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THERMAL PROCESSES FOR LIGHT OIL RECOVERY

Project BE11A, Milestone 7, FY90

By D. K. Olsen, P.S. Sarathi, S. M. Mahmood, and E. B. Ramzel

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Tom Reid, Project Manager
Bartlesville Project Office
U.S. Department of Energy

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IIT Research Institute
NATIONAL INSTITUTE FOR PETROLEUM AND ENERGY RESEARCH
P.O. Box 2128
Bartlesville, Oklahoma 74005
(918) 336-2400

TABLE OF CONTENTS

Page

Abstract 1
Executive Summary 1
Background 2
Objectives 4
Scope of Work 5
Task 1. Transfer technology in DOE's cooperative effort with Venezuela in thermal EOR by presenting the results of this project at the Annex IV meetings 5
Task 2. Determine the oil recovery potential of steamflooding previously waterflooded light oil reservoirs 5
Task 3. Contrast capillary pressure results obtained from centrifuge experiments with two-phase relative permeability experiments at high temperatures 5
Task 4. Conduct steamflood experiments using light crude oil and diverting mobility control agents 5
Task 5. Conducted scaling study and dimensional analysis in preparation of constructing a new 2-D steamflood apparatus 6
Acknowledgments 6
References 6

TASK 1. TRANSFER TECHNOLOGY IN DOE'S COOPERATIVE EFFORT WITH VENEZUELA IN THERMAL EOR BY PRESENTING RESULTS OF THIS PROJECT AT THE ANNEX IV MEETINGS 7
Objective 7
Background 7
Annex IV between U.S. DOE and Ministry of Energy and Mines, Venezuela 7
Results and Discussion 7
Conclusions and Recommendations 7
References 8

TASK 2. DETERMINATION OF THE OIL RECOVERY POTENTIAL OF STEAMFLOODING PREVIOUSLY WATERFLOODED LIGHT OIL RESERVOIRS WHICH ARE OIL-WET AND COMPARISON WITH RESULTS OF WATER-WET RESERVOIRS 9
Objective 9
Background 9
Results and Discussion 9
References 10

TASK 3. CONTRAST OF CAPILLARY PRESSURE RESULTS OBTAINED FROM CENTRIFUGE EXPERIMENTS WITH TWO-PHASE RELATIVE PERMEABILITY EXPERIMENTS AT HIGH TEMPERATURE 11
Objective 11
Background 11
Results and Discussion 12
Conclusions and Recommendations 12
References 13

TASK 4. STEAMFLOOD EXPERIMENTS USING LIGHT CRUDE OIL AND DIVERTING/MOBILITY CONTROL AGENTS 14
Objective 14
Background 14
Results and Discussion 14
References 16

TABLE OF CONTENTS — Continued

Page

TASK 5. SCALING AND DIMENSIONAL ANALYSIS OF 2-D STEAMFLOOD MODELS....18
Objective....18
Background....18
Summary of Progress....18
References....20

TABLE

1. Calculated values of heat loss in the NIPER 2-D physical model....19

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ABSTRACT

This status report summarizes the research conducted in FY90 under Project BE11A, "Thermal Processes for Light Oil Recovery" and completes milestone 7 of this project. Results of the tasks include transfer of technology in the U.S. Department of Energy's (DOE) cooperative effort under Annex IV with Venezuela on thermal processes for oil recovery, comparison of the oil recovery potential as determined by two-dimensional (2-D) laboratory physical model studies of steamflooding previously waterflooded oil-wet and water-wet sands, evaluation of steamflooding experiments using light crude oil and diverting-mobility control agents, and the results of a scaling and dimensional analysis study in preparation of construction of a new multidimensional steamflood apparatus. The topics are summarized as individual chapters.

EXECUTIVE SUMMARY

The National Institute for Petroleum and Energy Research FY90 Annual Research Plan outlines research for Project BE11A, "Thermal Processes for Light Oil Recovery."[1] This status report summarizes results and the methodology used in the individual tasks within this project.

Because of the agreement under which NIPER obtained Naval Petroleum Reserve, NPR No. 1 core and oil from Sub-Scalez, shallow oil zone, site of light oil steamflood pilot at Elk Hills, California, furnished by the DOE, co-owner with Chevron, NIPER has not included the detailed results of base case 2-D steamfloods or results of the use of surfactants as steam-diverter mobility-control agents in this report. Upon review by DOE and Chevron, these experimental results will be incorporated in a topical report which will include the base case steamfloods, results of screening of surfactants for steam diversion, and results of 2-D steamfloods using the surfactants chosen for steam diversion. The evaluation of steam diverters (surfactants) was undertaken because the 2-D steamfloods with Elk Hills oil and reservoir sand showed significant steam override. In NIPER's evaluation of steam-diverting agents, we found that surfactants used for steam foam diverters in heavy oil (Kern River) developed foam, whereas the same surfactants developed emulsions in steamfloods with light crude oil from the Sub-Scalez, shallow oil zone of Elk Hills. These emulsions led to significant pressure buildup similar to that of the best foams, and experiments are in progress to test these surfactants in a 2-D model to evaluate their capability to improve sweep efficiency.

The significant achievements from the FY90 BE11A research on Thermal Processes for Light Oil Recovery are listed in the following order of priority.

1. NIPER was issued U. S. Patent No. 4,957,164 on September 18, 1990, entitled "EOR Using Flash Driven Steamflood," as the result of NIPER research.

2. Two papers were accepted for publication and presentation at the 5th International Conference on Heavy Oil and Tar Sands, Caracas, Venezuela, and SPE paper 20224 was accepted for presentation at the SPE Western Regional Meeting in Long Beach, California, in 1991.

3. Steam diversion in light oil steamfloods can be achieved through the use of surfactants; however, some surfactants which produce foams when used for heavy oil steam diversion produce emulsions with light oil but develop pressure differentials similar to that of the best foams.

