FOSSIL ENERGY

DOE/ET/10145-64

A SURVEY OF ACTIVITY IN THE AREA OF INSTRUMENTATION FOR RESERVOIR DESCRIPTION FOR ENHANCED OIL RECOVERY

Final Report

Work Performed for the Department of Energy
Under Contract No. DE-AC01-76ET10145

Date Published—May 1981

Gulf Universities Research Consortium
Bellaire, Texas

U. S. DEPARTMENT OF ENERGY

DISCLAIMER

Available from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22161.

NTIS price codes
Paper copy: $8.00
Microfiche copy: $3.50

DOE/ET/10145-64
Distribution Category UC-92a

A SURVEY OF ACTIVITY IN THE AREA OF INSTRUMENTATION FOR RESERVOIR DESCRIPTION FOR ENHANCED OIL RECOVERY

Final Report

Gulf Universities Research Consortium
5909 West Loop South, Suite 600
Bellaire, Texas 77401

GURC Report No. 173

Technical Project Officers

Dr. Charles W. Perry
U.S. Department of Energy
Washington, D.C. 20545

and

Dr. Fred W. Burtch
U.S. Department of Energy
Bartlesville Energy Technology Center
Bartlesville, Oklahoma 74003

Work Performed for the Department of Energy
Under Contract No. DE-AC01-76ET10145
(Formerly No. EX-76-C-01-2025)

Date Published—May 1981

UNITED STATES DEPARTMENT OF ENERGY

FOREWORD

This report is the result of work performed under Task XXI, Special Technical, Economic and Engineering Tasks -- of DOE Contract No. DE-AC01-76ET10145 (formerly EX-76-C-01-2025), Sub-Task (e):

> "Review the state-of-the-art on electronic instrumentation applied to oil and gas reservoir definition and fluid flow. Recommend appropriate technology development areas for F.F.E.".

The report is based on a study of the literature and a survey of university and industry opinion. The contribution of Robert H. Maier to the basic framework of the report is gratefully acknowledged. Responsibility for the interpretations and opinions rests with Gulf Universities Research Consortium as contractor to the US-DOE.

Prepared by:

J. P. Brown
J. P. Brown
Consultant

Approved by:

James M Sharp
Dr. James M. Sharp
President

C R Hocott
Dr. Claude R. Hocott
Vice President for
Energy Programs

Table of Contents

Abstract

This report reviews the state-of-the-art and recent progress in the types of instrumentation which can be applied to reservoir description. The traditional sources of reservoir information are cores, wire line logs and well tests. There are, however, new techniques which involve geophysics, geochemistry and tracer testing. For the purposes of enhanced oil recovery, the instrumentation must be capable of measuring smaller scale effects with greater accuracy than was considered necessary in the past in oil exploration. The report concludes that considerable progress has been made in instrumentation but that greater precision in measurement is needed.

Active encouragement of synergy between engineers and geologists is a main factor which is recommended so that modern instrumentation can provide information to be used to model rock-fluid systems, geologically and chemically. An important step is to recognize the significance of environment of deposition as a factor in interpreting areas between control wells. Computer simulation utilizing geological detail can then project the behavior of the EOR processes selected for the reservoir. An ongoing Enhanced Recovery Instrumentation Program could optimize further progress toward fully effective oil production.

Executive Summary

The surveys conducted for this report show that, for Enhanced Oil Recovery, industry most of all wants people who can apply already existing tools and instruments and then make useful and reliable recommendations. There also is a critical need for more effective interpretation of data from existing instruments and from more sophisticated tools.

The instrumentation which is now available can be used to make an estimate of most of the parameters needed to characterize the reservoir rock in each well. The amount of residual oil in the vicinity of a well can be approximated. Using these types of information, Enhanced Oil Recovery projects can be designed and an attempt can be made to predict their effectiveness. Further progress is being made in methods which may be capable of keeping track of the oil bank as it moves through an EOR reservoir. With these tools and techniques, tertiary oil can be produced but there is now a need for a significant improvement in the effectiveness of production processes. When this improvement is achieved, there will be a significant increase in recoverable reserves.

The key to making this significant improvement relates to the realization that measurements which are made in bore holes provide only a widely spaced sampling of a very complex system. To optimize performance from an EOR project, a synergistic model of the whole reservoir rock-fluid system in the project area must be put together. This modelling

will require the cooperation of specialists from many disciplines. Those responsible for coordinating these efforts must set a goal of using a number of reasonable interpretations to build a comprehensive model.

Geologists will use regional and local information to build the framework of a model by reconstructing depositional patterns affecting directional permeability and intercommunication throughout the field area. These data will be derived from a range of types of instrumentation from a simple electric log to give basic dimensions to a Scanning Electron Microscope for very fine detail. Petroleum engineers will be able to extrapolate the observed rock and fluid properties through the reservoir system defined by the model. This will be achieved by reference to measurements from a range of types of instrumentation from single well testing through multi-well testing to tracer flow testing. Logging engineers and geophysicists may be able to use knowledge gained from the model to detect slight changes in the well bore and between wells to monitor and describe the movement of a front. Recognizable progress is being made in gathering, filtering and interpreting observations of dynamic processes using instrumentation ranging from seismic methods to tiltmeter surveys.

In light of this situation and a need for synergistic interaction, the recommendation of this report is that an Enhanced Recovery Instrumentation Program (ERINPRO) should be instituted to integrate the expertise of all these disciplines. Under the guidance of an Instrumentation Committee drawn from industry, academia and the government, specific needs would be identified, priorities would be set, and research and development would be monitored. Practical application of improved methods would be moved into field use with expedience and cross-disciplinary interactions would be encouraged by publication. A successful program would greatly increase the effectiveness of Enhanced Oil Recovery.

1.0 Introduction

Enhanced Oil Recovery (EOR) processes evolved in the laboratory and have continued to evolve under field conditions. Early field tests were conducted to develop the operational techniques of applying the EOR processes. At the same time, efforts were made to evaluate how each process would perform in relation to the reservoir environment involved.

The need for improved reservoir characterization soon became apparent, and the application of instrumentation to more detailed quantitative reservoir description for EOR became a prime concern. Tools and instruments were improved, and new ones were developed and tested. It was generally recognized that higher quality logging and observation would be essential. It also became apparent that efforts had to be made to develop a cadre of trained personnel, with close cooperation between engineers and geologists, and between research and operational teams.

It has been recognized that process design and evaluation for each of the EOR methods have somewhat different data requirements. Program planning for instrumentation on a specific project is dictated in large part by the choice of which EOR process is to be applied. At the same time, reservoir interpretations based on the first reconnaissance wells indicate the degree of heterogeneity to be expected. These data may have a profound effect on decisions made concerning density of control and sampling intervals. A reservoir which appears to be very heterogeneous will have a need for greater density of measurements than one with less heterogeneity.

Available tools and instruments are capable of generating large quantities of useful data which must be interpreted. Although further development of instrumentation will undoubtedly be helpful, there is a more critical need today for the proper application of available tools and for meaningful interpretation of the resulting measurements. This calls for the full coordination of interdisciplinary teams of geologists, geophysicists, logging specialists and reservoir engineers. It is referred to as Synergy because the total effect is greater than the sum of the individual efforts. Obviously, it depends on adequately trained manpower, carefully supervised. An important objective of these teams will be to make significant advances in the understanding and prediction of relationships between the reservoir environment and the performance of recovery processes. An example can be taken from the reduction in the number of wells considered necessary for primary production from some fractured fields. This economic improvement has been based on cooperative interpretation of the high resolution dipmeter.

Results like these can be accomplished through future programs integrating information gained from well logging, core analysis, surface and subsurface geophysics, tracer testing, pressure and production testing. Then a full geologic interpretation based on understanding of depositional environments and post-depositional diagenesis can be used to build geologic models for use in numerical reservoir simulation. Simulation results need to be compared, retrofitted, and recompared on the basis of process performance in field pilot recovery tests. In this way the tools that we have can be properly evaluated, and recommendations for improved oil development and interpretive techniques can be properly defined.

A survey was made under subcontract by Dr. L. Z. Shuck. As it is comprised of independent descriptions of specific projects it is included as Appendix A. This report, "Summary of Some Instrumentation and Methods Pertinent to Reservoir Characterization for Enhanced Oil Recovery", addresses the usefulness, potential and limitations of a number of measurement techniques based on information reported in the survey.

