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SUPRI HEAVY OIL RESEARCH PROGRAM

FINAL REPORT
February 22, 1987 – February 21, 1990

By
William E. Brigham
H. J. Ramey, Jr.
K. Aziz
Louis Castanier

Work Performed Under Contract No. FG19-87BC14126

U.S. Department of Energy
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005

Stanford University
Petroleum Research Institute
Stanford, CA 94305-4042

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INTRODUCTION

This report is a summary of the work performed under Department of Energy contract DE FG19-87BC14126 during the period February 22, 1987 to February 21, 1990. During that period the Stanford University Petroleum Research Institute has published twenty-two technical reports and professional papers. This report presents in general terms the scope of work of SUPRI which is divided in five main projects. The results obtained during the period of performance of the contract are then presented in the form of abstracts from the technical reports and papers written during the period of performance. A reference list allows the reader to find more detailed information on a given topic if desired. The report is organized by project following a brief description of SUPRI's scope of work.

SUPRI, A BRIEF SUMMARY

The Stanford University Petroleum Research Institute (SUPRI) was established in 1976 with the primary purpose of pursuing enhanced oil recovery research in heavy oil reservoirs. Principal financial support comes from the U.S. Department of Energy, augmented by grants from the oil industry. Industrial support was formalized in 1980 with the formation of the SUPRI Industrial Advisory Committee, whose representatives meet yearly with institute members to review and discuss the status of research projects and to discuss future plans. Eleven companies are members of the SUPRI Industrial Advisory Committee. A list of these organizations is attached at the end of this report. SUPRI is part of the Petroleum Engineering Department and coordinates its activities with the department.

Drs. H.J. Ramey, Jr. and K. Aziz are the present co-Principal Investigators. Faculty associates include Drs. W.E. Brigham, R.N. Horne, S.S. Marsden, Jr., F.M. Orr, Jr. and Professor A.J. Horn. Dr. L.M. Castanier is the Technical Manager and C.J. Tavares and P.A. Pettit are the senior technicians. An administrative staff of two support the 10-15 student research associates.

1. RESERVOIR PROPERTIES

The objectives of this task are to assess the effects of temperature and pressure on relative permeability to oil and water, and capillary pressure in petroleum reservoirs; and to correlate data obtained in a laboratory with those at reservoir conditions.

Earlier results had indicated that the absolute permeability to water decreases with a rise in temperature. These results were in agreement with some research work, but differed from other work. Our past results have shown that the absolute permeability to water is not dependent on temperature.

During this period, measurements were made of relative permeabilities to oil and water at moderate temperatures for unconsolidated sands. Results indicate that oil-water relative permeabilities are temperature-independent between 70^oF and 300^oF. This work will be continued with the help of the CT scanner.

An apparatus has been designed and built that will allow accurate and systematic measurements of capillary pressure curves on unconsolidated sands at reservoir conditions. Results will be compared with those obtained from a high temperature centrifuge.

A CT scanner was installed for measurements of core properties and in-situ saturations during flow experiments. Data on two and three phase flow were obtained. The scanner is operating satisfactorily.

A study comparing relative permeability data obtained from coreflooding to similar data from a centrifuge for the same core was completed in 1990.

Future plans in this project include determination of the end effects in oil-water relative permeability experiments.

2. IN-SITU COMBUSTION

The objectives of this task are to evaluate the different parameters affecting combustion field projects, including studies of reaction kinetics of combustion in the presence of reservoir matrix and crude oil.

In the past a model for the kinetics of the oxidation reactions was developed. A study was also made on the fuel deposition reactions. Work during this period has concentrated on studying the effect of metallic additives on the in-situ combustion process. Future work on the kinetics of combustion will focus on determination of residual oil saturation to steam and how this effects fuel formation in combustion.

Analytical work on multiphase flow in porous media with temperature changes was performed and published in 1989. This work applies to high oxygen combustion as well as to steam with CO_2 used as an additive.

A literature review of the various ignition techniques was completed in 1990.

Tube runs have been done at SUPRI for over ten years. In these experiments one can measure the parameters necessary to design a field test. The equipment has been updated by addition of computerized data acquisition and better controls. Work during the period of performance has focused on quantifying the effect of metallic additives on the performance of combustion for Huntington Beach and Hamaca oils. In the future we will examine high oxygen combustion and fuel deposition in tube runs.

3. IMPROVEMENT OF STEAM INJECTION BY ADDITIVES

The objective of this project is to develop a process to improve mobility ratio of steam drives to reduce gravity override and channeling of steam, primarily by use of surfactants/foams. We are also interested in foam flow behavior for gas drive improvement.

In the past, studies on temperature stability, adsorption and partitioning of surfactants had been performed at steam injection conditions. Characterization of different classes of surfactants in presence of oil at steam injection conditions has continued during the period of performance. Future work will focus on investigating the effect of oil on the foam flow behavior.

Micromodels have been built to observe the pore level flow patterns. This work will continue in the presence of oil and with various model pore geometries including real core thin section patterns.

Studies were done on two-dimensional flow of foam in sandpacks. Experimental data for one surfactant had been previously matched by an approximate model based on a combination of Buckley-Leverett equations for the gas and Dietz equations for the liquid surfactant. This work will be expanded to various surfactants and different geometries.

A study on transient foam flow has been initiated. Based on past results it appears that transient foam flow is likely to dominate any field operation. Work in progress includes one-dimensional foam flow with CT scanner observations of saturation distribution. We plan to continue this study in the future.

