LOG-DERIVED RESIDUAL OIL SATURATION
A Look at Basic Concepts and Field Case Studies

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ABSTRACT

Log-derived determination of residual oil saturation (ROS) for enhanced oil recovery projects requires accurate and reliable techniques. Therefore, special considerations have to be given to both the logging operation and associated interpretation methods.

Since the statistical uncertainty limits of conventional open - and cased - hole logging techniques are not sufficient for reliable ROS values, a key parameter in the evaluation of EOR candidates, several log-inject-log (LIL) techniques based on multiple repeat logging runs are available to provide more reliable ROS values.

Advantages and possible constraints of several LIL-techniques will be discussed.

INTRODUCTION

Significant oil reserves are frequently left behind after primary and secondary recovery, since average recovery factors are often low (35-75% for water drive, 20-40% for gas cap drive 5-30% for solution gas drive). Based on conservative estimates, application of well established tertiary oil recovery (EOR) methods (e.g., thermal, miscible, chemical) in known oil reservoirs could recover up to 55 billion additional barrels of oil in the United States alone.(1)

Geological, petrophysical, reservoir and production engineering factors plus economic considerations strongly control the selection, planning and implementation strategies of EOR projects.

Analytical, probabilistic models (2) reduce the uncertainty and risk in managerial decision making by incorporating (1) reservoir prospect screening, (2) pre-pilot and pre-commercial evaluation, (3) field pilot program and (4) commercial venture decision to screen projects by oil reserves, projected cost and probability of success.

Such models and, hence, corporate strategies are strongly dependent, upon two key parameters, residual oil in place and recovery factor.

RESIDUAL OIL SATURATION (ROS) DETERMINATION

In a given reservoir the residual oil saturation can be determined several different ways, including (1) material balance techniques based on reservoir engineering concepts, (2) core analysis techniques, (3) single well tracer tests, and (4) geophysical well logging techniques in open - and/or cased wellbores.

Residual oil saturation (ROS) and its bulk volume is defined as:

$$1 - S_w = ROS \quad (1)$$

$$\phi - \phi S_w = \phi ROS \quad (2)$$

An overview and appraisal summary of present day well logging concepts [3,4] for the determination of ROS is presented in Table I.

For a hypothetical, clean reservoir in which the parameters ϕ, R_t, and R_w are accurately known (i.e., uncertainty = 0) with only the saturation (n) and cementation (m) exponents varying, the expected uncertainty limits for the basic Archie equation can be calculated such as:

$$\Delta S_w \approx \pm \left\{ \left(\frac{\partial S_w}{\partial m} \cdot \Delta m\right)^2 + \left(\frac{\partial S_w}{\partial n} \cdot \Delta n\right)^2 \right\}^{1/2} \quad (3)$$

where

$$\frac{\partial S_w}{\partial m} = - \frac{S_w}{n} \ln\phi \qquad \frac{\partial S_w}{\partial n} = - \frac{S_w}{n} \ln S_w$$

for ϕ = 20%, m = 2.0 ± 0.2, n = 2.0 ± 0.2, S_w = 50% } S_w=50%±9%

Monte Carlo - type simulation studies can investigate the uncertainty (confidence limits) of log-derived ROS-values for a given set of optimum but yet realistic reservoir conditions. For a given porosity, the cementation (m) and saturation (n) exponents are responsible for the largest uncertainty in calculated ROS values, whereas effects of errors in R_w and R_t are less important. Furthermore, uncertainty in such log-derived S_w - values will increase with decreases in porosity and oil saturation (Figure 1).[3]

In other words, routine logging and interpretation techniques frequently do not provide ROS values within acceptable uncertainty limits, particularly in reservoirs of medium porosity and marginal ROS ranges.

However, several log-inject-log (LIL) techniques (Table I), using multiple repeat logging runs will determine ROS within ± (> 5) saturation percent. North American field data for ROS determinations based on LIL - techniques and core analysis data is given in Table II.[5]

Furthermore, proper planning of LIL operations, reservoir and well conditions and fluid injection procedures are an absolute must (Table III).

LIL techniques using pulsed neutron logs have already been used extensively to determine ROS in depleted reservoirs.

