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STUDY OF THE POTENTIAL FOR FUTURE WORK ON METHODS OF DETERMINING RESIDUAL OIL

Final Report

Date Published—April 1979

Work Performed Under Contract No. EW-78-C-19-0007

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Urbana, Illinois

U. S. DEPARTMENT OF ENERGY

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TABLE OF CONTENTS

Final Report

Study of the Potential for Future Work on Methods of Determining Residual Oil Saturation

Summary

Sixty ROS experts in 12 oil companies, 2 service companies, and 3 universities were interviewed. My recommendations concerning DOE funding in 18 potential research areas are summarized in Table 1.

Recommended funding for projects related to logging methods is approximately $2,400,000. Justification for some of the logging projects is based, in part, on benefits other than improvements in ROS determination. Recommended funding for coring is $400,000; for tracer methods $300,000; for running of suites of ROS methods, $900,000; and for miscellaneous activities (such as an ROS seminar), less than $100,000.

The report includes: a brief summary of the state-of-the-art of ROS determination; background information for various projects, with reasons for recommendations; and a list of projects not recommended, with reasons why they were not recommended.

FINAL REPORT

STUDY OF THE POTENTIAL FOR FUTURE WORK ON METHODS OF DETERMINING RESIDUAL OIL SATURATION

(Phase III, September 1 to December 31, 1978)

Introduction

In the contract for this study I agreed to consult with industry experts about needed research and development on methods of determining residual oil saturation (ROS). In particular, I was to obtain industry opinions about R & D that could be, and should be, supported by DOE.

I have visited 12 oil companies, 2 service companies, and 3 universities, where I interviewed about 60 experts on residual oil. In addition, I have made informal contacts with about 10 experts in other companies and institutions; these contacts were made by phone or letter and at several SPE and DOE meetings.

Acknowledgements

The following men made arrangements for interviews in their respective companies: R. J. Blackwell, Esso Production Research Co.; E. L. Cook, Mobil Research and Development Co.; L. Edwards, Dresser Industries; P. L. Gant, Continental Oil Co.; W. E. Kenyon, Schlumberger Well Services; F. R. Mitchell, Shell Oil Co.; R. B. Needham, Phillips Petroleum Co.; L. J. O'Brien, Union Oil Co. of California; W. W. Owens, Amoco Production Co.; F. H. Poettmann, Marathon Oil Co.; J. M. Price, Gulf Research and Development Co.; J. J. Rathmell, Atlantic Richfield Co.; V. W. Rhoades, Cities Service Research and Development Co.; and L. W. Thrasher, Chevron Oil Field Research Co.

I am grateful for the help they and their colleagues gave in the preparation of this report. Also, I thank these individuals for their assistance: H. A. Deans, Rice University; L. F. Elkins, Sohio Petroleum Co.; C. V. Kirkpatrick, University of Houston; E. H. Koepf, Core Laboratories, Inc.; J. H. Moran and N. R. Morrow, New Mexico Institute of Mining and Technology; and R. E. Wyman, Canadian Hunter Exploration Ltd.

All of the persons who were contacted gave freely of their advice and information. To some degree the report represents a consensus of those who were interviewed. But individual opinions differed. The judgments and recommendations given here are my own.

State-of-the-Art

To consider future research that may be needed on ROS, we should know the state-of-the-art of determining ROS. The Wyman and IOCC references, cited below, describe present methods in detail, so a complete description of these methods need not be given here. Appendix A of the present report is a brief summary of the state-of-the-art of determining ROS. This summary gives the background for discussion of various possibilities for research related to methods for determining residual oil saturation.

Interviews with Experts

In preparation for interviews with experts, a list of questions for discussion was prepared (Appendix B, attached). Sources for the list were various publications about residual oil, especially (1) "How Should We Measure Residual Oil Saturation," by R. E. Wyman, Bull. Can. Petrol. Geol., vol. 25, no. 2 (May, 1977), p. 233-270; and (2) "Determination of Residual Oil Saturation," a book prepared by the Research Committee of the Interstate Oil Compact

Commission, D. C. Bond, C. R. Hocott, and F. H. Poettmann, Editors, published in June, 1978.

In interviews with experts, these subjects were discussed: (a) the most pressing needs for research and development in methods of determination of residual oil saturation, (b) tools and techniques that need to be improved, and (c) possible new tools and techniques worthy of feasibility studies or development. In the interviews little time was spent on R & D being done by industry: oil companies, service companies, and suppliers. Also, little time was spent on R & D likely to be done by industry in the future. The problems emphasized were those not likely to be handled by industry in the normal course of events—worthy projects that probably will not be undertaken without support from DOE.

Results of Interviews

The course of the interviews varied from company to company. Considerable difference of opinion was encountered, even within a company. The subjects discussed depended very much on the experience of the company and the background of the people available for the interview. In only a few companies, which have done the most extensive research on residual oil, were we able to cover the complete list of methods commonly used.

From the interviews, as well as other sources, I developed a list of 25 potential areas of R & D that warranted consideration. (This list was given in my Phase II report, August 15, 1978.) I tabulated the opinions of the various interviewees about these potential areas and made tentative conclusions concerning each project area: priority, feasibility, and amount of DOE support warranted.

Then I contacted people in several of the companies that have done the most residual oil work. I asked for their opinions about the 25 potential areas. I compared my tentative conclusions with their opinions and revised my conclusions where good reason for change was given. Finally, I prepared a table of 18 potential R & D areas, giving my recommendations about priority and amount of funding, along with a few miscellaneous comments (Table I).

Projects Recommended for DOE Support

Following is a discussion of the areas in which DOE support is recommended*. For each project some background is given, along with reasons for doing the research. Note that the justification for some projects is based partly on benefits other than improvements in ROS determination. In some cases estimates are made of the feasibility of achieving the desired result. The recommended level of DOE support is stated.

In a few cases suggestions are made about how to proceed. For example, No. 1, on log calibration, probably will need cooperation with the API. No. 9, on untested L-I-L, may need a small industry committee to help select the best methods for testing—the choice will depend upon what wells and reservoirs are available and what companies are willing to participate in the research project.

Progress on some of the projects will depend on DOE policy decisions. Just how far should DOE go in supporting the development of a tool that may be profitable to the marketer? Or how far should DOE go in research on patented processes? How much cost-sharing should be expected? For example, the log calibration pits are desired by almost all logging experts, but several years after the API committee has completed its study and recommendations, no progress has been made. Should industry contribute a large part of the cost, to prove its interest and to make sure that the facility will be used?

Recommendations concerning these projects—priority, amount of DOE funding, and some miscellaneous comments—are summarized in Table 1.

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*Appendix C lists 19 projects not recommended for DOE support, with reasons why they are not recommended.

TABLE 1
RECOMMENDED DOE FUNDING FOR RESEARCH PROJECTS ON ROS DETERMINATION

No.	Project	Priority A, B, C (A = highest priority)	DOE Funding Recommended, Thousands of Dollars: Amt. per Year	Years	Total	Comments
1	Log calibration and testing facilities (for logging in general as well as for ROS determination)	A	250	3	750	Includes No. 2 and No. 3. Industry should contribute reasonable part of total cost.
2	Study of neutron diffusion effects	B				Combine with No. 1.
3	Precision and accuracy of logging tools, especially PNC tools	B				Combine with No. 1.
4	Measurement of neutron capture cross-section of fluids ($\Sigma > 40$)	B			50	State-of-the-art study
5	Routine measurement of neutron capture cross-section of cores	C			25	Feasibility study
6	Precise measurement of neutron capture cross-section of pure elements (for application to all kinds of nuclear logging, with incidental application to the use of these logs in ROS determination)	C			100	
7	L-I-L in water-saturated rocks	A	250	2	500	
8	Comprehensive study of the precision of the determination of ROS by various L-I-L methods	B	150	2	300	State-of-the-art documentation and some research
9	Log-inject-log with untested combinations	B	150	3	450	
10	Design of partially-conductive casing	C	100	2	200	
11	New, or improved, pressure core barrels with: —near-zero mud filtrate flushing	A	100	2	200	Desirable, but low feasibility. Run feasibility studies on novel ideas.
	—better pressure retention —higher pressure and temperature limits	B	100	2	200	Sandia to make proposal.
12	Single-well tracer method: —results in stratified reservoirs —sensitivity of derived value of S_{or} to various parameters —errors in S_{or} caused by difference between the compositions of trapped oil (behind the flood front) and produced oil—effect on distribution coefficient of tracer	A				Work by Deans in progress.
	—test of method in fractured wells —test of 2-well tracer method	B	100	3	300	Additional work desirable.
13	Correlations for errors in S_{or} (derived from log and core studies) caused by high pressure gradients	B				Present effort by Morrow is about the right level.
14	Application of complete suite of methods for determination of ROS, in TOR projects that have DOE support	A	300	3	900	
15	Determination of oil saturation in the parts of a water-flooded reservoir that contain mobile oil	A	25 (250)	1 (3)	25 (750)	Study the merits of any novel proposal. (Proceed if feasible method is proposed.)
16	Rate of advance of TOR front	A	(500)	(3)	(1500)	(Amounts listed are recommended if feasible new method is proposed.)
17	Survey of Russian literature on ROS determination	C	25	1	25	Make survey of availability of Russian publications on oil production and oil recovery.
18	Seminar on ROS determination	A	25	1	25	Sponsor 1½-day seminar for 50-100 ROS experts.

DISCUSSION OF INDIVIDUAL PROJECTS RECOMMENDED FOR DOE SUPPORT

No. 1 Log Calibration and Testing Facility

Background

At a meeting in February 1975 the API Subcommittee on Nuclear Logging Calibration Facility appointed a working group to consider the merits of a new facility. This facility was to be designed primarily for the testing of pulsed neutron logging tools. The working group, headed by W. R. Mills, was instructed to develop a specific proposal for the Subcommittee.

The working group met and considered location, cost, desirable pit parameters, and methods to be used. The work done in planning the present API neutron and gamma-ray pits, located at the University of Houston[2*], served as a guide in the consideration of a new facility. The working group arrived at preliminary specifications for a pulsed neutron logging calibration facility.[20] Recommendations covered combinations of absorption cross-section and porosity, matrix, fluids, thickness and diameter of zone, and borehole size.

In its report to the API Subcommittee the working group asked if there was sufficient support for a new facility to justify its construction. Publication of the report led to little response from industry logging people. The project was shelved because of lack of interest.

However, the present survey does not indicate a lack of interest in the problem. Logging experts in twelve companies, including two service companies, have said that a calibration facility for PNC logs is needed. Several have said that the facility should accommodate other kinds of logs as well. No opposition to a new facility was found.

We should note that justification for the construction of the proposed facility is based on the expectation of improvements in logs in general, for all uses, not just for logs used in determining residual oil. Benefits would

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*References are given at the end of this section, p. 56.

be expected in oil exploration and development, as well as ROS determination for TOR evaluation.

Type of Facility

Many experts recommend that if a new facility is to be built, it should be designed for the calibration of all types of nuclear logging devices. Opinion is divided about the number and kinds of combinations of test pits that should be incorporated into the facility. Various persons have recommended:

1. Two lithologies—sandstone and carbonate
2. Several porosities
3. Several saturations
   - —100% oil
   - —100% water
   - —water with residual oil
   - —oil with connate water
4. Several salinities
5. Two completions: cased- and open-hole
6. Different wettabilities of rock

Of course, to provide all of the possible combinations listed above would require an impractically large number of test pits.

The API working group recommended the following[20]:

1. Four combinations of macroscopic absorption cross-section and porosity should be available, as shown in the table below:

Sigma	Porosity
Σ_1	ϕ_1
Σ_1	ϕ_2
Σ_2	ϕ_1
Σ_3	100%

Particular values of the parameters must be determined by a compromise between availability of materials and the desire to span the range of sigma and porosity values most commonly encountered in pulsed neutron logging practice. Two zones with the same sigma and different porosities permit the diffusion effect to be examined. Two zones with the same porosity simplify the search for suitable matrix materials and permit comparison of tool responses to Σ.

2. The matrix should preferably be quartz in the form of sandstone blocks or stable mixtures of crushed silica. If this is not feasible the matrix should be limestone blocks.
3. The fluids that fill the matrix pore volume and the 100% porosity zone should be aqueous solutions of NaCl in such concentrations as to produce the desired values of Σ_1, Σ_2, and Σ_3.
4. Each zone should be about 6 feet thick and have a diameter of about 6 feet.
5. At least two borehole sizes should be available. Each hole should be cased and isolated from the simulated formations so as to allow the fluid in the borehole to be different from that in the formations.

Because of the amount of study by the working group, their recommendations must be given great weight. However, since we are here concerned with the determination of residual oil, we should urge the inclusion of some test zones containing residual oil, in addition to those listed by the working group.

Usage of Test Facility

The present neutron-gamma-ray log test facility at the University of Houston is used about 15% of the time. Logging companies use the facility to calibrate tools used in setting up secondary standards at the company research centers. After that, a company may not use the facility very much until a novel tool is developed. A tool that has been calibrated is not likely to be recalibrated unless the oil company requests it for a specific job. Oil company research people use the facility occasionally in their own research.