2.0 Coring

Coring is the best method for direct analysis of the reservoir. Many oil fields have had cores cut in the discovery well as part of an ongoing exploration program. After a field had been discovered it was sometimes the practice to core at least a few development wells to provide core analysis information for reservoir calculations and for log calibration. During the period of low oil prices this amount of core control was sufficient to characterize the relatively uncomplicated reservoirs believed to be present in the fields which were then profitable.

As the price of oil began to rise, fields became commercially valuable in which production was more difficult because of less favorable reservoir properties and greater reservoir heterogeneity. More frequent coring became necessary to determine variations in porosity and permeability and to provide samples to subject to analytical techniques such as the preparation of capillary pressure curves. At this stage the investigations were designed to study petrophysical properties. It was felt that simple interpolation would provide all the information needed between the control wells.

More recently it has become very important to produce as much oil as possible during primary and secondary recovery. At the same time some techniques of tertiary recovery have passed from the experimental to the operational stage. To be able to optimize every stage of recovery it has been found necessary to study the reservoir rock in great detail. Cores make this possible.

Not only is it desirable to be able to examine a core of reservoir rock that is as close as possible to being in its original condition but the contained fluids should be unchanged. The ideal that is aimed for is called "native state". The difficulties in achieving this objective have been partially overcome by the development of pressure core barrels. These are designed to bring pieces of core to the surface at reservoir pressure and with the minimum of alteration to the porous rock or its contents.

In a report prepared for the Department of Energy concerned with determining residual oil[1], D. C. Bond recommended DOE support for the development of new or improved pressure core barrels. In the book published by the Interstate Oil Compact Commission, "Determination of Residual Oil Saturation"[2] it is concluded that a pressure coring system has yet to be developed that completely eliminates flushing of oil by mud filtrate. It also is emphasized that core properties such as porosity and formation resistivity factor must be corrected from the laboratory conditions to the in-situ stress conditions of the actual reservoir.

A project at the Sandia Laboratories[3] for the development of an improved coring system is designed to give a greater degree of control on the pressure cores but it does not completely overcome the problems of flushing, pressure leak-off or fluid leak-off due to expansion. The same problems apply to correct use of this tool as they do to other wire line tools, especially the coring fluid design.

At the same time as these advances were being made with respect to reservoir properties in the bore hole, it became obvious that significant variations were present between bore holes. There is no direct method of collecting rock samples from the area between bore holes, but the study of cores together with "geologic modelling", will give the clearest indications of probable intermediate variations. Many of these variations are caused by the environment of deposition of the rock. The interpretation of depositional environment that can be made from cores will guide the delineation of such things as porosity trends and permeability barriers which are very important in drawing reservoir maps.

Cores are used in several distinct analyses often conducted independently under different departmental managements:

1. Displacement studies to determine the physical and chemical responses of the core and its resident fluids to a specific EOR process. In effect, a physical simulation of the EOR process.

2. Basic rock property and fluid saturation studies to determine and describe factors affecting storage capacity, transmission properties, and multiphase flow.
3. Geological/geochemical studies to help determine depositional and diagenetic factors.
4. Petrophysical analyses to calibrate well logs.
5. Highly specialized, EOR specific analyses including scanning electron microscopy, X-ray scanning, wettability, surface area and combustion studies.

These analyses almost always require samples from the same cored interval. Close interdisciplinary coordination for choosing where cores should be taken, for selecting the method of coring, for performing the analyses, and for interrelating the data should be recognized from the outset as essential in DOE sponsored projects.

The multiple uses of core material require the development of techniques (photographic, graphic, tabular, etc.) to disseminate core data in the most basic form possible and permit access to the highest degree practicable. The possibility of setting up core storage facilities should be considered. In Alberta, Canada, for example, the complete core is stored by the Oil and Gas Conservation Board. In the UK and Norway a slice of core is stored by the government.

Some of the logging techniques described in the next section give responses difficult to interpret when influenced by unanticipated constituents in the formation. Logging surveys must be supported by core analyses backed up with knowledge of mineral distributions throughout the reservoir. Useful information can be gained from side wall cores taken at selected intervals after logging, in wells where conventional coring is not considered necessary.

Coring References

1. Bond, D.C., "Study of the Potential for Future Work on Methods of Determining Residual Oil", prepared for the U.S. Department of Energy, BETC-0007-3, April 1979.

2. "Determination of Residual Oil Saturation", Interstate Oil Compact Commission, June 1978.

3. Project managed by Bartlesville Energy Technology Center: "The Construction and Evaluation of an Improved Pressure-Coring System", Sandia Laboratories, Albuquerque, N.M., Technical Project Officer: C. Ray Williams, BETC.

3.0 Logging

Wireline logging and other devices for making measurements in the bore hole and adjacent formations are the main source of information for reservoir description. Almost every well, whether a producer or a dry hole, has had some logs run. When there are indications of hydrocarbons a more complete logging suite is taken to determine the quantity and identity of fluids around the bore hole.

As had been mentioned in the previous section, when conventional or sidewall cores are taken, logs can be calibrated and used with greater precision. In most cases in the past this has been considered to be sufficient basis for a complete log-derived interpretation of the reservoir. The sophisticated logging tools which are now available use a combination of information including electrical resistivity, radioactivity, sonic velocity, density and reaction to bombardment with neutrons. Research and development of new ways to learn more about subsurface reservoirs has been successful and has increased the accuracy of estimation of rock and fluid properties close to the bore hole. The relative value of equity in oil properties during primary production is usually decided on the basis of this estimation. In future EOR projects, those making crucial decisions relative to taxation and the incentive program will have to rely on the best estimates that can be made at that time.

Although progress has been made, existing logging tools and interpretive techniques are continually being refined to yield better information for Enhanced Oil Recovery projects. Innovative tools are being developed in the course of research programs which are designed to answer specific questions raised by EOR technologists. The application of this instrumentation now needs to be the focus of attention. Experience in running the tools and interpreting the results should be carefully documented. A pool of expertise needs to be developed emphasizing EOR applications.

For example, results from tools for estimating oil saturation must be interpreted in the context of the location of the bore hole; i.e., is the bore hole near a well which was previously used for oil production or injection? Is it in the previously swept region, or the previously unswept region? Whichever it is, what is the consequence to interpretation of the logs? Is the measurement consistent with expected variations related to these location differences: by production history, geochemical processes, and geological principles?

Specific research programs have been sponsored by the Department of Energy in an effort to make it possible to use new tools more effectively. These include projects being conducted at Sandia Laboratories, Los Alamos Scientific Laboratory and Lawrence Livermore Laboratory, (see References 1a-e) results of which should be applicable to EOR.

At Sandia, very detailed mineralogical, physical and chemical analyses of core samples are being conducted as part of an investigation of nuclear magnetism logging. Another project concentrates on different aspects of electrical impedance logging as related to porosity, gas-water ratios, and fluid permeabilities. The usefulness of these logging techniques will be greatly increased by a better understanding of the response to be expected in different lithologies.

At Los Alamos, studies are being made of nuclear magnetic resonance with emphasis on rocks with low permeability. There is also a project to measure porosity and permeability under simulated in-situ conditions.

At Lawrence Livermore, a project involving measurements under simulated in-situ conditions will lead to an investigation of fracture mechanisms.

Some nationally supported projects such as the Hazardous Waste Management Program[2] include instrumentation research. Attempts are being made to measure subsurface parameters to gain as precise a knowledge as possible of potential storage and disposal sites.

Development of the Borehole-Gravimeter was partially supported by the United States Geological Survey and it has been applied by several companies. This instrument is now available commercially but little information about its usefulness has been published. The use to which this tool might be put in Enhanced Oil Recovery relates to the detection of density anomalies remote from the bore hole[3,4], which should be useful in estimating porosity and residual oil saturation in interwell areas.

An assessment of the state-of-the art of all types of exploration instrumentation has been prepared for the Director of Fossil Fuel Extraction[5]. That report covers coal, gas from coal and oil shale, as well as measurements relating to petroleum.