A study investigating the role of emulsions versus foams has been completed and reported. The report compares recovery from a two-dimensional model in a gas drive with surfactants. It was found that the best recovery occurred when the surfactant presented both foaming and emulsification characteristics.

A three-dimensional steam injection model is being built for observations of steam floods under the CT scanner.

4. WELL-TO-WELL FORMATION EVALUATION

The objective of this task is to improve the techniques of well-to-well formation evaluation such as tracer tests and pressure transient tests, and to facilitate the interpretation of such tests.

In the past, a method of interpretation was developed for fall-off tests at an injection well which gives the volume burned in in-situ combustion or the volume swept in steam injection. This technique for analyzing fall-off tests has been successfully tested with field data in a number of cases, and new models have been developed to improve reliability. These methods were also successfully tested on field data.

A study had been completed on the determination of properties of layered reservoirs through analysis of well-to-well tracer flow at unit mobility ratio. Another study combines well test and tracer results to study a heterogenous layer. It was shown that some single layer systems can give a response similar to the results of multilayered systems. This work will be extended to other mobility ratios and patterns. It will require a highly accurate computer simulation model in order to solve this problem.

An experimental study of crossflow in layered systems has been completed. Experiments were calculated at different mobility ratio and the effects of gravity, viscous and capillary crossflow were investigated. A report on this topic had been published in 1985; a paper was published in 1988.

A report on preliminary work on single well tracers had been published in 1985. Further work resulted in a paper published in 1989. A theoretical solution was devised for single well tracers when a slug is injected, allowed to react, and then produced to evaluate the residual oil saturation. This solution is however complex and difficult to use. More work is planned on this topic.

An analytical solution of flow through perforations has been derived for single phase flow. A report on this important analytical work will be published in 1990. Future work will include an investigation of the variables for optimization of the perforations and a study of the variable flow rate along the perforations.

5. FIELD SUPPORT SERVICES

The objective of this project is to provide technical support in design and monitoring of enhanced oil recovery field experiments.

The economics of the two main thermal recovery techniques have been compared. Comparison was made of in-situ combustion and steam drive for a typical California field using a range of integral and operating parameters. It was found that both methods produce comparable economic results.

Various numerical methods for optimization of computer programs have been tested. The goal there is to simplify and improve production optimization, data analysis and numerical simulation.

There is a need to create simple semianalytical models for thermal oil recovery techniques. These models can be run rapidly on microcomputers and provide the field engineer with an easy way to perform sensitivity studies and to screen prospects for enhanced oil recovery. A two dimensional x-y model was successfully developed, and futuer work will investigate the effects of arial sweep.

SUPRI has supported the Department of Energy International Agreements by participating in meetings with Intevep (Venezuela) and IFP (France) under bilateral Memoranda of Understanding. In addition, five papers were presented by SUPRI personnel at the scientific conferences organized by the International Energy Agency.

Also, a number of U.S. and foreign visitors have come to the laboratories to discuss their laboratory and field projects and how they relate to our research efforts. Technology transfer is an important aspect of this project.

The following pages summarize the reports and papers that have been written on the various topics of the research reported above. Copies of these reports and papers are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161 and from Stanford University Petroleum Research Institute, 117 Lloyd Noble Bldg., Stanford University, Stanford, California 94305-4042.

WORK DURING THE PERIOD OF PERFORMANCE
PROJECT 1. FLOW PROPERTIES STUDIES

This project involves measurements of reservoir parameters such as absolute permeabilities, relative permeabilities and capillary pressure at conditions of temperature and pressure likely to be encountered in thermal recovery processes.

1. **Shimbo, D.: "A Comparison of Relative Permeability from Centrifuging versus Coreflooding"**
   Relative permeability has traditionally been measured using unsteady-state coreflood tests. Procedures also exist for deriving relative permeabilities from centrifuge data, but the shapes of the curves are usually different than those from coreflooding. This research compared coreflood relative permeabilities versus centrifuge relative permeabilities by obtaining coreflood and centrifuge data from the same piece of Berea sandstone for gas/oil and oil/water systems. A one dimensional coreflood/centrifuge model, a least squares history matching algorithm, and the Corey relationships were used to reproduce the data. Jones-Roszelle and Hagoort relative permeability curves were compared with the Corey curves that were obtained from simulation history matching.

   Comparison of the two sets of relative permeability curves from centrifuging versus coreflooding for both oil/water and gas/water systems displayed similar shapes and endpoints for the wetting phase, but showed different shapes and endpoints for the nonwetting phase.

2. **Castanier, L.M.: "An Introduction to Computerized X-Ray Tomography for Petroleum Research"**
   This report summarizes the state of the art in the application of medical tomography (CT) to petroleum recovery problems. A brief review of the basic principles of x-ray computerized tomography is followed by a discussion of the governing equations of the method. Calculation techniques and appropriate correlations for continued testing are described and discussed. Existing medical software is reviewed. The specific software needed for petroleum engineering is described, as well as applications of new technologies such as image processing and computer networking.

Criteria are given for the choice of a machine suitable for most petroleum related applications. Emphasis is placed on flexibility, reliability, accuracy and price of the scanner. Two sections discuss positioning of the core and design of the core holders. Examples of possible applications of CT scanning to problems of geology, core analysis and EOR are discussed as well as operational process problems. An appendix presents the status of the CT research at the Stanford University Petroleum Research Institute.

The basic conclusion of this work is that computerized x-ray tomography is a powerful tool for petroleum industry researchers. Present technology allows its use in an effective manner providing that some simple criteria are met. Existing hardware is adequate and existing medical software can be adapted in combination with other sources.

