS should be based on wellbore conditions. For instance, NML has the best accuracy for determining ROS in open holes. Pressure coring is always recommended for new holes. Backflow tracer test becomes the only reliable method to measure formation ROS from a cased hole which has washed out or disturbed zone around bore-hole. And well testing and simulation methods are considered only as supplementary measurements of ROS today. To assure good results, it is recommended to determine ROS from one well twice (27), using each time a different method of first choice in table 3. The repeat measurements (37) (e.g. 6 to 10 times) of logging the same formation could reduce the random errors.

To determine interwell ROS, well-to-well tracer tests are recommended only for formations of high permeabilities and short well distances.

TABLE 3. - Suggested procedures for ROS determination*

Borehole Condition	Cores		Log-Inject-Log				Backflow Tracer	Well Testing or simulation
	Conv.	press.	Resist.	NML	PNC	C/O		
Open Hole								
New Hole		1		1	2		2	3
Old Hole			2	1	1		2	3
Washed Out (no cores)			2				1	3
Cased Hole								
Previously Cored	2				1		2	3
Not Cored					1	2	1	3
Washed Out or Disturbed Zone Around Borehole							1	3

* 1: First Choice
2: Second Choice or Backup
3: Supplementary Measurement

IMPROVEMENTS OF ROS METHODS

Each ROS technique has its own advantages, limitations, and discrepancies. Because of the high precision required, improvements in ROS determinations are essential to the success of an enhanced oil recovery process. The possible improvements for determining ROS are discussed below:

SINGLE-WELL ROS METHODS

Core Analysis

As discussed above, flushing of oil from cores by drilling mud filtrate is a significant problem for pressure coring. Pressure over-balance during coring operation results in flushing of core, thereby altering the core saturations. Hence, development of non-invading drilling fluid systems for pressure coring in pressure depleted reservoirs appears to be important. The low density of foam mud makes it as an ideal candidate of the non-invading drilling fluid. However, there are many elements such as foam degradation and nonlinear pressure gradients which can alter foam behavior during coring operations. It is also necessary to study the bottom hole pressure behavior resulting from variations in foam composition and annular backpressure during coring operations.

The existing equipment of pressure coring continues to show improved performance with increasing usage. Several improvements in core barrel technique and service unit capabilities can be accomplished. To improve the overall capability and reliability of pressure coring, work on the core barrel needs to be done to recover larger core under higher pressure and higher temperatures. Some of possible new developments (16) are listed below:

Core Barrel

1) larger core diameter to 3.5 inches
2) higher pressure to 10,000 psi
3) higher temperature to 400°F
4) oriented core option
5) special adaptations for unconsolidated formations, and
6) special bit designs (special materials or geometries) for special formations

Service Unit

1) increase pressure capability of surface facilities
2) improve non-invading and flushing fluids, and
3) investigate the present freezing practices.

Backflow Tracer Test

The accuracy of the backflow tracer test for measuring ROS depends on the interpretation program used. A public available program was developed by Antunez and Brigham (22) to interpret the tracer test. But this program does not consider drift effects, formation stratification, dilution problems, and any other mobility ratio but unity. To obtain an accurate ROS measurement in a non-homogenous reservoir using tracer test, the current interpretation program needs to be improved by considering these reservoir heterogeneities.

Effects on the injection of brine on the dissolved gas content of residual oil are also important. When a brine solution is injected, it will generally strip the residual oil of part of its dissolved gas. Then the volume of the oil and the partition coefficient of tracers are going to be altered. To obtain an accurate ROS measurement from tracer test, additional equations to describe gas stripping need to be incorporated in the computer model.

Well Logging

Conventional Logging

Logging tools respond to changes in elemental concentrations in the formation environment in addition to signals form the oil. To obtain accurate formation responses, the presence of elements in the borehole, casing, and cement must be corrected. Also, the relative effects of elements in these regions need to be determined through additional laboratory and field experiments. For example, responses of logging tools to lithology, clay compositions, and water salinity are important to the interpretations of resistivity log, PNC log, and C/O log. Laboratory measurements can provide a matrix characterization of the tool's response to these environmental variables. Mathematical modeling of complex formations and the development of more sophisticated interpretation models will provide even more accurate formation descriptions under a wide range of field conditions.