4. Scaled model studies were undertaken to identify the limitations of the current NIPER 2-D steamflood physical model and to suggest physical models to aid in the investigation of the feasibility of light oil steamflooding in consolidated porous media using horizontal injectors and horizontal and/or vertical producing wells.

5. NIPER participated in technology transfer between DOE and Venezuela at Annex IV meetings at Stanford University and at INTEVEP headquarters in Los Teques, Venezuela.

BACKGROUND

Steamflooding of heavy oil reservoirs (<20 °API) is a mature technology and currently contributes nearly 7% of domestic daily oil production; however, heavy oil constitutes only about 10% of the total domestic petroleum reserves. To exploit the potential of many shallow, pressure-depleted, and even previously waterflooded light oil reservoirs, steamflooding is being considered because it has demonstrated effectiveness in recovering commercial quantities of oil.

Although the principal mechanism for light oil recovery with steam is distillation, as opposed to viscosity reduction for heavy oil, even with 16° API, oil distillation accounts for approximately 20% of the oil produced, and this percentage rapidly increases as the oil gravity increases. Application of diverting agents to improve steam sweep efficiency will become as critical in light oil steamflooding as in heavy oil steamflooding. Research at NIPER has shown that contrary to some earlier simulation results, gravity override and fingering are still major problems.

Steamflooding light oil reservoirs has been tested in the field. Chevron conducted a light oil steamflood test in Buena Vista Hills (CA) field for more than 3 years.[2-3] Bechtel, as contractor for the partnership of Chevron and the DOE is conducting a 29-acre pilot test of light oil steamflooding at Elk Hills field, Naval Petroleum Reserve, NPR No. 1, Kern County California.[4] This test started in July 1987 with four injection wells and nine producing wells and produces from the unconsolidated sand (500 md) Sub-

Scalez, shallow oil zone which is at a depth of 2,800 ft. The 27° API gravity oil has a reservoir viscosity of 6 cP at reservoir temperature (120° F). The DOE is conducting a second pilot of light oil steamflooding in Teapot Dome field, Natrona County, Wyoming (Naval Petroleum Reserve, NPR No. 3). John Brown E & C or Lawrence Allison, as former contractor, converted the in situ combustion pilot to a 120-acre steamflood pilot with 22 injectors and 68 producing wells in the tight, consolidated (63 md), highly fractured Shannon sandstone at a depth of 325 ft. The 33° API gravity oil has a viscosity of 10 cP at the reservoir temperature of 65° F.[4]

The world's largest EOR project is the Duri steamflood, which could be classified as a light oil steamflood. The project is on the island of Sumatra in Indonesia where P. T. Caltex Pacific Indonesia operates the project under a production-sharing contract with the Indonesian state oil company, Pertamina, using technology developed by Chevron and Texaco.[4] This project produces about 160,000 bbl/d of 22.7° API oil from unconsolidated sand with 1,550 md permeability from a depth of 625 ft. The oil has a viscosity of 157 cP at reservoir temperature. Production is expected to peak in 1993 at 330,000 bbl/d. In early 1990, the Duri light oil steamflood surpassed the daily production of Kern River (CA) field.

In FY88, experiments in the 2-D steamflooding physical model and use of the DOE screening model predicted that steamflooding water-wet, light oil reservoirs that have been extensively waterflooded would be unfeasible. In the experiments, there was a long delay in oil production as steam heated the water and then followed previously waterflooded channels. The resulting poor oil recovery was the product of both low oil saturation and excessive heat loss to the aqueous phase. Steamflooding light oils, starting at initial oil saturation, did not experience similar time delays. Both processes, steamflooding light oils and waterflooding followed by steamflooding, reduced the oil saturation to lower than that of waterflooding alone. Not all waterfloodable reservoirs have been reduced to residual oil saturation before their average 30-year life. Oil-wet reservoirs release their oil slowly, and many oil-wet reservoirs become strippers or are abandoned but still contain significant oil. Changing the wettability of cores from oil-wet to more water-wet is one mechanism of oil production identified in the FY89 steamflooding research. The effects of steamflooding oil-wet light oil reservoirs need to be investigated to determine if this technology could economically recover significant volumes of light crude oil.

Evaluation and formation of model oil-wet surfaces have been pursued at NIPER over the past 5 years. A more convenient method for converting water-wet cores to oil-wet cores needs to be developed for both projects BE11A and BE11B, so that effects that the surface has on steamflood performance can be determined. In FY85, the use of polar and asphaltic fractions of crude oil for wettability alteration was investigated. A more promising method to generate oil-wet cores has been the use of silylating agents in chemical flooding during the past 2 years; however, they have been used only at low temperatures

(<205° F). The thermal stability of these treatments under steamflood conditions needs to be evaluated to determine if they can be used under steamflood conditions.

In FY89, the work on high-temperature capillary pressure measurements showed that increasing temperature greatly affects wettability and moves a system to a more water-wet environment. The correlation of capillary pressure data generated from well characterized cores in centrifuge experiments and two-phase relative permeabilities determined at elevated temperatures is needed for numerical simulators to predict the performance of steamflood projects. Capillary pressure centrifuge measurements require far less time and are easier to generate than two-phase relative permeability curves. If correlations and an empirical model can be generated, the design and evaluation of steamflooding projects will be accelerated.

The 2-D steamflood model which has been used for both light and heavy oil research is outdated, and a new physical model is needed. As part of a 2-year project to construct a new steamflood model, an analysis of scaling and design criteria of the physical model and of proposed experiments was conducted in FY90. The second year was devoted to construction and testing the physical model. This project could have been accelerated if an appropriate high-pressure chamber and supporting surplus equipment were available.