3. **Hagedorn, K.: "The Effect of Temperature on Relative Permeabilities of Consolidated Sands"**

Over the past 20 years, a number of studies have investigated the effects of temperature on relative permeability. The results of these studies have often been contradictory. It appears that experimentally measured relative permeability curves are often functions of the measurement system and measurement techniques.

Dynamic displacement experiments were performed on two Brown Sandstone cores using distilled water and white mineral oil. Relative permeabilities were calculated using the Johnson, Bossler, Naumann technique. Data were fit to a smooth, differentiable function in order to evaluate the required derivatives.

An increase was observed in both oil and water relative permeabilities with increasing temperature for the first of the two cores. A slight decrease in both permeabilities was observed for the second core. It was determined that the functional form used to match the data was not appropriate for the second core. The effects of temperature on the first core were almost reversible. Slight increases were observed in both oil relative permabilities and irreducible water saturations when the experiments were repeated at room temperature after the core had been subjected to high temperature runs.

PROJECT 2. IN-SITU COMBUSTION

This project evaluates the effect of different reservoir parameters on the in-situ combustion process. It includes the study of the kinetics of the reactions. A literature review on ignition methods has also been completed.

1. **Shallcross, D.C.: "Devices and Methods for In-situ Combustion Ignition"**
One of the most important tasks during a fireflood is to ensure the efficient and safe ignition of the oil-bearing stratum. Many different devices have been developed and employed to achieve this aim. The target zone may ignite spontaneously upon injection of an oxygen-containing gas without the aid of special equipment. Alternatively, ignition may be hastened or enhanced by the use of gas-fired downhole burners, catalytic heaters, electric downhole heaters, or other, chemical means. Other methods involve increasing the reactivity of the formation contents by doping the stratum with compounds that ignite and burn more readily than the reservoir oil.

This report surveys the range of ignition methods and devices that have been developed and applied in the field. Not only are successful ignition systems discussed, but also those designs that failed to ignite a formation. In discussing the various techniques, factors considered include reliablility, specialized equipment and materials requirements, and safety. Another consideration is whether a system or device may be easily reused if ignition is not successful on the first attempt. The use of oxidizing gases other than air is also discussed.

2. **Wingard, J.S. and Orr, F.M., Jr.: "Multi-Phase, Multi-Component Flow Modeling in Porous Media with Temperature Variations"**
Oxygen enriched combustion involves multiphase flow with temperature changes as does steam injection. A mathematical description of these types of flow is needed to simulate high oxygen combustion ahead of the front. It can also be useful for describing steam with CO_2 used as an additive, or where vaporization of the oil is an important mechanism.

A method of characteristics solution is presented for the differential equations describing multiphase, multicomponent flow in porous media. The model is extended to systems that have variation in temperature. The new model is then applied to a three component system of carbon dioxide, a heavy oil component, and water. The system contains vapor-liquid, liquid-liquid, and vapor-liquid-liquid regions over a wide range of temperatures and pressures. A composition grid for the system at 800°R and 250 psia is shown and the technique is described for tracing the temperature and composition path through the phase diagram from injection conditions to initial conditions.

3. **De los Rios, C.F., Brigham, W.E. and Castanier, L.M.: "The Effect of Metallic Additives on the Kinetics of Oxydation Reactions in In-situ Combustion"**
In-situ combustion is directly influenced by the rate of oxidation reactions in the rock matrix ahead of the front. Catalysts may have a significant influence on the reactions. The effects of catalyzing agents were therefore studied to gain a more thorough understanding of the mechanisms involved in the catalysis of crude oil oxidation.

Samples of a Huntington Beach oil/sand mixture were subjected to a continuous flow of air and a linear heating schedule. The effects of differing operating pressure and ten different metallic additives were examined in sixteen runs.

Data showed that at increased pressure, oxygen consumption and carbon oxides production increased over the entire temperature range of the experiments. These increases were the result of increased pre-exponential constants ($A_r P_{O_2}^m / \alpha$) for all three oxidation reactions. As expected, the activation energies (E/R) for the reactions were generally unaffected. The increase in oxygen reactivity due to higher pressure was larger when stannous chloride was present than when either ferrous chloride, copper sulfate, or no additive was present.

Ferrous chloride, stannous chloride, and aluminum chloride additives caused significant increases in the rates of oxidation, compared to the rate with no additive. Lower activation energies were found in the low temperature reaction, which in turn caused increased low temperature oxidation and fuel deposition. Greater reaction rates occurred in the medium temperature range as a result of the larger pre-exponential constants. With iron the activation energy was larger in this temperature range, which would ordinarily cause a lower rate, but the pre-exponential constant was so great that the reaction rate still increased. No significant changes occurred in the activation energies of the high temperature reactions due to these metals; however, the increased fuel deposition at lower temperatures led to higher reaction rates in the high temperature reaction.

Runs containing compounds of zinc, magnesium, chromium, and manganese showed that generally, higher reaction rates were apparent, resulting in increased low temperature oxidation and fuel deposition. These effects were more pronounced with zinc, magnesium, and chromium than with manganese. Each of these metals, however, caused a lower activation energy in the high temperature reaction. The net result was that the increased amount of fuel deposited at lower temperatures burned over wider temperature ranges at high temperatures.

The addition of compounds containing copper, nickel, and cadmium produced only small changes in the effluent gas composition curves compared to the results with no additive.

Several of the metallic salts caused fuel deposition to increase, particularly iron and tin. Such metallic salts could possibly be used with higher gravity oils in an in-situ combustion process to cause additional fuel deposition. Unfortunately, none of the additives induced the opposite effect.