The study by D. C. Bond on future work on methods of determining residual oil is an important analysis of the state-of-the-art and, we believe, supports the conclusion that so far nothing has been developed to make reliable direct measurements in interwell areas. Interpretive methods will have to be used for some time to come.

It is very instructive to examine the progress made by the National Geothermal Exploration Technology Program[7]. In response to needs which were recognized in 1977, the Department of Energy instituted the Geothermal Log Interpretation Program. With continuity provided by a steering committee of sixteen recognized experts from the universities, agencies, service companies and energy companies and with a steady output of publications, the program has made a valuable contribution. The key publications are a state-of-the-art review, cost benefit analyses of geothermal log interpretation and case history reports.

This type of approach applied to enhanced recovery instrumentation would help to identify the technology development areas called for in Sub-Task(e) mentioned in the Foreword of this report. Requirements for fundamental research could be defined and cost benefit analysis used to create priority lists, both for commercial developments and for possible DOE supported university projects.

Further advantages to be gained from an Enhanced Recovery Instrumentation Program (ERINPRO) would include:

(a) the possibility of organizing workshops on logging and interpretational methods.

(b) the collection of material for calibration and case history purposes.

(c) the application of relational data base techniques to the great mass of information on log types, lithological variations, reservoir fluids (static and dynamic) and physical limitations so that all possible combinations can be examined. This technique has already been shown to produce very useful results in the understanding of the Enhanced Oil Recovery cost-shared programs and the DOE supported research programs.

<u>Logging References</u>

1. These are some of the instrumentation projects managed by Bartlesville Energy Technology Center:

   (a) "Instrumentation For Formation Evaluation and Advanced Logging Techniques", Sandia Laboratories, Albuquerque, New Mexico, Technical Project Officer, Herbert B. Carroll, Jr., BETC.

   (b) "Study of Sonic, Neutron and Density Logging of Low-Permeability Gas Sands", Texas A&M Petroleum Engineering Dept., College Station, Tex., Technical Project Officer, Herbert B. Carroll, Jr., BETC.

   (c) "Remote Characterization of Fluid Saturation in Western Sands", Los Alamos Scientific Laboratory, Los Alamos, N.M., Technical Project Officer, Leonard Volk, BETC.

   (d) "Measurement of Formation Characteristics for Western Tight Sands", Institute of Gas Technology, Chicago, Illinois, Technical Project Officer: Clarence J. Raible, BETC.

   (e) "Low-Permeability Measurements in Productive Sands and Interbedding Material From Tight Western Reservoirs", Lawrence Livermore Laboratory, Livermore, California, Technical Project Officer, Clarence J. Raible, BETC.

2. Romig, P.R.: "Testimony Before the Interagency Review Group on Nuclear Waste Management", as reported in <u>Geophysics</u>, vol. 43, no. 7, December 1978, p. 1555.

3. Schmoker, J.W.: "Accuracy of Borehole Gravity Data", <u>Geophysics</u>, vol. 43, no. 3, April 1978, pp. 538-542.

4. Jageler, A.H.: "Improved Hydrocarbon Reservoir Evaluation Through Use of Borehole-Gravimeter Data", J. Pet. Tech., June 1976, pp. 709-714.

5. "Instrumentation State-of-the-Art Assessment", Program Development Branch, Fossil Fuel Extraction Division, U. S. Department of Energy, September 1979.

6. Bond, D.C.: "Study of the Potential for Future Work on Methods of Determining Residual Oil", prepared for the U. S. Department of Energy, BETC-0007-3, April 1979.

7. Ball, L., J.W. Salisbury, P.R. Kintzinger, A.F. Veneruso, and S.H. Ward, "The National Geothermal Exploration Technology Program", Geophysics, vol. 44, no. 10, October 1979, pp. 1721-1737.

4.0 Residual Oil Saturation

The importance of having accurate knowledge of the amount and distribution of oil in a reservoir has been recognized from the earliest days of oil production. Methods were developed to measure the amount of oil in cores taken from productive formations. From these measurements much was learned about the behavior of gas, oil and water when they occur together in a porous rock. Continuing research has resulted in an understanding of the theories of petroleum engineering from which it is possible to calculate the expected performance of a reservoir.

The difference between the theoretically derived values of oil saturation and the measured amount in cores has made it apparent that improved coring equipment is needed as described in the section on coring. The objective of making better measurements of residual oil also is the objective which has motivated the development of the new methods mentioned in the section on logging.

Progress in logging up to this time had made possible an increasing accuracy in estimation of oil saturation. While primary production predominated and while secondary production was limited to the simplest fields, currently achievable precision of measurement was sufficient. For tertiary oil (that remaining after primary and secondary production) and perhaps for marginal virgin reservoirs, improved accuracy of measurement can be critical. Small variations in estimates might quite easily make the difference between a decision to make large EOR investments or to stop production on a partially depleted field.

The Interstate Oil Compact Commission sponsored the publication in 1978 of a book, "Determination of Residual Oil Saturation"[1], with D. C. Bond, C. R. Hocott and F. H. Poettmann as the Editorial Board. Individual chapters by experts in each field cover all aspects of the subject. Particular reference is made to instrumentation in the chapters titled Logging Methods by Richard E. Wyman and Evaluation by L. F. Elkins. Under Recommendations, the main emphasis was on improvements in calibration and accuracy of existing well logging systems. In addition, stress is laid on the recognition that there are large variations in oil saturation remaining in reservoirs that are depleted by waterflood or water drive.

The ongoing DOE Residual Oil Program, managed by BETC, Ref. 2 includes a project at the Petroleum Recovery Research Center, New Mexico Institute of Mining and Technology, designed to achieve a theoretical understanding of what controls the entrapment and mobilization of residual oil. Also needed is the ability to predict the distribution of controlling factors (and hence oil saturation) in the areas where no measurement exists. This can be addressed using field production history, injector/producer well relationships, and geological/geochemical principles based on depositional and diagenetic processes. Other residual oil projects managed by BETC are listed in reference 2.

In a 1979 DOE report on "Future Work on Methods of Determining Residual Oil", written by D. C. Bond[3], the recommended expenditure is mainly related to logging methods. Proposed projects concentrate on existing techniques with work being encouraged on a novel proposal only if an untried new method can be shown to be feasible. This study was based on visits with 12 oil companies, two service companies and three universities.

Oil Saturation References

1. "Determination of Residual Oil Saturation", Interstate Oil Compact Commission, June, 1978.

2. "Measurement and Correlation of Conditions For Entrapment and Mobilization of Residual Oil", Petroleum Recovery Research Center, New Mexico Institute of Mining and Technology, Socorro, New Mexico, Technical Project Officer, James B. Jennings, BETC.

3. Residual oil projects managed by BETC:

   (a) "Residual Oil Saturation Technology Evaluation in an Unconsolidated Sandstone Reservoir-Wilmington Field, California, City of Long Beach, Long Beach, California, Technical Project Officer, Thomas C. Wesson, BETC.

   (b) "Bell Creek Residual Oil Saturation Technology Test", Gary Energy Corp., Englewood, Colorado, Technical Project Officer, Thomas C. Wesson, BETC.

   (c) "BETC Information Management System With Focus on ROS Estimation", Science Applications, Inc., Englewood, Colorado, Technical Project Officer, Ray Heemstra, BETC.

   (d) "Improved Accuracy and Interpretation of the Single-Well Tracer Method For Residual Oil Saturation Measurement", Rice University, Houston, Texas, Technical Project Officer, Ray Heemstra, BETC.

4. Bond, D. C.: "Study of the Potential for Future Work on Methods of Determining Residual Oil", prepared for the U.S. Department of Energy, BETC-0007-3, April 1979.

5.0 Geochemistry

As more is learned about enhanced oil recovery it is becoming essential to study the geochemical changes which may result from the injection of different aqueous solutions. Permeability has been shown to deteriorate when mica grains are exposed to sodium chloride or calcium chloride solutions. Permeability may also be affected if small grains become free to move in a sandstone matrix as a result of the dissolving of carbonate cement by injection fluid[1].

Adsorption of surfactant and other injected chemicals by various mineral components of the reservoir will require continued study because of its economic impact. Part of the problem is adsorption and part may be a result of precipitation[2]. An understanding of this type of effect will only come from very detailed petrographic studies of the original reservoir, using the Scanning Electron Microscope, and studies of possible changes in the reservoir resulting from geochemical processes. The measurement of local and interwell geochemistry will then be increasingly important to EOR processes.