Why is the current neutron log facility so little used? One opinion is that generally the customers of the logging companies are lackadaisical about demanding good, up-to-date calibration for the tools being used. If the customer insists on a recent calibration, he can get it, or he can go to another company that will furnish a recent calibration. The use of the facility is dictated by the demands of the customers of the logging companies.

What usage is likely to be made of a new facility—for calibration of PNC and other nuclear logs? We have no way of predicting this usage. But if the new facility is not used more than the present one, the cost of the new facility may not be warranted, at least as far as ROS determination is concerned.

But the usage pattern of the new facility will not necessarily be the same as for the current one. If meaningful ROS values are to be obtained, the procedures for determining ROS in a given reservoir must be planned and carried out with extreme care. The tools used must be stable and must have recent, accurate calibrations. The persons making these ROS determinations will usually be researchers who know about the need for extreme care. Those in favor of setting up a new facility are the same ones who will be planning and carrying out ROS determinations. Thus, they are likely to insist on good, recent calibrations, much more than those who now make general use of the neutron log. So long as accurate ROS values are needed for TOR evaluation, the new facility should be utilized.

Cost of New Facility

The present test-pit facility was constructed 20 years ago at a cost of about $50,000, not including the value of the land. Sufficient space is available at the present site for the proposed new test pits. The minimum facility for testing and calibration of PNC logs would probably cost about $500,000. If the facility were to be expanded for use with several kinds of logs—in rocks having different lithologies, porosities and saturations, in cased and open holes—the cost could easily be several million dollars. Evidently a judicious choice will have to be made if the cost is to be kept within the amounts likely to be available from DOE and industry.

Probably the parameters chosen by the API working group, plus the wettability parameter, could be incorporated into the facility for a total cost of about one million dollars.

Recommendation:

DOE should help to re-activate consideration of an expanded nuclear log calibration facility.

An industry group—such as the API Subcommittee on Nuclear Logging Calibration Facility—should poll the major oil companies and logging companies to determine:

- How serious is each company's interest in such a facility?
- How much money would it contribute to the project?
- How much would it be likely to use the expanded facility, or cause it to be used?
- How much of a contribution would be needed from DOE to get the project underway?

A DOE contribution of several hundred thousand dollars seems to be justified. But this contribution should be made only if the oil companies and service companies (a) are willing to demonstrate their interest by paying a major part of the expense, and (b) guarantee that the new facility will be used.

No. 2 Study of Neutron Diffusion Effects in PNC Logging

Background

The operation of PNC logging devices is briefly described in Appendix A of this report and in the IOCC book on the determination of residual oil saturation (Ref. 5, p. 95-103). More detailed descriptions are given in several other publications[38,44]. (The Schlumberger version of the PNC log is called the Thermal Decay Time (TDT) log. The Dresser-Atlas PNC log is called the Neutron Lifetime Log (NLL).

During the PNC logging operation two processes occur: neutron capture and neutron diffusion. The response measured by the PNC log may include both capture effects and diffusion effects. If the PNC log is to be used to characterize the formation, the so-called macroscopic absorption cross-section of the formation must be determined. Thus, the measured response of the PNC log must be corrected for diffusion effects, or diffusion effects must be eliminated, if the log is to be useful in determining the properties of the formation that is logged.

Several investigators have discussed the diffusion problem. For example, Wahl et al.[38] conclude that satisfactory corrections can be made. They present departure curves for the Schlumberger TDT log, for various parameters. One version, the TDT-L, a stationary device, is said to require no diffusion correction.[29]

With the Dresser-Atlas NLL tool Youmans et al.[44] claimed that neutron diffusion could be regarded as a second-order effect which need not be taken into account.

But various oil industry researchers appear not to be completely satisfied with the handling of the diffusion problem by the logging companies. For example, Murphy et al. (Ref. 22, p. 91) say, "These data are presented to emphasize the importance of reliable neutron diffusion corrections and to again encourage the service companies to conduct studies to provide meaningful pulsed-neutron diffusion correction data." Richardson et al.[27] (p. 604) say: "If these special [log-inject-log] techniques are to work, it is imperative that the possible influence of neutron diffusion be understood, and that methods to account for diffusion be available, if needed, for a wide range of logging environments." During the present survey a number of investigators expressed similar opinions.

Besides the need for better, more comprehensive departure curves, the need for a better understanding of the diffusion process itself has been emphasized by several persons interviewed. Some have suggested that a study of diffusion might be made at the proposed new facility described above (No. 1).

Although improved departure curves are needed, no one has suggested that the preparation of these curves be financed by DOE. This part of the problem is recognized as one that must be handled by the logging companies themselves.

On the other hand, there is a fair amount of support for the idea that DOE should sponsor a modest fundamental study of diffusion effects in PNC logging. This study should cover the basic theory of neutron diffusion and give some estimate of the magnitude of diffusion corrections. If possible, it should give a neutral, independent evaluation of the accuracy of the available diffusion corrections for various logging devices. Further, it should outline the specific areas where departure curves need to be improved or extended.

Even though information of this kind is desired by a considerable number of people, no single oil company is likely to undertake the study. Since the problem is of general nature and the results of the study can lead to better ROS values, it is appropriate that the study be sponsored by DOE.

Recommendation:

Neutron diffusion effects with available PNC tools should be studied. Perhaps $100,000 would suffice.

If possible, this study should be combined with No. 1, above.

No. 3 Precision of PNC Logging Tools

Background

Information about the precision of various PNC logging tools is available from the logging companies. But persons in several oil companies insist that more extensive information is needed about the precision of PNC tools, under a wide variety of conditions.

Furthermore, some express a desire for an independent, critical review and evaluation of the precision of PNC logging tools, by someone outside the logging companies. This study might be combined with the study of diffusion effects (No. 2 above), at the proposed log test facility.

Recommendation:

The precision of available PNC logging tools under various conditions should be determined in conjunction with the work on Project No. 1, above. Perhaps this work could be done at little extra expense.

No. 4 Measurement of Neutron Capture Cross-section of Fluids

Background

The use of the PNC log in log-inject-log (L-I-L) techniques for the determination of ROS often requires knowledge of the neutron capture cross-sections of various fluids. For example, in the L-I-L waterflood technique the formation is first logged while it contains natural formation water (Σ_{w1}); a water with contrasting salinity (Σ_{w2}) is injected and the formation is logged again (Wyman, Ref. 5, p. 96-98). The residual oil saturation, S_{or}, is given by the equation:

$$S_{or} = 1 - \frac{(\Sigma_{t2} - \Sigma_{t1})}{\phi\ (\Sigma_{w2} - \Sigma_{w1})}$$

where ϕ = porosity of the formation

Σ_{t1} = the measured capture cross-section of the formation, containing formation water whose cross-section is Σ_{w1}.

Σ_{t2} = the measured capture cross-section of the formation, containing residual oil and injected water whose cross-section is Σ_{w2}.

In the "L-I-L with strip" technique (Ref. 5, p. 98) the formation, containing residual oil and formation brine, is logged. Then the oil is stripped from the vicinity of the borehole by the injection of a water-soluble solvent such as alcohol. Formation brine is injected to sweep out the alcohol and the formation is logged again. The residual oil saturation is given by:

$$S_{or}\phi = \frac{\Sigma_{t3} - \Sigma_{t1}}{\Sigma_{w1} - \Sigma_{h}}$$

where Σ_{t3} = the measured capture cross-section of the formation after the residual oil has been swept out and the solvent has been replaced by formation water.

Σ_{h} = the capture cross-section of the oil.

In another variation of L-I-L (Ref. 5, p. 100), the residual oil is stripped from the vicinity of the well bore by the injection of a chlorinated hydrocarbon which has the same capture cross-section as the formation water, Σ_{wl}. Logs taken before and after the injection of chlorinated hydrocarbon enable one to calculate S_{or}.

In the application of these L-I-L techniques, knowledge of the neutron capture cross-section of various fluids is required: formation water, injected water, residual oil, or chlorinated hydrocarbon. The capture cross-sections of these fluids are measured preferably in special cells (Ref. 5, p. 96). Where enough liquid is available, measurements can be made in the field.[28] A large tank is filled with the liquid, the PNC tool is lowered into the tank, and the capture cross-section is read with the tool. Or the capture cross-sections can be estimated from the results of laboratory chemical analyses and published data.

These methods of estimating the capture cross-sections of fluids are often satisfactory. But researchers who have done the most L-I-L work say that we need ways of estimating the cross-sections of fluids more accurately. Especially we need better estimates for fluids whose Σ exceeds about 40 units. Better information is needed for use in all kinds of applications of PNC logs. But, in particular, better information is needed for use in L-I-L methods of determining ROS.

Some work is being done by the oil industry and by service companies. However, a cooperative industry study is needed to firm up the standards, evaluate available data, and referee disagreements where uncertainty exists. DOE should do what it can to catalyze such a study.

Recommendation:

A state-of-the-art study should be made of available methods for measuring the thermal neutron capture cross-sections of the fluids used in L-I-L methods. The feasibility of developing improved methods should be investigated.

Available data should be evaluated and improved standards should be set up.

This work should be done preferably by a cooperative industry group, with some support from DOE if needed.

About $50,000 from DOE should be enough to catalyze this effort.

No. 5 Routine Measurement of Neutron Capture Cross-section of Cores

Background

The total neutron capture cross-section of a formation, Σ_t, is the sum of the component cross-sections of the rock matrix, Σ_{ma}, and the cross-sections of the fluids (water, Σ_{wl}, and hydrocarbon, Σ_h) contained in the pores of the rock (Ref. 5, p. 96). Thus:

$$\Sigma_t = \Sigma_{ma} (1 - \phi) + \Sigma_{wl} S_w \phi + \Sigma_h (1 - S_w)\phi$$

In the conventional use of PNC logs for ordinary problems related to exploration and primary and secondary recovery, satisfactory values of Σ_{ma} often can be obtained from knowledge of the lithology, or from experience in the area. But Richardson et al.[27] (p. 594), say, " . . . Σ_{ma} is not easily derived and usually is the least certain . . ." Sometimes it would be helpful to know how Σ_{ma} changes from foot to foot, where the rock is heterogeneous. Under those conditions a simple scanning method of determining Σ_{ma} for cores could be useful.

However, most investigators are of the opinion: (1) the feasibility of developing such a method is low and (2) its utility might not be worth the cost of developing the method. If Σ_{core} is required, it can be obtained by the method of Allen and Mills.[1] The principal objections to the Allen and Mills method seem to be that it requires a large amount of sample (about 50 lb.) and considerable time.

Another method used, where better values of Σ_{ma} are required, involves PNC logging before and after the injection of water having the same cross-section as the residual oil. Solution of a set of simultaneous equations gives the value of Σ_{ma}. But, as far as ROS determination is concerned, little is gained by this operation. One could just as easily use an L-I-L technique for ROS that would eliminate the need for knowing Σ_{ma}.[23]

For ROS determination, the conventional PNC log alone usually does not give precise enough saturation values for TOR work. The use of the PNC log in

L-I-L techniques does give satisfactory values of ROS, but in such L-I-L techniques the need to know Σ_{ma} is eliminated.

A simple, rapid scanning method of determining Σ_{ma} from cores would be "nice to have." The results could have application where PNC logs are used, other than in L-I-L applications. If a novel method can be suggested, it would probably be worth a feasibility study.

Recommendation:

No action is needed at this time.

If a promising method can be suggested, a feasibility study should be made.

No. 6 Neutron Capture Cross-section of Pure Elements

Background

In No. 5, above, the use of the capture cross-section of the rock matrix, Σ_{ma}, was described. The estimation of Σ_{ma} from the lithology was mentioned. Where Σ_{ma} is to be estimated from the lithology, we need to know the composition of the rock and values of Σ for the elements of which the rock is composed.

For elements that are used in nuclear power technology, like boron, values of Σ are known with great accuracy. But for certain other elements found in reservoir rocks, such as calcium and silicon, values of Σ may be subject to an uncertainty of 10% or more.

Better values of Σ for elements are needed in the general use of PNC logs. Better Σ values can eventually improve the accuracy of PNC tools. Although L-I-L techniques can eliminate much of the need for knowing Σ_{ma} in ROS determination, better Σ values for elements might result in some incidental improvement in ROS determination.

Data from this project may not be used routinely. But the results will be used in research and in the development of better nuclear logging tools of various kinds, including the PNC tool.

The primary purpose of this project should be to study the capture cross-section of about a dozen pure elements for thermal neutrons. Determination of the capture cross-section for epithermal neutrons might also be considered, as a secondary purpose of the project.

This work could not be justified on the basis of its benefits to ROS determination alone, but it is of some importance for logging in general. It has low priority.

Industry does not have an economic incentive to do this work. A small DOE project is warranted.

Recommendation:

The thermal-neutron capture cross-section of about a dozen pure elements should be determined accurately.

About $100,000 should suffice for this work.