Such pulsed neutron logging devices utilize different gating systems. Whereas some devices, such as the Neutron Lifetime Log® [6], have their optimum application in high porosity reservoirs with known high-salinity formation waters, other pulsed neutron devices, such as the Continous Carbon/Oxygen Log [7], are not affected by such salinity constraints.

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Statistical variations are inherent to all pulsed neutron measurements. Therefore, averaging of multiple (5 to 10) repeat logging runs are recommended for log-quality control (e.g., unreliable logging runs are omitted from the averaging calculations) to provide an improved average log response over zone of interest and its statistically significant standard deviation. Five Σ-runs, the average Σ-value and standard deviation of approximately ± 0.7 Σ-unit are shown in Figure 2 [8]. Another field case shows three C/O logging passes over a zone of interest, with the mean standard deviation computed for each of the ratios (Figure 3(A) and 3(B)). [7]

WATERFLOOD LIL TECHNIQUE

As a single-step injection technique the method is applicable only in reservoirs at ROS conditions. The three operational steps include : (1) base log (Σ, Σ_{w1}) (2) injection of brine of preselected salinity, (3) repeat log (Σ_2, Σ_{w2}). Then ROS is determined such as [9, 10]

$$ROS = 1.0 - (\Sigma_2 - \Sigma_1) / [\phi(\Sigma_{w2} - \Sigma_{w1})] \qquad (4)$$

where ϕ = reservoir porosity; Σ_w= capture cross section of formation water; $\Sigma_{w2} \neq \Sigma_{w1}$ = largest feasible, preselected salinity contrast.

This technique is independent of reservoir matrix and the hydrocarbon capture cross sections. Σ - fluid values can be calculated provided the chemical compositions are accurately known or can be measured at the wellsite on small fluid samples in the Dresser Atlas Sigma - Fluid Cell (Figure 4).

Multi-step injection extends application of the water-flood LIL-technique to reservoirs of unknown salinity or still containing significant amounts of movable oil. The initial injection brings the reservoir under ROS conditions at a well defined salinity (Σ_{w2}). ROS is then calculated such as

$$ROS = 1.0 - (\Sigma_3 - \Sigma_2) / [\phi(\Sigma_{w3} - \Sigma_{w2})] \qquad (5)$$

If during fluid injection no complete water displacement is achieved, then the calculated ROS is too optimistic. Under certain conditions one can estimate and correct for the effect of incomplete water displacement. The proposed procedure has been developed in a special field test, i.e., LIL in a water sand. [11]

CHEMICAL FLOOD LIL TECHNIQUE

The reservoir does not have to be at ROS conditions and the rock matrix capture cross section does not have to be known. The operational steps include: (1) base log (Σ_1) , (2) removing oil (Σ_{HC}) within depth of investigation of logging device (Σ_w = constant), (3) resaturation with formation brine, (4) repeat log (Σ_2). ROS is then calculated as follows:

$$ROS = (\Sigma_2 - \Sigma_1) / [\phi(\Sigma_w - \Sigma_{HC})] \quad (6)$$

The Continuous C/O Log [7] can independently evaluate ROS such as:

$$ROS = [(C/O) - (C/O)_w)] / [(C/O)_0 - (C/O)_w] \quad (7)$$

where C/O is the log measurement, whereas $(C/O)_w$ and $(C/O)_0$ represent the water - and oil saturated reservoir rocks respectively.

Applied in LIL operations the C/O Log not only determines ROS but also gives a check on fluid injection and possible stripping of hydrocarbons in the vicinity of the wellbore. Equally important, however, is the independence of the C/O ratio measurement to the presence of free gas and unrecognised fluid salinity effects.

