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Evaluation of NIPER Thermal EOR Research,
State-of-the-Art and Research Needs

Topical Report

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MASTER

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EVALUATION OF NIPER THERMAL EOR RESEARCH, STATE OF THE ART AND RESEARCH NEEDS

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

ABSTRACT

The Thermal Oil Production Research Group at NIPER has conducted research on behalf of the U.S. Department of Energy on thermal methods of oil production (steam and for 1 year, in situ combustion) since 1983. Research projects performed by this group have attempted to adapt to the needs and direction of the DOE's oil research program and that of industry. This report summarizes the research that has been conducted, analyzes the contributions of the research, describes how the technology was transferred to potential users, analyzes current trends in thermal research and thermal oil production, and makes suggestions for future research where NIPER could contribute to advances in thermal oil production.

EXECUTIVE SUMMARY

The purpose of this report is to provide a comprehensive overview of NIPER's thermal oil production research activities and outline the extent that the program has succeeded in advancing technology and addressing the needs of the industry and recommend future areas of research

The thermal enhanced oil recovery (TEOR) research at NIPER evolved with the Energy Production Research (EPR) department over the 10-year period (1983-93) and during this time frame the group performed both long-range, high-risk research and research oriented towards fulfilling DOE's near-term objectives, including support of DOE's light oil steamfloods at Naval Petroleum Reserve (NPR-1, Elk Hills field, CA, and NPR-3, Teapot Dome field, WY). NIPER's thermal research efforts were divided into two areas: (1) heavy oil research and (2) light oil research.

During the past 10 years, NIPER addressed the thermal research needs of the industry by conducting research in several areas including elucidation of the mechanisms of steam oil recovery; effect of steam temperature on wettability modification; quantification of the temperature dependency of capillary pressures; development of techniques to measure capillary pressure of unconsolidated cores at steamflood conditions; elucidation of the mechanism of steam diversion with foam; development and evaluation of analytical and numerical thermal oil recovery models; field-scale simulation studies to assess the steamflood potential of non-California heavy oil reservoirs; domestic heavy oil data base development; domestic heavy oil resource and refinery

capacity assessment; TEOR environmental impact assessment; and laboratory automation software development and testing.

During this period, the NIPER Thermal Research Group made significant contributions toward the advancement of the technology. The major accomplishments of the NIPER thermal research program includes the following:

- Compiled the environmental regulations of importance to TEOR operations and outlined the procedures to be followed for obtaining environmental permits. The resulting publication received high marks from industry for its timeliness and thoroughness.
- Reviewed heavy oil resources in the United States and assessed the feasibility of producing heavy oil. Particular emphasis was placed on identifying and quantifying areas where potential heavy oil could be produced in the future to slow the rate of increase in importing oil.
- Assessed the limitations of existing refineries to accept potential increases in domestic heavy oil. This assessment was used to evaluate various production and refining scenarios and the cost for developing the refining capacity to handle the increasing U.S. heavy oil production.
- Determined the usefulness and limitations of micromodels as a steamflood research tool and identified factors that must be considered in the construction of newer models. The resulting report, written in 1986, was considered a classical work on micromodels and is an often cited reference for researchers planning to develop newer micromodels. Reservoir rock micromodels were developed for studying foams and emulsions.
- Developed correlations for the prediction of the effectiveness of a surfactant as a steamflood mobility control agent. These correlations are often cited by researchers involved in screening and selecting surfactants for use in steamflood applications.
- Investigated the mechanism of oil recovery by steam-foam and was the first to document that the ability of a surfactant to foam in the presence of a crude oil depends on the oil saturation and for each surfactant there exists a critical oil saturation above which the surfactant will not foam. The NIPER Thermal Research Group was also the first to document that the ability of a surfactant to foam is very much dependent upon the oil composition. Thus, a surfactant that foams in the presence of one crude may or may not foam in the presence of another crude oil.
- The NIPER Thermal Research Group was among the first to describe the features of a high-pressure, high-temperature two-dimensional (2-D) sandpack physical model and its usefulness in studying the problems associated with steamflooding such as gravity segregation, poor areal and vertical sweep efficiencies, and fingering of steam through zones of high permeability. NIPER was also the pioneer in demonstrating the effect of

oil composition on light oil steamflood recovery. NIPER demonstrated that crudes with identical API gravity but differing chemical composition will respond differently to steam, and estimations of steam injection oil recovery based on empirical API-gravity-based correlations are likely to be in error.

- Investigated and measured the changes in the wettability of cores subjected to steamflooding as a function of time and temperature, and demonstrated for the first time that steamflood performance differs significantly in water-wet, intermediate-wet, and oil-wet porous media.
- As part of the ongoing communication with industry, NIPER's Thermal Research Group hosted a symposium on field applications of foam and, in cooperation with NPR-3, presented to industry a case history of the NPR-3 light oil steamflood operation.
- As a result of NIPER's thermal EOR research, a patent (U.S. Patent No. 4,957,164) entitled "EOR Using Flash Driven Steamflood," was issued to NIPER.

To transfer technology to the independent operators, a steamflooding handbook was written that introduces independent operators to the fundamentals of steamflooding technology and presents design, engineering, and equipment requirements for a successful steamflooding project. In a separate technology transfer activity, field-scale simulation studies were conducted for an Arkansas reservoir to assess the feasibility of steamflooding in reservoirs other than those in California where the overwhelming majority of U.S. TEOR activities are taking place. The NIPER Thermal Research Group also has worked with DOE and the field operators of the light oil steamfloods at the NPR-1 and NPR-3. Operations at these sites were reviewed and suggestions made on improving operation efficiency. Also, as part of technology transfer, NIPER researchers participated in the biennial technology exchange meetings between DOE and Venezuela Ministry of Energy and Mines (MEM). These and other NIPER TEOR research activities are detailed in this report.

We believe that these and other research accomplishments and the popularity of NIPER Thermal Research Group publications and presentations among petroleum industry and academia researchers are indicators that NIPER's Thermal Research Group largely succeeded in its research efforts and accomplished its set of goals fulfilling DOE's objectives, namely advancing the technology and transferring the results to industry.

The U.S. is the world's largest producer of thermally enhanced oil, accounting for about 39% of the world's thermally produced oil. It is also the global thermal technology leader. Industry and service companies responsible for the Nation's technology lead have drastically curtailed their research efforts in recent years because of declining oil prices. To maintain the Nation's technology lead in TEOR, it is vital that DOE continue funding TEOR research. Some of

the recommended areas of research are given as follows (additional recommended areas of research are given in Chapter 14):

1. Use the field as a laboratory and conduct research to optimize field operations.
2. Establish a laboratory to study phase splitting problems in steam distribution lines.
3. Update the steam injection process handbook.
4. Conduct a steamflood reservoir management practice study to optimize recovery.
5. Investigate novel recovery techniques to produce heavy oil.
6. Identify target reservoirs and support DOE and independents in implementing thermal projects.

CHAPTER 1

INTRODUCTION

NIPER was established October 1, 1983, and was operated under a cooperative agreement between the U. S. Department of Energy (DOE) and the IIT Research Institute (IITRI). The agreement provided for the operation of NIPER as a not-for-profit organization performing research both for the federal government and for private companies over a 5-year period, with a 5-year optional renewal period. Completion of the FY93 research program fulfilled this 10-year agreement. This report summarizes the achievements and accomplishments of IITRI/NIPER thermal research personnel during this 10-year period; describes the advancement of thermal oil recovery technology, provides state-of-the-art assessment in each technical area; and suggests recommendations for future research.

NIPER ORGANIZATIONAL AND OPERATION STRUCTURE

NIPER Organization

The organization at NIPER is shown in Fig. 1.1. The research effort was divided between two departments: Energy Production Research (EPR) and Fuels Research (FR). The EPR Department had primary responsibility for enhanced oil recovery and geosciences research and was divided into three sections: Geotechnology, Chemical and Microbial Displacement, and Thermal and Gas Displacement. The FR Department was divided into Processing and Thermodynamics, Fuel Chemistry, and Fuels/Engines sections.

Facilities and Personnel

NIPER utilized DOE-owned facilities located in Bartlesville, Oklahoma, consisting of 19 buildings with a total floor space of 156,000 square feet on 17 acres. Many of the buildings were specifically designed for petroleum research activities.

NIPER had a staff of approximately 175 people with more than 90 technically trained scientists and engineers having background experience and competence in areas of petroleum research and technology transfer. Major areas of strength were enhanced oil recovery, geoscience, hydrocarbon processing, fuel characterization, mass spectrometry, thermodynamics, and fuels/engines research.

Program Structure

Under the cooperative agreement, NIPER's research program consisted of three elements. The Base Program was specifically designed to assist the DOE in meeting its objectives through EOR processes and geoscience research and fundamental studies for the conversion of available hydrocarbons to quality transportation fuels. The second segment was the Supplemental

FIGURE 1.1 - NIPER organizational structure.

Government Program, which included research for non-DOE government agencies as well as DOE work not included in the Base Program. The third segment was the Work for Others Program which encouraged research work from the private sector and others.