The previous NIPER research used light crude oils from a number of fields, none of which are now being considered for steamflooding because of both technical and economic constraints within those specific fields. Elk Hills is a prime candidate for future work because the oil reserves in the Sub-Scalez, shallow oil zone are large, and potential exists for expansion of the pilot to field scale if the process is economic. There also exists the potential to expand light oil steamflooding to adjacent fields with similar depositional environments.

OBJECTIVES

The objective of Project BE11A, "Thermal Processes for Light Oil Recovery," in FY90 was to improve the understanding of basic mechanisms responsible for the improvement of light oil production using steam, and to use that understanding for further development of this production technology.

Specifically for FY90, the objectives were as follows:

(1) transfer technology in DOE's cooperative effort with Venezuela in thermal EOR by participating in the Annex IV meetings;

(2) determine the potential of oil recovery by steamflooding previously waterflooded light oil reservoirs which are oil-wet rather than water-wet;

(3) correlate capillary pressure experimental results obtained from high-temperature centrifuge data with two-phase relative permeability experiments performed at high temperatures;

(4) investigate the use of novel steam diverters for steamflooding of light oils; and

(5) design a scaled, two-dimensional steamflood physical model with capability to model various steamflooding conditions.

SCOPE OF WORK

Task 1. Transfer technology in DOE's cooperative effort with Venezuela in thermal EOR by presenting the results of this project at the Annex IV meetings. (Start date: November 1989. Completion date: May 1990.)

This task was designed to exchange technology under Annex IV of the DOE/Venezuelan Ministry of Energy and Mines (MEM) agreement, Annex IV, which is to increase oil production by thermal methods. Activities within this task included attendance at joint meetings, participation in joint discussions, and presentations of results (both oral and written) obtained from light oil research performed in this project.

Task 2. Determine the oil recovery potential of steamflooding previously water-flooded light oil reservoirs which are oil-wet and compare results with those from water-wet reservoirs. (Start date: October 1989. Completion date: July 1990.)

This task was designed to compare the performance of steamflood recovery of light oil from waterflooded water-wet (work completed in FY88) and oil-wet reservoirs in the NIPER 2-D model. Experiments used crude oils to minimize duplication of previous experiments.

Task 3. Contrast capillary pressure results obtained from centrifuge experiments with two-phase relative permeability experiments at high temperatures. (Start date: October 1989. Completion date: September 1990.)

This task was designed to provide an empirical model that can be used in numerical simulation of steamfloods that will use capillary pressure data from centrifuge experiments rather than the more time-consuming and costly two-phase relative permeability measurements as input for steamflood design. A correlation was developed between relative permeability and capillary pressure as a function of temperature by measuring capillary pressures and unsteady-state, two-phase relative permeabilities of a well characterized set of oil- and water-wet cores at different temperatures. The centrifuge drainage data were then history-matched, and the generated relative permeability data were compared with the measured value. The parameters of the model were then history-matched, and the generated relative permeability data were compared with the measured value. The parameters of the model were then adjusted to obtain a satisfactory match between measured and generated relative permeability. The task also allowed the evaluation of the thermal stability of artificially oil-wet surfaces to determine if the gas-phase silylation procedure of converting water-wet cores to oil-wet cores provides a suitable oil-wet surface that will allow this method to be used to simulate oil-wet reservoirs for steam recovery experiments.

Task 4. Conduct steamflood experiments using light crude oil and diverting-mobility control agents. (Start date: October 1989. Completion date: August 1990.)

This task was designed to evaluate a series of novel diverting agents for increasing the oil recovery from steamflooding light oils. One- and two-dimensional sandpacks were used to evaluate foam and emulsion for steam diversion using Elk Hills oil and sand.

Task 5. Conduct scaling study and dimensional analysis in preparation of constructing a new 2-D steamflood apparatus. (State date: October 1989. Completion date: September 1990.)

The objective of this research was to design a new 2-D physical steamflooding apparatus that is scaled or partially scaled. The experience gained over the past 3 years using the 2-D, unscaled, thick-wall physical apparatus was used to design the scaled apparatus. Scaling criteria accommodating various parameters to be investigated and the constraints of the design imposed by a number of different designs were analyzed. Through analyses, the critical scaling factor was determined and steamflooding experiments were designed for each apparatus using statistical techniques of experimental design to minimize the number of experiments and maximize the quality of results compared with the cost and difficulty involved in construction and operation.

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REFERENCES

1. National Institute for Petroleum and Energy Research. FY90 Annual Research Plan. Department of Energy Report No. NIPER-420, November 1989.

2. Rintoul, B. Chevron to Steam Light Oil. Pacific Oil World, July-August 1981, pp. 48-50.

3. Chevron Shuts in Buena Vista Hills Steamflood. Enhanced Recovery Week, Sept. 14, 1987, p. 3.

4. Moritis, G. Annual Production Report, Biennial EOR Survey 1990. Oil & Gas J., Apr. 23, 1990.

TASK 1. - TRANSFER TECHNOLOGY IN DOE'S COOPERATIVE EFFORT WITH VENEZUELA IN THERMAL EOR BY PRESENTING RESULTS OF THIS PROJECT AT THE ANNEX IV MEETINGS.

OBJECTIVE

The objective of this task was to exchange technology under Annex IV of the U. S. Department of Energy (DOE)/Venezuelan Ministry of Energy and Mines (MEM) cooperative effort in thermal EOR. Technology transfer would be accomplished by participating in the Annex IV meetings and preparing papers for presentation at these meetings summarizing the research conducted at NIPER on light oil steamflooding.

BACKGROUND

Annex IV between U.S. DOE and Ministry of Energy and Mines, Venezuela

Annex IV between the DOE and MEM, Venezuela is designed for technology transfer between the countries in the area of thermal oil production. Each country is to pursue its own research, but the Annex is to minimize duplication of efforts and accelerate the advancement of the technology. The Annex promotes cooperation of the researchers and open discussion of the technical problems facing both laboratory and field development of thermal processes for oil production.