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Table 1
Logging Concepts for Oil Determination

Techniques	Instrumentation	Open-Hole (OH) Cased-Hole (CH)	Field Experience	ROS-Accuracy
Conventional	Resistivity	OH	Tested	Fair
	Dielectric Constant	OH	Tested	Fair
	Nuclear Magnetism	OH	Tested	Poor
	Pulsed Neutron			
	DNLL*, TDT**	CH	Tested	Fair
	Carbon/Oxygen (C/O)(1)	CH	Tested	Fair/Good
Inject-Log	Nuclear Magnetism	OH	Tested	Good/Excellent
Log-Inject-Log	Resistivity	OH	Tested	Good/Excellent
	Dielectric	OH	Not Tested	Unknown
	Gamma Radiation	CH	Unknown	Unknown
	Pulsed Neutron			
	Waterflood *(DNLL,TDT)(1)	CH	Tested	Good/Excellent
	(C/O)(1)	CH	Tested	Good/Excellent
	Chemical Flood (DNLL,TDT)	CH	Tested	Limited experience
	(C/O)	CH	Tested	Limited experience
	Chlorinated Oil (DNLL,TDT)	CH	Tested	Limited experience

* DNLL = Dual Dectector Neutron Lifetime Log
** TDT = Thermal Neutron Decay Time Log
(1) Continuous and/or stationary logging measurements

Table 2
ROS Estimates Using Log-Inject-Log and Core Analysis Methods[5]

			ROS (%)					
			Log-inject-log		*Pressure core*		*Native state core flood*	
Test	*Formation and location*	*Interval analyzed (ft)*	*Range*	*Average*	*Range*	*Average*	*Range*	*Average*
1	Sims, Oklahoma	120	9-60	33				
2	Muddy "J," Well 1, Nebraska	16	21-42	33			19-24	21
3	Muddy "J," Well 2, Nebraska	13	14-46	31				
4	Grayburg, Texas	115	12-70	34	0-45	32[a]	12-50	34
5	Morrow, Texas	6		25				
6	San Andres, Field A, Texas	74	20-63	34			18-45	32
7	San Andres, Field B, Texas	72	11-48	36	4-54	31[a]	15-60	28
8	First Wall Creek, Wyoming	78	13-54	34			20-33	25
9	Second Wall Creek, Wyoming	66	25-53	34			13-36	21
10	Tensleep, Wyoming	29	14-36	25			15-25	20
11	Beaverhill Lake, Well 1, Canada						12-42	33
12	Beaverhill Lake, Well 2, Canada	20	20-41	33				

Source: Murphy, Foster, and Owens, 1976.
[a]Core saturation corrected to bottom-hole conditions.

Table 3
Considerations for Log-Inject-Log for Residual Oil (ROS) Determinations

Reservoir	Logging devices	Well conditions	Injection
1. High porosity, high residual oil saturation and good permeability.	1. Properly functioning, calibrated instruments.	1. Enough rat-hole so entire zone can be logged.	1. Non-uniform injection profiles suggest poor fluid displacement in stratified formations.
2. Select uniform reservoir. 3. Avoid fractured or fracturing of reservoir which is very detrimental to sweep efficiency. 4. Availability of reliable porosity information. 5. Gas saturation is zero in subject reservoir.	2. Multiple repeat runs (6 to 10) at proper logging speed, time constant etc., to reduce statistics. 3. Zones investigated by logs must be completely covered by the injection. Does not necessarily guarantee complete fluid replacement around the cased wellbore.	2. Evaluate a short single zone rather than a too long zone or multiple zones to facilitate control of proper injection procedures. 3. Newly perforated intervals rather than zones with old perforations to avoid formation slumping, sand production, and resulting drastic porosity changes. 4. Avoid tests in old injection wells, since ROS may be drastically reduced due to "stripping effects." 5. Satisfactory well completion and zone isolation.	3. Proper control of injection pressure (versus fracture gradient) and rates. 4. Injection fluids prepared under controlled conditions (i.e. batch mixing, calculated and/or measured Σ_w-values).

NOTE:
Do not be concerned about what at the first appears to be conflicting ROS-data obtained from reservoir engineering concepts, single well tracer tests, core analyses, and log-derived tests. Closely study the valid reasons for apparent discrepancies, which are many. Keep in mind that results may be weighted by permeability, porosity, depth of investigation and vertical resolution of logs, etc. Also note that no single method alone gives totally meaningful results of both the amount and the distribution of residual oil saturation.