No. 7 L-I-L in Water-saturated Rocks

Background

Certain L-I-L techniques have been discussed above (No. 4 and No. 5). Details of these techniques are presented by Richardson et al.[27], Murphy and Owens[23], Murphy et al.[22], and Wyman[5].

In the various L-I-L techniques a given well may be subjected to the sequential injection of one, two, or three different fluids. After each injection the well is logged, each time with the same tool. Often fluid is injected and another log is run, to ensure that a stabilized condition has been established in the region around the well bore investigated by the logging tool. Of course, the volume of injected fluid is designed to fill the porous rock around the well bore, well beyond the radius of investigation of the logging tool that is being used. In some cases the adequacy of invasion is confirmed, say, by the use of certain resistivity logs (Richardson et al.[27], p. 597).

In all of these L-I-L procedures one very fundamental assumption is made: "The injected fluids invade all intervals of interest and completely displace the intended formation water or oil." (Murphy and Owens[23], p. 233). But in any given L-I-L application how can one be certain that the injected fluid goes into the proper intervals? How can we be certain that the injected fluid completely displaces the intended fluid from the pores of the rock around the well bore?

One can argue that these questions can be answered through the intelligent application of sound engineering principles by one skilled in the art of obtaining information by manipulations in well bores. For example, Trantham and Clampitt[36] (p. 496) say, "Separation of the three curves [TDT-K] indicates good displacement of one fluid by another." Murphy et al.[22] (p. 91) say, "The logs run after chlorinated-oil injection followed closely the logs after salt water injection. This indicates that the chlorinated oil failed to enter the formation matrix to displace oil as desired . . ."

But clear-cut information of this kind is not always available. Sometimes a definite assessment of the degree of displacement cannot easily be given. Thus, Murphy et al.[22] (p. 93) say, "The injection and production of fluids had little or no influence on the response of the logs . . . Since the flushing of fluids . . . *did not appear to be* complete . . ." Vargo[37] (p. 359) says, "The apparent residual oil saturation of 38% . . . is *believed to be* a result of the incomplete displacement of fresh water by brine." Robinson et al.[30] (Table 4) say, "Incomplete displacement of paramagnetic complex into formation *probably* resulted in some measured water signal." (Italics mine).

When investigators use expressions like "did not appear to be," "believed to be," and "probably," they may be doing the best that can be done under the circumstances. But the use of such vague, indefinite expressions indicates that the degree of displacement of fluids in L-I-L tests may not always be known with certainty. We may wonder how much the L-I-L results reflect the true condition of the reservoir. How much do the ROS results represent a rationalization of observations? The problem has been brought into the limelight by the results of certain experiments reported by Bragg et al.[7] Incidental to the determination of residual oil in some waterflooded oil sands in the Louden Field, Illinois, L-I-L tests were run in the Tar Springs, a sandstone known to contain no oil. In the oil sands (the Weiler and the Bethel) satisfactory ROS values were obtained, consistent with the values obtained by other means. But in the L-I-L tests in the Tar Springs, results were obtained which could be interpreted as indicating 30 to 60% oil saturation in this water-saturated sand. (At the Illinois State Geological Survey we recently inspected drill cuttings from the Tar Springs in an offset to the well that was tested by Bragg et al. The samples contained clean sand with no trace of oil.)

The authors investigated various explanations for this anomaly and concluded (p. 377), "The 'high oil saturations' calculated are believed to have resulted from incomplete displacement of formation fluids close to the wellbore by the injected low-salinity water."

In the tests by Braggs et al., the Bethel well was completed open-hole, while the Tar Springs tests were run in a cased hole perforated with 6 shots per foot. Otherwise, the procedures were said to be identical. Repeat passes of the NLL tool were made. Then low-salinity water (3,000-ppm total dissolved solids) was injected until a stabilized response of the NLL was obtained. In this process the high-salinity formation water (104,000-ppm total dissolved solids) was intended to be completely displaced by the low-salinity water. A stabilized NLL response was obtained after about 2 bbl/ft. of low-salinity water had been injected. However, to make sure that a stabilized condition was reached, water injection was continued until about 5 bbl./ft. had been injected.

If we take the Tar Springs results at face-value, we must conclude that in L-I-L procedures very serious errors can be introduced by incomplete displacement of one fluid by an injected fluid, especially where the hole is a perforated cased hole. Perhaps the anomalous results of Bragg et al. were caused by some defect or some obscure error in the procedures. We have no way of knowing this. But we do know that the same investigators, using the same procedures, obtained reasonable results in other tests at Louden.

Regardless of the merits of the Bragg et al. results, the question of the degree of displacement by injected fluids warrants serious study. One would think extensive investigations in water-saturated rocks would have been carried out to test the basic assumption that injected fluid completely displaces formation fluid and that the displacement of fluid can be measured by the logging tool. But a search of the literature reveals no field investigations other than the Bragg et al. study. In interviews with various researchers I have found no one who knows of such experiments. Some tests of this kind are said to be underway at Prudhoe Bay.

All of the L-I-L work done thus far (except the Bragg et al. study) has been done in reservoirs where the results are complicated by the presence of residual oil. Criteria of the kind used by Murphy et al. and by Trantham and Clampitt (cited above) have some value. But the reasoning is always complicated by the presence of residual oil—oil whose saturation is the unknown value which is the object of the whole investigation—and oil whose physical configuration can change as different fluids are injected. And the reasoning may be complicated further by unknown variations in the salinity of the waters of various strata in the reservoir.

Conclusion:

An extensive investigation is needed. This investigation should test L-I-L techniques in 100% water-saturated rocks. The purpose should be to determine the degree to which an injected fluid displaces another fluid, in the region logged near the injection well. We should test our ability to measure, by logging methods, the displacement of one fluid by another in the reservoir. The tests should cover:

1. Perforated cased-hole vs. open-hole
2. Various numbers of perforations per foot
3. Different lithologies, especially stratified vs. homogeneous rock

Initially the work should be done with the PNC tool. Later the work might be extended to cover other tools that might be used in L-I-L work.

An ideal place for carrying out these tests would be in certain underground gas storage projects in northern Illinois. Different aquifers have waters of different salinities, from fresh water to quite saline water. Various kinds of reservoir rock are present, from very clean sand to shaly sand and sand with shale streaks. Observation wells are present around the periphery of the gas storage "bubble" which would be suitable for much of the work.[8] The problem would be to induce the gas storage companies to undertake the study. At present it appears they would not be willing to do such research, even if supported by DOE.

Another possibility would be to carry out the displacement tests in the "water leg" of a reservoir in which oil is underlain by formation water. If the tests were carried out in a well downdip from the oil, the lithology could be similar to that of the oil zone. Thus, the results obtained in the water-saturated part of the reservoir could be applied directly in the interpretation of L-I-L results for the waterflooded oil zones.

Recommendation:

The L-I-L technique should be thoroughly tested in 100% water-saturated rocks. The purpose of the tests should be to determine the degree to which one fluid is displaced by another fluid, as shown by PNC logs, under various hole conditions and in different kinds of reservoir rock.

Several hundred thousand dollars should be spent on this study.

No. 8 Comprehensive Study of the Precision of Determination of ROS by Various L-I-L Methods

Background

Richardson et al.[27] (p. 599-603) discuss some of the factors that contribute to the uncertainty of ROS determinations that are made by L-I-L techniques. In particular, they show how changes in various parameters affect ROS values that are derived from PNC logs. Wyman[42] (p. 265-266) gives qualitative estimates of the accuracy to be expected from various methods of determining ROS, including L-I-L methods. Elkins[5] (p. 284-285) gives similar estimates, based upon Wyman's recommendations and upon data gathered by Elkins in the preparation of the IOCC book.

All of these estimates are helpful. They have some utility, as far as they go. But a need exists for a comprehensive study that would cover:

(A) A review of all available data on ROS determinations by L-I-L methods.

(B) A critical point-by-point assessment of the possible influence of various parameters on the derived ROS value.

(C) A modest amount of field testing in which carefully selected parameters are varied. These field tests would not be run just to determine ROS, but rather to obtain information about the influence of various parameters on ROS.

(D) An evaluation of the above, to give the best estimate of the precision of determination of ROS by L-I-L methods.

Possibly the log calibration and test facility described above (No. 1) could be utilized for some of this research.

Recommendation:

A few hundred thousand dollars should be spent on a comprehensive study of the precision of determination of ROS by L-I-L methods.

No. 9 ROS Determination by L-I-L, with Various Untested Combinations of Logs and Injection Fluids

Background

Many variations of the L-I-L technique are possible. Among the methods that have been proposed are:

(A) Log with resistivity tool. Inject water whose salinity differs from that of the formation water. Log with resistivity tool.

(B) Log with resistivity tool. Remove residual oil by injection of water-soluble solvent such as isopropyl alcohol. Inject formation brine. Log with resistivity tool.

(C) Log with PNC tool. Remove oil by injection of alcohol. Inject formation brine. Log with PNC tool.

(D) Log with PNC tool. Inject water whose salinity differs from that of the formation water. Log with PNC tool.

(E) Log with PNC tool. Inject chlorinated hydrocarbon-oil mixture with capture cross-section equal to that of the formation water. Log with PNC tool.

(F) Inject water containing paramagnetic ions. Log with NML.

(G) Run gamma-ray log. Inject water containing radioactive tracer. Run gamma-ray log.

(H) Inject brine containing two radioactive tracers, one preferably soluble in brine, the other preferably soluble in oil. Run spectral gamma-ray to distinguish between water and oil and give S_{or}.

Some of these methods have been tested in the field. Method D is used routinely (Ref. 5, p. 96-98, 278-283). Method C has had at least one partially successful test (Ref. 23, p. 235). Method E has been tested (Ref. 22, p. 90-91). No documented tests of method A are known, but it is said to have been field-tested. Method F has been successfully applied in the field.[30]

To a considerable extent the problem of determining ROS by L-I-L techniques has been solved. In open-hole completions the NML inject-log technique (F) gives good results. In cased holes the use of the PNC log, before and after injection of water having contrasting salinity, (Method D) is routine.

No doubt industry researchers have weighed the relative advantages of different methods as they planned the tests that have already been made. Even so, potentially worthwhile methods have not been tested. Perhaps all of these methods will be tested by industry eventually. But this possibility becomes less and less likely as fairly satisfactory methods are developed and used.

A systematic study of untested L-I-L techniques is not likely to be made by industry because the economic incentive is not as great as it was, say, ten years ago. Such a study should be made by DOE to make sure that a valuable addition to the present methods is not being overlooked. Many times we cannot predict how a given procedure will turn out—we can learn this only by field testing. Furthermore, we need novel ideas about ROS determination. Field work on new methods always helps to generate creativity among researchers.

A review of all proposed L-I-L techniques (plus others that may be devised) should be made. The possible advantages and limitations of the various untested techniques should be weighed. A limited number, say, five or six, of the most promising techniques should be selected. These techniques should be field-tested, preferably in the same reservoir.

Recommendation:

About five or six of the most promising untested L-I-L methods should be field tested. DOE funding of a few hundred thousand dollars is warranted.

No. 10 Design of Strong, Partially-conductive Casing

Background

In certain cases it is desirable to make oil-saturation measurements through casing. For example, measurements might be made in a cased observation hole, to follow the progress of an injected fluid or an oil front in a TOR project. Or measurements might be made in a reservoir that contains mobile oil.

At present such measurements can be made through steel pipe with the PNC log. Or measurements can be made through ordinary plastic pipe with the induction log. But the induction log often does not give the desired vertical resolution, and the PNC log does not give the deep investigation that can be obtained with the Laterolog and other resistivity tools.

A casing material is needed which will have some conductivity (resistivity = 1 to 5 ohms/cm.), so some of the resistivity logs can be run in a hole cased with the material. Field tests have been run on some material of this kind by Shell. Our understanding is that the material failed because it lacked the required mechanical strength.

A design study should be made to obtain the specifications for a casing that will perform in the manner described. Besides having the desired resistivity (1 to 5 ohms/cm.), the casing should have properties that permit the use of PNC, neutron, DLC and other logs that might be required. Satisfactory logging would probably require that the resistivity of the casing be quite uniform. Of course, the casing should be strong enough to withstand stresses imposed in field usage. Probably it will be necessary to prepare and test samples of the material in the laboratory.

Recommendation:

A strong, partially-conductive casing should be designed and tested in the laboratory. After the feasibility of making such a casing has been demonstrated, efforts should be made to have a few test lengths of the casing made up and tested in the field. The contribution of DOE should be limited to the design and laboratory testing stage (perhaps \$100,000 to \$200,000). Further development and field application should be left to the oil industry and the plastics industry.

No. 11 New or Improved Pressure Core Barrels

Background

The pressure-retaining core barrel is a device that provides for (1) cutting a core, (2) sealing the core and its fluid contents at the bottom of the hole, and (3) keeping the core and its contents unchanged until the core is analyzed in the laboratory.

At various times a number of different pressure core barrels have been tested. The device currently most used is a variant of the Carter core barrel, developed and patented by Esso Production Research Co. Details about the operation of this device are given by Koepf (Ref. 5, p. 28). In recent years, Loomis International, Inc. has supplied pressure-coring service to the industry. Within the past year Diamond Oil Well Drilling Co. (Dowdco) has improved the tool and offered a pressure-coring service.