Geochemistry References

1. Reed, M.G.: "Formation Permeability Damage by Mica Alteration and Carbonate Dissolution", J. Pet. Tech., September 1977, pp. 1056-1060.

2. Celik, M.: "The Role of Surfactant Precipitation and Redissolution in the Adsorption of Sulfonate on Minerals", SPE paper 8263 presented at 54th Annual Technical Conference, Las Vegas, Nevada, September 23-26, 1979.

6.0 Pressure Testing

Progress in the application of pressure testing to the study of oil and gas fields has paralleled the work done on logging. At first, simple pressure readings were taken at the surface when the well was flowing and when it was shut in. A great advance was the development of a continuous recording tool which measured pressure at the bottom of the well. The accuracy and convenience of bottom-hole pressure measurement methods and interpretation techniques still is being improved.

Single well tests of relatively short duration and single well pressure recording during long term production both can give important information about the reservoir. Some of this information is related to the reservoir near the hole and makes it possible to estimate the ability of a given well to produce. There may be indications that the reservoir has been damaged during the drilling of the well and that it might react favorably to stimulation by acidizing or fracturing. From longer term production testing it may be possible to tell whether there are any major barriers within the reservoir in the vicinity of the well. Some engineers feel that faults and other interruptions can be detected and their distance estimated using these methods. Anomalous behavior during the long term tests should alert the operator to possible heterogeneities. Separate testing of individual parts of the reservoir may show that the interruptions are limited to one part of the section and that the rest of the section will produce satisfactorily.

Multi-well tests are designed to evaluate communication through the reservoir between the bore holes and to learn more about the intervening rock properties and fluid content. As the pressure in one well is lowered by fluid production or raised by injection, the changes in pressure of neighboring wells are observed and recorded. Measurement of bottom hole pressure as a function of time yields important information about transmissibility. These multi-well tests, which provide information on relative interwell transmissibility, can be a source of guidance in developing data for use in numerical simulation.

A clue to the complexities in pressure response that can arise in fractured reservoirs is reported in a study concerning an oil field in Pennsylvania[1]. Another report, on the interference testing of sixty-four well pairs, describes the DOE/Cities Service project in Kansas[2]. The results of this testing made it possible to select a well pattern to give more uniform sweep.

In describing the use of a sensitive down-hole quartz pressure gauge, a paper on geothermal reservoirs in California and Idaho[3] shows that very weak pulses can now be measured. The variation of fluid pressure caused by earth tides is less than one pound per square inch, but it was measured repeatedly, and a correction was made for the effect.

The use of pressure transient tests to arrive at descriptions of different reservoirs has been demonstrated in fields in Nebraska and Texas[4]. Homogeneous and heterogeneous reservoirs react in predictably different ways which can be used to arrive at an interpretation of the areas between control points. The advances being made in pressure testing and its interpretation hold great promise for a better understanding of interwell areas.

Pressure Testing References

1. Shuck, L.Z. and C.A. Komar: "The Dynamic Pressure Response of a Petroleum Reservoir", SPE paper 8349 presented at the SPE-AIME 54th Annual Fall Meeting, Las Vegas, Nevada, September 23-26, 1979.

2. Swift, S.C. and L.P. Brown: "Interference Testing for Reservoir Definition -- The State of the Art", SPE paper 5809 presented at the SPE-AIME Fourth Symposium on Improved Oil Recovery, Tulsa, Oklahoma, March 22-24, 1976.

3. Witherspoon, P.A., T.N. Narasimhan, and D.G. McEdwards: "Results of Interference Tests From Two Geothermal Reservoirs", J. Pet. Tech., January 1978, pp. 10-16.

4. Kamal, M.M.: "The Use of Pressure Transients To Describe Reservoir Heterogeneity", J. Pet. Tech., August 1979, pp. 1060-1070.

7.0 Reflection Seismic

Reflection seismic is beginning to be used in reservoir definition and, when used in conjunction with well logs and cores, may be capable of providing quantitative information about lithology and gas/liquid ratios in the areas between wells[1,2].

Instrumentation for acquiring data is already adequate for some purposes and in some situations and is available in price ranges from tens of thousands to hundreds of thousands of dollars. The cost is primarily a function of the number of channels (geophone groups) to be recorded simultaneously, the fidelity in capturing the signal and translating it to digital (numerical) form, and the recording medium.

Technology for processing and interpretation of data continues to need improvement and the state-of-the-art is highly variable from organization to organization. Given the same data, different processors will produce different results - especially in the very fine detail necessary for EOR. Although processing and interpretation are to some degree conducted separately (analogous to well-logs where the log analyst is given a "processed" final print), there should be a direct iterative feedback of interpretation to processing as well as concurrent input from log and core analysis, geologic theory, and engineering and production data. Often re-interpretation requires re-processing. Given an operating situation suitable for the seismic method, the main barriers which would prevent the use of high resolution technology in EOR are primarily non-technical. An example is the apparent high cost of using sophisticated exploration technology on the small scale of an EOR project. This can only be justified if there is mutual understanding and good communication between the geophysical group and the production engineering group.

The field application of EOR is an emerging technology and so is the field application of geophysics to reservoir description in support of EOR. A continuous feedback of new data, new interpretations, and new questions must occur to develop, assess, and refine the new technology. The high costs can be expected to decrease when, in a manner analogous to offshore platform site selection, a technology develops that is a merger of "scaled-up" engineering geophysics and "scaled-down" exploration technology; developed jointly by geophysicists, engineers, and geologists[5,6,7].

Applicable technology from outside the petroleum industry has been generated at METC, most recently in support of the coal gasification program[7,8,9]. The U. S. Bureau of Mines supports a program to detect faults, sand channels, or other potential hazards to mine roof integrity in coal seams prior to mining. The USBM program developed a seismic system, including a vibratory source, for this purpose[10].

Probably the most pertinent experience for very high resolution work comes from engineering site-selection work (dams, nuclear plants, etc.) which has used petroleum exploration instrumentation and expertise to detect geologic hazards in fine detail.

Newer reflection methods which promise to augment conventional reflection seismic are shear wave reflection profiling, and vertical seismic profiling.

Shear wave reflection technology is developing rapidly and is being applied in the field on a full-scale basis. Shear wave propagation is a function of rock rigidity only; that is, there is no effect from the compressibility of liquids/gases. A change in seismic response to shear wave propagation can be attributed to a change in the rock matrix and distinguished from a response due to a change in gas/liquid content. An anomalous seismic response on conventional pressure wave data without corresponding response in a shear wave data should be attributable to a change in gas/liquid content[3].

Vertical seismic profiling (VSP) is run as a log in a well. It records reflection and transmission data from a surface source with a vertical array of detectors in the bore hole. When this is displayed it looks like a piece of a seismic section. The frequency range, energy source, recording and display are similar to the surface reflection methods, and, thus, generate directly comparable data. The fact that the VSP detector is in the bore hole gives a direct tie to acoustic logging tools, cores, and other bore hole tools. VSP, therefore, provides a "bridge" between bore hole derived data and surface reflection data[4]. Vertical Seismic Profiling experiments in Bell Creek Field by the USGS (unrelated to the DOE/GARY cost-shared chemical EOR project) provide data in the public domain for that technology and perhaps an opportunity to do analytical studies applicable to EOR.

With detailed information on the relationship of surface reflection data to formation characteristics at the wellbore, it is possible to extrapolate outward from the wellbore by surface profiling. When other wellbores are available the continuous reflection data obtained by surface profiling from well to well permits the examination of horizontal consistency in the interwell area. The use of "permanently" emplaced geophones planted at or near the surface to monitor changes in reflectivity over time has merit for tracking flood front movement. Monitoring flood progress should be done both as an end in itself and to verify predicted performance in support of production research.

Reflection Seismic References

1. Ausburn, B.E., A.K. Nath, and T.R. Wittick: "Modern Seismic Methods - An Aid for the Petroleum Engineer", J. Pet. Tech., November 1978, pp. 1519-1529.