RESULTS AND DISCUSSION

Annex IV meetings were held at Stanford University, Palo Alto, California, on October 13-14, 1989, and at INTEVEP headquarters at Los Teques, Venezuela, on February 6-7, 1990. The papers, "Effects of Elevated Temperatures on Capillary Pressure and Wettability," by M. E. Crocker, J. Bentancourt, P. Sarathi, and D. K. Olsen[1] and "Evaluation of Artificially Wetted Surfaces for Use in Laboratory Steamflood Experiments," by D. K. Olsen and M. E. Crocker,[2] were presented by D. K. Olsen. These papers have subsequently been accepted for presentation and will be published in the proceedings of the UNITAR/UNDP 5th International Conference on Heavy Oil and Tar Sands, February 17-22, 1991, in Caracas, Venezuela. Research conducted in the last half of FY90 was presented as Task 46 at the Annex IV meeting held at Stanford University, Palo Alto, California, on October 25-26, 1990. The proceedings and papers presented at these meetings will be assembled after the October 25-26 meeting and published as the cooperative effort of DOE and MEM.

CONCLUSIONS AND RECOMMENDATIONS

Annex IV follows not only the guidelines but also the intent of this technology transfer program. The published record of the proceedings and the goals of each project, the methodology within the research, and the conclusions from the research are discussed openly and frankly with the intent of advancing the technology. The meetings build working relationships between researchers in each country and between countries and between petroleum production operations and research staff. They

provide a relationship of cooperative effort to solve common laboratory and numerical simulation problems and reduce "reinvention of the wheel" by the independent research organizations. This program fosters cooperation between institutions in other areas of petroleum production research other than thermal oil production.

REFERENCES

1. Crocker, M. E., J. Bentancourt, P. Sarathi, and D. K. Olsen. Effects of Elevated Temperatures on Capillary Pressure and Wettability, NIPER Paper No. EPR/OP-90/1, 1990.

2. Olsen, D. K., and M. E. Crocker. Evaluation of Artificially Wetted Surfaces for use in Laboratory Steamflood Experiments, NIPER Paper No. EPR/OP-90/2, 1990.

TASK 2. - DETERMINATION OF THE OIL RECOVERY POTENTIAL OF STEAMFLOODING PREVIOUSLY WATERFLOODED LIGHT OIL RESERVOIRS WHICH ARE OIL-WET AND COMPARISON WITH RESULTS OF WATER-WET RESERVOIRS.

OBJECTIVE

The objective of task 2 was to determine the potential of oil recovery by steamflooding previously waterflooded light oil reservoirs which are oil-wet rather than water-wet.

BACKGROUND

Most light oil reservoirs are waterflooded after primary production; however, waterflooding oil-wet reservoirs leaves significant oil in place at the economic limit of a waterflood, and these reservoirs become stripper operations. In strongly oil-wet porous media, oil covers all surfaces, and the trapping mechanism differs from that in uniformly water-wet rock. Oil flow persists at diminishing rates until the smallest oil channels can no longer transmit fluid under the prevailing pressure gradient. When oil is displaced by water, flow channels develop, and additional water follows these flow channels. The economic limit is reached early in these displacements leaving significant oil in the formation. In an effort to investigate if there is potential for further oil production after waterflooding via steam from these reservoirs, a series of steamfloods were conducted on water-wet porous media in 1989 to study the effect of oil composition.[1-2] To investigate the effect of wettability on steamflood oil recovery, a similar series of experiments in the 2-D model were conducted during the first quarter of FY90 using quartz sand and crushed Berea sandstone of different wettability (intermediate-wettability or strongly water-wet). This study used New London (AR) crude oil (32°API), and the 2-D model was waterflooded before steamflooding.[1-3]

RESULTS AND DISCUSSION

A series of 2-D waterfloods followed by steamfloods on sandpacks of various wettabilities was undertaken. One set of experiments was conducted on crushed Berea sandstone and another on crushed quartz sandpacks. These waterflood and subsequent steamflood experiments were conducted with 32° API New London crude. New London field is in south-central Arkansas and is operated by Murphy Oil Company. These experiments complement our earlier study in which waterflooding followed by steamflooding was compared with steamflooding without waterflooding using water-wet sandpacks. However, these experiments also incorporated oil-wet and intermediate or mixed wettability porous media and analyzed steamflood performance after waterflooding.

The silylation procedure used to prepare sands of various degrees of wettability has been described.[5] The thermal and hydrolytic stability of the oil-wet surface has also been discussed, and the method of determining wettability on these unconsolidated sands has been described.[5] The results of

this section are being written as both a topical report and SPE paper 21769 which will be presented at the SPE Western Regional meeting in March 1991.[6]

This year, light oil steamflood experiments were conducted in the 2-D physical model to compare oil recovery from sandpacks of different wettability that have been previously waterflooded. In contrast to water-wet porous media, oil-wet porous media were characterized by higher initial and residual oil saturation and responded to steam quickly. However, irrespective of wettability, the final steamflood residual oil saturation was the same for all experiments. Sandpacks prepared from field sand exhibited intermediate wettability and yielded a recovery between that of strongly oil-wet (S_{ow}) and strongly water-wet (S_{ww}) sandpacks. The overall recovery was higher for S_{ow} sandpacks than for S_{ww} sandpacks. Further, a comparison of the recovery performance of S_{ww} and S_{ow} sandpacks with the elevated temperature wettability measurements for the same sand indicated that steam gradually altered the wettability of S_{ow} sandpacks to an intermediate wettability state.

From the above results, it was concluded that oil-wet light oil reservoirs which are poor waterflood candidates may be potential candidates for light oil steamflooding.

REFERENCES

1. Strycker, A. Thermal Recovery of Light Crude Oils Using Steam — A Laboratory Study Using a Two-Dimensional Physical Model. Dept. of Energy Report No. NIPER-347, June 1988.