For the Base Program, initial guidance in terms of funding profile by work area was given by DOE. Under DOE guidance, work statements were prepared by NIPER and reviewed by BPO Program Coordinators and Technical Project Officers and DOE Headquarters Program Managers. Final approval was provided by the Program Guidance Committee. The Base Program projects were designed to support the objectives of the Federal Oil Program and recently the DOE's Advanced Oil Recovery Program.

Scope of EPR Research

Research in the EPR Department has evolved over the years in conformance with the evolution in the focus and goal of the Federal Oil Research and Development program. In the early 1980s, coincide with the establishment of NIPER, the scope of the Federal program included: (1)

long-range fundamental extraction research oriented toward immobile oil and EOR, (2) initiation of new reservoir characterization research in recognition that inadequate understanding of reservoir properties contributed greatly to the failures of both cost-shared and incentive projects, and (3) performance/prediction discrepancies analyses. The EOR research during the period of 1983-1988 included research targeted towards understanding the recovery mechanisms of EOR processes, fluid rock interactions and methods to improve recovery efficiency. A new reservoir characterization project, and a relative permeability project were initiated. Microbial enhanced oil recovery and its effect on the environment was also studied in a project started in 1983. Support research to the TORIS program was also performed. In the late 1980s and early 90s, alarmed by the rapid abandonment of domestic stripper wells, the goal of the Federal Oil Research program was changed to maximize the producibility of domestic oil. Both mobile and immobile oil have become the targets of the research program. The program orients research to near- and mid-term objectives to stem the tide of reservoir abandonment; to decrease the rate of decline of domestic production through application of current technology; to develop, test, and transfer the best currently defined advanced technologies to operators; and to maximize the economic producibility of the domestic oil resource. It includes a balance of disciplinary research in reservoir characterization. Extraction system engineering and environmental protection complement interdisciplinary, problem-oriented research focused on specific geological targets. To disseminate the research results, aggressive technology transfer activities were also built into the research program. In other words, the near- to mid-term objectives of the DOE program are to maximize the recovery efficiency of discovered oil and gas through improved understanding of the resource; to develop advanced extraction and instrumentation techniques; and to work closely with oil producers through DOE-sponsored technology transfer programs. The objective also emphasizes an expanded understanding of the environment in relation to new and improved extraction technologies. In view of these changes in emphases, the research projects at NIPER were reoriented to support DOE's Oil Research program which was promulgated by the DOE in April 1990 in a document entitled National Energy Strategy—Advanced Oil Recovery Program (NES-AORP). NIPER's DOE-funded Base Program provided supporting research in most areas outlined in the Oil Recovery Program Plan to include (1) reservoir description methods, tools, instrumentation, and modeling; (2) extraction techniques for secondary and tertiary recovery, and (3) technology transfer. A fourth area, the environment, is considered as a part of all research planning and process implementation. Because of its past experience and developed expertise, NIPER was uniquely positioned to test and transfer new oil, gas, and fuels technology. This was accomplished by performing research for the DOE and other government agencies and by participating with industry in the Work for Others Program and in government-industry cooperative R & D programs.

Thermal EOR Research

The thermal oil production research evolved with the EPR Department over the 10-year period. Initial research on the effect of metallic crude oil compounds on the combustion kinetics of crude oil was replaced by research on steamflooding of light and heavy oil because of the lack of interest in the application of in situ combustion in the U.S. Fundamental research in steamflooding covered a variety of subjects, including the effect of steam temperature on wettability modification, crude oil composition on recovery efficiencies, and the importance of distillation in light oil recovery. Because of the problem of poor sweep efficiency due to gravity override and channeling in the field, both disciplined and targeted foam and emulsion research were performed. An effective method for screening surfactants for steam-foam application was developed, and a 2-D model to study the effectiveness of foam in improving reservoir conformance was designed, fabricated, and used in steam-foam research. A new model that could be operated at higher temperature and pressure was designed, and new process control and data acquisition systems were developed. This new model placed strong emphasis on safety and automation. As part of the targeted research activities, the feasibility of applying foam to NPR-1 and NPR-3 fields where light oil steamflooding projects experienced early steam breakthrough was studied.

In addition to the laboratory studies, the Thermal Oil Production Research Group also developed a steamflood simulator for use in the laboratory and performed steamflood simulations to screen and select a number of reservoirs in Arkansas to determine the feasibility of applying steamflooding technology to recover remaining oil in those reservoirs. This was an attempt to demonstrate to operators (especially independents) the feasibility of applying steamflooding processes to reservoirs other than those in California where the overwhelmingly majority of TEOR activities are taking place. The Arkansas reservoirs were chosen based on a study of heavy oil resources in the U.S. by the Thermal Group that identified several regions in the Gulf Coast with unconsolidated sand reservoirs as potential candidates for the application steamflooding processes. In this study, resource identification and determination of geological, engineering, transportation and refining capacity constraints to the exploitation of these resources were also performed.

As an effort to transfer technology to independent operators, a steamflooding handbook that introduces newcomers to this technology by explaining the fundamentals of steamflooding, design and equipment requirements, and suppliers of steamflooding facilities and services was produced. In a separate technology transfer activity, a report detailing regulations and permit requirements for thermal oil recovery operations was written by NIPER researchers. Both publications have received wide acclaim and are being used by universities and independent operators.

OBJECTIVE, SCOPE OF THE STUDY AND STRUCTURE OF THE REPORT

The purpose of this report is to provide DOE with a comprehensive overview of NIPER's thermal oil production research activities and to outline the extent that the program has succeeded in advancing that technology and addressing the needs of industry.

BACKGROUND

Thermal recovery processes fall into two categories, those in which a hot fluid is injected into a reservoir and those in which heat is generated within a reservoir. The first category includes the injection of hot water or steam into a reservoir, and the second category includes the in situ combustion process. Both steam injection and in situ combustion processes have been commercially successful in the U.S., but steam injection is clearly the preferred process. The in situ combustion process, although simple in concept, is highly complex to implement and requires high levels of manpower to operate. For these reasons, the in situ combustion process has not found widespread acceptance.

Thermal processes (especially steam injection) have been commercially successful. Although they accounted for 61% of total U.S. EOR production in 1992, they are far from being problem-free, and there are many areas where the processes need improvement and have been improved in the past decade (Moritis, 1992). The Thermal EOR Research Group at NIPER was organized to address some of these problems. Although the group performed long-range, high-risk research in previous years, more recently the research was more focused on fulfilling DOE's near-term objectives.

Organization of NIPER's TEOR Research Group

NIPER's thermal oil production research efforts were divided into two areas: (1) heavy oil research and (2) light oil research. The Thermal EOR Research Group was headed by the Section Manager whose duties were to oversee the financial and administrative aspects of research conducted by the research group and to act as an intermediary between the project leaders, members of the Thermal Research Group, and the U.S. DOE Bartlesville Project Office (BPO). He was also responsible for the timely completion of the research activities under his jurisdiction. The light and heavy oil research groups were each led by a project leader (for many years the same person) as principal researchers and authors responsible for delegating research tasks to research group members, conducting the research, preparing the research reports, and generating new research ideas and proposals.

NIPER's Thermal EOR Capabilities and Facilities

NIPER's Thermal Oil Production Research Group in 1993 included four highly qualified and experienced engineers and one senior technician to perform research and development in the area of thermal oil production. The composition of the group changed with only one of the original

research members remaining. The group routinely called upon other disciplines such as geoscientists, database specialists, and environmental and economists to interface with the group. The staff developed experience in every facet of thermal oil production technology and ranging from fundamental laboratory studies on oil displacement mechanisms, to thermal EOR simulation, to analysis of the design and operation of field projects. Major areas of strength included laboratory steamflood studies, elucidation of the mechanisms of steamflood oil recovery, steam diversion with foam and emulsions, development and evaluation of analytical and numerical thermal oil recovery models, field-scale thermal simulation studies, domestic heavy oil data base development, domestic heavy oil resource and refinery capacity assessment, TEOR environmental impact assessment, steam injection project facility design and project implementation, laboratory and pilot plant automation software development and evaluation, and in situ combustion research and economic assessment of field projects.

As part of its investigations, the Thermal Research Group has developed the following laboratory facilities and evaluation tools.

Steamflood: The steamflood laboratory facilities include one- and two-dimensional steamflood assemblies to investigate oil recovery by steam and steam sweep efficiency. The one-dimensional steamflood assembly enables the determination of oil recovery by steam under reservoir conditions from consolidated and unconsolidated reservoir cores. The two-dimensional steamflood assembly enables, under reservoir conditions, the investigation of gravity override phenomena and evaluation of additives to improve volumetric sweep efficiency. The laboratories are highly automated through the use of in-house developed laboratory automation software.

Surfactant Screening: This laboratory permits the evaluation of the thermal stability and high temperature foaming characteristics of surfactants used in steamflooding. Other screening facilities include tools to evaluate the adsorption of surfactant into rocks, precipitation of surfactants in the presence of monovalent and divalent cations, partitioning of surfactant into oil, and the foaming ability of surfactants in the presence of crude oils.