(A) Improved core barrels

In past years many persons have had poor success with the pressure-retaining core barrel. The principal problem seems to lie in sealing the core and bringing it to the surface without losing some of the fluids trapped in the core when it is cut. Therefore, there has been some demand for a core barrel that would do a better job of holding the trapped fluids.

To a considerable degree the Carter tool, as improved by Dowdco, appears to have solved the sealing problem. Those who have used the Dowdco tool report much better recovery of pressurized cores than was experienced previously with the Christiansen tool.

Besides achieving better recovery of pressurized cores, Dowco appears to have accomplished another improvement. By design changes (opening ports, etc.) they are said to have decreased the pressure gradient across the rock that is cored; thus, the invasion of the core by mud filtrate is decreased and less displacement of reservoir fluids by filtrate occurs.

A number of persons have said that pressure core barrels are needed that will operate at higher pressures and temperatures than the current devices. These devices designed for more stringent conditions are needed especially for ROS determinations on deep reservoirs that are candidates for CO_2 flooding.

Core barrels designed for extreme conditions may be developed in the normal course of business, as demand increases. Sandia Laboratories is to prepare a proposal to DOE covering the fabrication and testing of one such device. Sandia's proposal may also cover a study of the influence of design on fluid invasion of the core.

Work by Dowdco, Christiansen, and others probably will result in satisfactory pressure core barrels and coring services. To the degree that a conventional pressure core barrel can be expected to supply reservoir samples of rock and fluid, this barrel appears to be approaching the theoretical limit of its development.

But any pressure-retaining core barrel of the type now in use always recovers cores that may have been flushed by mud filtrate to some degree. So a need still exists for a device that will take an undisturbed, unchanged sample of the reservoir rock and its fluids, bring it to the surface and on to the laboratory, without loss of fluids. This problem is discussed next.

(B) Zero-flush core barrels

Many people have studied the problem of obtaining cores so flushing by mud filtrate is eliminated. A study of the feasibility of devising such a system has been made by Ward and Sinclair.[39]

Ward and Sinclair propose two coring systems, denoted by Phase I and Phase II:

> <u>Phase I</u>—In this system the hole is drilled out and enlarged by a main bit. The core is cut by a replaceable pilot bit, which drills ahead of the main bit. During drilling most of the mud is diverted away from the core being cut. Within the pressure core barrel the core displaces—

and is surrounded by—a stationary nonpenetrating, nonfreezing gel. The displaced gel is extruded through the replaceable pilot bit (Ref. 5, p. 229).

Sandia Laboratories has been awarded a contract to identify or develop fluids for use in a system like the one described above.

Phase II—This is a much more complex system. It envisions coring under a packer, without the possibility of having drilling fluids come into contact with the core or the reservoir rock at the bottom of the hole. The core is to be analyzed at the bottom of the hole, by logging methods and other means. The results of analysis are to be sent to the surface by telemetry.

There are no current plans to develop Phase II.

Utility of zero-flush core barrel:

As far as virgin reservoirs are concerned, a zero-flush pressure core barrel would be very useful—it would enable one to obtain the original oil saturation at the time of discovery of the reservoir.

As far as waterflooded reservoirs are concerned, a zero-flush device would have some utility. But we should not overestimate the need for it. In a water-wet reservoir, after the flood front has passed, the passage of additional water has little effect on the oil saturation—little or no mobile oil is present. The passage of a small amount of mud filtrate is not likely to affect the oil saturation very much. In an oil-wet or partially oil-wet reservoir, considerable amounts of mobile oil may be present behind the main oil bank (Ref. 25, p. 12). But the displacement of this mobile oil requires the passage of relatively large amounts of water. Again, if precautions are taken to minimize mud filtrate loss, the volume of mud filtrate that enters the core may not be large enough to displace an appreciable amount of oil from the core. Of course, if a partially-flooded reservoir is being studied, large amounts of mobile oil will be present and a zero-flush coring device will be very useful.

In any case, if doubt exists about the degree of filtrate invasion, a tracer, such as tritium, can be used in the mud to check this point (Ref. 5, p. 48). For example, Bilhartz and Charlson[3] (p. 142) show how to use the difference between the tritium content of annular donuts and center plugs cut from cores, when a tritium tracer has been added to the mud. When mud-filtrate invasion is small, as shown by the tritium content, the measured oil saturation approaches the actual value that exists in the reservoir. On the other hand, samples that have a high tritium content are assumed to be flushed to near end-point saturation.

Conclusion

In virgin reservoirs a zero-flush core barrel would be very useful. It could greatly improve the accuracy of determination of initial oil saturation. Therefore, it would lead to better values of ROS, as determined by the material balance method.

In partially-flooded reservoirs, where mobile oil exists, a zero-flush core barrel could give better values for the oil saturation that exists in the reservoir. Thus, better estimates of "target oil" for TOR could be made for these reservoirs.

In reservoirs that are thoroughly waterflooded, a zero-flush core barrel could be useful, but it is not essential. In many cases other methods of obtaining the desired information are available for reservoirs of this type.

Most of the people who were interviewed expressed great skepticism about the possibility of ever obtaining "true" samples of reservoir rock and fluid. Still, the need for such samples warrants a modest expenditure, in the hope that a solution to the problem will be found.

Recommendation:

DOE should continue to support feasibility studies on any proposed system for obtaining "true" reservoir samples that appears to have merit. About $100,000 per year should be the maximum for this type of study. Of course, if any proposed system should appear to have high probability for successful operation, an all-out effort to perfect that system would be warranted.

As the need for evaluation of deeper reservoirs grows, the pressure-temperature limitations of conventional core barrels probably will be extended by the manufacturers and service companies. But a modest support by DOE is warranted, to catalyze this development.

No. 12 Research on Tracer Methods

Background

Several problems related to the single-well tracer method are being studied by H. A. Deans.[12] These include:

A. Tracer tests in multilayered reservoirs.

B. Effects of parameters such as drift and dispersion of tracer.

C. Errors caused by the difference between the compositions of trapped oil and produced oil.

Several other questions related to tracer methods appear to be worthy of investigation:

A. Water-saturated reservoirs. Single-well tracer tests in a water-saturated reservoir might yield useful information, especially in multilayered reservoirs. In such reservoirs, the interpretation of tracer tests can be difficult. The effects of residual oil may be complicated by the effects of striation. Perhaps the results of a tracer test in the "water-leg" of a well would help in the interpretation of a tracer test in the oil zone of a reservoir.

B. Hydraulically-fractured wells. Many people think that the single-well tracer method cannot give valid results in a well that has been hydraulically fractured. But suppose we know (from impression casts or other sources) that a single vertical fracture exists across such a well. For the volumes of brine injected during a tracer test the flow from the fracture into the reservoir is essentially linear. If the theory for this linear case were developed, the tracer method might be applied to many wells now excluded from the use of this method. Tests should be made in a fractured and an unfractured well in the same reservoir to learn whether or not valid ROS results can be obtained in a fractured well.

C. **Two-well tracer method.** Cook[9] suggests the use of two tracers, having different distribution coefficients between oil and water. A solution of the two tracers is injected into one well, travels through part of the reservoir that contains residual oil, and is produced at a second well. From the distribution coefficients of the two tracers and the arrival times of the tracers the residual oil saturation can be calculated. Drawbacks of this two-well method are: (1) Transit times of the tracers may be impractically long. (2) Production of each tracer may be spread over an extended time span. (3) Permeability differences among the strata may produce broad residence-time distributions (Ref. 5, p. 159).

But under certain circumstances the two-well tracer method may still have merit. For example, in a TOR test often one or more observation wells are drilled near an injection well. Tracers could be injected ahead of TOR fluids and be collected at the observation well; thus, the ROS could be obtained for the part of the reservoir that is being evaluated for its TOR potential. Judicious use of packers might permit the determination of ROS in various strata.

Recommendation:

The DOE work on tracers that is in progress under Contract No. EW-78-S-19-0006 is worthwhile and should be continued.

Some tracer work in water-saturated reservoirs and in hydraulically-fractured reservoirs is warranted. Also, the two-well tracer method should be field-tested to determine if it is worthy of further development. Depending upon a policy decision, support for these studies could come from the owner of the tracer patents, Exxon, or from DOE. If DOE should decide it can give further support to tracer work, about $100,000 per year for 3 years is recommended.

No. 13 Correlations for Errors in S_{or} (derived from log and core studies) Caused by High-Pressure Gradients

Background

At a given stage in the waterflooding of a reservoir, the amount and the distribution of oil in the flooded part result from complex viscous and capillary forces on the fluids in the reservoir. For a given combination of reservoir rock, water and oil—as well as reservoir history—the amount of oil that remains depends upon the pressure gradient. Other factors being equal, the greater the gradient, the less the oil saturation that remains.

The interfacial tension, σ, as well as the pressure gradient $(\frac{\Delta P}{L})$, affects the value of S_{or}. The capillary number, $(\frac{\Delta P}{L\sigma})$, has been proposed as a criterion for determining if oil will be displaced under given circumstances.[32a] For a given rock, oil is displaced below the normal residual value only if the capillary number exceeds a critical value that is specific for that rock.

The effect of pressure gradient is important in the determination of residual oil for TOR evaluation. In coring (by conventional or pressure-core barrel) an excessive gradient across the part of the rock that is cored can reduce the oil saturation.[18a] In conventional log interpretation, wells must be avoided that have been subjected to high injection pressure.[32a] In log-inject-log methods, displacement of residual oil may be possible if the fluids are injected at too high rates. Likewise, in the single-well tracer test, injection of brine (containing tracer) might cause displacement of oil.

These effects of pressure gradient are well-known. In a general way, in any ROS determination, efforts are made to minimize the movement of oil that might be caused by excessive pressure. Some information is available that helps one to set acceptable pressure limits under certain conditions.[32a] But more critical capillary number data are needed, especially for specific reservoir rocks under conditions encountered in normal practice. Further, in certain cases where oil has been displaced, because of excessive pressure gradients, corrections for the errors in the derived values of S_{or} might be useful.

The above discussion on critical capillary number applies primarily to a water-wet reservoir rock. But the wettability of the rock, as well as pressure gradient and interfacial tension, affects the displacement of oil by water during the flooding process. For example, in a water-wet rock at floodout the residual oil exists as globules or ganglia in the main flow channels of the rock. In an oil-wet rock the residual oil is in the smaller pores of the rock and on the surface of the larger pores of the rock[36] (Ref. 25, p. 8).

A change in the wettability of a reservoir rock can change the distribution and the amount of residual oil in a reservoir. As a matter of fact, the process of "Wettability Alteration Flooding" depends upon a changing of the reservoir rock from preferentially oil-wet to preferentially water-wet, by the action of surface-active chemicals in the injection water.[19] Even a small change in wettability can appreciably alter the value of the oil saturation at the end of a flooding process.

For these reasons investigators generally take precautions to avoid changes in interfacial tension and wettability when they undertake the determination of the oil saturation in a reservoir. For example, Koepf (Ref. 5, p. 37) points out that in coring, surfactants in drilling mud can have an appreciable effect on the degree of flushing of oil from cores by mud filtrate. In L-I-L techniques Wyman (Ref. 5, p. 113) emphasizes the need for precautions against the introduction of chemicals that might alter the residual oil. In the application of the single-well tracer method, Deans (Ref. 5, p. 163) specifies that the tracer should not be surface-active in the oil-brine system.

The ideal—zero introduction of surface-active materials—may be difficult to achieve in practice. Furthermore, if we are to rationalize the results of various ROS tests, we need to understand the mechanism of waterflooding in the reservoir tested. Thus, research on reservoir rock wettability is justified.

Work in Progress

Work is now being done by Morrow[21] on capillary-number correlations and corrections for errors in S_{or} determination, caused by excessive pressure gradients. Attempts are being made to modify the capillary number to account for wettability effects. Factors involved in the determination of S_{or}—and the physical configuration of the residual oil itself—are being studied.

Conclusion

Current activity concerning capillary number and wettability is worthwhile. Research on wettability and related topics should be continued, at the present level, for several years.

Recommendation

Continue present activity.

Extend the investigation beyond the limits of the present study, at current level, for several years.

No. 14 Application of Complete Suite of ROS Methods, in DOE-Supported TOR Projects

Background

When a given method of determining oil saturation is applied in a reservoir, we have no way of knowing how closely the derived oil saturation value approximates the true value—the saturation that exists in the reservoir. The best that we can do is to apply two or more methods in the same reservoir. If the results obtained with different methods agree, we have some assurance that the methods are valid.

But even though different methods give essentially the same results, the agreement between the results may be coincidental. Or the agreement may result from compensating errors in the methods tested. Of course, the larger the number of comparative tests made, the less likely it is that agreement can be the result of coincidence or compensating errors.