Most published studies on C/O log provide only a semi-quantitative analysis of ROS with little theoretical basis. The empirical cross-plotting approach (60) has better certainty in interpreting C/O response. But, the constraint upon this approach is that porosity is assumed to be constant to apply a cross-plot. This constraint makes this cross-plotting approach applicable only to non-carbonate reservoirs of good porosity. To extend the capability of cross-plotting method to carbonate reservoirs, it is required to improve the C/O log interpretation by considering porosity variation effect.

Log-Inject-Log Technique

The LIL technique can improve ROS measurements of resistivity log and other logs to an accuracy of ±2 to ± 5 percent. LIL techniques have been applied to resistivity log, PNC log, and C/O log, but not to dielectric constant log and electromagnetic propagation log. The application of LIL technique to dielectric constant log and electromagnetic propagation log appear to be helpful in eliminating the uncertainties of measuring the wave propagation time through the formation matrix.

The inject-log technique makes NML the most accurate logging method for measuring ROS. This is accomplished by injecting water containing paramagnetic ions into the formation. The paramagnetic ions rapidly dampen any signal from the water, therefore only the signal from oil (I_O) is measured. With known formation porosity (ϕ), ROS can be derived as:

$$ROS = I_O/\phi \qquad \text{Eq. 7}$$

As observed from the above equation, the accuracy of the NML inject-log method depends largely on the certainty of formation porosity. The following LIL method is proposed with NML to eliminate the uncertainty of formation porosity for measuring ROS. After logging of an oil-bearing zone with a NML (I_{t1}), a water solution containing paramagnetic ions is injected to dampen the signal from the water. Then the formation is logged again (I_{t2}). The total NML signal (I_t) of the formation is the sum of the component signal of oil

(I_o) and water (I_w). So, NML signals measured before and after injection can be expressed as:

$$I_{t1} = I_o + I_w = a(ROS)\phi + b(1-ROS)\phi \qquad \text{Eq. 8}$$

$$I_{t2} = I_o = a(ROS)\phi \qquad \text{Eq. 9}$$

where a, b are induced magnetization measuring constants for oil and water, respectively.

Formation porosity can be calculated by subtracting equation 9 from equation 8:

$$\phi = \frac{I_{t1} - I_{t2}}{b(1 - ROS)} \qquad \text{Eq. 10}$$

The ROS can be derived by substituting equation 10 into equation 9 as:

$$ROS = \frac{b\ I_{t2}}{(I_{t1}-I_{t2}) + b\ I_{t2}} \qquad \text{Eq. 11}$$

Material Balance Calculation

Improvements of formation characterization are critical to the success for measuring ROS using material balance calculations. The stochastic approach and understanding of geological influence appear to be a way to characterize the formation structure. Stochastic methods have been used to characterize aquifers in hydrology. Stochastic models provide a statistical estimation of formation properties between wells based on geological informations and well data. Geological variables such as dispositional history, lithification mechanism, pore habitat, and migration paths will provide significant help to establish the reservoir model. Physical geological factors which determine the oil saturation and movement need to be identified, and methods need to be developed to quantify these factors in terms of oil saturation. Once reliable areal variations of formation porosity and initial oil saturation are obtained, a good oil saturation can immediately be calculated using material balance equation.

The remaining oil saturation in various parts of the reservoir after waterflooding can be predicted with a reasonable degree of accuracy using computer simulation. However, a comprehensive reservoir model and an accurate reservoir description are essential to the success of this simulation method. To obtain accurate areal distributions of remaining oil after certain production using computer simulation, we need to develop more sophisticated programs to take into account formation heterogeneities.

Well Testing

Analysis techniques of transient pressure testing need to be further developed to measure permeability for fractured formation, tight formation, and formations with significant wellbore damage. Computer programs appear to be useful to interpret the well testing of heterogenous formations including layered reservoirs. Computer programs should be developed to interpret the anisotropic heterogeneity from interference and pulse testings.

A representative relative permeability curve of the formation is critical to the improvement for determining ROS using well testing method. The reservoir characterization is important to obtain this goal from core analysis data. The understanding of formation physical geology may help people to derive a representative relative permeability curve.

INTERWELL ROS METHOD

The success of a resistivity method in measuring interwell ROS depends largely on the apparent resistivity across the formation measured between two wells. The electrical current generated between two wells must be large enough for the resistivity measurement. Therefore, developments of a sensitive amperemeter and a method to generate strong currents are important to make this resistivity method feasible for field ROS measurements.