4. **Baena, C., Castanier, L.M. and Brigham, W.E.: "Effect of Metallic Additives on In-situ Combustion of Huntington Beach Crude Experiments"**
Through kinetic studies on crude oil oxidation in porous media, metals have been shown to affect the nature and the amount of fuel formed. The aim of this work was to use combustion tube studies to determine quantitatively, how the nature and the amount of fuel formed could be changed by metallic additives.

Combustion tube runs were performed using iron, zinc and tin as additives. These metals were selected from the results seen in De los Rios' kinetic studies. The nature of the fuel formed and its impact on the combustion parameters were determined and compared with a control run with no additive. It was found that the metallic additives increased the atomic hydrogen to carbon ratio of the fuel from 0.07 for the control run to 0.13 in the presence of ferrous chloride, 0.61 with zinc chloride and 0.79 with stannic chloride. The H/C ratio of the fuel coupled with the extent to which the oxidation formed CO_2 in preference to CO affected the following combustion parameters: velocity of the combustion front, heat of combustion of the deposited fuel, air requirements at 100% combustion efficiency, the air/oil ratio and the oil recovery rates. As a result of the increased hydrogen content of fuel, the heat of combustion and the air requirements at 100% combustion efficiency increased as the H/C ratio increased. The metallic additives increased the burning front velocity and the oil recovery rate. However these were found to be affected by the oxygen utilization efficiency, the nature and the amount of fuel formed and the air flux.

5. **Tavares, C.J.: "Tube Runs with Metallic Additives"**

Combustion tube runs were conducted with metallic additives in a heavy (10°API) Hamaca oil from Venezuela. Previous kinetics measurements have shown that metallic additives can significantly modify the reactions of combustion and fuel deposition. The equipment and procedure as well as the data analysis techniques are described in detail in a technical report that is in the draft stage. This report will also provide a description of the procedure and equipment used in the tube runs. As an example, we show the results of the four runs on the heavy oil compared to the results with the previous work performed on the lighter Huntington Beach oil.

PROJECT 3 STEAM WITH ADDITIVES

This project aims at improving steam injection by the use of foaming additives. It involves screening of surfactants and studies of flow behavior of foams. The rheology of foam flow through porous media is studied and attempts are made to model foam flooding behavior.

1. **Farrell, J. and Marsden, S.S., Jr.: "Foam and Emulsion Effects on Gas Driven Oil Recovery"**
   The aim of this research was to investigate the gas mobility reducing effects that a gas driven surfactant slug has on enhanced oil recovery (EOR). Three chemically similar surfactants whose properties graded from foaming agent to emulsifying agent were used to study the relative effects that foam and emulsion formation have on gravity override and oil recovery in an unconsolidated Ottawa sand model at room temperature. Both the foam lamellae and the emulsion droplets can act to reduce the mobility of the injected gas in the swept zone thus increasing the vertical sweep efficiency. Shell's Enordet series of alcohol ethoxylate surfactants were used in the study at three different concentrations of, 0.01%, 0.03% and 0.10% (wt.).

   The experimental procedure consisted of displacing oil from a two-dimensional (x, z slice) porous medium at residual water saturation by injecting carbon dioxide, followed first by the injection of a surfactant solution, then by carbon dioxide gas at low pressure. At these low pressures, carbon dioxide acts as an inert gas. Measurements were made of the cumulative produced gas and liquids. The data showed that a product having both foamer and emulsifier properties gave the best recovery.

   The main conclusion from this study is that combining the foam and emulsion mechanisms may lead to more efficient oil recovery than either mechanism alone.

2. **Shallcross, D.S., Castanier, L.M. and Brigham, W.E.: "Characterization of Surfactants as Steamflood Additives"**
   The efficiency of a steamflood can be increased by the use of surfactants that generate steam foam within the oil reservoir. Ideally the foam should preferentially block high permeability streaks and oil-depleted regions of the reservoir. This was an experimental study into the foam-forming characteristics of seventeen different surfactants. Both commercially-available, and experimental surfactants were tested in a one-dimensional sandpack under controlled conditions of pressure and temperature similar to those for

steam injection in California oil fields. The surfactant solutions were injected into the sandpack in discrete slugs of a finite duration allowing transient phenomena, such as the persistence of the foam, to be studied. Nitrogen was also injected at low rates as a non-condensible gas. Four surfactants were found to cause foaming and additional pressure drop within the sandpack at low concentrations. They were Alpha Olefin Sulfonates, Linear Tolume Sulfonates and Chevron SD1000.

Another aspect of the study was to link the foamability of surfactants with their chemical structure. Surfactants studied included, alpha olefin sulphonates, internal olefin sulphonates, linear alkyl-xylene sulphonates and linear toluene sulphonates. Under the conditions of the experiment, long chain alpha olefin sulphonates were found to generate the strongest foams. Internal olefin sulphonates, linear toluene sulphonates and linear alkyl-xylene sulphonates generated just as strong foams, but only at successively higher concentrations. In addition, by the novel use of heat flux sensors attached to the outside of the sandpack, heat loss from the one-dimensional model was studied. This allowed a better understanding of the heat transfer mechanisms operating within the tube. Such an understanding is important in correctly interpreting the experimental observations.

3. **Shallcross, D.C. and Wood, D.G.: "The Accurate Measurement of Heat Flux Using Thin Film Heat Flux Sensors with Application to Petroleum Engineering"**
A thorough understanding of the thermal processes occurring within an experimental system is usually vital in correctly interpreting experimental observations, yet most researchers rely solely on temperature-measuring devices such as thermocouples to study these thermal processes. Heat flux is a process variable that is rarely, yet readily measured. This report details how commercially-available thin film heat flux sensors may be used to accurately measure heat flux.