Many investigators have made studies of residual oil saturation in which two or more techniques for ROS determination have been used in the same reservoir. Following are some of the studies of this kind that have been made:

1. Murphy and Owens[23]—Conventional cores, pressure cores, waterflood of cores, relative permeability, L-I-L.
2. Murphy, Foster, and Owens[22]—Native-state core floods, pressure cores, L-I-L.
3. Trantham and Clampitt[36]—Relative permeability on cores, microlaterolog, L-I-L.
4. Cordiner, Gordon, and Jargon[10]—Core analysis, WOR and laboratory relative permeability, transient tests, log calculations.
5. Rathmell, Braun, and Perkins[26]—Cores, laboratory waterflooding of cores.
6. Strange and Baldwin[33]—Coring, logging.

7. Howes and Murphy[18]—Laboratory waterflood of cores, L-I-L.
8. Robinson, Vajnar, Loren, and Hartman[30]—Core analysis, restored-state countercurrent imbibition, conventional resistivity core analysis, NML inject-log.
9. Richardson, Wyman, Jorden, and Mitchell[27]—Pressure core, resistivity log, L-I-L with PNC log.
10. Thomas and Ausburn[35]—Pressure cores, complete suite of logs, NML inject-log, laboratory relative permeability, countercurrent imbibition, single-well tracer.
11. Sheely[32]—Electric logs, laboratory waterflood of cores, single-well tracer.
12. Vargo[37]—Waterflood of cores, resistivity logs, L-I-L with PNC log.
13. Bragg et al.[7]—Electric log, C/O log, pressure cores, L-I-L, single-well tracer.
14. Weinbrandt[40]—Conventional cores, pressure cores, electric logs.

Elkins (Ref. 5, p. 278-283) summarizes the ROS results obtained in 74 wells. In most cases more than one technique was used. Elkins' data were obtained from the literature and from an industry survey that was conducted in preparation for the writing of chapters in the IOCC book on residual oil. His Table 2 probably includes data from most of the studies listed above, in which multiple methods for ROS determination were used.

Thus, a considerable body of information is at hand for making comparisons of ROS values obtained by different methods in the same reservoir. To some degree all of the methods that have been used can be checked against one another. But few studies have been made in which all of the principal methods have been used in the same reservoir.

What group of methods would constitute a complete suite, for purposes of comparison of the results of the methods? Opinions differ. Furthermore, the choice of methods will depend upon the kind of reservoir and the kind of wells available. For example, if the reservoir contains little dissolved gas, expensive pressure cores may not be needed. If the well is cased, L-I-L tests with the PNC log are in order; if the well is open-hole, an NML inject-log procedure is needed. For our purposes probably we should aim at studies in which these tests are run:

1. L-I-L with PNC log <u>or</u> inject-log with NML
2. Pressure coring
3. Single-well tracer
4. Waterflood-relative permeability tests on cores
5. Material balance (supplemental information)

Tests on reservoirs having different lithologies (sandstone, limestone, unconsolidated sand) should be made.

Of the investigations listed above, only the Thomas and Ausburn and the Bragg et al. studies appear to have used a complete suite of methods. Even these studies leave some gaps in the comparisons that we would like to make. (No criticism of the other investigations is intended here. Most of them were made to obtain a useful ROS value, not to make a comparison of all possible methods).

We need more studies in which a complete suite of ROS methods is tested in the same reservoir. No doubt some studies of this kind will be made by industry. But, since these studies are expensive, few are likely to be made. Therefore, the technology of ROS determination can be advanced considerably if DOE underwrites the running of suites of ROS methods—especially in TOR tests that receive DOE support.

Objectivity of Interpretation of Tests

In each of the ROS methods the results depend upon certain subjective choices made by the investigator. What pay zones are to be studied? Which core test results are to be accepted? What weight is to be given to the effects of parameters such as porosity and permeability? In the single-well tracer test, which calculated curves give the best fit to the observed results? In L-I-L tests, which results should be discarded because of incomplete displacement by injected fluids?

Even the most honest investigator can be unconsciously influenced in these choices if he knows the results obtained in some of the tests. It is important that precautions be taken to ensure that the interpretations of all the ROS results be made as objectively as possible. Ideally, each method should be applied and interpreted by a separate group, without knowledge of the results obtained by the other groups. Whatever can be done to make the interpretation of the results objective should be done.

Conclusion

As many experiments as possible should be run in which two or more methods of ROS determination are applied in the same reservoir. To the degree that is practical, complete suites of methods should be applied in the same reservoir. The information from these multiple determinations will give us a better idea of the true value of ROS in the reservoirs that are studied. Thus, we will have standards by which we can test and compare the accuracy of present methods, as well as methods that may be developed in the future.

Industry will conduct some of these multiple ROS determinations. However, as techniques are perfected, individual companies will have less and less incentive to do this expensive, time-consuming research. Under the circumstances DOE is justified in sponsoring a considerable amount of this work, to advance our knowledge of residual oil saturation.

The work on ROS that is in progress in the Bell Creek Field, Montana (Ref. 41, Task 110) is a step in the right direction. As opportunities develop, complete suites of ROS determinations should be run in other reservoirs, as described in Task 120 and Task 130 of the above planning document.

Recommendation:

The work outlined in Tasks 110, 120, and 130 of the "Residual Oil Project Planning Document" should be done.

DOE support of about $300,000 annually for 3 years is recommended.

No. 15 Determination of Oil Saturation in the Parts of a Waterflooded Reservoir that Contain Mobile Oil

Background

In this report I have used the term "Residual Oil Saturation" (ROS) loosely. I have used it to mean the oil saturation that exists at points within a reservoir, after the reservoir has been waterflooded.

In a water-wet reservoir the oil saturation that exists throughout the flooded part of the reservoir usually is not very different from the "irreducible-minimum" or "ultimate-residual" saturation that can be achieved in laboratory waterfloods. That is, behind the flood front little mobile oil is present.

But in an oil-wet, or partially oil-wet, reservoir, considerable amounts of mobile oil exist after the passage of the main flood front (Ref. 25, p. 12). In such a reservoir a substantial gradient in the value of the oil saturation can be expected. In these reservoirs a method is needed for determining the total oil saturation—the mobile oil plus the oil that would remain after the passage of large volumes of water. (Strictly speaking, the total oil saturation here is not the "residual oil saturation," as the term is ordinarily used. A better term is "current oil saturation," as defined and used by Trantham and Clampitt[36].)

Probably the best way to find total, or current, oil saturation is the method used by Trantham and Clampitt. They use several backflow and injection steps; PNC (TDT-K) logs are taken between the various steps:

1. The well is back-flowed to re-establish the fluid environment that existed before the well was drilled.
2. TDT-K log is run.
3. Fresh water is injected.
4. TDT-K and MLL are run.

5. Strong sodium chloride brine is injected.

6. TDT-K is run.

The ultimate residual oil saturation (S_{or}) and the current oil saturation (S_o) are given by the equations:

$$S_{or} = 1 - \frac{\Sigma_{log-s} - \Sigma_{log-f}}{\phi(\Sigma_{ws} - \Sigma_{wf})}$$

$$S_o = \frac{\phi(\Sigma_{we} - \Sigma_{wf}) + \Sigma_{log-f} - \Sigma_{log-e}}{\phi(\Sigma_{we} - \Sigma_o)}$$

where: Σ_{log-e} = log reading after backflow

Σ_{log-f} = log reading after fresh water

Σ_{log-s} = log reading after salt water

Σ_{we} = capture cross-section of formation water

Σ_{wf} = capture cross-section of fresh water

Σ_{ws} = capture cross-section of injected salt water

Σ_o = capture cross-section of oil

In this case the mobile oil saturation is the difference: (S_o - S_{or}).

Under ideal conditions this method should yield satisfactory results. But each step in the process leads to some uncertainty in the result. When a well is back-flowed, how can we be sure that we have re-established the same distribution of fluids that existed before the drilling of the well? (See, for example, Swanson[34] regarding the effects of movement of fluids on contact angles.) Can we be sure that in each step the existing fluid is completely replaced by the injected fluid? Note that Trantham and Clampitt[36] (p. 498) say their value for current oil saturation is " . . . probably of rather low accuracy."

Conclusion:

A survey should be made of possible methods for finding oil saturation where some mobile oil is present. The study should include the applications and limitations of present methods. The purpose of the survey would be to try to generate ideas about a possible novel approach to determining mobile oil saturation.

Recommendation:

New logging tools are needed—tools with larger radius of investigation than present tools—or tools not affected by changes in salinity. Research on such tools is under way in the logging companies and in some oil company laboratories. No need for DOE support of this activity is foreseen.

DOE should support a survey of possible ways to find total oil saturation, where mobile oil is present. If a novel, feasible, improved method can be generated by this study, DOE should consider sponsoring the development of the method.

No. 16 Rate of Advance of TOR Front

Background

In applying TOR processes to reservoirs, knowledge of the rate of advance of the injected fluids, as well as the reservoir fluids, is important. To some degree the required information can be obtained from logging and sampling studies in observation wells. But only a limited number of such observation wells is practicable in a given TOR application. In a heterogeneous reservoir the cost of observation wells required to follow the course of a TOR process could be prohibitive.

There is no question about the need for an improved method to follow the advance of a TOR front. Ideally, such a method would give the saturations of the reservoir fluids and TOR fluids throughout the reservoir, at various elevations, without requiring a large number of costly observation wells. But how is this to be accomplished?

Multiple-well pressure-pulse tests can be used to estimate average saturations (Ref. 5, p. 149). Work is in progress on exotic well-to-well methods based on the use of electric pulses or sonic pulses. Such methods probably can be made to yield useful information about the rock strata. But the feasibility of applying such interwell methods to the measurement of fluid saturation distribution throughout the reservoir is very low.

As far as observation wells are concerned, a few suggestions have been made about methods that might be developed. For example, neutron activation—along with a sophisticated gamma-ray spectrum analyzer—might yield detailed information about the TOR front. Radioactive tracers (water- or oil-soluble) likewise might be used. Some development of this kind is said to be under way in certain laboratories. In the absence of concrete proposals, no need for DOE funding for this particular kind of work is foreseen.

Recommendation:

At present no method of investigating interwell space is known that is likely to yield useful information about the saturations of oil and TOR fluids throughout the reservoir. Some of the methods being tested may have merit for other purposes, such as description of the rock strata.

If a novel interwell method should be developed later that appears to be feasible, as far as saturation determination is concerned, DOE should consider testing and development of the method.

No. 17 Survey of U.S.S.R. Literature on ROS Determination

U.S. research people who have studied U.S.S.R. technology and have visited Russia have the opinion that U.S. oil recovery technology is many years ahead of Russian technology.

So far as I have been able to determine, little or no Russian work has been done on the problem of determining residual oil saturation. But the results of a number of Russian studies have potential for application in U.S. research related to ROS determination. For example, Wyman (Ref. 5, p. 112) says that Russian scientists have been active in the field of dielectric logging for many years. Wahl et al.[38] cite several references to pioneering work on PNC logging that has been done by Russian investigators.

Most U.S. researchers rely upon the University of Tulsa "Petroleum Abstracts" for information about Russian oil recovery technology. Apparently the University of Tulsa is fairly thorough in its coverage of Russian work. No significant Russian developments in ROS determination are likely to be overlooked by "Petroleum Abstracts."

For ROS work alone, a DOE study of Russian literature is not warranted. But a number of people have expressed a desire for a more thorough coverage of Russian technology of oil production and oil recovery. Several people have said that we should have some improved mechanism of obtaining copies and translations of significant Russian papers.

Perhaps a small study of the coverage of Russian literature on oil production and oil recovery would be warranted. This study could be made, say, by an SPE committee, with some representation from API and the University of Tulsa.

Recommendation:

An industry committee should look into the question of availability of results of U.S.S.R. research on oil production and oil recovery. In particular, the committee should determine if there is a need for a better mechanism of obtaining English translations of U.S.S.R. publications.

No. 18 Seminar on ROS Determination

Background

The biennial SPE-AIME Symposium on Improved Oil Recovery serves as a medium for interchange of technology and presentation of results of research on ROS determination. The annual fall SPE meeting offers additional opportunity for exchange of information.

But some people who were interviewed expressed a desire for some other kind of meeting, on ROS alone. This meeting could be a seminar or colloquium—perhaps similar to a Gordon Research Conference or a Penrose Conference. The purpose of the seminar would be to generate new ideas, new concepts, and new approaches to the problem of determining residual oil saturation.

If a general open meeting were held, either as an adjunct to another SPE meeting or separately, probably several hundred people would attend. Such a large attendance would defeat the purpose, however -- to generate new ideas and novel approaches. Some good would be accomplished by a large open meeting; but many persons are opposed to "one more large meeting." They think we already have too many meetings of this kind—they interfere with productive work.

The possibilities for a smaller, restricted meeting were explored. The 1979 Gordon Research Conference related to oil recovery is said to be already planned. One of the new SPE "Forums" might suffice. However, only two such Forums have been authorized for 1979 by the SPE Board of Directors; two Forums, on other subjects, have already been planned.

A DOE-sponsored seminar would serve our purpose. Industry participation in planning for the seminar is desirable. A 1½-day meeting, with an attendance of 50-100, at a quiet location near good transportation facilities, is needed.