2. Olsen, D. K. Quarterly Technical Report for Oct. 1-Dec. 31, 1989. Dept. of Energy Report No. NIPER-463, v. 11, Energy Production Research, February 1990, p. 64.

3. Olsen, D. K. Thermal Processes for Light Oil Recovery, Project BE11A, FY89. Dept. of Energy Report No. NIPER-435, September 1989.

4. Olsen, D. K., P. S. Sarathi, J. Bentancourt and M. E. Crocker. Effects of Elevated Temperatures on Capillary Pressure and Wettability. To be presented at UNITAR/UNDP V International Conference on Heavy Oil and Tar Sands, Caracas, Venezuela, February 1991.

5. Crocker, M. E. and D. K. Olsen. Evaluation of Artificially Wetted Surfaces for Use in Laboratory Steamflood Experiments. To be presented at UNITAR/UNDP V International Conference on Heavy Oil and Tar Sands, Caracas, Venezuela, February 1991.

6. Olsen, D. K., P. S. Sarathi, S. D. Roark, E. B. Ramzel and S. M. Mahmood. Light Oil Steamflooding: A Laboratory Study of Oil Recovery from Water and Oil-Wet Porous Media in 2-D Sandpacks. To be presented at Society of Petroleum Engineers Western Regional Meeting, March 20-22, 1991, Long Beach, CA. SPE paper 21769.

TASK 3. - CONTRAST OF CAPILLARY PRESSURE RESULTS OBTAINED FROM CENTRIFUGE EXPERIMENTS WITH TWO-PHASE RELATIVE PERMEABILITY EXPERIMENTS AT HIGH TEMPERATURE

OBJECTIVE

The objective of this task was to correlate capillary pressure experimental results obtained from high-temperature centrifuge data with two-phase relative permeability experiments performed at high temperature.

BACKGROUND

A correlation of capillary pressure data generated from well characterized cores in centrifuge experiments and two-phase relative permeabilities determined at high temperature is needed. Capillary pressure centrifuge measurements require far less time and are easier to generate than two-phase relative permeability curves. Relative permeability curves are needed for numerical simulation to predict steamflood performance. If correlations and/or an empirical model can be generated, the design and evaluation of both heavy and light oil steamflooding projects can be accelerated. The correlation of relative permeability from centrifuging and coreflooding has been recently reviewed.[1]

Relative permeability curves generated from centrifuge data and corefloods often differ in both shape and endpoint saturations. Centrifuge curves because of the greater range of forces cover a wider range of saturations and in general show a lower residual wetting phase saturation. Relative permeability corefloods, because of pressure and rate limitations, require extrapolation to residual saturation endpoints, and the measurement of the slope of the curve in these plots is subject to interpretation.

NIPER's approach was to choose cores with previously determined capillary pressure measurement and with well characterized cores. Then, during FY90, two-phase relative permeability measurements were conducted at the same temperature and with the same brine and crude oils. Development of a method to correlate readily obtainable capillary pressure data to two-phase relative permeability data will give the petroleum industry a new tool in evaluating oil production. NIPER had previously evaluated data used for the initial experimental series. The first objective of this phase of work was to accumulate previous data performed on Berea core and to determine if adequate correlations can be made. A generalized model was developed to enable comparisons of the centrifugal data to the two-phase relative permeability data. Final history-matching of the centrifuge data versus the two-phase relative permeability data completed the initial phase of this work. As each phase was completed, additional experiments were performed to ensure reliability with the developed system.

RESULTS AND DISCUSSION

In FY90, NIPER conducted a series of wettability experiments on both consolidated and unconsolidated core material such as Berea sandstone and crushed Berea as well as field core in support of steamflooding experiments conducted under other tasks. Professor Bill Brigham presented the results of David Shimbo's research (entitled "A Comparison of Relative Permeability from Centrifuging Versus Coreflooding,"[1]) at the FY90 Fall Annex IV meeting (Stanford University, October 13-14, 1989). As a result of the presentation and while waiting for a copy of the research report, NIPER concentrated its research efforts on: (1) advancing the data reduction computer programs and facilities for determining high-temperature centrifuge capillary pressure measurements, (2) selecting the core for these studies where capillary pressure measurements had been made, (3) setting up the laboratory equipment for high temperature two- and three-phase relative permeability measurements, and (4) developing data for two UNITAR papers until such time that a printed copy of the research was available. Shimbo's research was subsequently published as a SUPRI Topical Report No. 72.[1]

As part of the Annex X agreement between the U.S. Department of Energy and the Ministry of Energy and Mines, Venezuela, NIPER was fortunate to host Mr. Jesus Bentancourt, visiting scientist from INTEVEP. Mr. Bentancourt chose to work on correlating capillary pressure data as obtained from centrifuge experiments with two-phase relative permeability measurements. At the present time, much of his effort has been built upon his background in the two-phase relative permeability section at INTEVEP. Some of the computer programming and mathematical limitations in solving the data reduction have been advanced beyond where P. S. Sarathi of NIPER had developed Rajan's method[2] in FY89.[3] A topical report on these advancements will be prepared next year.

Wettability analyses have been conducted on sand samples, both before and after steamflooding, and the results will be summarized in a status report for this project. The papers, "Effects of Elevated Temperatures on Capillary Pressure and Wettability,"[4] and "Evaluation of Artificially Wetted Surfaces for Use in Laboratory Steamflood Experiments,"[5] have been accepted for presentation and will be published in the proceedings of the UNITAR/UNDP Fifth International Conference on Heavy Oil and Tar Sands, February 17-22, 1991, in Caracas, Venezuela.