As with many other devices, the presence of the sensor may change the magnitude of the quantity to be measured. It is possible to correct the measured value to obtain the true undisturbed value. In this report the data reduction equations required to perform the corrections are derived for two different experimental systems.

To illustrate the proper application of the sensor and the correct interpretation of the experimental results, a laboratory investigation is described. Five thin film heat flux sensors were used to study heat transfer processes occurring within a one-dimensional sandpack which was first steam flooded, then injected with a surfactant solution and a non-condensible gas to spontaneously generate steam foam. The sensors were attached to the outside of the sandpack beneath a layer of insulation. Their use allowed determination of parameters such as the steam front velocity and inclination, and the quality of the flowing steam. The rates of heat transfer from the sandpack to the surroundings proved to vary significantly with both time and position along the model. The sensors proved to be valuable tools to help understand the heat transfer mechanisms occurring within the system and to correctly interpret the experimental results.

4. **Castanier, L.M.: "Steam with Additives: Field Projects of the Eighties"**
Surfactants as additives, sometimes in conjunction with noncondensible gases, have recently been tested under various conditions to improve both steam drive and cyclic steam injection in field projects. The objective of this technique is to reduce gravity override and channeling of the steam. When successful this technology seems to be economic even at today's low oil price. However the results have ranged from excellent to negative. This paper is a general evaluation of the field projects published to date.

Sixteen field tests of steam with additives have been studied. They cover a broad spectrum of reservoirs, oils, depths and pressures. The type of surfactant used, the surfactant concentration, the presence or absence of noncondensible gases and their nature, and the mode of injection of the additives also varied widely. The effect of these factors on the efficiency of the projects is discussed. Some of the field tests have been performed after extensive laboratory work. The data published on laboratory screening of additives and on field support are used to explain some of the results observed in field testing.

A brief description of each of the field tests is given. Emphasis of this work is on explaining some of the possible causes of failures or partial success and on suggestions for possible improvements for future field tests.

Evidence of mobility control has been sought through pressure measurements, tracer testing, injectivity profiling, logging, temperature monitoring and observation wells. Production data have also been analyzed.

The results of this study show that additives used with steam can provide significant benefits over steam alone. Indeed addition of surfactant to the steam has been proven as both technically and economically successful as long as some relatively simple criteria are met. These criteria are discussed in the paper.

PROJECT 4 FORMATION EVALUATION

The goal of this project is to better understand and improve reservoir definition techniques such as well to well tracer tests, single well tracer tests and transient well testing techniques.

1. **Ahmed, G., Horne, R. and Brigham, W.E.: "Theoretical Development of Flow into the Well Through Perforations"**
   A technical report on this topic was in the draft stage. The following is an abstract of this work.

   A theoretical solution to flow into a well via perforations is synthesized using Green's functions. The solution is three dimensional and applies to steady-state single phase homogeneous flow. The complete solution for a cylindrical perforation involves a double infinite summation and triple integration, which is difficult to compute. A useful approximation is made by treating the perforation as a line-sink. This reduces the solution to a double infinite summation and a single integration, which is still difficult, but manageable.

   The solution contains expressions of Bessel functions and their derivatives. The infinite summation is over the order and the argument of these functions. An array of eigenvalues are first computed from an implicit equation. These eigenvalues are then used for computation of solutions.

   The solution involves five physical parameters: wellbore diameter, perforation diameter, perforation length, perforation density (vertical spacing) and phasing (angular spacing). These parameters influence the cost as well as the efficiency of a well completion. A sensitivity analysis can be done for an optimization of the completion design using this analytical solution.

   Perforation length is the most important parameter. Initially, even a small increase in length gives a significant improvement in production rate. Perforation density is an important parameter, but beyond an optimum number of shots per foot there is little gain in productivity ratio. The phasing of perforations also influences the performance. A phasing of 90° in the same horizontal plane or along a spiral gives a significant advantage over 0° phasing, and this improvement increases with an increase in perforation length.

Further work is needed to study the effects of variations in the parameters on the efficiency of the completion. These will be useful for perforation design and optimization. Also, further work is needed to extend the solution for uniform potential but variable flow rate along the length of a perforation.

2. **Ambastha, A. and Ramey, H.J., Jr.: "Pressure Transient Analysis for Composite Systems"**
A composite reservoir model was used to analyze well-tests from a variety of enhanced oil recovery projects, geothermal reservoirs, and acidization projects. A composite reservoir is composed of two or more regions. Each region has its own rock and fluid properties. This study considers transient pressure derivative behavior for a well in a two-region composite reservoir to establish the applicability and the limitations of different methods to estimate front radius or swept volume. A finite-radius well with wellbore storage and skin was assumed to produce (or inject) at a constant rate. Three outer boundary conditions were considered: infinite, closed, and constant-pressure. A study of drawdown and buildup responses resulted in a set of correlating parameters for the pressure derivative responses, and new design and interpretation relations were devised for well-tests in composite reservoirs. Guidelines were presented for the applicability of different methods to estimate front radius. Producing time effects on buildup responses showed that analyzing a well-test after a short producing (or injection) time may be difficult.