Thermoanalytical Laboratory: This facility includes a computer-controlled thermogravimetric analyzer and differential scanning calorimeter to study in situ combustion process parameters such as fuel availability, ignition temperature and air requirements.

Other investigative tools developed by the group to study thermal oil production process phenomena include high-temperature wettability and capillary pressure estimation techniques, including centrifugal, and thermal simulators to study field-scale thermal recovery projects.

Type of TEOR Research Performed by NIPER

In line with DOE's directives, the NIPER thermal oil production research program including heavy and light oil was designed to achieve the following: (1) analyze field data to identify near-term opportunities for operators, (2) develop techniques and methodologies that focus on resolving

the technological and economic uncertainties that limit applications of technologies that are 'unfamiliar' to operators, (3) develop programs to provide independents with information on a wide range of TEOR related topics, (4) conduct research directed toward improving understanding of the mechanisms in TEOR processes, and (5) provide background information to assist the DOE Program Manager in program planning.

The past NIPER thermal oil production research included the following:

- Prepared a thermal oil production handbook to describe current state-of-the-art practices and guidelines used by engineers performing steamfloods in California.
- Reviewed environmental literature for regulations that applied to thermal oil production.
- Conducted field-scale steamflood simulation studies to assess the technical and economic feasibility of using steam to recover heavy oil in fields outside of California.
- Reviewed the steam injection operations in DOE-managed fields and made recommendations of improving efficiency and profitability.
- Conducted laboratory and field assessments in support of Naval Petroleum Reserve oil fields.
- Developed techniques and procedures for conducting micromodel studies of fluid displacement in actual porous media networks as well as etched glass models.
- Reviewed heavy oil resources in the continental United States and assessed the feasibility of producing heavy oil by EOR methods. Particular emphasis was placed on the potential of thermal methods in fields outside of California.
- Assessed the limitations of existing refineries outside of California to accept potential increases in heavy oil production. This assessment was used to evaluate various scenarios for increasing U.S. heavy oil production by thermal EOR.
- Measured gravity override, distillation, and oil composition effects on steamflooding in a two-dimensional sandpack.
- Evaluated the effects of wettability on production for waterflooding and steamflooding.
- Evaluated various wettability alteration methods for converting water-wet Berea sandstone to more reservoir-like intermediate to oil-wet sandstone.
- Developed and improved a centrifuge procedures for evaluating capillary pressure and wettability measurements in unconsolidated cores at elevated temperatures.
- Evaluated different surfactants under a variety of temperatures, salinities, and oil compositions for foam generation, foam stability, foam transport properties, and thermal stability.
- Developed technology to test multilayer experiments in a single two-dimensional core apparatus.

- Compared the effectiveness of different injection strategies for foam at elevated temperature and pressure.
- Developed a laboratory compositional simulator for predicting the effects of process parameters on oil production and the heat transfer of volatile crude oils.
- Evaluated the use of emulsions for diversion of steam.
- Developed laboratory automation software that can be used in petroleum testing laboratories or pilot plant applications.
- Conducted studies of effect of metals on the kinetics of in situ combustion.
- Obtained a U.S. Patent (Patent No. 4,957,164), entitled "EOR Using Flash Driven Steamflood."

Organization of the Report

The scope of this report includes (1) documentation of NIPER's thermal oil production research activities for the past 10 years, (2) objective reviews of the accomplishments and shortcomings of the research programs, and (3) recommendations for future work.

The report has 14 chapters. Chapter 1 introduces the NIPER organizational and operational structure, NIPER thermal EOR capabilities, facilities, and type of thermal research performed at NIPER. Chapter 2 is a review of the state-of-the-art of TEOR, and it also discusses industrial needs in the area of TEOR. Each of Chapters 3 through 12 reviews the methodology used in that particular area of research and the highlights of that research followed by a critical analysis of the research. These chapters cover research related to (Chapter 3) in situ combustion, (4) light oil and heavy oil steamflooding, (5) steam-foams and emulsions, (6) laboratory automation, (7) environmental aspects of TEOR, (8) thermal simulator development and evaluation, (9) micromodel development, (10) capillary pressure and wettability studies, (11) field related projects, and (12) U.S. heavy oil recovery and refining assessment. Chapter 13 covers technology transfer of NIPER's TEOR research results. It includes a chronological list of presentations and publications, abstracts and conclusions of each of these, and highlights the contributions that these presentations and publications made towards technological advancement and their usefulness to researchers. Chapter 14 offers an analysis of NIPER's thermal research programs and makes recommendations for future NIPER TEOR research.

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Moritis, G., EOR Increases 24% Worldwide; Claims 10% of U.S. Production, *Oil & Gas J.*, v. 90, No. 16, Apr. 20, 1992, pp. 51-79.

CHAPTER 2

REVIEW OF THERMAL EOR—BACKGROUND AND DISCUSSION OF INDUSTRY NEEDS

INTRODUCTION

The United States has about 80 billion barrels of heavy original oil-in-place (OOIP) in 248 large reservoirs (Kuuskraa, 1988a). An additional 20 billion barrels of heavy oil is estimated to exist in smaller reservoirs (less than 20 million barrels of OOIP). The total U.S. heavy oil resource represents about 20% of the estimated 500 billion barrels of crude oil discovered to date (Kuuskraa, 1988b). The U.S. heavy oil resource base includes a diverse collection of oil fields, ranging geographically from Alabama to Alaska originally deposited in fluvial, deltaic or turbidite deposits with some reservoirs in other depositional systems. Over half of the U.S. heavy oil resource is found in California, and more than half of that is in the San Joaquin Valley, mostly in four massive, shallow oil fields—Midway-Sunset, Kern River, South Belridge, and Coalinga.

The recovery of heavy oil by thermal methods involves the introduction of heat into a reservoir to reduce the viscosity of the oil and improve its ability to move through the reservoir to a producing well. The effect of heat on oil viscosity and the idea of using heat to enhance the recovery of viscous crude oil were described in detail in a 1917 U.S. Bureau of Mines publication devoted to oil recovery methods (Crawford, 1964). Heat may be introduced into a reservoir by burning a portion of the oil in the reservoir or by the injection of a hot fluid such as steam or hot water. Both techniques are being used commercially, with injection of steam being the most preferred technique. The first reported U.S. steamdrive was performed in a reservoir near Woodson, TX, at a depth of 380 ft in 1931 (Stoval, 1934). The first reported U.S. in situ combustion field operation was performed accidentally in an Oklahoma field in the mid-1920s (Crawford, 1964).

Thermal oil production technology has developed rapidly in the United States since the 1950s. Most of the U.S. TEOR effort has been focused on recovering the heavy oil reserves of California, where TEOR technology has been more highly developed, customized to the specific reservoir conditions and has been shown to be an economic oil recovery technology. In 1992, TEOR production accounted for 61% of all U.S. EOR production as shown in Table 2.1 (Moritis, 1992). In 1991, the U.S. thermal oil production was nearly twice as much as Venezuela, and four times that of Canada. World TEOR production was 1,200,500 BOPD. The downward trend in U.S. TEOR production is also reflected in the number of thermal projects, Table 2.2 (Moritis, 1991).

TABLE 2.1
U.S. EOR Production (After Moritis, 1992)

	Barrels of Oil Per Day						
	1980	1982	1984	1986	1988	1990	1992
Thermal							
Steam	243,477	288,396	358,115	468,692	455,484	444,137	454,009
In situ combustion	12,133	10,228	6,445	10,272	6,525	6,090	4,702
Hot water				705	2,896	3,985	1,980
Total thermal	255,610	298,624	364,560	479,669	464,905	454,212	460,691
Thermal as % of Total EOR	77	80	79	79	75	69	61
Chemical							
Micellar-polymer	930	902	2,832	1,403	1,509	617	254
Polymer	924	2,927	10,232	15,313	20,992	11,219	1,940
Caustic/alkaline	550	580	334	185			
Surfactant						20	
Total chemical	2,404	4,409	13,398	16,901	22,501	11,856	2,194
Chemical as % of Total EOR	0.7	1.2	2.9	2.8	3.6	1.8	0.3
Gas							
Hydrocarbon miscible/immiscible	15,448	12,615	14,439	33,767	25,935	55,386	113,072
CO ₂ miscible	21,532	21,953	31,300	28,440	64,192	95,591	144,973
CO ₂ immiscible		490	702	1,349	420	95	95
Nitrogen (miscible and immiscible)	2,027	1,400	7,170	18,510	19,050	22,260	22,580
Flue gas (miscible and immiscible)	35,200	35,200	29,400	26,150	21,400	17,300	11,000
Other	600	370					6,300
Total gas	74,807	72,028	83,011	108,216	130,997	190,632	298,020
Gas as % of Total EOR	22	19	18	18	21	29	39
Other							
Microbial							2
Total other	0	0	0	0	0	0	2
Grand total	332,821	375,061	460,969	604,786	618,403	656,700	760,907
1991 Thermal oil production	U.S.	Venezuela	Canada	C.I.S.	China	Indonesia	
Barrels of oil per day	460,500	234,200	106,800	75,000	144,000	180,000	
Percent of world TEOR production	38	20	9	6	12	15	