CONCLUSIONS AND RECOMMENDATIONS

In FY90, NIPER was unable to complete the correlation of capillary pressure data (determined from high-temperature centrifuge runs) with high-temperature two-phase relative permeability data obtained on the same core as originally planned due in part to the Gramm-Rudman adjustments to the budget of the project. A letter has been sent to BPO explaining the adjustment. The question posed by the task has been answered in part by Shimbo's research. However, the ability to analyze not only the effluent with time, but also the determination of the saturation profile within the core (at any time within the core in either

centrifuge studies or in two- and three-phase relative permeability measurements) would then answer the question of whether centrifuge studies are correlatable with relative permeability measurements.

Several of the recommendations made at the end of Shimbo's research[1] were in effect in the NIPER Three-Phase Relative Permeability Group in the Fall of 1989, including X-ray CT-SCAN of cores to determine saturation throughout the centrifuge experiments and determining capillary pressure/saturation hysteresis.[6-7]

REFERENCES

1. Shimbo, D. T. A Comparison of Relative Permeability from Centrifuge vs. Coreflooding. SUPRI TR72, Dept. of Energy Report No. DOE/BC/14126-18, May 1990.

2. Rajan, R. R. Theoretically Correct Analytical Solution for Calculating Capillary Pressure-Saturation from Centrifuge Experiments. Pres. at the 27th Annual Logging Symposium of SPWLA, Houston, TX, paper O, June 9-12,1986.

3. Olsen, D. K. Thermal Processes for Heavy Oil Recovery, Dept. of Energy Report No. NIPER-436, September, 1989, pp. 23-31.

4. Crocker, M. E., P. Sarathi, J. Bentancourt, and D. K. Olsen. Effects of Elevated Temperatures on Capillary Pressure and Wettability, NIPER Paper No. EPR/OP-90/1, 1990.

5. Olsen, D. K., and M. E. Crocker. Evaluation of Artificially Wetted Surfaces for use in Laboratory Steamflood Experiments, NIPER Paper No. EPR/OP-90/2, 1990.

6. Honarpour, Matt, Dan Maloney, Shogo Suzuki, and Liviu Tomutsa. Investigation of Cycle Dependent Centrifuge Capillary Pressure and Wettability Index Behavior for Water-wet High Permeability Sandstones. Paper SCA 9006, NIPER Paper EPR/OP-90/5, 1990.

7. Maloney, D. A., A. D. Brinkmeyer, and M. M. Honarpour. Relative Permeabilities and Other Characteristics of 700-Millidarcy, Fired Berea Sandstone, Dept. of Energy Report No. NIPER-496, October, 1990.

TASK 4.- STEAMFLOOD EXPERIMENTS USING LIGHT CRUDE OIL AND DIVERTING-MOBILITY CONTROL AGENTS

OBJECTIVE

The objective of this task was to evaluate steam diverting agents for possible application in light oil steamfloods such as those currently being conducted by DOE at Elk Hills or Teapot Dome. The task focused on methods to reduce the surfactant requirements to provide steam diversion during the steamflood. The scope of this task was expanded to include an analysis and formating of NIPER experimental steamflooding information obtained during FY84 through FY89 such that it could be easily used by the numerical laboratory steamflood simulator being developed under the BE11A and BE11B steamflooding programs.

BACKGROUND

The ability of surfactants to reduce the mobility of steam has been demonstrated both in laboratories, under somewhat idealized conditions, and in field tests. In field trials, the generated foam and/or emulsion has resulted in increased oil recovery by diverting the injected steam to regions of the reservoir that were previously unswept. Comprehensive literature reviews have been published[1-4] in which pertinent issues of foam and/or emulsions as steam diverters have been discussed.

Diversion of steam from a steam swept zone to unswept areas, in either light or heavy oil reservoirs, can greatly influence the economics of steamflooding. Analyses of field-scale foam application to divert steam have been published; however, discussions with operators indicate that previous foam applications have at best provided a breakeven return on additional investment.[5] Loss of surfactant through adsorption, partitioning into the oil-phase, or precipitation prohibits its use in diversion either as foam or emulsion and contributes to the high cost of steam diversion.

RESULTS AND DISCUSSION

NIPER conducted a series of base case 2-D steamfloods using core and oil from Naval Petroleum Reserve, NPR No. 1,Elk Hills California, Sub-Scalez, shallow oil zone. Bechtel is the contractor for the partnership of Chevron and the U.S. DOE and operates a 29-acre pilot test of light oil steamflooding in Elk Hills field, Naval Petroleum Reserve, NPR No. 1, Kern County California.[6] This light oil steamflood pilot started in July 1987 with four injection wells and nine producing wells and produces from the unconsolidated sand (500 md) Sub-Scales, shallow oil zone which is at a depth of 2,800 ft. The 27° API oil has a reservoir viscosity of 6 cP at the reservoir temperature (120° F). Viscosity reduction plays a minor role, whereas repressurization and steam distillation contribute substantially to the oil recovery.

NIPER has not included the detailed results of base case 2-D steamfloods or results of the use of surfactants as steam diverter mobility-control agents in this report. Upon review by DOE and Chevron, these experimental results will be incorporated in a topical report which include the base case

steamfloods, results of screening of surfactants for steam diversion, and results of 2-D steamfloods using the Chevron and Shell surfactants chosen for steam diversion. The evaluation of steam diverters (surfactants) was undertaken because the 2-D steamfloods with Elk Hills oil and reservoir sand showed significant steam override. In NIPER's evaluation of steam-diverting agents (~430° F), NIPER found that surfactants used for steam foam diverters in heavy oil (Kern River) developed foam, whereas the same surfactants developed emulsions in steamfloods with light crude oil from the Sub-Scalez, shallow oil zone of Elk Hills. These emulsions led to significant pressure buildup similar to that of the best foams, and experiments are in progress to test these surfactants in a 2-D model to evaluate their capability to improve sweep efficiency.