In a well-to-well tracer test, a substantial length of time is often required to move tracers form one well to another. This limits field application of well-to-well tracer test. A computer program is developed by Abbaszadeh (89,90) to study reservoir stratification from well-to-well tracer tests. The development of a comprehensive computer program could extend this tracer tests to a heterogenous reservoir and determine ROS vertical distributions and reservoir heterogeneities form tracer test data.

RECOMMENDATION

The amount of the residual oil left behind is one of the critical parameters to the selection of an enhanced oil recovery process. Each ROS technique has its own advantages, limitations, and discrepancies. The errors and uncertainties involved in different ROS methods are studied in this report. Although advances on these measurement methods have been obtained in the past, there are still several aspects left for improvements in both instrumentation and data interpretation. Additional research and development of ROS requires the following:

(i) Pressure coring:

- a. Work on the core barrel to yield higher temperature, higher pressure, large core diameter, oriented core option, and special adaptations for unconsolidated formations.
- b. Work on the service unit to improve non-invading and non-flushing fluids under higher pressure conditions.

(ii) Backflow tracer test:

- a. Improve the current test interpretation program by considering drift effects, stratification, dilution corrections, mobilities other than unity, two-phase flow, fracture effects, and coexistence of mobil oil.
- b. Develop new tracers (e.g. radioactive tracers) with more versatility

(iii) Well logging:

- a. Get additional experimental logging data such as responses to lithology, salinity, and the presence of elements in the borehole, casing and cement. Develop more sophisticated interpretation models to reduce wellbore effects, increase signal-noise ratio, and produce more accurate formation description for PNC, C/O, NML, gamma ray, electromagnetic propagation and dielectric constant logs.
- b. Improve the C/O log interpretation by considering porosity variation effect in the "cross-plotting approach" (60) for carbonate formation.
- c. Apply log-inject-log technique in NML to eliminate the uncertainty of formation porosity.
- d. Apply log-inject-log technique in dielectric constant log and electromagnetic propagation log to eliminate the uncertainties of measuring the wave propagation time through the formation matrix.

e. Improve injection procedure to get a complete sweep over the investigation area in the log-inject-log technique.

(iv) Material balance calculation:

Identify and quantify physical geological factors which influence the oil saturation. Develop a stochastic model of reservoirs to characterize the oil saturation in the field.

(v) Simulation program:

Develop more sophisticated simulation programs to take into account the permeability distribution and other formation heterogeneities.

(vi) Well testing:

Develop the analysis technique of pressure transient testing using computer programs. Obtain a representative relative permeability curve from cores through reservoir characterization approach.

(vii) Interwell ROS measurement:

a. Improve the electrical measurements and the current generation methods to make the interwell ROS determination by the resistivity method feasible in field tests.

b. Develop programs to study a well-to-well tracer test for determining interwell ROS and formation heterogeneity at the same time.

(viii) Correlation:

a. Correlate various logging-coring and tracer test results against each other.

b. Correlate ROS with rock-fluid properties of reservoirs.

CONCLUSIONS

1) Pressure coring is an accurate method of ROS determination. However, cost of drilling new well makes it prohibitive. Accuracy of this method is in the range of ±2 to ±4 percent.

2) Single-well tracer is an excellent method of ROS determination with large depth of investigation and accuracy of ±2 to ±3 percent. It can also be run in cased hole and only one average value of ROS is obtained.

3) None of the conventional logging methods provide required accuracy in ROS determinations. Log-inject-log techniques are designed to reduce the

uncertainties of ROS measurements in conventional logging methods. These techniques provide good to excellent accuracy in ROS measurement. NML inject-log has the best accuracy among all logging techniques but it has to be run in the open hole.

4) Gravity logging method has been developed but more field tasks are required for its evaluation.

5) Material balance, transient pressure testing, and production testing methods of ROS estimations provide average values of ROS and are not generally considered reliable.

6) Interwell ROS determination methods such as resistivity and tracer methods have been considered but not proven.

7) More accurate ROS determination requires two different tools to be run several times.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the financial support of the United States Department of Energy which made this research possible. This work was conducted as a part of the Cooperative Research Contract Number DE-FC01-83FE60149 managed by the Bartlesville Project Office. Grateful thanks are also due M. M. Honarpour for his recommendations and assistance in preparing this report.

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*U.S. GOVERNMENT PRINTING OFFICE: 1986-0-659-031/40018