TABLE 2.2
Active U.S. EOR Projects (Moritis, 1992)

	Number of projects										
	1971	1974	1976	1978	1980	1982	1984	1986	1988	1990	1992
Thermal											
Steam	53	64	85	99	133	118	133	181	133	137	117
In situ combustion	38	19	21	16	17	21	18	17	9	8	8
Hot water								3	10	9	6
Total thermal	91	83	106	115	150	139	151	201	152	154	131
Chemical											
Micellar-polymer	5	7	13	22	14	20	21	20	9	5	3
Polymer	14	9	14	21	22	55	106	178	111	42	23
Caustic/alkaline		2	1	3	6	10	11	8	3	2	
Surfactant										1	
Total chemical	19	18	28	46	42	85	138	206	124	50	26
Gas											
Hydrocarbon miscible/ immiscible	21	12	15	15	9	12	16	26	22	23	25
CO ₂ miscible	1	6	9	14	17	28	40	38	49	52	52
CO ₂ immiscible						1	18	28	8	4	2
Nitrogen (miscible and immiscible)					1	4	7	9	9	9	7
Flue gas (miscible and immiscible)					3	3	3	3	2	3	2
Other					4	3					1
Total gas	22	18	24	29	34	50	84	104	90	91	89
Other											
Microbial								1			2
Total other	0	0	0	0	0	0	0	1	0	0	2
Grand total	132	119	158	190	226	274	373	512	366	295	248

The principles of thermal oil recovery processes and their design are well documented in numerous texts (Boberg, 1988; Butler, 1991; Prats, 1982; Burger, 1985; Sarathi and Olsen, 1992) and reviewed in classic papers on field applications (Farouq Ali, 1979; Chu, 1982; Chu, 1985; Kuuskraa, 1984). Therefore, this review focuses on recent developments in TEOR technology and the future outlook for TEOR in the United States.

Previous Projections of Heavy Oil Productivity

In 1984, the National Petroleum Council (NPC) published a study on the potential of Enhanced Oil Recovery in the U.S. (National Petroleum Council, 1984). The study concluded that EOR could significantly contribute to the Nation's future domestic crude oil supply. However, the study cautioned that "this potential is highly dependent on a broad spectrum of economic, technological, and policy considerations and constraints, which will require the concerted attention of both industry and government in order for the nation to realize the benefits of this resource."

The NPC study made projections of thermal oil production in the U.S. (light and heavy oil), and these projections are shown in Figs. 2.1 and 2.2. Figure 2.1 shows oil projections using thermal oil production technology for both implemented and advanced technology with \$30/bbl oil. Figure 2.2 shows the case for thermal oil production using 1983 implemented technology under a variety of oil prices (constant 1983 dollars). Advanced technology includes steam foams for mobility and profile control, insulated tubulars and other advanced heat management methods, gas-fired steam generators, and cogenerators. The 1984 NPC study adjusted oil prices for the difference in API gravity between the nominal 40° API gravity oil (nominal oil price as used in the NPC figures) and heavy oil price (NPC, 1984, pp. F-7 and F-8). The NPC study did not anticipate the low oil prices that were experienced in 1986-87 and 1989. Low oil prices have contributed to weak investment in heavy oil production, with some exceptions by major oil companies in California. These exceptions include investments made by several vertically integrated major oil companies (i.e., possessing their own heavy oil resources, production technology, heated pipelines, California refinery capacity to handle refining heavy oil, and service stations to market their transportation fuels) (Gill, 1990).

Recently, projections by ICF Resources (Brashear et al., 1991) in support of the 1991 National Energy Strategy indicated that with implementation of advanced technology and an expanded research and development program, thermal oil production (heavy and light oil) could be increased by an additional 930,000 BOPD by the year 2010. For oil production to be economic, it must have supporting infrastructure downstream, including heated pipelines or adequate light oil diluent to transport heavy oil to a refinery designed to process heavy oil. Both transportation and processing entities must make an acceptable rate of return on processing heavy oil, or they will either take on medium and light oil (domestic or imported) or close (Olsen et al., 1992; Grigsby, 1990; Olsen and Ramzel, 1991).

To achieve the projected thermally produced oil production rate forecast in the 1984 NPC study, heavy oil production in California and the Gulf Coast States would have to increase significantly (Olsen et al., January 1991). Achieving the projected goals in the NPC advanced technology case at \$30/bbl (nominal) is doubtful in light of oil production trends and low oil prices (within California, the U.S. and the world). The 1984 NPC study cautioned "... (although) the study was conducted by experts in the field of enhanced oil recovery and other specialists from the petroleum industry, the resulting ultimate recoveries and production rate projections are nonetheless subject to a great deal of uncertainty. Comprehensive studies tend to converge on a best estimate answer. The shortcomings of such a rigorous approach is not what is included in the analysis but the unknowns that are either outside the scope of investigation, or that cannot be

FIGURE 2.1 - Projected production rates for thermally produced oil from the 1984 NPC study. Comparison of implemented and advanced technology rates - at \$30/bbl nominal oil price and 10% minimum rate of return.

FIGURE 2.2 - Projected sensitivity of thermal recovery production rate to nominal crude oil price (constant 1983 dollars with 10% minimum rate of return) from the 1984 NPC study - implemented technology.

precisely determined. These factors lie in the areas of economics, technology, and methodology. While there are a great many factors that may contribute to the overall economic uncertainty, oil price is considered the most significant." (NPC, 1984). The oil pricing and base case used in the 1984 NPC study used "Both present (1983) and anticipated oil prices (before and after) they substantially affect EOR activity. The results of the \$30 per barrel base case are strongly influenced by the events that occurred from 1978 to 1982, when the real price of oil approached \$40 per barrel and was projected to rise even higher. EOR projects benefited and gained much momentum during this time, as shown by the substantial investments made to develop CO₂ resources and pipeline systems to serve the miscible flood projects in the West Texas area. Also, expansions were made to most of the large steamflood projects in California. This increased activity became part of the ongoing EOR base on which the study results are constructed" (NPC, 1984).

A best correlation of actual 1990 thermal oil production of 495,300 (Conservation Committee of California Oil Producers, 1991) versus projected performance in the 1984 NPC study occurs under the implemented thermal technology and \$20 per barrel oil scenario as shown in Fig. 2.2 During most of the post-1986 time period, the posted price for California heavy oil has been substantially lower than the lowest price scenario considered in the 1984 NPC study.

Thermal Oil Production and the World Oil Market

The dramatic drop in oil prices in 1986 is illustrated in Fig. 2.3 and Table 2.3, which show oil prices and ratios of oil prices between West Texas Intermediate (WTI) crude and Kern River (CA) heavy oil (Maples, 1990; Oil & Gas J., 1990-1993). In the U.S. the typical benchmark oil for thermal operations has been the performance of Kern River crude, 13° API gravity. The oil price per barrel has generally trended upward since 1988 but has wide price swings within the last few years creating difficulty in planning investments. Kern River heavy oil (Fig. 2.4), has averaged about two-thirds of the price of WTI during much of the past decade. The price ratios between Kern River crude and Arab crudes tend to be increasing, whereas the price ratios between Kern River and WTI remain at two-thirds. Heavy oil has historically (previous 25 years) sold for about \$5/bbl less than WTI, but the price gap has expanded to beyond the \$7/bbl range since the 1987-1988 drop in oil prices. Since thermal heavy oil production depends on maintaining long-term steam injection and constant cash flow, fluctuating oil prices—especially the low oil prices—make heavy oil production risky. For independent oil producers, operation depends on being able to sell their oil either at the posted price or under a long-term contract which is usually tied to the posted price. If the independent producers (or in some cases major heavy oil producers who are producing in excess of what their downstream or refinery operations can handle) require a higher price, they must be willing to pay shipping charges which can be substantial. Heavy oil profit

FIGURE 2.3 - Average yearly oil price per barrel and ratio to Kern River oil price. (Maples, 1990; Oil & Gas J., Weekly Production Report 1990-1993.)

TABLE 2.3 - Average Annual Crude Oil Prices of the Past Decade
(Maples, 1993)

Year	West Texas Intermediate, \$/bbl	Kern River, \$/bbl	Kern River / WTI Ratio
1983	30.33	20.14	0.66
1984	29.37	20.89	0.71
1985	28.01	20.18	0.72
1986	15.04	9.42	0.63
1987	19.17	13.34	0.70
1988	15.98	9.79	0.61
1989	19.69	12.77	0.65
1990	24.51	16.15	0.65
1991	20.16	12.14	0.60
1992	19.89	13.09	0.66
Average of 1983-1992			0.66

FIGURE 2.4 - Kern River (13° API gravity) oil price (Oil & Gas J., Weekly Production Report 1980-1993).

margins on heavy oil refining are low compared to those of light oil, and unless oil production, pipelining, refining, and marketing (sales of gasoline, etc.) are provided within a vertically integrated company, it is much more difficult for heavy oil to compete effectively with light oil.