The steam diverters (surfactants) were chosen with the intent that NIPER could test the use of an alkaline agent to reduce the amount of surfactant required to develop a steam foam. The work at Shell by Lau et al.[7-10] indicated that weakly alkaline agents could not only reduce the surfactant requirements but also accelerate foam buildup leading to earlier oil production.

NIPER approached the evaluation of steam diverters/mobility control agents for Elk Hills and the evaluation of alkaline agents to reduce surfactant needed by: (1) Using 1-D quartz sandpacks (oil-free and then at steamflood residual oil saturation), NIPER could evaluate the physical model and data collection system and could choose the best surfactants for diverters and evaluate the effect of added alkaline agent (knowing that the quartz sand would have little adsorption, and the alkaline agent would primarily affect the foam strength and stability). These tests evaluate steam foam buildup (rate of pressure generation), maximum pressure obtainable when surfactant is injected on a continuous basis, and foam degradation (pressure decline rate when foam injection is stopped). (2) Using 1-D sandpacks composed of reservoir sand (as received - not cleaned), NIPER could evaluate the effect of adsorption of the surfactant and the effect of addition of the alkaline agent. The field sand would be used only once and mass balance on the surfactant and chemical analysis of the effluent would be conducted. These tests would be conducted at steamflood residual oil saturation. (3) Using the best formulation of surfactant and alkaline agent, the effect of steam diverter would be evaluated in the 2-D model to evaluate its effect on reducing the gravity override we observed in the basecase 2-D steamfloods with Elk Hills oil and sand.

NIPER conducted a series of experiments on steam foam buildup (rate of pressure generation) and foam degradation (pressure decline rate when foam injection is stopped) using Chevron Chaser 1020 and a series of Shell surfactants in linear (1-D) quartz sandpacks. These sandpacks were either oil-free or at steamflood residual oil saturation. The experiments tested the effect of adding weak alkaline agents to either accelerate steam foam buildup, increase the foam strength, or decrease the rate of foam degradation. These additives were expected to reduce the amount of surfactant needed for surfactant-aided diversion of steam.

In FY90, NIPER has nearly completed the experiments in 1-D quartz sandpacks both oil free and then at steamflood residual oil saturation. Significant difficulty has been encountered in duplicating the experiments. This is due in large part, we believe, to the backpressure regulator on the system. An electronic backpressure regulator has been requested. Data is being analyzed such that in FY91 NIPER will write a topical report on this topic.

The effect of liquid/vapor ratio (LVR), rate of steam, non-condensable gas (N_2) and the rate and concentration of surfactant all contribute to the rate of foam formation, maximum foam strength and rate of foam degradation.[11] NIPER has tried to match the LVR suggested in the paper by Lau[10] and the literature supplied by Chevron on its Chaser 1020 surfactant.[12]

Performances of surfactants as steam foamers are dependent upon the test conditions: temperature, salinity, surfactant structure, surfactant concentration, oil composition, oil saturation, liquid/vapor ratio, and frontal advancement rate. NIPER found that surfactants which are good foamers under the 315° F and experimental conditions described by Shallcross et al.[13] (AOS 20-24 developing the best foam while Chaser 1020 was less effective) behave quite differently when the temperature is raised to 430° F. At this higher temperature, Chaser 1020 develops pressure significantly higher and faster than LTS-18 or AOS-24.

REFERENCES

1. Schmidt, R. L. Thermal Enhanced Oil Recovery - Current Status and Future Needs. Chemical Eng. Progress, January 1990, pp. 47-59.

2. Marsden, S. S. Foams in Porous Media. SUPRI Topical Report No. 49, Stanford, California. Department of Energy Report No. DOE/SF/11564-15, May 1986.

3. Farouq Ali, S. M. and R. J. Selby. Function, Characteristics of EOR Foam Behavior Covered in Laboratory Investigations. Oil & Gas J., Feb. 3, 1986, pp. 57-63.

4. Chu, C. State-of-the-Art Review of Steamflood Field Projects. Pres. at the 1983 Soc. Pet. Eng. California Regional Meeting, Ventura, Mar. 23-25, 1983. SPE paper 11733.

5. Eson, R. L. and R. W. Cooke. A Comprehensive Analysis of Steam Foam Diverters and Application Methods. Pres. at Soc. Pet. Eng. California Regional Meeting, Bakersfield, Apr. 5-7, 1989. SPE paper 18785.

6. Moritis, G. Annual Production Report, Biennial EOR Survey 1990. Oil and Gas J., Apr. 23, 1990.

7. Lau, H. C. Alkali-Enhanced Steam Foam Oil Recovery Process. U. S. patent 4,609,044, Sept. 2, 1986.

8. Lau, H. C. Trona-Enhanced Steam Foam Oil Recovery Process. U. S. patent 4,727,938, Mar. 1, 1988.

9. Lau, H. C. and S. M. O'Brein. Surfactant Transport Through Porous Media in Steam-Foam Processes. SPE Reservoir Eng., November, 1988, pp. 1177-1185.

10. Lau, H. C. and J. K. Borchardt. Improved Steam Foam Formulations: Concepts and Laboratory Results. Pres. at Soc. Pet. Eng. California Regional Meeting, Bakersfield, Apr. 5-7, 1989. SPE paper 18783

11. Falls, A. H., J. B. Lawson and G. J. Hirasaki. The Roll of Non-Condensable Gas in Steam Foams. J. Pet. Tech. Jan 1988. pp. 95-104; Trans., AIME, 285.

12. Personal communication with Adrian D'Souza, Chevron Chemical Co, Apr. 23, 1990.

13. Shallcross, D. C., L. M. Castanier and W. E. Brigham. Characterization of Steam Foam Surfactants Through One-Dimensional Sandpack Experiments, SUPRI Technical Report 73. Dept. of Energy Report No. DOE/BC/14126-19, May 1990.