2. Lindseth, R.O.: "Geophysics as an Engineering Tool", J. Pet. Tech., November 1978, pp. 1627-1630.

3. Omnes, G.: "Exploring With SH-Waves", paper presented at the CSEG National Convention, Calgary, May 11, 1978.

4. Omnes, Gildas: "The Vertical Seismic Profile: A Bridge Between Velocity Logs and Surface Seismograms", paper SPE 7436 presented at the SPE-AIME 53rd Annual Fall Meeting, Houston, Texas, October 1-3, 1978.

5. Farr, J.B.: "How High is High Resolution?", paper presented at the 46th Annual Meeting of the SEG, Houston, Texas, October 24-28, 1976.

6. Farr, J.B.: "How seismic is used to monitor EOR projects", World Oil, December, 1979.

7. Widess, M.B.: "How Thin is a Thin Bed?", Geophysics, vol. 38, no. 6, December 1973, pp. 1176-1180.

8. *Kirk, K.G.: "A Reflection Seismic Analysis of the Underground Coal Gasification Sites Near Princeton, West Virginia", West Virginia University, Dept. of Geology and Geography, Morgantown, West Virginia.

9. Kirk, K.G.: "Geophysical Survey Characterization of Underground Coal Gasification Sites Near Princetown, West Virginia", Proceedings of the Fifth Underground Coal Convention Symposium, Alexandria, Virginia, June 18-21, 1979, pp. 253-267.

10. Kerman, R.F.: "Development of a Shallow-Penetration Acoustic Reflection Technique for Mining Geology", prepared by Westinghouse Electric Corporation for the U.S. Bureau of Mines, December 1977, under contract number HO262002.

*Now with U.S. Bureau of Mines, Denver Federal Center, Denver, Colorado.

8.0 Cross-Borehole & Deep Probing Borehole Geophysics

Cross-borehole methods have the energy source(s) in one borehole and receiver(s) in another. Two methods, one using acoustic energy and another using electromagnetic energy, are being utilized.

The DOE currently is supporting an electromagnetic cross-borehole probing system[1]. The system, originally developed for mining, is being considered for testing in a DOE cost-shared in-situ combustion project.

An interesting, and apparently unique, cross-borehole acoustic experiment was carried out by METC[2]. Although Shuck[*], one of the METC experimenters, is not enthusiastic about the method, recent advances in equipment, and signal processing technology could allow a more optimistic view. A trench experiment has reported the use of a cross-borehole technique in an attempt to define anomalous zones between wells[3]. These acoustic techniques merit evaluation as possible methods of confirming stress-field or directional permeability conditions.

Deep-probing methods rely on back scatter or reflection of energy from a source back to a receiver(s) in the same borehole. The Birdwell Televiewer uses acoustic energy and may have successfully recorded reflected signals from a radius on the order of 100 feet. The achievement of 300 feet penetration is a long range goal. In an EOR project

[*] See Appendix A.

with very close well spacing, this depth of penetration could make it possible to map heterogeneities in great detail. As a result, production techniques could be fine-tuned to give optimal results.

Cross-Borehole References

1. Lytle, R.J., E.F. Laine, D.L. Lager, and D.T. Davis: "Cross-Borehole Electromagnetic Probing to Locate High Contrast Anomalies", Geophysics, vol. 44, no. 40, October 1979, pp. 1167-1676.

2. Shuck, L.Z., K.H. Frohne, G.E. Rennick and D.M. Evans: "Directional Acoustic-Velocity Distribution in a Petroleum Reservoir", Soc. Pet. Engr. Jour., June 1975, pp. 234-246.

3. Bois, P., M. LaPorte, M. Lavergne, and G. Thomas: "Well-to-Well Seismic Measurements", Geophysics, vol. 37, no. 3, June 1972, pp. 471-480.

9.0 Tracer Flow Testing

Tracer testing methods rely on the flow of fluids, to which a tracer has been added, from injection well to production well[1]. Tracers include tritium, iodides or bromides, and stable organic compounds. The produced fluids are sampled continuously and analyzed. For reservoir description purposes, there can be a source of ambiguity if the flow regime (injection/production rate) is not the same as will be used in the actual flood. However, tracer testing is an excellent tool for monitoring relative flow rates from different injectors, and emplaced monitoring instrumentation could be a further improvement. Sandia is studying the use of down-hole emplaced instrumentation for tracers in the Deep Steam Project[2].

A single well tracer testing method has been developed[3,4], to determine residual oil saturation. The primary tracer, ethyl acetate for example, is injected with brine into a reservoir so that it penetrates for a significant distance, say 15 feet. After remaining shut in for a number of days, the test well is allowed to flow and the water samples are analyzed. Some of the ethyl acetate will have hydrolyzed to ethanol. The analytical results make it possible to determine the average oil saturation in the volume that has been contacted by the injected tracer bank. Tracer testing is being offered as a commercial service.

Analysis of the effects of reservoir layering on EOR processes is receiving attention both in reservoir simulations and in field studies. Horizontal barriers may have considerable effect on recovery efficiency. The DOE has sponsored work on the analysis of tracer flow testing to determine reservoir layering.

Tracer Flow Testing References

1. Wagner, O.R.: "The Use of Tracers in Diagnosing Interwell Heterogeneities - Field Results", J. Pet. Tech., November 1977, pp. 1410-1416.

2. Project Deep Steam, Sandia Laboratories, Albuquerque, New Mexico, Technical Project Officer, R.L. Fox.

3. Deans, H.A., and L.K. Shallenberger: "Single-Well Chemical Tracer Method to Measure Connate Water Saturation", Paper SPE 4755 in Proceedings of SPE Symposium on Improved Oil Recovery, Tulsa, Okla., April 22-24, 1974, pp. 239-244.

4. "Determination of Residual Oil Saturation", Interstate Oil Compact Commission, June 1978.

5. Yuen, D.L., W.E. Brigham, and H. Cinco-L: "Analysis of Five-Spot Tracer Tests to Determine Reservoir Layering", prepared for the U.S. Department of Energy, SAN-1265-8, February 1979.

10.0 The Role of Synergistic Reservoir Studies

Synergistic reservoir studies combine the efforts of engineers and geologists[1]. The information which modern analyses assisted by instrumentation derive from individual wells can be integrated into a geologic model which allows a three dimensional understanding of the reservoir. A very important step is the recognition of the environment of deposition because each depositional environment tends to have its own predictable reservoir quality and distribution[2,3,4].

The correct sequence for synergistic reservoir studies begins with careful measurement of rock properties. The previous sections of this report have covered some of the latest techniques by which geologists and engineers can gather this basic information.

The second phase consists of the efforts necessary to characterize the framework of the reservoir. Geophysical mapping will show the structural configuration of the reservoir and may identify interruptions such as faults or discontinuous beds. Geological investigation will identify the environment of deposition from cores, logs and dipmeter information. For example, recognizable deposits such as wind blown sands, braided streams and beach sands tend to be more homogeneous whereas meandering streams and deltaic sequences are more likely to have depositional discontinuities. Engineering studies during this phase will interpret test results and use the petrophysical information from cores and logs to derive the basic properties of the reservoir.

The third phase concentrates on any notable variations in the properties of the reservoir. The geologist will consider the evidence of post-depositional processes which may increase the pore volume in the case of leaching or fracturing but are more likely to reduce porosity and communication as in the case of compaction or cementation. Engineering studies at this stage will have single well production test results and multi-well interference tests to consider and will be concerned with interpretations of the areal distribution of porosity and fluid conductivity.

The fourth phase of a project for enhanced oil recovery is an integrated study concerned with the distribution of estimated residual oil and decisions about the most effective recovery process.

In practice these phases overlap and an integrated team works together from the beginning. In a recent example in Oklahoma[5], the team recognized at an early stage that the reservoir was not of marine origin, as had been thought previously, but was fluvial with great variation in properties from well to well. Directional fracturing was also detected and consequently tracers were used yielding information which could be used in framework studies and in the design and conduct of pilot operations.

The decision to proceed to commercial development can be made with confidence when all potential variations have been taken into account. An optimal recovery efficiency can be predicted for the resulting full scale EOR project.

Synergistic Reservoir Studies References

1. Harris, D.G., and C.H. Hewett: "Synergism in Reservoir Management - The Geologic Perspective", J. Pet. Tech., July 1977, pp. 761-770.