TECHNOLOGY CHANGES IN THERMAL EOR

Steam Injection

Screening Criteria

Numerous screening guides and criteria have been presented by many authors and institutions (Prats, 1981; Farouq Ali, 1970; Lewin and Associates, 1981) that have been used to screen reservoir and fluid properties needed for successful implementation of the steam injection process. Several authors (Prats, 1982; Dougdale and Belgrave, 1989) have indicated the use of engineering judgment in the application of these criteria to target reservoirs. Since many of the criteria are being violated in commercial operations, each criterion must be examined on an individual basis. Dougdale and Belgrave (1989) questioned the assignment of values to a set of reservoir parameters and suggested that the only criteria that a steam injection process must meet are the following:

- (a) Can the process heat the reservoir efficiently and economically?

(b) Can the process produce oil economically?

A recent case history of the light oil steamflood at Teapot Dome field, Wyoming, presented by Olsen et al. (1993) clearly demonstrates that a TEOR project can defy some or all established screening guides and yet produce oil efficiently and economically.

Improved Reservoir Conformance

Injection of steam into a non- or low-dipping reservoir with nonzero vertical permeability will result in steam override and poor vertical sweep. A review of steamflood field projects (Tham et al., 1991) identifies gravity segregation and reservoir heterogeneities as problems that limit the efficient application of steamflooding. An example of such a case is the steamdrive in the Mecca lease of Kern River (CA) field (Dilgren et al., 1980; Patzek and Koinis, 1988). Injection of foaming agents with steam has been used to improve the steamdrive efficiency in such reservoirs (Duerksen, 1986; Robin, 1987; Friedmann and Jensen, 1986). However, in steeply dipping reservoirs where gravity drainage is the dominant production mechanism, the steamdrive process is very efficient with updip steam injection and downdip production. In such situations, foam will contribute very little to augment production. Other situations, where there is very little potential for foam, include thick, high vertical permeability reservoirs and reservoirs having line-drive communication between injectors and producers (very high-permeability reservoirs).

In most reservoirs, steamdrive suffers due to gravity override and channeling of steam through high-permeability streaks. Channeling is defined as the loss of steam to isolated 'thief zones' that take a disproportionate amount of the injected steam (Hirasaki, 1989). The thief zone could be a zone of high-permeability sand, or a gas-filled, desaturated zone that is isolated from other zones except at the wellbore. In reservoirs with no crossflow, the foam mobility in the vicinity of the injection well is much more important than it is farther into the reservoir because in such reservoirs the resistance to radial flow from an injection well is concentrated near the wellbore vicinity (Hirasaki, 1989). In such a situation foam can improve the injection profile without invading the entire reservoir.

The use of foam to control the mobility of steam in a channeling interval has been practiced in the oil patch since the early 1970s. It should be pointed out, that the process of injecting small slugs of foam forming surfactant to control injection profiles in cyclic steam operations is different from the continuous injection of steam foam to enhance oil recovery. The slug application method in the cyclic steam process is called a "steam-foam treatment" and the continuous injection of steam foam into the reservoir to improve oil recovery is called the "steam-foam process." Unfortunately, in the literature, "steam-foam treatment" and "steam foam process" are used synonymously. As previously mentioned, the "steam foam treatment" method began to be used in the early 70s and continues to this date. More than 4,000 such treatments have been performed (Eson, 1989). The "steam-foam process" on the other hand was started in 1979 with two DOE-funded field

demonstration projects (Doscher, 1982) in Kern Front field. An example of a "steam-foam process" pilot is Union Oil Company's "Dome-Tumbador" steam foam pilot (Mohammadi, 1989b). The incremental cost of producing a barrel of crude by the application of foam, one of the technologies the 1984 NPC study considered as advanced technology, is shown in Table 2.4 (Eson and Cooke, 1989; Mahmood et al., NIPER-554, 1991). In some of the cases the cost of incremental oil with this "advanced technology" was prohibitive, because when added to the cost of steam and lifting costs, the cost of oil production was higher than the crude oil market price.

Several successful "steam-foam process" pilots have been reported (Castanier and Brigham, 1988; Patzek and Koinis, 1988; Yannimaras and Kobbe, 1988; Mohammadi et al., 1989a, b; Eson and Cooke, 1989). In most cases, the steam foam was applied to a mature steamdrive (10 or more years of steam injection). An exception to this is the Bishop lease steam foam pilot in Kern River field (Patzek and Koinis, 1988), which had been under active steamdrive for only a year before foam injection began. Substantial increases in oil production and improvement in oil-steam ratio were observed in all cases. However, a breakdown of the percent increase in oil production that is directly attributable to foam is difficult. Since most reported steam-foam pilots showed an

TABLE 2.4 - Analysis of published field applications using steam foam diverters—uses and costs

Ref. ¹	Operator	Field	Sand	Treatment	Surfactant consumption and cost per incremental bbl	
					lb/bbl	\$/bbl
Greaser	Getty	Kern River		Slug	0.6	0.49
Farrell	Petro Lewis	Kern Front	-	Slug	2.0	1.80
Doscher	Santa Fe Energy	Midway Sunset	-	Cont.	0.7	0.57
	Conoco	Cat Canyon	-	Cont.	Ineffective surfactant due to high temperature Too small a slug and too short a pilot period	
	Texaco	San Ardo	-	Cont.		
Palzek	Shell	Kern River	Mecca	Cont.	7.1	5.44
			Bishop	Cont.	15.1	11.58
Mohammadi	UNOCAL	Santa Maria	-	Cont.	8.7	11.75
Mohammadi	UNOCAL	Midway Sunset	-	Cont.	5.8	4.5
Chiang	Petro Lewis	Kern River	-	Semi-cont.	3.3	4.42
Malito	Chevron	Midway Sunset	-	Semi-cont.	1.0	1.35
Ploeg		Midway Sunset	Monarch	Semi-cont.	3.3	4.42

¹ First author of paper.

improvement of the cumulative oil-steam ratio, this can be considered as equivalent to an increase in net oil recovery because the accelerated production conserves steam and results in the saving of crude oil burned as fuel for generating steam. Since the improvement in oil-steam ratio is likely to be high for a steam-foam pilot undertaken in a nonmatured steamdrive reservoir, the steam-foam process should be started soon after steam breakthrough rather than after the economic limit of conventional steamdrive (Hirasaki, 1989).

Most of the reported steam-foam process pilots were conducted in the friable or unconsolidated sands of Kern River and Midway-Sunset (CA) fields. Kern River field has multiple zones (group of sands), each with net pay of 65 to 100 ft. The individual sands within the zone are in vertical communication. Gravity override of steam is the primary problem associated with steamdrive in Kern River. Midway-Sunset field's Tulare zone, the main production zone, is a 500-ft-thick sand reservoir which is characterized by large permeability contrast (variation in horizontal permeability) and vertical flow barriers. Channeling into high-permeability zones and gravity override are the major steamdrive problems in Midway-Sunset reservoirs. Response to injection of foam in these reservoirs varied from pattern-to-pattern with the best results being in confined patterns (Castanier and Brigham, 1988). Because of the existence of vertical flow barriers in Midway-Sunset field, improvement in vertical sweep efficiency was achieved by controlling the injection profile only, and the consumption of surfactant was much lower, indicating the avoidance of foam propagation across the entire reservoir (Mohammadi et al., 1988b).

In the reported pilots of the steam-foam process, surfactants were added to the injected steam either (1) continuously at some specified concentration (Patzek and Koinis, 1988; Dilgren et al., 1980; Mohammadi and McCollum, 1988a; Mohammadi et al., 1988b) or (2) as periodic slugs in a semicontinuous manner (Ploeg and Duerksen, 1985; Lee and Kamilos, 1985) or (3) as periodic concentrated slugs (Doscher et al., 1983; Brigham et al., 1986). Small amounts of noncondensable gas were always added to surfactant to stabilize the collapse of foam bubbles due to steam condensation (Falls et al., 1988). Eson and Cooke (1989) recommended the injection of surfactant on a semicontinuous basis rather than as a concentrated periodic slug. However, if the intent of the process is to improve injection profiles in a reservoir without vertical communication, then slug injection is the preferred alternative (Hirasaki, 1989). Although most of the reported steam-foam process pilots were technically successful, the economics were variable due to generally high surfactant consumption per barrel of incremental oil produced.

Another method being developed for improving production is the development of emulsion blocking (French et al., 1986; French, 1987; Farouq Ali and Thomas, 1991). The advantage of this method would be more complete blocking and lower cost than other methods. Emulsion

formation may be one of the mechanisms at work in 'foam' projects that do not have inert gas injected with steam.

Horizontal Wells and Steam Injection

The increasing interest in using horizontal wells in combination with steam injection for optimizing production from heavy oil reservoirs is evidenced by the number of recent research studies and field developments.