Dynamic phenomena, such as phase changes and multi-phase flow effects in a region near the front, can cause a sharp pressure drop at the front. This sharp pressure drop was modeled as a thin skin at the front in this study. A thin skin at a front can explain a short-duration pseudosteady state even for small mobility and storativity contrasts. The effects of a skin at a front are similar to the effects of storativity ratio. Thus, neglecting a thin skin at the front can cause large errors in parameter estimation using a type-curve matching method.

3. **Riley, M.: "Detecting Linear Barriers by Type Curve Analysis"**
The effect of a linear barrier (the semi-infinite system) on the pressure behavior of a well test has been recognized for many years. The characteristic doubling of slope on a semi-log graph has been used to determine the existence of a fault and its distance from the well tested. The equations governing this behavior are quite straightforward; hence the presence of a sealing fault is often used to explain anomalous pressure behavior even when it is not justified. Alternatively, when a change in slope is not observed, the

absence of a second straight line is used to calculate a minimum fault distance. Although, this is reasonable in theory, the radius of investigation method normally used for this calculation will overestimate this distance.

This study uses the pressure derivative, coupled with the equivalent drawdown time to present type curves for a semi-infinite system on a single log-log graph. This presentation allows the determination of permeability, skin and fault distance from a single match. The type curves can be used to analyze data from either drawdown or buildup tests, and there is no restriction on production time for buildup testing. Prior to this study, there was no method available to analyze such buildup data following a short flow period.

Type curves are also presented for a well with wellbore storage and skin producing near a boundary. These type curves show that reasonable values of wellbore storage and skin can completely mask the effects of a boundary.

4. **Ambastha, A. and Ramey, H.J., Jr.: "Thermal Recovery Well Test Design and Interpretation"**

A composite reservoir model is used to analyze well-tests from a variety of enhanced oil recovery projects, geothermal reservoirs, and acidization projects. A composite reservoir is made up of two or more regions. Each region has its own rock and fluid properties. This paper deals with analysis of field data from composite well tests based on the theoretical analysis described earlier.

Pressure derivative behavior of a well in a homogeneous, or a three-region composite reservoir is also discussed. Several well tests from composite reservoirs are analyzed to establish the applicability and the limitations of the deviation time method to estimate front radius.

5. **Falade, G.K. and Brigham, W.E.: "Analysis of Radial Transport of Reactive Tracers in Porous Media"**

The paper presents new closed-form analytical solutions of equations describing radial transport of reactive tracers in porous media under conditions of tracer adsorption, nonuniform convection, and variable coefficients of dispersion. Three different types of variable dispersion coefficients were considered, and exact solutions presented in Laplace space. The special case where shear-mixing or convection dominates dispersion, which is important for tracer test studies, was programmed to calculate concentration profiles for continuous and slug-injection test models.

6. **Mishra, S., Brigham, W.E. and Orr, F.M., Jr.: "Analysis of Pressure and Tracer Test Data for Characterization of Areally Heterogeneous Reservoirs"**
This study compares simulated well-to-well tracer tests and transient pressure tests in a quadrant of a repeated 5-spot with spatial variations in permeability. The computations were performed to examine (a) the sensitivity of test responses to the presence of heterogeneity, and (b) the quantification of permeability variation from the analysis of test data.

Single-layer heterogeneous media with an autocorrelated and log-normal permeability distribution were generated using a stochastic moving average method. Finite-difference simulation of pressure behavior in these systems indicates that the geometric mean of effective permeabilities around the injection and production wells is a good approximation for the steady-state interwell permeability. A dimensionless permeability difference defined in terms of these quantities was found to correlate with a heterogeneity index, defined as the product of permeability variance and a dimensionless correlation length scale.

Tracer flow simulations with a method of characteristics procedure show that when the heterogeneity index is small, tracer response can be matched with solutions of the convection-dispersion equation using a constant dispersivity proportional to the heterogeneity index. For larger values of heterogeneity index preferential flow paths are created, which cause tracer breakthrough curves to behave as if they were the result of flow in a layered system. A method is proposed to estimate the heterogeneity index from pressure test data, and thus to predict qualitatively the nature of the tracer response.

PROJECT 5 FIELD SUPPORT SERVICES

This project aims at helping field projects in enhanced oil recovery. It involves diverse topics such as studies of the economics of various thermal recovery techniques, use of micro-computer based models to predict thermal recovery and investigation of numerical methods for better reservoir simulation.

1. **Barua, J.: "A Study on Newton Related Nonlinear Methods in Well Test Analysis, Production Schedule Optimization and Reservoir Simulation"**

   This is a study on the use of alternative nonlinear methods in automated well test analysis, production and injection schedule optimization and in reservoir simulation. In automated well test analysis the advantages and disadvantages of second-order partial derivatives are investigated. Newton's method is shown to be prone to difficulties. However by adjusting the eigenvalues of the Hessian matrix, performance can be substantially improved.

   In optimizing the cyclic steam injection process, Newton's method is compared with the Quasi-Newton method using a simplified model to simulate the process. The Quasi-Newton method does significantly better than Newton's method in saving function evaluations. Specific operating strategies for the process are identified: the need to eliminate soak, the need for greatly increased steam volumes and temperatures, and the need to optimize a combination of economic objectives.

   The two methods are then compared in reservoir simulation. Tests show that while it is possible to use the Quasi-Newton method to build up inverse Jacobians as the iterations proceed, for difficult problems the method requires the use of matrix solution techniques. The method then becomes directly comparable to Newton's method. Tests show that depending upon the linear scheme used, and the difficulty of the problem, the Quasi-Newton method may prove to be less expensive than Newton's method in certain cases.