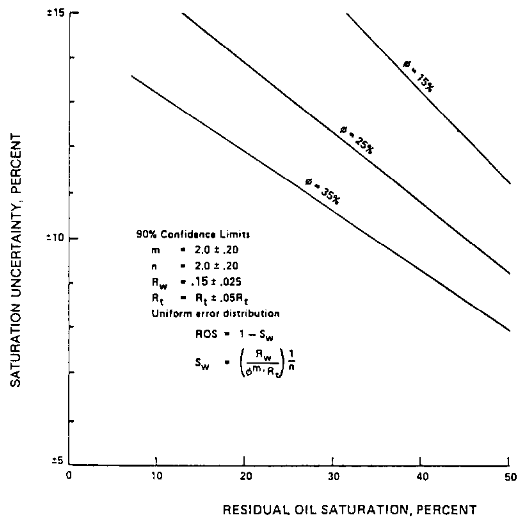

Figure 1 - Uncertainty limits in ROS-evaluation based on Archie equation[3]

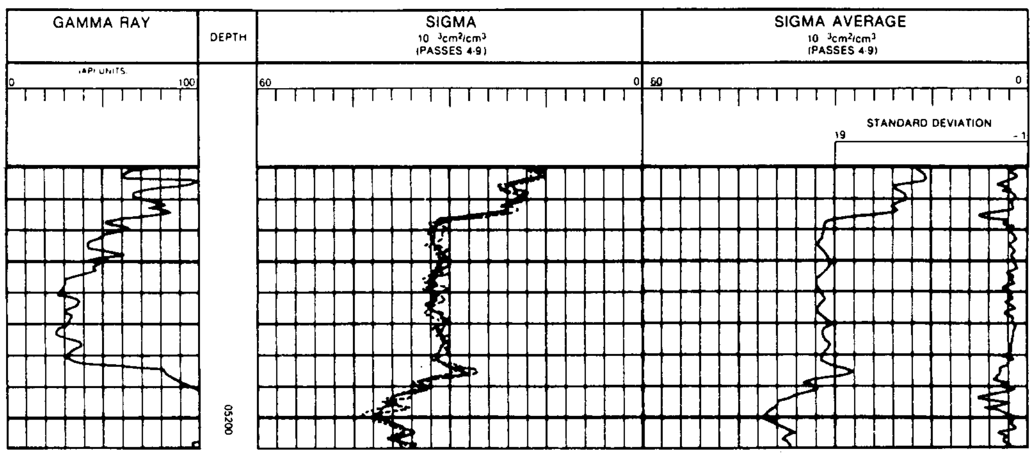

Figure 2 - Σ and $\Sigma_{avg.}$ comparison for five logging runs

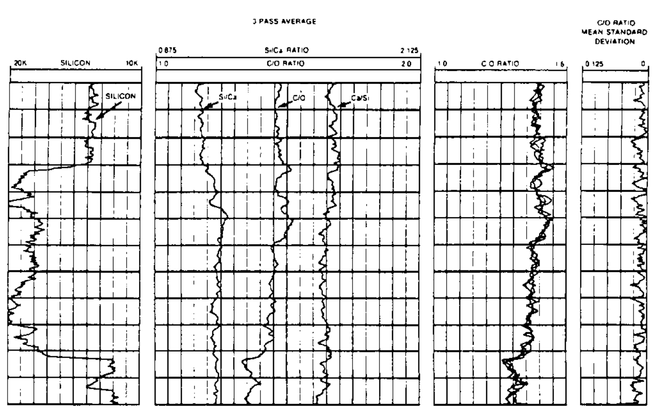