One advantage of horizontal wells over vertical wells is the greater direct contact area between wellbore and pay zone (Butler, 1984; Huang et al., 1986; Gussis, 1985; Joshi, 1986). This geometric feature during steamflooding leads to increased heat transfer from a wellbore filled with hot fluids to a cold reservoir. This, in turn, may improve significantly the injectivity and the oil flow. Simulation studies indicated horizontal well patterns are mainly attractive for thin, viscous oil reservoirs with low initial mobility, where steamdrive using vertical wells only would be economically unprofitable (Combe et al., 1988)

Horizontal wells are also attractive in thermally stimulating thick massive unconsolidated sands as evidenced by the results of a recently terminated DOE-sponsored horizontal steam stimulation demonstration pilot in California (Nees et al., 1991). This project was implemented in the massive Potter sands of Midway-Sunset field at a depth of 1,200 ft. Although the horizontal well was completed in only a 30 ft open-hole zone, its daily production exceeded that of a recently completed vertical producer with 400+ ft open-hole completion.

Light Oil Steamflooding

Steam distillation, rather than viscosity reduction, is the major recovery mechanism in light oil steamflooding ($>20^\circ$ API gravity and/or <100 cP viscosity). A state-of-the-art review of light oil steamflooding was published by Strycker and Sarathi (1988). Several laboratory studies (Madden and Sarathi, 1984; Sarathi et al., 1990) indicated that recovery efficiency of light oil steamflooding is strongly influenced by the chemical nature of the crude oil. Gravity override of steam remains a potential problem in light oil steamflooding (Sarathi et al., 1990). Numerical simulation studies indicated that up to 60% of OIP at the start of a steamflood can be recovered economically (Hong, 1986; Chu, 1988). Although this technique has had several field pilots, only the light oil steamflood at NPR-3, Teapot Dome Field, Wyoming (Chappelle et al., 1986; Olsen et al., 1993), and the largest thermal oil recovery project, the Duri steamflood in Indonesia (Pearce and Megginson, 1991) have been expanded to commercial scale. The Duri steamflood (22° API gravity and 150 cP viscosity) is anticipated to produce 330,000 BOPD by mid-1993, up from 180,000 BOPD at the beginning of 1992, and will exceed oil production of Kern River and Midway-Sunset fields combined. The field is a classic example of a well designed project implementing an oil recovery technology in a field amenable to the technology. The field was

discovered in 1941 but not put in production until 1958. Due to low oil production, EOR screening was conducted and a 250-acre steamflood pilot and 15.5-acre caustic pilot flood were initiated in 1975. The caustic flood was terminated in 1979 when it was concluded that the process failed to provide any significant increase in oil recovery. The steamflood was expanded to commercial scale. Pilot light oil steamflood tests have been tried in NPR-2, Buena Vista Hills field, California, (Hong, 1986; Cathles et al., 1987), and in the same age sand, the Shallow Oil Sand (SOZ), in the adjacent anticline at NPR-1, Elk Hills field, California (Hong et al., 1992; Gangle, 1990). Both floods experienced severe scale deposition at producing wells, and high carbon dioxide production from the steam and the reaction with the high carbonate sand in the formation. Light oil steamfloods require high quality reservoirs with low permeability contrasts for successful uniform heating, distillation, and sweep factors according to Blevins (1990). However, recent review of the steamflood at NPR-3 shows that light oil steamflooding can be economic, even in less than ideal (tight, very heterogeneous shallow) reservoir, if the project is well designed (Olsen et al., 1993).

Steam-Assisted Gravity-Drainage Process (SAGD)

A process not yet completely developed is the “steam-assisted gravity-drainage (SAGD) process” which exploits the tendency of oil heated by steam to flow from the top to the bottom of a reservoir to improve production (Butler, 1985). Unlike the cyclic steam process, which can only recover 15 to 20% of oil contacted in a low dip reservoir, SAGD promises an ultimate recovery of 50% or more (Chung and Butler, 1988). Several field pilots using SAGD are underway in Canada; the most visible being the one conducted by the Alberta Oil Sands Technology and Research Authority in an underground test facility.

Heated Annulus Steamdrive (HAS Drive) Process

This process, mainly applicable to tar sand reservoirs, involves circulating steam through a horizontal conduit placed in a heavy oil formation between an injector and producer (Anderson, 1988). This circulation then results in a heated annulus around the conduit creating a zone of reduced heavy oil viscosity. Fluids move along the annular region around and along the horizontal conduit toward the producing well. A combination of steamdrive and gravity-drainage mechanisms contributes to oil and steam condensate production. This process is currently being field tested by Alberta Oil Sands Technology and Research Authority in an underground test facility.

Water-Alternating-Steam Process (WASP)

The Water-Alternating-Steam Process (WASP) was conceived to treat the problem of early steam breakthrough and poor reservoir conformance. It should be pointed out that WASP is different from the technique of injecting water or low quality steam in mature steamflooded

reservoirs as a way to terminate the project and recover some additional oil. WASP is implemented early in the life of a steamflood project to save steam generation costs and increase the salable oil from a reservoir whose performance was impaired by early steam breakthrough and well production problems. WASP uses alternating slugs of steam and water injected over several cycles to recover oil. The process is analogous to the water-alternating-gas (WAG) process used in gas floods. WASP was successfully field tested in a pilot area (Section 13D) of West Coalinga field and is currently being extended to other areas of Coalinga field and in a steeply dipping reservoir in Cymric field (Hong, 1990). WASP is being tried as part of the tailout of steam injection in the light oil steamflood at NPR No. 3, Teapot Dome field, Wyoming. It is still too early to tell if the technology is applicable to this steamflood (Olsen et al., 1993).

Due to the drop in oil prices in 1986, many steamflood operators reduced heat injection (a major cost of operations) by either cutting steam injection rate, steam quality or conversion to waterflood. Several operators found that injection of water to scavenge heat, as proposed in some patents, caused collapse of the steam zone and resaturation with oil of previously steam swept areas resulting in or severely reduced oil production, and large heat sink. It then required significant steam to displace the water and sweep the oil from the zone. Many operators now practice reduced steam injection or reduced steam quality as their tailout of steam injection.

Single-Well Injection/Production Steamflood (SWIPS) Process

Since horizontal well, heavy oil, thermal recovery processes such as SAGD and HAS Drive must bear the high costs and complexities associated with drilling, completion and operation, the concept of a vertical HAS Drive process was proposed. In this process, steam is injected through the tubing string and allowed to circulate in the wellbore from just above the bottom packer to the injection perforation near the top of the production sand (Duerksen, 1991). This circulating steam creates a heated annulus around the conduit and provides communication between the steam injection perforation near the top of the sand and the fluid production perforation near the bottom of the sand. This concept is being tested in a California extra heavy oil reservoir (oil gravity less than 8° API).

Injection of Noncondensable Gases With Steam

Interest in using noncondensable gas with steam to improve oil recovery and production performance has increased in recent years. Development and use of the steam foam process in light oil steamflooding of several field pilots (Anon, 1989) and laboratory studies involving steam with the addition of CO₂, nitrogen, and/or flue gas (Harding et al., 1983; Harding et al., 1987; Redford, 1982) indicate a modest improvement in total oil recovery compared to that of steam injection only. The steam noncondensable process is not effective in improving oil recovery when applied to a live oil situation.

Improvement of Thermal Efficiency

Since thermal processes are energy intensive, any improvement in energy utilization will improve the profitability of a project. The thermal efficiency of a steam injection process is characterized by the coefficient of performance, defined as the ratio of the heating value of the oil produced to the amount of energy expended to produce that oil (Burger, 1985). Significant research in the field and simulation has been devoted in recent years to optimizing the use of the thermal energy input. These include (a) cogeneration of steam and electricity (Western, 1990); (b) better control of steam quality at the wellhead (Jones, 1991; Anderson et al., 1984); (c) new insulated tubing for steam injection (Kutzak, 1989); (d) conversion of steamflood to waterflood, with optimized size and quality of the steam slug (Ault, 1985); and (e) water-alternating-steam process WASP (Blevins, 1990).

The advances in insulated tubulars now permit injection of steam into deep reservoirs (Borregales, 1987). Laboratory and simulation studies have shown that by properly choosing steam quality and injection duration, the energy efficiency of the steamflood process can be maximized (Lemonnier, 1981). Measuring heat loss and verifying simulation of heat loss for design calculations was advanced by a DOE cooperative project with industry instrumenting a well, measuring heat loss and developing a heat loss computer model (Traynor, 1992; Traynor et al., 1991).

Operation Improvement and Reservoir Management

The oil price collapse of the mid-1980s forced steamflood operators to reevaluate operating practices and improve reservoir management techniques. Industry now places major emphasis on measuring downhole parameters and altering operations strategy based on in situ data (Blevins, 1990). Data obtained during steamflood operations are used to update reservoir descriptions and alter production practices. Temperature and pulsed neutron logs are used to determine steam sweep, location of reservoir heterogeneities, liquid desaturation, steam zone pressures and heating rates. Data from reservoir monitoring are analyzed to formulate better reservoir management practices and to lower operating costs. It is expected that for the rest of the century emphasis will be on improving the efficiency of the operation, rather than improving the technology (Stosur, 1988).

Steamdrive Problems

Although steamdrive is the most successful of all EOR processes, there are many areas where steamdrive needs improvement. Some common problems exist that have considerable impact on oil recovery by steam injection. These are detailed in the following paragraphs.