2. Sneider, R.M., C.N. Tinker, and L.D. Meckel: "Deltaic Environment Reservoir Types and Their Characteristics", J. Pet. Tech., November 1978, pp. 1538-1546.

3. Harris, D.G.: "The Role of Geology in Reservoir Simulation Studies", J. Pet. Tech., May 1975, pp. 625-632.

4. Modern Reservoir Description for Improved Oil Recovery", Interstate Oil Compact Commission, Enhanced Oil Recovery, Vol. 3, expected publication date, first quarter 1980.

5. Trantham, J.C., C.B. Threlkeld, and H.L. Peterson: "Reservoir Description for a Surfactant-Polymer Pilot in a Fractured, Oil-wet Reservoir - North Burbank Unit Tract 97", paper SPE 8432 presented at the 54th Annual Fall Meeting, Las Vegas, Nevada, September 23-26, 1979.

11.0 The Role of Numerical Simulation

The success of numerical simulation depends on the degree of understanding of EOR processes in reservoirs. A numerical simulator is a combination of computer software which reduces the assumed controlling factors to machine instructions, and computer hardware which executes the instructions and displays the results. The state-of-the-art of the understanding of an EOR process is reflected in the complexity of the interrelationships built into the program to simulate the applied process, and how it interacts with the reservoir rock and the resident fluids. It is unfortunately true that most reservoirs are not performing in the subsurface the way they are being modelled in the computer.

Progress, however, is being made and advantages are being gained in the process. Not only can many discrete types of specialized knowledge be integrated, but a consistency is imposed on data gathering and interpretation[1,2,3]. A series of simple cases can be assumed and the simulated results can be studied. These results will only be as good as the interpretations on which they are based, but it is invaluable to be able to compare the outcomes of multiple hypotheses. If the observed performance does not match the simulation, it may be possible to identify which parts of the interpretation or the influential parameters are at fault and to modify them. When a match is achieved, some part of the interpretation may be valid and ready to be used for further studies. By pursuing the best possible match, new methods of prediction and evaluation can be developed.

<u>Numerical Simulation References</u>

1. Craig, F.F., P.J. Wilcox, J.R. Ballard, and W.R. Nation: "Optimized Recovery Through Continuing Interdisciplinary Cooperation", J. Pet. Tech., July 1977, pp. 755-760.

2. Bansal, P.P., J.L. Harper, A.E. McDonald, E.E. Moreland, and A.S. Odeh: "A Strongly Coupled, Fully Implicit, Three Dimensional, Three Phase Reservoir Simulator", SPE paper 8329 presented at the SPE AIME 54th Annual Conference held in Las Vegas, Nevada, September 23-26, 1979.

3. Mrosovsky, I., J.Y. Wong and M.W. Lampe: "The Construction of a Large Field Simulator on a Vector Computer", SPE paper 8330 presented at the SPE AIME 54th Annual Conference held in Las Vegas, Nevada, September 23-26, 1979.

12.0 Conclusions and Recommendations

The application of instrumentation as currently utilized for the description of reservoir properties for EOR has made considerable progress. Individual specialized tools are now capable of estimating most of the useful reservoir properties close to the well bore. The consensus of those consulted for this report is that the next step in the development of logging tools and interpretive methods should be based on analyses of actual examples where the synergistic approach can expedite an increase in oil production and an understanding of reservoir behavior while promoting EOR.

The type of future project in instrumentation which is recommended for consideration would be structured to take advantage of the capabilities of industry and the universities to gain a synergistic understanding of the reservoir and its reaction to the EOR processes being used. The dissemination of this understanding in the public domain with the support of the Department of Energy could have an important effect on the future level of oil production throughout the country.

The potential for further progress in this technology development area is high. Our interviews and contacts resulted in offers of cooperation from industry ranging from personnel to give technical advice, data for "post mortem" analysis of completed EOR projects, and the supplying of a test site for a reservoir description project.

Any synergistic program which the Department of Energy sponsors and supervises will have much to gain from each of the sources of expertise in instrumentation and its application. The use of industrial advisors in the definition, planning and implementation of such a program is a critical requirement. Participation of the universities is needed for several factors including contributions to theoretical knowledge and innovative potential. Consultants, consulting firms and service contractors will be needed for their manpower and technical resources. Broad based generalists are needed for advisory input on matters of synergy and integration. Technical specialists are essential to provide in-depth knowledge based on actual experience and peer-system awareness.

As a result of the work which went into the preparation of this report, the techniques and the instrumentation which needs improving can be listed. Such preliminary lists can often be helpful but it is clear that they need continuous revision. Since the early days of EOR, progress has been made from month to month by research workers, service companies and project operators. Partial solutions to problems have been found and with additional knowledge and experience new problems have been recognized. In such a rapidly moving situation frequent interactions among involved academic, industrial and government personnel can provide special insights to those planning, directing and managing EOR reserach, development and field test activities. It is for this reason that the recommendation has been made that a continuing Enhanced Recovery Instrumentation Program should be instituted.

Specifically, the Enhanced Recovery Instrumentation Program (ERINPRO) would be centered around an advisory group of university and industry experts similar to the Energy Program Panel of the Gulf Universities Research Consortium (GURC) or the Steering Committee of the Geothermal Log Interpretation Program (GLIP). This Instrumentation Committee would be able to identify the areas of greatest need and could recommend projects such as the calibration of existing measurements, the development of new logging methods, the collection of sample materials and the publication and dissemination of many types of information. As a forum for discussion and a nucleus for innovative development, this organization would receive active support from those promoting EOR. The successful implementation of this program would ensure that Enhanced Oil Recovery would make its full contribution to the energy needs of the nation.

LIST OF PRIORITIES

A. Instrumentation that needs improving.

Static

Measurements which contribute to estimates of oil saturation before, during and after an EOR process.

Dynamic

Measurements which contribute to detection and measurement of relative fluid movements and to the monitoring of active EOR processes.

B. Techniques that need improving.

All aspects of simulation need to be improved so that the variations of reservoir and fluid properties between control points can be taken into account. The emphasis here should be on realistic modelling rather than mechanical interpolation.

C. Specific examples of Instrumentation priorities.

Coring

1. Further improvement of pressure core barrels and their use.
2. Continued attention to improving core analysis techniques such as those listed on pages 10 & 11 of this report.

Logging

1. The new types of instrumentation described in Section 3 include nuclear magnetism and borehole - gravimeter logging. As the instruments are improved it becomes very important to develop interpretive techniques to translate the results into useful information.
2. Results from the various proprietary Pulsed Neutron Logs need to be accumulated and studied so

that optimum use can be made of this type of instrumentation for estimates of oil saturation behind casing.

Geochemistry

1. As more is understood about the effects of geochemical changes on EOR it will become necessary to devise or modify instrumentation to measure the critical parameters. Undoubtedly the existing tools which investigate the petrophysics and fluid content of reservoirs will be useful in this regard. Until there has been more research into the effects of such factors as diagenetic clay it is too early to assign priorities to instrumentation for this purpose.

Pressure Testing

1. Studies of pressure transient tests should continue to be given close attention because of the invaluable information to be gained concerning reservoir behavior between control points.

Reflection Seismic

1. Great importance should be assigned to experiments being conducted to track flood front movement by monitoring changes in seismic reflectivity.

Cross-Borehole and Deep Probing Borehole Geophysics

1. Continued research in these applications of

instrumentation should lead to important advances in the typed detailed mapping needed for EOR projects.

Tracer Flow Testing

1. Instrumentation and interpretation of Tracer Flow Testing should be given high priority because the changes being measured are more closely related to similar aspects of EOR processes than with any other investigative tool.

APPENDIX A

SUMMARY OF SOME INSTRUMENTATION AND METHODS PERTINENT TO RESERVOIR CHARACTERIZATION FOR ENHANCED OIL RECOVERY

Submitted to:

GULF UNIVERSITIES RESEARCH CONSORTIUM

by

L. Zane Shuck, Ph.D., P.E.

September 15, 1979

TABLE OF CONTENTS

FOREWORD

This report describes some of the existing and emerging methods and instrumentation believed to have potential for analyzing and evaluating petroleum reservoirs for enhanced oil recovery processes. This list is not intended to be comprehensive either in terms of methods or their capabilities, but rather, a brief survey based largely upon "reported information". Brief opinions as to the usefulness, ultimate potential, and limitations of methods are given based upon the experiences of the author.