The seminar should:

1. Identify the areas where industry research on ROS is being carried out.
2. Identify areas where other research is needed.
3. Uncover techniques and tools not being used, that are worthy of testing, development, and application.
4. List new tools needed and summarize progress toward the development of these tools.
5. Catalyze action on needed research and development.
6. Generate industry support for needed development on processes or tools, either current or projected.
7. Generate new concepts
   —new ideas about ROS
   —new approaches to the problem
   —new combinations of known techniques

Such a seminar might lead to simpler, better, less expensive methods of determining ROS.

<u>Recommendation:</u>

DOE should sponsor, with industry help in planning, a 1½-day seminar on ROS. Attendance should be kept between 50 and 100. The purpose should be to generate new ideas—new approaches to the problem of determining ROS.

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- 2 -

Log-Inject-Log

What about the log-inject-log method with chemical stripping of the oil? Is this an area that DOE should support?

Log-inject-log techniques might be developed using radioactive water and gamma-ray logs (described by Wyman, "How Should We Measure Residual Oil Saturation," Bull. Can. Petrol. Geol. Vol. 25, No. 2 (May, 1977), p. 233-270). We might inject radioactive water before and after removal of residual oil, thus eliminating need to know porosity. Should DOE support this work?

What other log-inject-log procedures merit development?

APPENDIX A

BRIEF SUMMARY OF THE STATE-OF-THE-ART WITH RESPECT TO DETERMINING RESIDUAL OIL SATURATION

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BRIEF SUMMARY OF THE STATE-OF-THE-ART WITH RESPECT TO DETERMINING RESIDUAL OIL SATURATION

Why Do We Want to Know the Residual Oil Saturation in a Reservoir?

When we are evaluating the tertiary oil recovery (TOR) potential of a waterflooded reservoir, we would like to know the total amount of oil remaining in the reservoir and we would like to know how this oil is distributed. Especially we would like to know the amount of oil, the oil saturation, and the spatial distribution of the oil in the part of the reservoir that has been subjected to waterflood—the part of the reservoir likely to be affected by injected fluids in a TOR process.

In some cases (100% water-wet, homogeneous reservoirs) the oil saturation in the waterflooded part of the reservoir can be expected to equal the theoretical saturation attained in laboratory tests on cores. These tests may be waterfloods on preserved or reconstituted cores, relative permeability tests, or capillary imbibition tests. In other cases (oil-wet or partially oil-wet reservoirs) the theoretical residual oil saturation may not have a unique value. In any case, what we want to know is the oil saturation—and its distribution—in the waterflooded portion of the reservoir. We want this information to enable us to estimate the amount of oil potentially recoverable in a TOR process.

We use the term "Residual Oil Saturation" here because we do not have a short-hand way of saying: "Oil Saturation in that Part of the Reservoir that Has Been Subjected to the Passage of the Waterflood Front and is Likely to be Subjected to the Effects of Injected Fluids in a TOR Process."

We need to keep in mind the likely possibility that S_{or} will vary within the waterflooded reservoir. Variations in S_{or} can be caused by pattern effects, heterogeneity of rock, especially stratification, and wettability-relative permeability effects. After water breakthrough occurs in a flood, the flood pattern expands in a direction approximately perpendicular to the flow lines. Because the region near the edge of the pattern is subjected to the action of smaller volumes of floodwater than the region swept by the main part of the flood, a gradient in S_{or} exists in the outer part of the pattern, perpendicular to the direction of flow. Stratification of the reservoir rock leads to variations in S_{or} that are well known and need not be discussed here. (The problem of heterogeneity in reservoirs is treated in a book: "Modern Reservoir Description for Improved Oil Recovery," now being prepared by the Research Committee of the Interstate Oil Compact Commission.) In reservoir rock that is not 100 percent water-wet, S_{or} can vary substantially with the number of pore volumes of floodwater that have flowed through a given part of the reservoir; thus, a gradient in S_{or} can be expected along the direction of flow.

These variations in S_{or} —variations caused by pattern effects, stratification, and wettability—are difficult to measure. But they should be kept in mind in any evaluation of a TOR prospect.

List of Methods Currently Used for Determining Residual Oil Saturation

Residual oil saturation is determined by the following techniques or tools:

- Material balance method
- Analysis of cores (conventional or pressure core barrel)
- Laboratory tests on preserved or reconstituted cores
- Single-well tracer method
- Logging tools
    - Resistivity
    - Pulsed Neutron Capture (PNC)
    - Nuclear Magnetism (NML)
- Log-inject-log methods that employ these tools, especially the PNC log

In addition to the above, certain techniques and tools have been proposed or are currently being developed and tested:

- Resistivity log-inject-log
- Gamma radiation log-inject-log
- Dielectric constant log
- Carbon/oxygen log

Radius of Investigation of Methods for the Determination of ROS

In a general way we can classify methods of determining ROS according to the amount of the reservoir sampled, or the radius of investigation of the tool that is used.

The material-balance method gives information about the entire reservoir. The single-well tracer method usually tells something about an average sample out to a distance of 10 to 20 feet from the well; the radius of investigation is limited only by the volume of tracer fluid that can be economically injected. Certain logs (laterolog, induction log, PNC log) sense the physical properties of the rock out to a radius of several inches to perhaps two feet. Other logs (NML, dielectric constant log) have shallow depth of investigation (1 to 2 inches). Finally, cores give a sample of the actual reservoir itself; the problem, of course, is to take this sample without changing it in the process of coring.

Advantages, Disadvantages, and Limitations of Various Methods for Determining Residual Oil Saturation

Each method for determining ROS has certain advantages and disadvantages. No single method is the best one to use universally. The applicability of each is limited, depending upon the nature of the reservoir, the kinds of wells available, and other factors. Following is a brief discussion of the advantages, disadvantages, and limitations of methods for determining ROS. For more detailed descriptions the reader is referred to the Wyman and IOCC references mentioned above (page 1 of this report).

Material Balance Method

In this method the amount of oil produced by primary production and by conventional secondary recovery is subtracted from the estimated initial oil-in-place in the reservoir, at the time of the discovery of the reservoir. The initial oil-in-place is calculated by means of the equation:

$$\text{Initial Oil-in-Place} = N = Ah\phi\, S_{oi}/B_i$$

Where A = area
h = thickness of pay zone
ϕ = porosity
S_{oi} = initial oil saturation
B_i = initial formation volume factor

The weakness of the material balance method lies in the great uncertainty about the value of N. The area A is seldom known accurately. Sometimes not all of the oil-saturated rock is considered to be productive; the thickness of oil-producing rock, h, is often, at best, an estimate.

The porosity of the reservoir rock can be determined from cores. However, in a heterogeneous reservoir it may be very difficult to obtain cores that give a representative sampling of the whole reservoir. There is always the problem of trying to determine the porosity under reservoir conditions—especially under reservoir pressure. Porosity can be estimated from various logs (neutron, density, sonic); however, it is not easy to determine porosity in this manner with the accuracy required for ROS determination in TOR evaluations.

Probably the best way to determine S_{oi} is to core with lease oil, determine S_{wi} (initial water saturation) in the cores, and calculate S_{oi} from the equation: $S_{oi} = (1 - S_{wi})$. But many operators are reluctant to core with crude oil. Furthermore, where a transition zone exists between the oil and water sands, mobile water can be displaced during coring; incorrect values of S_{oi} are obtained, greater than the true values.

Of course, S_{oi} can be estimated by means of conventional resistivity log interpretation, using the classic Archie Treatment: $S_w = \left(\frac{R_w\phi^{-m}}{R_t}\right)^{1/n}$. But this treatment requires that formation-water resistivity—R_w, porosity—ϕ, lithology exponent—m, and saturation exponent—n all be known accurately for the particular zones that are being studied. Furthermore, the quantities ϕ, m, and n must be evaluated under reservoir conditions.

Uncertainties about the parameters A, h, ϕ, and S_{oi} lead to a corresponding uncertainty about the values of N and S_{or}. Therefore, S_{or} seldom can be evaluated by the material blance method with sufficient accuracy for TOR evaluation. However, the material balance values of S_{or} can be useful. For example, if the material balance value of S_{or} is twice the value of S_{or} obtained by other methods, perhaps substantial areas exist in the reservoir where infill drilling would be profitable.

Analysis of Cores—Laboratory Tests on Cores

Conventional cores. In general, fluid saturations in conventionally cored rock are subject to change, either during the process of coring or as the cores are raised to the surface. Any mobile oil present in the reservoir rock will be flushed from the cores by mud filtrate, to some degree. Even though the oil content of the rock is not mobile with respect to the normal pressure gradients that exist during waterflooding, some of the residual oil can be flushed out by mud filtrate because of the abnormally high gradient that can exist across the rock being cored. Of course, evolution of dissolved gas, as the core is brought to the surface, can cause the expulsion of some oil and water from the core.

If the reservoir contains no mobile oil and if the residual oil contains a negligible amount of dissolved gas, under low pressure, cores, properly taken, may have oil saturations not greatly different from the oil saturation in the reservoir. We can be confident that the oil saturation in the reservoir is at least as great as the saturation found in the cores.

Attempts have been made, in the laboratory, to reproduce the processes that occur during coring and to deduce corrections for the effects of mud filtrate flushing and gas expulsion. In some special cases these corrections appear to lead to fairly accurate values of S_{or}. But, as Wyman puts it:

"We are still far from being able to make reliable corrections to account for flushing and blowdown in conventional cores."

Pressure corings. The pressure core barrel enables one to cut and recover cores without the evolution of gas that occurs during conventional coring. Thus, the loss of oil caused by expulsion of gas, as well as the shrinkage of the oil in the core, is prevented (Hagedorn, A. R. and Blackwell, R. J.: "Summary of Experience with Pressure Coring," SPE Paper 3962 presented at 47th Annual Fall Mtg. of SPE-AIME, Oct. 8-11, 1972, San Antonio, Texas).

The pressure core barrel itself does not prevent flushing of the core by mud filtrate. Generally, in pressure coring, attempts are made to minimize flushing by using mud that has: low weight; no surface-active chemicals; low spurt loss and low water loss; particulates sized for the formation being cored; and a tracer, such as tritium, for monitoring filtrate invasion. At the surface the core is frozen so it can be transported to the laboratory for analysis.

Under ideal conditions pressure coring is one of the best ways to obtain S_{or}. Of course, as with conventional coring, a new hole is required and no mobile oil should be present in the cored interval. (Under unusual conditions the drilling of a new hole may be avoided; for example, sometimes it is possible to deepen a shallow hole into part of the reservoir that has been flooded by natural water drive.)

We have no absolute standard with which values of S_{or} determined by various methods can be compared. We can only compare the values of S_{or} with what appear to be the best values, as determined by other methods. In one study involving five determinations good agreement was obtained between S_{or} as determined by pressure coring and the best estimate of S_{or} by other methods. In the IOCC book, a similar comparison for about twenty determinations showed fair agreement in about two-thirds of the cases.

Although the pressure core barrel gives reliable estimates of S_{or} under ideal conditions, these ideal conditions are difficult to obtain. One company reports poor results in about 50 percent of its pressure coring, due to partial loss of pressure and other factors. Another company reports "great difficulty" in obtaining satisfactory pressure cores. In part, the problem appears to be that not enough pressure coring has been done to make it worthwhile for the service company to maintain a trained, experienced stand-by crew available at all times. Also, maintenance of the equipment may suffer when the core barrel is used on an intermittent basis. Anyone who contemplates use of the pressure core barrel should investigate these problems. Considerable improvement in the available service for pressure coring has been claimed recently, as a larger volume of business has been generated.

Laboratory Tests on Cores

In the laboratory various special tests are used to obtain an estimate of the value of S_{or} to be expected in the flooded part of a reservoir. The cores studied may be cores that are preserved, as taken from the core barrel, or they may be reconstituted cores, where an attempt is made to duplicate reservoir conditions. The principal tests involve waterfloods, relative permeability measurements, imbibition measurements, and centrifuge experiments. Preferably these tests are made under reservoir conditions, with reservoir oil and the interstitial water present in the reservoir.

The estimation of S_{or} by these methods is an art in itself. As with other methods, we are handicapped by lack of knowledge of an absolute standard of comparison. There is some evidence that in water-wet cores reliable estimates of S_{or} can be obtained by waterflood or imbitition experiments. In oil-wet rocks, or rocks of intermediate wettability, we may sometimes obtain fairly reliable values of S_{or} if proper precautions are taken. But in such rocks we always have two problems:

(1) we can never be certain we have duplicated the capillary fluid distribution that exists in the reservoir, and

(2) the oil saturation is likely to be a function of the volume of flood water, so a unique value of S_{or} does not exist. In reservoirs that contain such rocks the oil saturation behind the flood front is likely to exhibit a gradient, further complicating the estimation of the amount of oil susceptible to injection of TOR fluids.

Experts in this field of investigation agree that further research is needed. In particular, more studies should be made in which S_{or} as determined by these methods is compared with the best estimates of S_{or} by other methods. But, if the results are to be meaningful, these studies must be done by those highly skilled in the art of running tests of this kind.