Gravity Override

Since steam is lighter than oil, the gravity override phenomenon in many cases causes steam to rise to the top of a sand shortly after it leaves an injection well, sweeping only the topmost portion of the sand. The problem of reaching the lower portion of the sand with steam is one of the most important problems yet to be solved satisfactorily. Some of the methods that have been tried with limited success, but lacking in general application, are as follows:

- One method has been to follow steamdrive with injection of water or low quality steam in an attempt to gravity underdrive the steam zone and displace heated oil to the producer. This method was apparently successful in only limited cases, and the failed cases had such a detrimental effect on oil production that industry no longer uses this process to produce oil from bypassed zones (Blevins, 1990).
- Another method has been to inject foam forming surfactants and inert gases into the reservoir along with steam to divert steam to unswept zones to improve reservoir sweep. While this method was apparently successful in many cases, the process failed to recover additional oil economically in many cases. Abnormally high injector to producer pressure differentials are required for long-range foam propagation (Hirasaki, 1989). Foam qualities and consistencies change rapidly away from the injection well, and foam is sensitive to the presence of oil (Jensen, 1987) and composition of the oil (Strycker, NIPER-295, 1987).

Steam Quality

Another serious problem associated with steamdrive is the difficulty of determining the quality of steam delivered at the wellhead and at the sandface. The 80% quality steam generated by oilfield steam generators is delivered to a wellhead through a complicated surface distribution system. Because of the heat losses in the distribution network, the quality of steam delivered at a wellhead is different from the generator effluent quality. Fieldwide checks of wellhead conditions revealed quality of steam delivered at wellheads varied from 4 to 100% (Jones, 1991). Because of the nonavailability of accurate, inexpensive, and reliable steam quality and flow measurement hardware, rates of flow and steam quality are often estimated at the wellhead.

In recent years, steam quality measurement instruments based on vibrating densitometer principles (Strome, 1987) and thermal neutron transmission principles (Wan, 1990) have been made available to the operators. These instruments, in conjunction with a flow metering device such as a flow nozzle or an orifice meter, are used to measure steam quality at the surface line. However, these instruments are expensive and must be calibrated for various field conditions. Recent field tests revealed that these devices are difficult to calibrate and require periodic recalibration.

Rudimentary downhole measurements indicate that a two-interval steam system at downhole separates into liquid and vapor phases, with the liquid phase entering one sand and the vapor the

other. Currently, most operators estimate downhole steam quality using computer programs, based on wellhead data (i.e. flow rates, temperatures and wellhead steam quality). This precluded the estimation of how much heat is injected into formations and into which interval it is going. Use of limited-entry perforation schemes and downhole critical velocity chokes may allow operators to exercise some control over where steam enters a reservoir (Hone, 1987); however, lack of field or laboratory data prevents an evaluation of the effectiveness of these schemes. Use of radioactive tracer surveys to control steam injection profiles has been suggested (Nguyen, 1988); however, data interpretation is difficult because of lack of knowledge or low streamlines in injection wells (Schmidt, 1990). Shut-in static temperature surveys can be used to locate steam injection intervals, but not to determine the total heat injected. Experimental and theoretical work is needed in this area.

Other Technical Problems

Since typical oilfield steam generator feed water always contains some bicarbonate, which decomposes in the hot steam generator (Reed, 1980) into CO₂ and hydroxides, steam can be very reactive in a reservoir. This decomposition results in a low-pH steam vapor phase and a high-pH liquid phase (pH 9 to 11). These high and low-pH phases cause significant dissolution of rock matrix and generate CO₂ from the carbonate mineral phases (Cathles et al., 1987). The generated CO₂ significantly affects in situ process performance and contributes to production well and surface facilities problems (Schmidt, 1990).

The high temperature in steamdrive restricts the types of instruments and materials that can be used in wells. There is a critical need for equipment that can withstand a harsh steamflood environment. Better monitoring tools and techniques are needed to define steam, hot water, and produced oil zones and to characterize their movement through reservoirs.

Research is needed to better define the effect of temperature on wettability changes and oil-water relative permeabilities. Better well completion and sand control techniques are needed. Research that focuses on reducing thermal stress corrosion and extending the service life of downhole steam generators will contribute to applications of steamfloods to deeper heavy oil wells.

Other problems are more relevant to 'marginal' or 'less than ideal' reservoirs. These problems are summarized in Tables 2.5 through 2.7.

In Situ Combustion (Fireflood)

Although both steam injection and in situ combustion processes have been commercially successful in the United States, steam injection has clearly been the preferred process. There appears to be several reasons. The instant success of the cyclic steam process, the result of its low initial investment and immediate production response coupled with the complexity and the high

TABLE 2.5 - Reservoir problems

-
- Too deep, thin and/or tight
 - Reservoir too small
 - Reservoir pressure too high
 - Severe heterogeneity and/or lenticularity
 - Water sensitive
 - Unconsolidated vs. consolidated sands
 - Scale-forming or corrosive connate water
 - Oil relatively non-viscous or too viscous
 - Oil saturation too low
-

TABLE 2.6 - Unattractive economics

-
- High oil viscosity
 - Costs increasing faster than crude prices
 - Complicated projects require more people
 - Fuel prospects uncertain
 - Pollution problems increase costs
 - Water supply and disposal
 - Royalty and surface damage
 - Front end loads and delayed response
 - Crude price structure and cyclic demands
-

TABLE 2.7 - Technical difficulties

-
- Reservoir definition
 - Poor conformance and capture efficiency
 - Low injection/production rates
 - Excessive heat losses, poor net energy ratio
 - Sand control
 - Wellbore damage
 - Boiler feedwater and low-grade fuel options
-

level of manpower required to operate a combustion project, retarded the widespread acceptance of the combustion process in the United States (White, 1985). Further, since the early in situ combustion projects were poorly engineered and implemented in often noncommercial producing properties, they were a disappointment to the sponsors. Although the properly engineered combustion projects on desirable properties were highly successful, the failed projects outnumbered the successful ones and slowed the ready acceptance of the combustion process in the United States.

The latest *Oil & Gas Journal* EOR survey (Moritis, 1992) reported eight active in situ combustion projects in the United States, and no new projects were planned. Together, these projects produce about 4,700 BOPD which is 1% of the U.S. TEOR production. The daily U.S. in situ combustion oil production is twice the combined production of all chemical EOR processes.

Fireflooding is widely practiced in other parts of the world, and large-scale commercial in situ combustion operations are currently ongoing in Canada, Russia, and Romania (Moore, 1988). Unlike other parts of the world, the U.S. in situ combustion technique is often used as a means to repressurize the reservoir and not as a recovery technique. West Heidelberg, MS (Benton, 1981) and Forest Hill, TX (Hvizdos, 1983) in situ combustion projects are prime examples of in situ combustion pressure maintenance operations. This technique is used in the U.S. is because it is easier and more cost effective to produce oil from deep reservoirs by repressurization than by pumping. In spite of the lack of interest in the United States for the combustion process, research continues on various aspects of the combustion process, and pilots are being undertaken in other parts of the world. One reason for using in situ combustion is reservoir repressurization.

Laboratory Research on Factors Affecting the In Situ Combustion Process

In situ combustion is a very complex process involving many chemical and physical processes. To improve its efficiency, it is necessary to have more knowledge of the factors influencing the process and how these affect the combustion of oil. Consequently, in recent years, extensive work has been devoted to understanding qualitatively and quantitatively the chemical reactions in natural porous media.

The mineral matrix significantly affects the extent of reactions involved within in situ combustion and plays a vital role in the viability of the process in light oil reservoirs (Hardy et al., 1972; Burger and Sahuquet, 1972). Effects of rock minerals on the kinetics of combustion were the focus of some recent combustion tube studies (Vossoughi et al., 1982; Fassihi et al., 1984 a,b; Hughes et al., 1987). Although combustion tube experiments achieve the closest approximation to field conditions and provide comprehensive information, the tests are very expensive and time consuming. Consequently, many researchers have used thermal gravimetric analysis (TGA), differential thermal analysis (DTA), and differential scanning calorimetry (DSC) techniques to elucidate certain features of the process and the effects of various variables (Bae, 1977; Yoshiki and Phillips, 1985; Drici and Vossoughi, 1985; Kharrat and Vossoughi, 1985; Jha and Verkoczy, 1986; Phillips et al., 1982; Madden and Maerefat, 1985).

These laboratory studies indicated that the performance of combustion within a given reservoir is dependent on the selection of operating conditions and that the operations must be tailored to the reservoir under consideration. Further, the combustion behavior depends upon the complex interrelationships between the kinetics of thermal cracking and the low- and high-temperature oxidation reactions. In recent years, there has been increased advocacy for the use of enriched air or oxygen for in situ combustion (Hansel, 1982). It is claimed that the use of enriched air will result in faster oil production, reduced compression costs, and better combustion efficiency and will generate enough CO₂ to decrease the viscosity of the produced oil (Pate, 1985). However, significant oxygen leakage can occur ahead of a combustion front into a steam bank

where low-temperature oxidation and other reactions occur with the oil present (Moore, 1988). Further, the enriched air combustion data suggest that the process performs best at lower pressures, and the degree of oxygen enrichment is reservoir specific (Shahani, 1984). Adequate oil mobility is essential for the success of a combustion project. Combustion tube tests revealed stalling and backburning when the thermally upgraded oil failed to be displaced from the high-temperature region (Moore, 1988).