   The study also addresses the issue of building scalable parallel reservoir simulators. Residual constraints are used to improve the robustness of the parallel matrix solution scheme. The solution of the constraint matrix is shown to be a critical point

2. **Barua, J. and Horne, R.: "Improving the Performance of Parallel (and Serial) Reservoir Simulators"**

   Parallel computers hold much promise for scientific computation. So a great deal of effort has been devoted to finding ways to parallelize *linear* equation solvers. However in fully implicit reservoir simulators the real problem is the solution of *nonlinear* equations. This paper shows how a judicious combination of linear and nonlinear solution techniques can lead to the fastest overall simulator. It uses a combination of an approximate iterative solution of the Jacobian and a Quasi-Newton method. The proposed method makes it possible to use the highly parallelizable Jacobi matrix solution techniques, which are poorly convergent, and still get good serial performance. Experiments on a parallel computer show that even with a highly parallel method, problem sizes need to be quite large to get good efficiency. The proposed method can also be used to speed up serial programs by simply using a good serial technique to iteratively solve the linear equations.

3. **Gajdica, R.J., Brigham, W.E. and Aziz, K.: "A Semianalytical Thermal Model for Linear Steam Drive"**

Thermal recovery by steam injection has proven to be an effective means of recovering heavy oil. Forecasts of reservoir response to the application of steam are necessary before starting a steam drive project. Thermal numerical models are available to provide forecasts. However, these models are expensive and consume a great deal of computer time. An alternative to numerical modeling is to use an analytical model. Analytical models are fast, but the assumptions necessary to generate the solutions may lead to poor results. Common assumptions in analytical models are: (1) a horizontal reservoir, (2) incompressible oil, water, and formation, and (3) no thermal expansion of the oil, water and formation. Furthermore, many analytical models require steam zone saturation as input, or do not consider the water front when calculating production rates. Finally, one-dimensional analytical models do not correctly consider gravity override of steam.

A semianalytical model (SAM) has been developed for one-dimensional linear systems and two-dimensional linear cross-sectional systems. Wells are located at both ends of the reservoir. At the injection well, wet steam is injected at a constant rate and enthalpy. The production well produces at a constant flowing bottom hole pressure. The SAM includes formation dip, compressiblity and thermal expansion of formation, water, and oil. The model automatically calculates the steam zone steam saturation and includes the water front and overburden heat losses. The two-dimensional model also includes gravity override of steam, and underride of water.

The system of equations is solved by iterating on the injection well pressure. For each iteration, the lengths of the steam, water, and oil zones are determined. The pressure drop is calculated for each of these zones and at each well to compute the production well pressure. In the process, front locations, temperatures, pressures, and phase saturations are determined for each of the zones. Oil and water production rates are calculated by material balance. In the two-dimensional model, a new empirical method is presented which determines the shape of the steam front, and an extension of an existing water flooding correlation is used to determine the volumetric sweep efficiency for the reservoir.

Many cases were run on both the SAM and a numerical model. The Computer Modelling Group's general purpose thermal simulator ISCOM was used for comparisons. The SAM runs were several orders of magnitude faster than the thermal simulator, yet matched thermal simulator results accurately in over 2,000 runs over a wide range of variables. The result is a computer program that can be run rapidly on a personal computer by a field engineer. The SAM is ideal for: (1) preliminary studies before running a numerical model, (2) running many cases for sensitivity analysis and optimization, (3) screening prospective field projects, and (4) providing guidance for operating decisions.

4. **Ramage, W.E., Castanier, L.M. and Brigham, W.E.: "The Comparative Economics of Thermal Recovery Projects"**

In 1980, Williams, *et al.*, developed a model for the economic evaluation of steam floods and in-situ combustion recovery projects. This study augments that work.

The purpose of this study was two-fold. First, predictions were made of the oil recoveries for the two thermal recovery methods. The Marx and Langenheim model was used to determine the ultimate oil recovery in a steam-injection project, while the Gates and Ramey oil recovered, volume burned, model was used to determine the oil recovery in an in-situ combustion project. Second, an economic analysis using the Monte-Carlo simulation technique was used on both methods. The main variable was the oil price for the Monte Carlo method. Spacing, depth, operating procedures and oil saturations were investigated during sensitivity studies. A discounted net present value was obtained from the oil recovery schedules to facilitate comparison between the two thermal methods. It was found that the methods are economically competitive.

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PUBLICATIONS

PROJECT 1 FLOW PROPERTIES STUDIES

1. Shimbo, D.T.: "A Comparison of Relative Permeability from Centrifuging Versus Coreflooding," SUPRI TR-72, Stanford University [DOE/BC/14126-18] (May 1990).

2. Castanier, L.M.: "An Introduction to Computerized X-Ray Tomography for Petroleum Research," SUPRI TR-66, Stanford University [DOE/BC/14126-7] (June 1989); also Mossotti, V.G. and L.M. Castanier: "The Measurement of Water Transport in Salem Limestone by X-ray Computer Aided Tomography," Proc. IAEG International Symposium on the Engineering Geology of Ancient Works, Vol. 4, Athens (1988); also Mossotti, V.G. and L.M. Castanier: "Water Transport in Limestone by X-ray CAT Scanning," Proc. of ASCE Symposium on Structure of Materials, San Francisco (1989).

3. Hagedorn, K.: "The Effect of Temperature on Relative Permeabilities of Consolidated Sands," MS Thesis, Stanford University, Stanford, CA (June 1988).