Single-Well Tracer Method

The single-well tracer method makes use of a hydrolyzable tracer, such as ethyl acetate. This tracer is dissolved in formation brine, which is injected into a well to fill the reservoir pore space (minus the space occupied by residual oil, of course) out to a radius of about 10 to 20 feet from the well. Some of the primary tracer, ethyl acetate, hydrolyzes in the reservoir to form a secondary tracer, ethyl alcohol. The ethyl alcohol dissolves mostly in the brine, but the ethyl acetate is soluble in both brine and oil, distributing itself between brine and oil according to its partition coefficient between these two fluids.

When the well is back-flowed, the ethyl acetate and alcohol move at different rates. Analysis of the produced fluids, versus time, gives S_{or} by means of a curve-fitting technique. Curves for various assumed values of S_{or} are calculated by means of a computer program based upon the partition coefficient and chromatographic theory.

Certain precautions must be taken. The partition coefficient used must be the coefficient for the distribution of the primary tracer between the formation brine and the residual oil actually left behind the flood front in the reservoir. The composition of this residual oil is not necessarily the same as that of the produced crude oil. Further, the partition coefficient should be determined under reservoir temperature and pressure. Large volumes of pre-flush brine-tracer solution should be avoided, to keep from dissolving light ends from the residual oil and thus changing the partition coefficient. Finally, of course, a new well is preferable.

The main advantage of the tracer method is that it gives information about the oil saturation in a large volume of the reservoir. Thus, some of the problems with shallow-investigation tools (overflushing, capillary end effects) are minimized. Also, the method can be used in either cased or open holes. The method gives a single value of S_{or}, rather than a saturation profile with depth. This single value is considered to be weighted in favor of the more permeable zones in the reservoir. Such a weighted average may or may not be advantageous in TOR evaluations; more study is needed about this question.

In the IOCC study cited above, comparisons were made between S_{or} determined by the tracer method and by other methods, for 14 wells. In all cases except one the tracer gave value of S_{or} about equal to, or less than, the value obtained by other methods. Apparently we can be fairly confident that the oil saturation in the reservoir is at least as great as that given by the tracer method.

Certain major oil companies are licensed by the patent holder (Exxon) and have acquired the know-how required to use the tracer method. These companies also have the equipment and the trained personnel to do the extensive analytical and computer work required in applying the method. Formerly this kind of work was done by a service company licensed for that purpose; it is understood that this company no longer offers this service. Probably any company that undertakes the use of the tracer method will need to develop its own capabilities with respect to chemical analyses and computer calculations, for the time being at least.

Logging

When we estimate the oil saturation in a reservoir by means of a single conventional geophysical log, we need to know certain physical properties of the reservoir rock and the reservoir fluids. For example, to calculate S_{or} from a resistivity log we need to know: the porosity of the rock, its cementation (lithology) exponent and saturation exponent, the clay content of the rock and the clay conductance, and the resistivity of the interstitial water in the rock. In general, we do not know the values of these parameters with sufficient accuracy to yield accurate values of S_{or}; an error of 5 to 10 saturation percent or more can be expected. In a virgin reservoir, where we want to know whether or not to complete a well, such an error is tolerable. But for TOR evaluation of a waterflooded reservoir we would like to know S_{or} with an accuracy of about 2 to 5 percent, so a single log may not yield satisfactory saturation values.

In some reservoirs it may be possible to compare log-derived values of S_{or} with values of S_{or} determined by core analysis or other methods. In effect, through this comparison the logs are calibrated and the uncertainties due to errors in the values of the physical parameters are minimized. But in general we need better methods of determining S_{or} from geophysical logs. The various log-inject-log procedures fill this need.

Log-Inject-Log Methods

In these methods a log is run in a well, fluid of one kind or another is injected into the reservoir, and the same log is run again. About ten different types of log-inject-log (L-I-L) techniques have been used or proposed.

The principal ones are based on the use of resistivity, pulsed neutron capture (PNC), or nuclear magnetism (NML) logs.

Resistivity L-I-L. In this method first the desired resistivity tool is run in the hole to give R_t, the resistivity of the reservoir rock, containing interstitial water plus residual oil at saturation S_{or}. Next, a solvent, mutually soluble in oil and water,is injected into the reservoir to remove the residual oil. This solvent is displaced by water having the same composition as the original interstitial water. Finally, the same resistivity tool is run again to give R_o, the resistivity of the reservoir rock saturated with interstitial water. The residual oil saturation, S_{or}, is calculated from:

$$S_{or} = 1 - (R_o/R_t)^{1/n}$$

Of course, the saturation exponent, n, must be known, from imbibition experiments or other sources. The procedure does eliminate the need to know the porosity and the lithology exponent.

This method should measure whatever oil is present, whether it is mobile or immobile. It has the additional advantage that a deep investigating tool can be used, along with deep injection of solvent; thus, a larger, more representative fraction of the reservoir can be examined than with some of the other logging methods.

So far as is known, the resistivity L-I-L method has not been tested in the field.

Pulsed Neutron Capture L-I-L

The pulsed neutron capture (PNC) tool has a neutron generator which emits pulses of high-energy neutrons. In the rock around the bore-hole these neutrons lose energy until they arrive at the thermal state. The thermal neutrons are captured by nuclei of various atoms in the reservoir. Gamma rays are emitted as capture occurs. Measurement of these gamma rays by the logging tool, at various times after the pulse, gives a means of measuring the capture cross section of the various nuclei in the reservoir.

The measured capture cross section is the sum of the cross sections of the rock matrix and of the fluids (water and hydrocarbons) within the pores. The capture cross sections of the fluids can be estimated from laboratory analyses and published correlations. Or, preferably, the cross sections of the fluids themselves are measured in special cells or tanks. The cross section of the rock matrix is estimated from the lithology of the rock or from experience in the area. (In some cases the capture cross section of the rock matrix has been determined from cores; large amounts of core material are required. Thus far, this procedure has not proved very practical.)

In the log-inject-log procedure most often used, a PNC log is first run, with formation water and residual oil in the pores of the rock. Water is injected whose salinity differs as much as possible from the salinity of the formation water. The PNC log is then run again.

This procedure eliminates the need to know the capture cross section of the rock matrix. Simultaneous equations can be formulated which permit the calculation of S_{or} from the capture cross sections of the two waters and the cross sections measured by the two PNC logs. The calculation requires knowledge of the porosity, which is obtained from cores or logs.

In the PNC L-I-L procedure best results are obtained when the contrast between the salinity of initial and injected waters is at a maximum. As with other methods, injection rates should be low enough to avoid displacement of oil by viscous forces. The volume of injected water should be kept as low as possible, to minimize solution of light ends from the residual oil. Of course, no surfactants should be injected which might change the oil saturation in the reservoir.

In the PNC L-I-L procedure the assumption is made that all of the water that is initially present in the vicinity of the well-bore is displaced by the injected brine. Recent results from L-I-L tests on a cased hole in a water sand, reported by Exxon, cast grave doubt on this assumption (J. R. Bragg et al., "A Comparison of Several Techniques for Measuring Residual Oil Saturation," SPE Paper 7074, SPE Symposium on Improved Oil Recovery, April 16-19, 1978, Tulsa, Oklahoma, p. 375-388).

Other variations of the PNC L-I-L procedure have been used or proposed: (a) log-inject-log with alcohol strip, (b) log-inject-log with chlorinated hydrocarbon strip, and (c) log-inject-log with water having capture cross section adjusted to equal that of the residual oil. Each of these variations has certain advantages described by Wyman in the reference cited on page 2 of the text. For example, with proper procedures the need to measure water capture cross sections and porosity can be eliminated.

The PNC L-I-L procedure can be run in open or cased hole. The effects of borehole, casing and cement are minimized or eliminated by the use of two successive logs.

In the IOCC study cited above, comparisons were made between S_{or} from the PNC L-I-L and from other methods. In most cases S_{or} as derived by the PNC method was at least as large as S_{or} from other methods. In about one-third of the cases the PNC value of S_{or} was significantly greater than the value given by other methods. Perhaps the PNC method is able to "see" oil saturation that is not measured by some of the other methods. On the other hand, perhaps some of the initial water is not displaced by the injected water, so that an erroneously high oil saturation is derived from the results of the test. This question needs to be investigated thoroughly.

Nuclear Magnetism-Inject-Log

In logging with the nuclear magnetism (NML) tool, a strong magnetic field is imposed on the fluid in the pores of the rock by sending a current through a coil in the bore-hole. The magnetization in the fluids approaches an equilibrium value that depends on the strength of the applied field. When the field is removed, protons in the fluids precess about the earth's magnetic field, causing an oscillating, exponentially-decaying voltage which is measured by the tool. For a given induced magnetization the magnitude of the signal depends on the total amount of hydrogen present.

To blank out signals from the mud in the hole, magnetite or other ferromagnetic particles are added to the mud. The measure of oil alone in the pores of the rock is accomplished by injecting into the reservoir an aqueous solution containing paramagnetic ions; these ions deaden any signal from the water phase. Thus, the signal is a measure of the bulk oil-in-place ($S_{or} \cdot \phi$). The value of ϕ from cores or logs is used to calculate S_{or}.

The NML inject-log procedure probably is the most accurate one available for determining S_{or}. Unfortunately it cannot be run in a cased hole. A relatively large hole (7 inches diameter) is required.

The NML tool which has been in use has relatively low signal-to-noise ratio. A new tool has been developed by Schlumberger which appears to give greatly reduced noise, resulting in greater signal-to-noise ratio. However, the stability of this new tool needs to be tested. Also, some experts have said that the validity of S_{or} values derived in L-I-L procedures with this tool needs to be thoroughly evaluated and verified, as was done with the other tool.

Other Possible Logging Techniques

Carbon/Oxygen Log

The Carbon/Oxygen log utilizes a pulsed 14 MeV neutron source and a gamma-ray detector. The tool is optimized for the production of "prompt" gamma rays caused by inelastic scattering of neutrons by carbon. Although the present tool responds to large differences in oil saturation, it is not accurate enough to give S_{or} for TOR evaluation. There is optimism in some quarters about the possibility of eventually developing a satisfactory tool for S_{or} determination.

Dielectric Constant Log

Schlumberger has a new dielectric constant logging tool claimed to be the best tool available for the determination of S_{or} in open hole. Uncertainties caused by salinity changes are minimized or eliminated. The tool has shallow depth of investigation—about one inch. It is said to be much more stable than the NML tool. It has the further advantage of giving vertical resolution within about 2 inches. The tool needs to be thoroughly tested before judgment is passed on its merits.

Summary—Logging

When logs are used to estimate residual oil saturation for TOR evaluation, some kind of log-inject-log (L-I-L) procedure is required. In open hole best results have been obtained with the nuclear magnetism log (NML). The NML has the disadvantage of being a shallow investigating tool. An L-I-L procedure employing a resistivity tool could give a deeper radius of investigation. In cased hole the L-I-L procedure with the PNC tool is preferred. However, further work is needed to establish the validity of the assumptions made in this procedure; in particular, tests are needed in water-saturated sands.

In all types of L-I-L procedure the rate of injection must be kept low, so that the critical value of the capillary number is not exceeded during the injection phase of the test, causing the displacement of some of the residual oil. That is, the ratio of viscous to capillary forces must be kept as low as possible (J. J. Stosur and J. J. Taber, "Critical Displacement Ratio and Its Effect on Wellbore Measurement of Residual Oil Saturation," J. Petr. Tech. 28, 865-868 (Aug. 1976). This precaution is especially important where tools with shallow radius of investigation are used. Further, procedures that employ these tools are susceptible to errors caused by: (1) invasion of the reservoir rock by mud particles, and (2) end effects caused by capillary imbibition. Research is needed to obtain quantitative estimates of all of these errors that may occur when shallow investigation tools are used.

Of course, in any L-I-L procedure no surfactant should be injected. Drift, caused by pressure gradients within the reservoir, should be counteracted by the injection of sufficient water. But the volume of injected water should be kept as low as possible.

CONCLUSIONS

STATE-OF-THE-ART OF DETERMINING ROS

Following is a brief digest of the methods preferred by many of the persons who have worked on the problem of determining residual oil saturation.

Some operators have the opinion that one or more pressure cores should always be taken in any reservoir being evaluated for TOR. Other operators do not take such cores because they consider the cost of pressure coring to be excessive in view of uncertainties about core recovery and the results obtained from the cores.

The logging procedures preferred are the NML inject-log (in open-hole completions) and the PNC log-inject-log (in cased holes).

Single-well tracer tests often are run as a check on the results of pressure coring and log-inject-log tests. The tracer results probably are weighted toward the residual oil saturations that exist in the more permeable parts of the reservoir.

Other sources of information are used, to the extent that they are available, to supplement the results of the procedures described above. These supplemental sources include data from: material balance calculations, production tests and pressure-transient tests, conventional core analyses and log analyses, and injection profiles. In obtaining these supplemental data certain laboratory work may be involved; the laboratory data should always by converted to reservoir conditions, where this is possible.