Figure 3A - C/O Log statistical variations

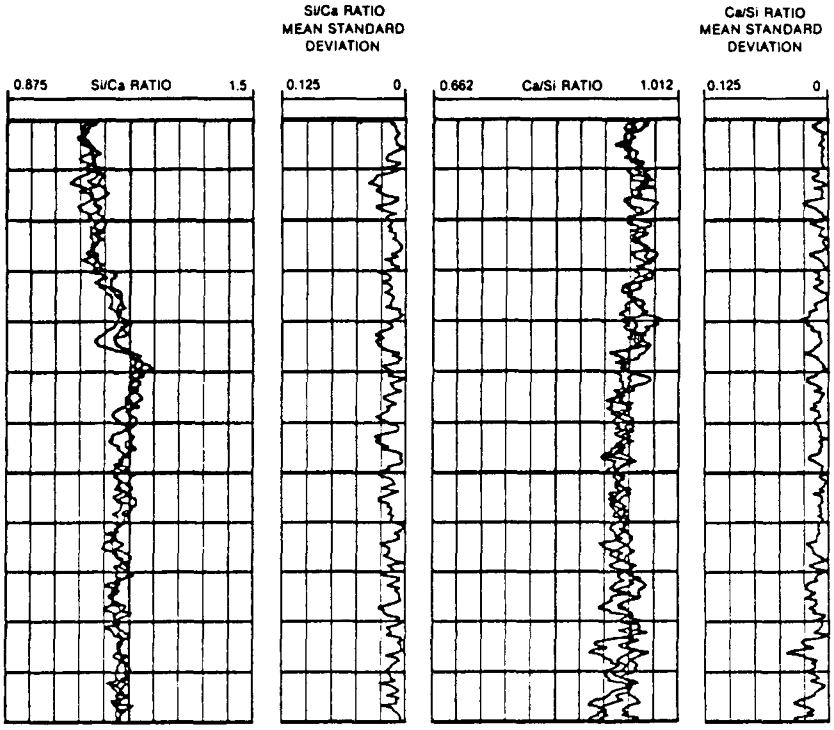

Figure 3B - Si/Ca and Ca/Si statistical variations

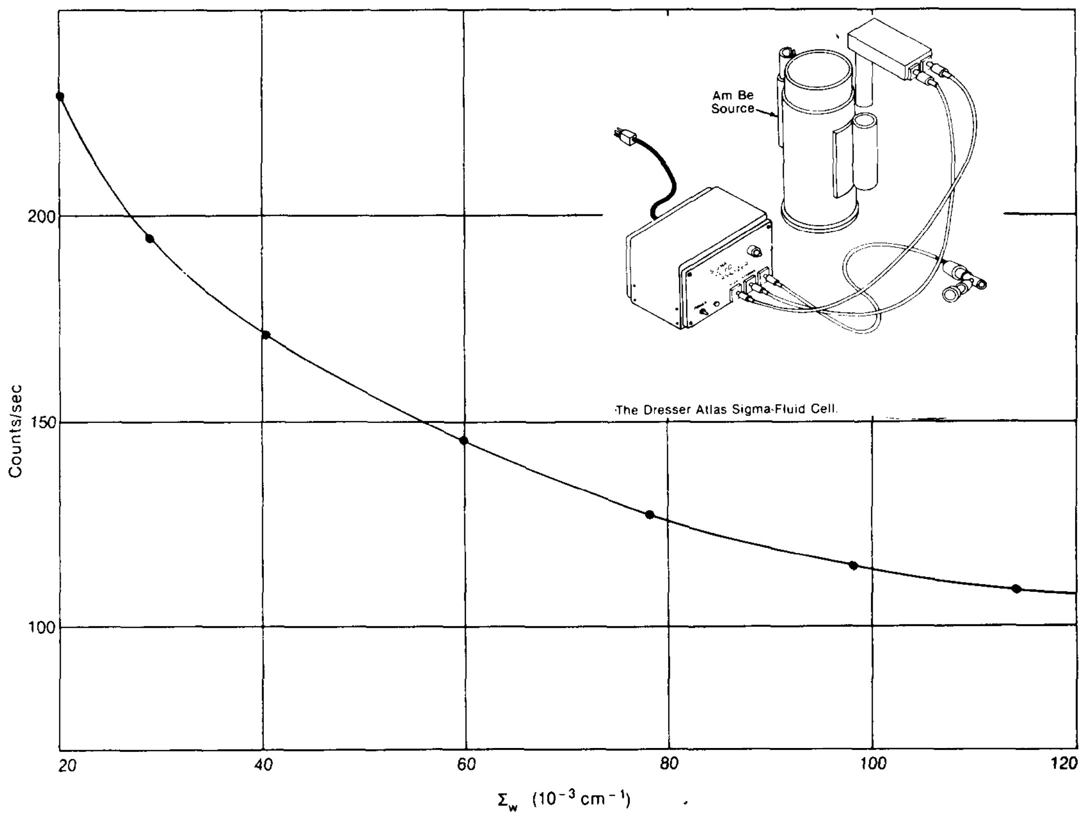

Figure 4 - Sigma-Fluid Cell responses vs. fluid capture cross section