In view of the ERA DOE late August '79 "Final Rule" contained in 10 CFR Part 212 Docket No. ERA-R-79, it would appear that unprecedented incentives now exist, at least for 2 years, to characterize and evaluate reservoirs for EOR. These incentives should carry beyond the initial 2 year programs giving rise to both a short and longer term demand for manpower with special interdisciplinary experience to utilize and develop the various principles useful in reservoir characterization.

INTRODUCTION

Reservoir characterization and evaluation for enhanced oil recovery encompasses many disciplines. No attempt is made here to discuss or evaluate methods for measuring all the parameters needed for thorough planning and design. Only some of the information believed to be of critical importance and inadequately known or insufficiently used in planning EOR experiments will be discussed. For convenience some of these "unknowns" are listed below:

- .. Oil saturation distribution in bedding plane directions
- .. Lenticularity or continuity of oil bearing strata
- .. Natural fracture or fissure spacing, size, orientation and uniformity
- .. Large fault zones and orientations
- .. Stress field (maximum and minimum) magnitudes and orientations
- .. Difference between maximum and minimum stress magnitudes
- .. Regional uniformity of stress field in 3 principal directions
- .. Degree of jointing and angles between networks
- .. Joint fluid and mechanical properties
- .. Directional matrix permeability
- .. Tension, compression and shear properties of the reservoir rocks

- Pressure and specie gradient distributions during early phase of an EOR project
- Hydraulic fracture orientations and lengths

These are some of the parameters not used extensively because they are very difficult to evaluate. Nevertheless they play an important role in the manner fluids flow through the formation, the success of stimulation treatments, and other EOR planning. Most of the methods and instrumentation described in the following material are focused on evaluating the above mentioned parameters. Established, conventional wellbore logging techniques are, in general, not discussed. Emphasis is placed upon instrumentation and methods developed at or in cooperation with the METC.

HIGH-RESOLUTION SEISMIC REFLECTION SYSTEM

R. T. Williams, J. E. Tuotsala of WVU and Keith Kirk now of the U. S. Bureau of Mines, Denver, Colorado.

Objectives and Description:

The objective of this work is to develop a system with high resolution to identify smaller targets, in particular to be able to separate the reflection arrivals from the top and base of thin beds. The goal is to increase the resolution by 10 times the standard in the petroleum industry. Signals are recorded in the 300 to 1000 Hz frequency range compared to the usual 100 Hz and lower range. Both the energy source and high frequency geophones are placed in boreholes that penetrate top soil layers to avoid the near-surface attenuation of high frequencies by the consolidated soil. The subsurface boreholes also eliminate most of the surface noise (Raleigh waves).

Status and Results:

The viability has been demonstrated by a number of field tests. The quality of data obtained has been outstanding. Data obtained at the Cottageville, West Virginia, gas field using the WVU system have compared very favorably with results from advanced industry methods.

Comments - Opinions:

This technique has demonstrated a high potential for identifying bed thickness variations and other anomalies where good contrast, such as for coalbeds, exists. It appears to have considerable potential for EOR. This work is being done under DOE contract with the major emphasis being to detect gas-filled fracture zones in the Devonian Shales.

SEISMIC MAPPING OF HYDRAULIC FRACTURES

The capabilities and potential of this technique have been thoroughly evaluated by the Morgantown Energy Technology Center during theoretical, laboratory and field projects from 1970 to 1976. The author of this document was principal investigator and manager of the program. The conclusions of this research are summarized in the following discussion.

Perhaps the best conditions for seismically mapping fractures in a petroleum or natural gas reservoir that could ever be hoped for were available during the MERC Tests, i.e.,

a) Close 250' average spacing between wells
b) Open hole liquid filled within the producing horizons
c) Use of specially designed high sensitivity - low noise hydrophones located in the open wellbore (in the bedding plane elevation) of the producing and fractured zone
d) Special noise reduction and isolation systems used
e) Broad-band and narrow-band pass filtering of raw data

f) Special purpose designed surface instrumentation and full wave train analog recording

g) Use of analog and digital filtering and sophisticated stochastic processes for laboratory data reduction and analysis

h) Background noise environment characterized

i) Use of specially designed coincident detectors to detect related events on multiple channels of high frequency seismic data (20 Hz to 500 Hz) at various delay times and amplitudes during laboratory analysis

j) A new research well was drilled and fractured in the center of an optimally arranged array of monitoring wells so the induced fracture events could be detected by 12 different hydrophones

k) A highly capable, interdisciplinary research team of about 15 petroleum, mechanical, electrical engineers, physicists, geologists, mathematicians, computer scientists and associated technicians worked primarily on the project for about 5 years.

Thus, the conditions were truly excellent for evaluating the hydraulic fracture seismic mapping method.

Conclusions from this research are:

a) After about 2 years of reducing the data, 5 definite unquestionable points of fracture extension were determined. For the first time the seismic mapping of an extending hydraulic fracture was accomplished.

b) The points mapping the fracture agreed with all the other fracture orientation data on the reservoir indicating a N 70° E direction.

c) The overall best frequency range for detection, resolution, etc., was the band between 75 Hz and 200 Hz.

d) Maximum distance that seismic signals were received in the bedding plane from the propagating fracture was about 800 feet with the more probable distance of under 600 feet.

e) Due to far-field stress modification and stress relaxation during and for long periods (hours) following fracture extension from the wellbore, many seismic sources occur far away from the extending fracture. These sources are random and distracting and of no apparent use in mapping the fracture. They apparently represent other joints or fractures opening, closing, sliding or shearing or formation bending, compression or tension failing.

f) It appears that for all but a very few reservoirs with unusually close well spacing, and wellbore conditions the technique is <u>not</u> technically feasible due to the low level signals of acoustic emission or other seismic signals intimately associated with the fracture created.

g) The complicated nature of the phenomena and the seismic mapping process demands sophisticated, interdisciplinary manpower, expensive, specially-designed hardware and software, and excessive data reduction and analysis time.

h) For the above reasons the seismic method of mapping the propagation or extension of hydraulic fractures is not recommended either on a commercial or special research basis. There are today much better alternatives.

One Alternative:

One method that needs to be evaluated through field testing is the use of a surface or near-surface geophone or hydrophone array to detect the propagation of a detonating propellant or liquid explosive injected into a propped open hydraulic fracture for mapping purposes. The successful detonation of liquid explosive injected in a fracture has been demonstrated. This concept is described in detail in U. S. Patent No. 4,057,780, "Methods for Describing Fractures in Subterranean Earth Formations".

ELECTRICAL POTENTIAL MAPPING OF HYDRAULIC FRACTURES

Sandia Laboratories (Albuquerque) seem to be the major investigators of the method at the present. They have a DOE enhanced gas recovery contract to characterize and map fractures under which they are evaluating this technique. Their effects involve the use of current generators with short risetimes (order of 30 milliseconds).

Comments - Opinion

It has been this author's experience through theoretical and field experiments that electrical potential mapping of hydraulic fractures poses problems that are not likely to be overcome even with major improvement in instrumentation technology. The time and manpower requirements, are also such as to render the technique uneconomical as a service to industry unless subsidized in some other way. The technical feasibility appears marginal under most reservoir conditions, but better, for example, than seismic mapping of extending hydraulic fractures.

SHORT-TERM INJECTIVITY TESTS (STI)

As distinguished from "Pulse-Testing" and "Interference" tests, STI has been developed and used very successfully by Shuck and Komar of METC to delineate fracture systems. The phenomena evaluated and the results or interpretations from STI are likewise different from pulse or interference tests. The results of STI experiments in the Bradford Third Sand are the subject of the DOE 30-minute film, "Transient Pressure Response of a Petroleum Reservoir: A Field Case Study".

This test is designed for negligible flow through the rock matrix in order to delineate existing open fracture systems or the opening of other fractures or joints at prescribed pressures. This is a valuable technique for reservoir characterization in advance of any EOR project. Existing open or induced hydraulic fracture orientations constitute the most fundamental information needed for planning EOR field development.