PROJECT 2 IN-SITU COMBUSTION

4. Shallcross, D.C.: "Ignition Devices and Methods for In-Situ Combustion," paper presented at the 3rd International Symposium on Heavy Crudes, Maracaibo (February 20-22, 1989). also Shallcross, D.C.: "Devices and Methods for In-situ Combustion Ignition," SUPRI TR-69, Stanford University [DOE/BC/14126-12] (October 1989);

5. Wingard, J.S. and Orr, F.M.: "An Analytical Solution for Steam/Oil/Water Displacements," SPE No. 19667, paper presented at the SPE Annual Technical Meeting, San Antonio (October 8-11, 1989); also Wingard, J.S.: "Multicomponent, Multiphase Flow in Porous Media with Temperature Variation," SUPRI TR-71 (to be published) (July 1989).

6. De los Rios, C.F., Brigham, W.E. and Castanier, L.M.: "The Effect of Metallic Additives on the Oil Oxidation Reactions in In-Situ Combustion," IEA Meeting, Copenhagen (September 12-13, 1988); also De los Rios, C., Brigham, W.E., and Castanier, L.M.: "The Effect of Metallic Additives on the Kinetics of Oil Oxidation Reactions in In-situ Combustion," SUPRI TR-63 Stanford University [DOE/BC/1126-4] (November 1988).

7. Baena, C., Castanier, L.M. and Brigham, W.E.: "Effect of Metallic Additives on In-situ Combustion of Huntington Beach Crude Experiments," SUPRI TR-78, Stanford University [DOE/BC/14126-26] (August 1990).

8. Tavares, C.: "Tube Runs with Metallic Additives," to be published.

PROJECT 3 STEAM WITH ADDITIVES

9. Farrell, J. and Marsden, S.S., Jr.: "Foam and Emulsion Effects on Gas Driven Oil Recovery" SUPRI TR-62, Stanford University [DOE/BC/14126-3] (May 1988).

10. Shallcross, D.C., Castanier, L.M. and Brigham, W.E.: "Characterization of Surfactants as Steamflood Additives," 3rd International Symposium on Heavy Crudes, Maricaibo (February 20-22, 1989); also Shallcross, D.C., Brigham, W.E. and Castanier, L.M.: "Characterization of Surfactants Through One-Dimension Sandpack Experiments," SUPRI TR-73, Stanford University [DOE/BC/14126-19] (May 1990).

11. Shallcross, D.C. and Wood, D.G.: "The Accurate Measurement of Heat Flux Using Thin Film Heat Flux Sensors with Application to Petroleum Engineering," SUPRI TR-74, Stanford University [DOE/BC/14126-20] (July 1990).

12. Castanier, L.M.: "Steam with Additives, Field Projects of the Eighties," 3rd European EOR Symposium, Hamburg, Germany (November 1987); Also presented at IEA Meeting, Sydney, Australia (October 1987); also Castanier, L.M.: "Steam with Additives, Field Projects of the Eighties," Jour. of Pet. Science and Tech. 2 (April 1989) 192-206.

PROJECT 4 FORMATION EVALUATION

13. Ahmed, G., Horne, R. and Brigham, W.E.: "Theoretical Development of Flow Into the Well Through Perforation," SUPRI TR-77, Stanford University [DOE/BC/14126-25]) (August 1990).

14. Ambastha, A.K.: "Pressure Transient Analysis for Composite Systems," SUPRI TR-68, Stanford University [DOE/BC/14126-11] (October 1989).

15. Riley, M.: "Detecting Linear Barriers by Type Curve Analysis," SUPRI TR-61, Stanford University (May 1988) [DE-FG19087BC14126].

16. Ambastha, A.: "Thermal Recovery Well Test Design and Interpretation," SPE 62nd Technical Conference, Dallas (Sept. 27-30, 1987); also Ambastha, A.K. and Ramey, H.J., Jr.: "An Analytical Study of Transient Behavior of Nonhomogeneous Linear and Radial SUPRI TR-60, Stanford University [DOE/BC/14126-1] (November 1988).

17. Falade, G.K. and Brigham, W.E.: "Analysis of Radial Transport of Reactive Tracer in Porous Media," SPE Reservoir Engineering (February 1989).

18. Mishra, S., Brigham, W.E. and Orr, F.M., Jr.: "Analysis of Pressure and Tracer Test Data for Characterization of Areally Heterogeneous Reservoirs," SPE 17365, Paper presented at the IEA Cooperative Project on Enhanced Oil Recovery, Australia (September 27-30, 1987); also Mishra, S.: "On the Use of Pressure and Tracer Test Data for Reservoir Description," SUPRI TR-65, Stanford University [DE-FG19-87BC14126] (April 1989).

PROJECT 5 FIELD SUPPORT SERVICES

19. Barua, J.: "A Study on Newton Related Nonlinear Methods in Well Test Analysis, Production Schedule Optimization and Reservoir Simulation," SUPRI TR-70, Stanford University (August 1990).

20. Barua, J. and Horne, R.: "Improving the Performance of Parallel (and Serial) Reservoir Simulators, SPE 18408, 10th SPE Symposium on Reservoir Simulation (February 1989).

21. Gajdica, R.J., Brigham, W.E. and Aziz, K.: "A Semianalytical Thermal Model for Linear Steam Drive," SPE 20198, SPE/DOE 7th Symposium on Enhanced Oil Recovery, Tulsa (April 22-25, 1990); also SUPRI TR-75, Stanford Univeristy [DOE/BC/14126-21] (May 1990).

22. Ramage, W.E., Castanier, L.M. and Ramey, H.J., Jr.: "The Comparative Economics of Thermal Recovery Projects," TR-56 [DOE/SF/11564-22] (July 1987).

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