The reader should be aware that the technology of ROS determination is in a fluid state. Old tools are being improved. New tools are being developed and tested. The availability of tools and services changes almost from month to month. Anyone who is considering the determination of ROS for the evaluation of TOR prospects should be alert for improvements that may be made in the art of making such determinations.

APPENDIX B

QUESTIONS FOR DISCUSSION—R & D NEEDS IN DETERMINATION OF RESIDUAL OIL SATURATION

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Logging, Miscellaneous

What is the depth of investigation of various tools and methods used in the determination of ROS?

Should improved casing materials be developed that will permit better resistivity logging in cased holes?

Should an NML tool be developed that will go into small holes (<7 inches diameter)? Is this feasible?

Can a Nuclear Magnetism Log be developed that will investigate as deeply into the reservoir as the Resistivity Logs?

Will industry develop NML logging devices with higher signal/noise ratio?

Can a reliable, stable carbon/oxygen log be developed that will give S_{or} with sufficient accuracy for TOR evaluations?

Dieletric Constant Logging—can we refine this to permit estimation of residual oil content?

Can a down-hole gravimeter be perfected that will give S_{or} with sufficient accuracy for use in evaluation of TOR applications?

Should we investigate the effects of the following on ROS values that result from use of shallow investigation tools: (a) Displacement of residual oil when critical capillary number is exceeded? (b) End effects and capillary imbibition? (c) Invasion of rock by drilling mud particles?

Log-Inject-Log

What about the log-inject-log method with chemical stripping of the oil? Is this an area that DOE should support?

Log-inject-log techniques might be developed using radioactive water and gamma-ray logs (described by Wyman, "How Should We Measure Residual Oil Saturation," Bull. Can. Petrol. Geol. Vol. 25, No. 2 (May, 1977), p. 233-270). We might inject radioactive water before and after removal of residual oil, thus eliminating need to know porosity. Should DOE support this work?

What other log-inject-log procedures merit development?

Logging, PNC

Should an installation be set up containing rocks of different porosities, and different lithologies, with accurately known fluid saturations, for testing and calibrating various tools (PNC, C/O, NML, etc.). For example, rocks containing (a) 100% oil, (b) oil with connate water, (c) residual oil, and (d) 100% water?

What is the degree of precision of available PNC equipment? What precision is potentially feasible?

Can a routine method be developed for the determination of the neutron capture cross-section of cores of various sizes?

Is industry developing adequate charts (departure curves) for correcting for diffusion effects in PNC logging?

Are departure curves needed for the PNC log, to correct for the effects of borehole size, casing configuration, porosity, and salinity?

Is field research warranted on log-inject-log methods in water-saturated rocks? For example, effect of kind of completion (cased, uncased, casing centered and not centered), effect of porosity, effect of salinity (fresh water, 50,000, 100,000 p.p.m. TDS, etc.), effect of heterogeneity of reservoir rock?

Could the results of the above study tell the degree of flushing during ROS determination by the log-inject-log technique?

Should the neutron capture cross-section of pure elements (Si, Ca, and other elements found in reservoir rock) be measured accurately, to improve on interpretation of PNC logs?

Coring and Core Analysis

What are the chances of developing a practical core barrel with zero flushing of cores by mud filtrate? (See Maurer Engrg. Rpt., etc.)

What are the chances of combining such a core barrel with pressure coring to give essentially unflushed cores under in situ conditions? Are these projects that DOE should support?

Would there be merit in a coring device that would trap all fluids in the cored interval, after the reservoir pressure was released? Feasibility? DOE support?

Is an improved pressure coring device needed to core in deeper wells (higher temperature and pressure)? (For example, for evaluation of potential high-pressure CO_2 floods.) DOE support?

Should more work be done on the effect of reservoir temperature and pressure (vs. ambient temperature and pressure) on porosity and formation resistivity factor of cores? Can better rules-of-thumb be developed for taking into account the effects of temperature and pressure, permitting use of results obtained under ambient conditions? Is this an area for DOE support?

More work may be needed on the determination of the factor to be used in converting from $(\bar{S}_o)_{core}$ to $(S_o)_{res}$—in order to develop better rules-of-thumb to correct for the effects of flushing by mud filtrate and expulsion by gas evolution?

Should laboratory determinations of S_{or} be done on (a) restored-state cores <u>or</u> (b) fresh, native-state cores? Is more work needed in this area?

Can oil saturations deduced from cores be used to deduce gradients in saturation over the reservoir, even though uncertainty exists about the absolute value of the oil saturation?

Tracer Methods

In tracer methods we need to know how stratification of the reservoir rock affects the results. The tracer method yields S_{or} that usually is less than the average S_{or} determination by other methods. Why?

Is research needed on the application of the single-well tracer method in the determination of ROS in a gas cap?

Can the single-well tracer method be used to determine reservoir relative permeability in situ?

What about computer studies (in single-well tracer determinations of ROS) on the sensitivity of the ROS value to changes in various parameters?

Core Laboratories, Inc. formerly offered, as a service, the running of single-well tracer tests for determination of ROS. Should DOE help to set up a not-for-profit service of this kind (for example, at Rice University)?

Would it be worthwhile to run some single-well tracer tests on fractured wells (before and after fracturing)?

Miscellaneous

Should DOE require a complete suite of S_{or} determinations (logging, coring, log-inject-log, tracer, material balance, etc.) on every DOE field test of an enhanced oil recovery process?

Should DOE support other studies involving complete suites of S_{or} determinations in other reservoirs that may or may not be candidates for TOR?

How can we explain results of Murphy et al. (SPE 5804, 1976 Symposium on Improved Oil Recovery) "contrary to expectations, high residual oil saturations were measured in some high permeability intervals."? Should this Murphy et al. anomaly be studied?

Conceivably a TOR process, using viscous polymer chaser, could have a higher pattern efficiency than a prior waterflood. Thus, we may need to know the S_{or} even in parts of the reservoir that are <u>not</u> contacted by flood-water. How much of the reservoir is likely to be affected by such a TOR process? How can we determine the S_{or} in the part affected by such a TOR process, but not by waterflood?

How much of the oil that is by-passed by the tracer fluid will a TOR fluid contact if the mobility ratio of the TOR fluid, with respect to the reservoir fluid, is favorable?

Should more material-balance studies be made, using core data taken under <u>true</u> reservoir conditions, to obtain better estimates of original oil in place—which might lead to better estimates of residual oil after waterflooding, in turn give rules-of-thumb for estimation of S_{or} in potential TOR projects? Should DOE support these studies?

Miscellaneous (Continued)

How about a small feasibility study concerning the determination of ROS by seismic methods (well-to-well, etc.)?

Should more work be done on the estimation of S_{or} from total compressibility of reservoir rock and fluids, as calculated from the results of interference tests?

Can we use statistics (design of experiments) to design the program of coring, logging, etc. that will give the most ROS information for the least expenditure of money?

Is research needed on methods of determining oil saturation in unconsolidated sands containing heavy oil, at high temperature (for steam floods)? DOE support?

Does Russian literature merit a search (sponsored by DOE) with respect to methods of determination of residual oil saturation? Is a "State-of-the-Art" report on Russian work on ROS determination warranted?

Should we organize a seminar (± one week), similar to Gordon Research Conference, limited to 40-60 experts, to study intensively methods of determination of ROS and attempt to develop new concepts and new approaches?

APPENDIX C

PROJECTS NOT RECOMMENDED FOR DOE SUPPORT

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PROJECTS NOT RECOMMENDED FOR DOE SUPPORT

Various persons who were interviewed suggested projects not included in my recommended list above. These projects are listed here, along with reasons why they were not recommended for DOE support.

Many of these projects are worthwhile. Some of them most likely will be studied by oil companies or service companies. Some represent long-shot ideas that have low feasibility. Others await the perfecting of a specific tool now being developed. In a few cases the proposal needs to be spelled out in more specific detail. And some of the projects are in proprietary areas where DOE should not be involved.

As the situation changes, some of these suggestions might be fleshed out later into viable projects worthy of DOE support.

SUGGESTED PROJECTS
NO DOE SUPPORT RECOMMENDED

1. Invasion of reservoir rock by drilling mud particles—effect on ROS and its measurement.

   This area is well covered by the work of Jenks, Fertl, and others.

2. Determination of porosity and resistivity of cores under reservoir conditions.

   —effect on derived value of S_{or}.

   Most companies make this determination routinely. The techniques are known. No work supported by DOE is needed.

3. Experiment design in the planning of a program of coring, logging, etc. to obtain the maximum quality and amount of information about ROS, with minimum cost.

   Most companies do this routinely. No DOE project is needed.

4. Estimation of S_{or} from velocity of micellar flood front, in a mini-test. (U.S. Patent 3,874,451).

   This is an ingenious idea, but it is not likely to give accurate values of S_{or}. Probably it could be tested by using data that are available.

5. Use of gravimeter in determination of S_{or}.

   The gravimeter is not likely to be used directly, in a single measurement, to give an accurate estimate of S_{or}—the density change caused by a small change in S_{or} is too small, in comparison with the other parameters that must be known. But if the gravimeter is improved sufficiently, there is some hope of eventually developing an L-I-L method that would give the value of S_{or}.

6. Development of standards to check the calibration of various logs at the well site.

   The calibration of logs is not easy under laboratory conditions. The value of field calibration is not likely to be worth the effort required to carry out the work in the field.

7. Development of germanium detector (propane-cooled) for quantitative down-hole gamma-ray spectroscopy.

   Work of this kind is under way in various research centers. Because of the proprietary nature of the results, this does not appear to be an appropriate area for DOE sponsorship.

8. Gamma-ray spectrum of gamma-rays resulting from the absorption of epithermal neutrons.

   This is fundamental information that might have some application to logging in general. It might have some application to the determination of porosity. The results would have minimal application in the area of ROS determination. No project for DOE.

9. Development of new logging tools with improved characteristics.

   Improvements are needed in various tools; C/O log, NML, dielectric constant log, and others. A tool is desired that will give good depth of investigation, will be subject to minimum bore-hole effects, and will not be sensitive to changes in salinity. To the degree practicable, work on these tools is now being done by service companies and a few oil companies. DOE support is not needed here. Small studies of specific logs may be in order.

10. Coring tool designed to retain all core fluids under reservoir pressure.

    American Coldset Corp. has designed a core barrel intended to retain all of the core fluids, under reservoir pressure, even though the seal around the core itself may leak. A prototype was tested in a hole; it failed to perform as expected. An improved model is being built, which may be ready for testing in about a year. No DOE support is needed.

11. Use of gamma-ray spectral log and radioactive tracers in L-I-L technique.

    Two radioactive tracers, one preferentially soluble in brine and the other in oil, are proposed. Comparison of the gamma-ray spectral logs, before and after injection of brine that contains the tracers, is to give S_{or}.

    If the details of this method can be worked out, tests on the method might be included in the work on untested L-I-L combinations (No. 9 in the list of recommended projects).

12. "hydrogen index" measurements of minerals and compounds.

    Measurements on certain materials, such as CO_2, steam, petroleum sulfonates, limestone, dolomite, silica, and clays, might help in the interpretation of neutron logs obtained in the course of TOR projects.

As far as ROS is concerned, the use of L-I-L techniques makes these measurements have little value. No DOE project is warranted.

13. Use of single-well tracer method to determine oil saturation in a gas cap.

This method will be tested by industry. No help from DOE is needed.

14. Study of "anomalous" high residual oil saturations in highly permeable intervals (Murphy et al., J. Petrol. Tech., Feb. 1977, p. 178-186.)

Often real reservoir rocks show a definite trend—the lower the porosity and the permeability, the higher the value of S_{or}; in some cases, though, S_{or} appears to be independent of porosity and permeability. Therefore, the Murphy et al. results are not necessarily anomalous. There is no justification for a DOE project.

15. Depth of invasion of various logging tools.

Information on this subject is available from the logging companies. A comprehensive up-to-date summary of this information should be published by the logging companies. No DOE support is needed.

16. Laboratory determinations of S_{or} —use of native-state vs. restored-state cores.

Techniques for these determinations have been perfected. They are made routinely in oil-company and service companies' laboratories. No DOE support is needed.

17. Well-to-well seismic method for determination of S_{or}.

The feasibility of using well-to-well seismics for accurate determination of S_{or} is so low that a DOE project is not warranted.

18. Well-to-well resistivity measurements, for determination of ROS.

Resistivity depends upon so many parameters whose values are uncertain that an accurate determination of ROS from such measurements is not likely. Because of low feasibility, no DOE support is recommended.

19. Use of Bodine sonic core drill to obtain "true" samples of reservoir rock and its associated fluids.

The sonic core drill has been developed by Bodine Soundrive Company. The principle of the drill is said to be based upon a resonating pipe which vibrates at its natural resonant frequency. If the Bodine drilling system could be modified to permit the sealing of fluids within the core that is cut, a satisfactory method for obtaining "true" reservoir samples might result.

Possibilities for the development of such a system are being explored by Bodine and various service companies. No need for DOE participation is foreseen.

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