WELLBORE ELECTROMAGNETIC WAVE METHOD OF MAPPING SUBTERRANEAN EARTH FORMATIONS

This concept is described in U. S. Patent No. 4,045,724, August 30, 1977, by Shuck, Fasching and Balanis. Several small DOE contracts were let to Dr. Balanis, EE Department, WVU, to develop the concept including the fabrication of a prototype system. The application however was detection of burn zones during in situ coal gasification (UCG). Budget limitations of the UCG project prevented the final assembly and use of the system. After all the theoretical investigation and laboratory testing it is still believed to be a technically viable scheme for anomaly detection up to 25 feet from the wellbore or farther depending upon the "anomaly" characteristics.

Applications to EOR would be directional flow characteristics of a conducting fluid slug or mapping of fracture orientation by injecting a conducting fluid slug. The design of the instrument called for rotation in the wellbore to measure azimuthal variations in the bedding planes. Instrumentation, logging time and data analysis would be somewhat more expensive than for most conventional logging schemes. The limiting factor is that the higher the frequency the more attenuation per unit length of travel, and the lower the frequency used the longer the horn (wave-guide) has to be which quickly calculates to be larger than the wellbore diameter. This is the reason for the limited 25 foot estimated usefulness of the technique. Unfortunately, due to this limitation, I cannot recommend that this technique has at this time as much merit as others for EOR purposes.

SURFACE TILT INSTRUMENTATION FOR HYDRAULIC FRACTURE MAPPING

This technique called FRAC-MAP^{tm} as developed by M. D. Wood involves the measurement of surface tilt angles as small as nanoradians. While it may appear as an unlikely technique due to surface cultural and fracturing associated background noise and that it would have extremely limited resolution of fracture orientation, the results obtained cannot be discounted. Fractures have apparently been mapped at nominal depths from 200 to 11,400 feet.

Certain types of structural anomalies, nonhomogeneities or faults in an overlying region of hydraulic fracturing could give surface slope changes during fracturing that do not correspond to the orientation of induced fractures. Thus any surface slope monitoring scheme would be subject to error in such cases. As a rule, this may not be a problem. The size of the monitoring instrument array-diameter is of the same order as the depth, much like electrical potential or seismic mapping methods. The technique has the distinct advantage that it does not in any way interfere with the drilling, completion or stimulation operations.

With the results obtained to date it is highly recommended that this technique be further developed as it now appears currently to be the best available for fracture orientation mapping beyond the wellbore. Specific recommendations are to use sophisticated 3-D codes, such as NASTRAN, with small grid sizes to aid in calculating the surface slope changes and 3-D displacements corresponding to a given frac design and through recursive techniques enhance the data analysis and interpretation. This technique needs to be independently tested and demonstrated including mineback verification, to convince the industry of its validity and usefulness as a fracture mapping tool. The knowledge of fracture orientation in the development of any significant reservoir for primary, secondary or tertiary recovery project should far outweigh economically any conceivable cost for this particular service. The total manpower requirements are 2 for site preparation, 2 for field installation, 2 for numerical analysis and 1 for interpretation, some of which can obviously be the same individuals. The average time requirements are 30 days maximum and 15 days minimum. An estimated cost of this service is $50,000 - 60,000 depending on the depth of the fracture.

IMPROVEMENTS IN WELLBORE LOGGING

Many of the conventional wellbore logging tools could be improved to yield much more information than obtained from the present designs. By locking temporarily onto the wall of the wellbore and rotating 360° with narrow angle detecting and probing these modified instruments could yield considerably more information about directional variations of several properties in the bedding plane. An example is the Fracture Identification Log. This wireline instrument consists of 4-arm electrical pads that rotate slowly and wipe the sides of the wellbore as the wireline is twisted or pulled in or out of the wellbore. The basic intent of fracture detection in the wellbore is very worthwhile. However, the instrument concept and technique appear to fall way short of the needs and potential for such an instrument. Perhaps the instrument should lock against the wellbore and take azimuthal readings giving detailed fracture sizes and densities with orientation in the bedding plane.

Another instrument that should be used more is the 3-D and 4-way borehole seisteleviewer. While this instrument has been used and offered on a commercial basis by various logging companies it is now only available as a service through Birdwell. Even though the information obtained is only of wellbore surface-near surface type the information generated is of perhaps greater importance than usually recognized. The usefulness in evaluating cement jobs and methods may be underestimated.

Sandia is developing an induction probe that may be useful in further defining the reservoir parameters of porosity, fluid salinity and permeability. This technique however depends upon some optimistic assumptions in applying the constitutive equations and their solutions involving the Duhamel integrals. This author does not believe that this technique will yield any information with any better qualities than that currently available from conventional logging methods. This work is being done by Carl Schuster's group.

MISCELLANEOUS INFORMATION AND COMMENTS

.. A dry-hole sonic log is under development at the Lawrence Livermore Labs, Livermore, California. This instrument is intended to detect fractures some distance away from the wellbore through a single wellbore scan.

.. Sandia is developing a Pressurized Core Barrel and New Mud System to prevent invasion of drilling/coring fluids into cores. It involves the encapsulation of core with an impermeable membrane or boot. Ray Williams, BETC, is the TPO. This device will be of considerable value in the evaluation of liquid, gaseous and solid composition of formations.

.. More research needs to be done on the NMR and Dielectric Schemes to determine fluid compositions. Apparently much improvement is needed in calibration and interpretation of the data.

.. Single-Well Tracer Injectivity Tests. This technique utilizes the injection of fluids that hydrolize indicating the amount of oil contacted after flowback and analysis. The fluid resonance time, temperature and other factors are critical in the interpretation. However, this technique has a lot of potential, depending upon how it is used. Being developed by BETC.

.. Wellbore Gravimeter. This instrument, introduced by Jim Smoker of the USGS in Denver, Colorado, is now available commercially. The purpose of the instrument is to evaluate density away from the wellbore. This instrument may have applications beyond its initial design purpose and should receive additional support to develop to its full potential.

.. Downhole In Situ Stress Tool. Terra Tek is developing this instrument under a METC contract with

C. A. Komar as the TPO and contract initiator. This instrument is being developed to measure the minimum principal stress magnitude and orientation. It represents one of the most important tools under development today since it is finally beginning to be recognized in the petroleum industry that tectonic stress controls predominately the orientation of hydraulic fractures. The instrument still leaves a lot to be desired unfortunately, because in this author's opinion the difference between maximum and minimum principal stresses is also very important, contrary to the belief of several "experts" working in the area today. Means of measuring both the maximum and minimum stress magnitudes and orientations remotely in deep wells, however, are not public knowledge at this time.

Well-to-Well Techniques - Comments

Seismic, tracer, electrical resistivity, electromagnetic, well-pulsing interference, short-term injectivity and many other between-wellbore schemes have been considered and evaluated by this author during the past nine years for general petroleum and natural gas reservoirs and coalbed characterization. The between-wellbore seismic velocity determinations with all combinations of direction between 12 monitoring wells and 60 shots in 10 other wells allowed a mapping of the velocity distribution in a petroleum reservoir. The maximum velocity in general agreed with the minimum tectonic stress and hydraulic fracture orientation. However, as a useful tool in EOR reservoir characterization even with the ideal conditions like at the Bradford test site, I could not recommend it as a very valuable tool and it could not be justified economically.

Between-wellbore resistivity measurements were taken in attempt to improve upon the hydraulic fracture surface mapping experiment at Bradford and its interpretation. After considerable theoretical calculations and conducting numerous measurements between wells the technique was abandoned.

Tracer experiments were conducted but with the small token experiment design and data analysis the results were not as meaningful as they should have been. The tracers used were also not ideal for the reservoir. This technique however <u>if properly designed</u> can be very informative.

The short-term injectivity (STI) tests followed by interference tests are believed to be the most effective means today to evaluate away-from-the-wellbore conditions that can mean the difference in success of an EOR project. These techniques give real data directly and do not depend upon various theoretical models and assumptions that must be used along with field data to calculate indirectly the desired information. Of course analysis of STI data using various modelling techniques can aid in further analyzing the reservoir if the modelling techniques and the interpretation are proper.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981—771-031/39