TASK 5. - SCALING AND DIMENSIONAL ANALYSIS OF 2-D STEAMFLOOD MODELS

OBJECTIVE

The objective of this task was to analyze NIPER's current two-dimensional (2-D) physical steamflood model and to design a scaled, multidimensional steamflood physical model with capability to model various steamflooding conditions. As a result of this task, it was hoped that a new physical model would be built in FY91 or later as funds, manpower, and equipment permit.

BACKGROUND

NIPER's current 2-D physical steamflood model was constructed in 1984-85 and has served as a primary tool for the investigation of steamflooding, evaluation of additives to steam for diversion of steam to unswept areas thus increasing the oil production from the model, and simulating in 2-D a cross section of a reservoir being steamed. This model has not been upgraded since initial construction, thus heat-stress cracks and wear as well as advancements in technology (backpressure regulators, temperature sensors and data collection systems) limit the capabilities of the physical model. Analyses of the current capabilities, research planned for future years, direction of other thermal research groups efforts and funding level all impact on upgrading of the physical model. An assessment of current model and design of a new multidimensional physical steamflood model was needed. The model had to serve as part of the overall objective of Project BE11A: "to improve the understanding of the basic mechanisms responsible for the improvement of light oil production using steam, and to use this understanding for accelerating development of this production technology."

SUMMARY OF PROGRESS

Task 5 involved the following steps: reviewing the literature on scaling, modeling and dimensional analysis; evaluation of the current model; evaluation of other researchers physical models; outlining the critical considerations in design and selection processes for construction of a large high-pressure physical model; proposing example models; developing a multi-year experimental plan; defining areas of research that are needed, and making recommendations to carry out such a program.

To evaluate the technical feasibility the applying scaling laws to our existing and a future physical model(s), the role of scaling for thermal EOR was carefully examined. A summary of our observations is being prepared as part of a topical report on light oil steamflooding. Geometric similarity, an important requirement for proper scaling of physical models had to be ascertained between our 2-D model and typical candidate reservoirs being steamed. The model was found quite suitable for nonthermal processes as it has shown mechanical integrity and a history of operational success. However, we encountered significant difficulty in modeling heat propagation typical of most reservoirs being cyclic steamed or steamflooded. For thermal processes, the current physical model was found to approximately model a

hypothetical thin-layered oil reservoir with over and underburden layers of hard, laminated, fine grain shale. Heat loss calculations were performed, as shown in table 1. The analysis indicates a great need to reduce heat losses in the current model if it is to simulate thermal oil recovery processes.

TABLE 1 - Calculated values of heat loss in the NIPER 2-D physical model

Run time, t (hr)	Heated Area, A (ft^2)	Percent heat loss, H_{Loss}	Percent heat loss, H_{Loss}	Percent heat loss including the heat in unswept zone
(Experimental)	(Experimental)	(Kimber)[1]	(Heat balance)	(Heat balance)
0.58	0.05	86	87.27	43.62
3.5	0.11	95	95.36	78.98
6.5	0.37	91	91.60	83.87
9.5	0.59	90	90.83	86.89

[1] See reference 1.

A design for a scaled-model to study steamflooding performance of a five-spot or line drive pattern with horizontal and vertical steam injectors and vertical producers is presented in the topical report being prepared. It features a 3-D sector model, associated cap and base rocks, and appropriate confining pressures. The suitable scaling criteria were selected and applied. A front tracking mechanism incorporating both electrical resistivity measurements and temperature measurements are described in the report. Use of NIPER's X-ray CT scan capabilities were considered. Because of the physical limitations of a high-pressure steamflood model and the low power of NIPER's X-ray source (model would exceed the space available between the X-ray source and crystal detector, and the X-ray source does not have enough energy to penetrate a composite confining vessel and give adequate density resolution) this option of front tracking has not been proposed. To facilitate X-ray imaging with a high-pressure steamflood model (using field core, crude oil and steamflood conditions), an industrial X-ray imaging facility would be required at a cost in excess of $1,500,000 and a multi-year commitment for setup and operation.

Since all scaling requirements cannot be satisfied simultaneously, designing a good scale model study requires critical decision-making. The suitable choices for NIPER's program will be given in the topical report. The degree of scaling and modeling required for the process, choice of low-pressure versus high-pressure models, choice of front tracking mechanisms, and use of overburden and underburden rocks will be discussed in the report.

An examination of previously proposed scaling groups for steamflooding experiments did not show any scaling group that can incorporate steam distillation -- an important mechanism for light oil recovery. The possibility of developing new scaling criteria which could take into account distillation in steamflooding

light oils was considered, but seemed inappropriate because of the need for relaxing some additional though important scaling requirements. The scaling criteria proposed by the University of Alberta research group[1] were chosen in the selection of designs for a scaled steamflood physical model.

Based on a review of the published literature and analysis of laboratory physical models, this study shows the need for a new physical model that can accommodate a flexible experimental program to cope with changing research requirements. It is recommended that the use of the current 2-D physical model be continued, but only after modifications in design (new backpressure regulator, pressure sensors, internal insulation and repair of stress cracks). This would ensure that the existing operating experience and functional equipment are fully utilized. Even though this model has limited application for many thermal processes, its use can be justified in some specialized situations. Construction of a new high-pressure multidimensional physical steamflood model would address long-term research goals; however, upgrading the existing 2-D model would comply with the short-term research emphasized in the DOE Oil Research Program Implementation Plan.[2]

REFERENCES

1. Kimber, K. D. and S. M. Farouq Ali. New Options for Scaling Steam Injection Experiments. Pres. at California Regional Meeting held in Bakersfield, Apr. 5-7, 1989, pp. 53-678. SPE paper 18751.

2. Oil Research Program Implementation Plan, U.S. Department of Energy Assistant Secretary for Fossil Energy, Deputy Assistant Secretary for Oil, Gas, Shale and Special Technologies. DOE/FE-0188P, April 1990.