Multipurpose thermal simulators have also been used extensively to determine the kinetic parameters of the three main reactions involved with in situ combustion: low-temperature oxidation (LTO), high-temperature oxidation (HTO), and high-temperature coking of crude oils in porous media. Good laboratory or experimental data are needed as input to the simulator to predict kinetic parameters reliably. Obviously, inaccurate data will yield incorrect parameters. Further, since the actual reaction zones (less than 3 ft) are much smaller than the size of the grid blocks generally used for modeling the process, the predicted results may be unsatisfactory (Islam et al., 1989).

Current Status of In Situ Combustion Field Projects

Reports on in situ combustion field activities are scarce compared to reports on laboratory research. Reported field activities include oxygen-enriched combustion pilots (Hvizdos, 1983; Pebdani, 1988), performance review of ongoing combustion projects (Pebdani et al., 1989; Curtis, 1989), and postmortem analysis of terminated projects (Langley, 1985; Farquharson, 1985; Pate, 1988; Choquette, 1991).

Although oxygen enriched air combustion projects generally have resulted in higher oil recovery compared to that of nonenriched-air combustion projects, they have been plagued with more severe safety and operational problems. Some of the safety issues associated with enriched-air (oxygen) combustion projects include: oxygen compatibility with metal, combustion of metals, safe delivery of oxygen to the wellhead, wellbore ignition, and explosions (Hvizdos, 1983). The operational problems associated with enriched-air projects are similar to those encountered in nonenriched-air combustion projects, but are much more severe. These include injection well failure due to tubing leaks, production well failure due to casing collapse, severe corrosion of downhole equipment resulting from combustion products, and production of tight emulsified fluids that are difficult to treat (Pebdani et al., 1988; Langley, 1985).

Postproject analysis of the terminated projects led to the conclusion that it is very difficult to implement an economically justifiable combustion project in geologically complex heavy oil reservoirs, and the recipe for a successful project must include proper coordination of engineering, geoscience and laboratory personnel (Farquharson, 1985). Postcoring results of a Texas oxygen combustion pilot revealed the role of gravity and localized diagenetic hard streaks on combustion sweep (Choquette, 1991). While gravity strongly influences the combustion sweep, shaley streaks

have minimal effect. Economic analyses (Pate, 1988; Pebdani et al., 1989) indicated that in situ combustion projects in Texas may be more profitable than those in California because of a more favorable economic climate and less stringent environmental constraints. Thus, viability of in situ combustion projects depends on the local economic environment (Pebdani et al., 1989).

One of the oldest and most successful in situ combustion projects in the U. S. is the Bellevue In Situ Combustion Project conducted by Getty Oil Company (Long, 1981). Sequential development of the project has permitted the determination of the effect of key variables on oil recovery. Postmortem analysis of project performance revealed that the wet combustion process (simultaneous injection of air and water) is superior to a dry combustion process which is followed by water injection to scavenge heat. Details of this project are discussed by Tham et al. (1991). Another DOE-sponsored in situ combustion project in the same field was also technically and commercially successful (Trantham, 1982).

Other Thermal Processes

Electromagnetic Oil Well Stimulation Process

Electromagnetic oil well stimulation is a thermal stimulation process that employs electromagnetic energy as the agent to transfer energy from the surface to the reservoir (Spencer et al., 1988). Fanchi (1990) presented an algorithm for estimating the temperature profile associated with the electromagnetic irradiation of the reservoir. The process is applicable to reservoirs in which oil is mobile at reservoir conditions and in which sufficient pressure exists to push oil into the wellbore. The process is successfully being field tested in the United States, Canada, and European heavy oil reservoirs.

Thermal Oil Production Economic and Environmental Constraints

Economic Constraints

Major constraints to the more widespread application of thermal oil production are economic and environmental in nature as well as technical. Some of the economic constraints include:

- (a) lower crude oil prices due to, as a rule, lower crude oil gravity, higher sulfur and heavy metal content of the produced crude yielding less high value product when refined;
- (b) large front-end investments and delayed production responses;
- (c) absence of cost-effective technology to upgrade low-quality, low-gravity crude into higher value, more salable products; and
- (d) absence of cost-effective technology that permits the use of low-grade fuel such as coal, petroleum coke, high sulfur crude oil, and brackish water to generate steam without violating the environmental regulations or excessive cost.

Environmental Constraints

Future TEOR production will be severely constrained in California where the air quality regulations are stricter than the federal counterparts. The San Joaquin Valley, California, where 90% of the U.S. thermal EOR activities are concentrated, is classified as a nonattainment area with respect to ozone and particulates. Current regulations mandate new thermal EOR operators to use the 'best available control technology' (BACT) on their facility. BACT technology is often costly, and in California, BACT requirements vary from district to district. This, in many cases, results in the use of BACTs that have not been previously tried. Further, new operations are subjected to the 'Prevention of Significant Deterioration' (PSD) review and 'offsets' must be obtained for new projects. Obtaining offsets for new projects is the single most difficult and costly aspect of obtaining permits for new facilities (Blevins, 1990).

CONCLUSIONS

Although thermal EOR processes contribute almost 7% of the total U.S. oil production, which constitutes 61% of the U.S. EOR production, the technology is far from being mature, and additional research needs to be done.

Additional understanding of basic reservoir properties and geology, refinement of data-gathering instruments, improved steam usage and generation, better well and surface equipment, improved mobility control techniques, and improved reservoir description techniques must be developed if the large amount of additional oil available from heavy oil reservoirs is to be recovered economically.

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CHAPTER 3

IN SITU COMBUSTION (FIREFLOOD) RESEARCH

OBJECTIVE

The objective of this research was to determine the effects of various metals and minerals, often associated with oils and reservoir material, on the kinetic parameters of combustion and cracking which occur during in situ combustion. In particular, the effects of vanadium, nickel, and iron on the in situ combustion reaction were investigated.

The research was performed in FY83-84 and discontinued at the end of the fiscal year.

METHODOLOGY USED

The combustion and cracking reactions were examined using thermoanalytical techniques. The thermoanalytical experiments were performed using the differential scanning calorimetry (DSC) and thermogravity (TG) instruments. The DSC was calibrated using the phase transition temperatures of indium (156.6° C), lead (327.47° C), zinc (419.47° C), potassium sulfate (580.0° C) and potassium chromate (670.5° C). The magnetic transition temperatures, curie points of alumel (163° C), nickel (354° C), perkallor (596° C) and iron (780° C), were used to calibrate the TG.

Oil/rock matrix samples were prepared by mixing crushed Berea sandstone with three different heavy oils at a constant and predetermined ratio. All samples were prepared using a variable speed mixer to assure as uniform a mixture as possible. A 40° C/min heating rate was used in all DSC and TG runs. The sample weights used in the runs were 2.5 milligrams (mg) for the DSC runs and 3.5 mg for the TG runs. Organic derivatives of vanadium, nickel and iron were dissolved in the crude oil prior to preparing the samples.

TG experiments were performed in either flowing oxygen or nitrogen, while all DSC experiments were performed in flowing oxygen. The purpose of the nitrogen experiments was to identify the effects of the metals on distillation and cracking processes. The experiments with oxygen were to show the effects of metals on the oxidation processes.

HIGHLIGHTS OF THE RESEARCH

The results of this research indicated that iron, vanadium, and nickel present in the crude oil act as a catalyst during combustion reaction. In particular, the presence of iron and vanadium in the crude oil caused an increase in the fuel (coke) deposition and lowered the reaction temperature. These results have practical significance. In the in situ combustion process, the greater the amount of fuel available for combustion, the greater the recovery. However, a greater amount of air is required, which raises the operational costs.

Since metallic additives increase the fuel deposited, they could be used to solve the problem of insufficient fuel deposition in light oil reservoirs. Use of metallic additives in heavy oil

reservoirs will probably produce higher levels of fuel (coke) deposition and may render the process uneconomic because of high air requirements. Further, since these metallic additives lower the reaction temperatures and increase the heat generation, they impact process ignition.

CRITIQUE

The effect of metals, especially iron, on the in situ combustion oxidation reaction is well known and previously documented (Burger and Sahuquet, 1972). The study could have been made more useful by investigating and reporting the kinetic parameters and the approximate fuel deposition rate.

The results obtained from this study are specific to the crude oils used. Crude oils are affected to different extents by the same metallic additive, particularly when they are of significantly different composition or API gravity. Further, since the study was performed using crushed Berea cores, the results cannot be extrapolated to field situations. Use of field cores would be more representative.

Since the research findings were preliminary in nature, NIPER did not present the results at a SPE meeting. However, the results were conveyed to the industry and academia through DOE publications (quarterly reports and NIPER annual report).

REFERENCE

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PUBLICATIONS RESULTING FROM THIS RESEARCH

Madden, M. P. and H. Maerefat. The Effect of Metals on In-Situ Combustion Process. Presented at the 1st International Symposium on EOR, Maracaibo, Venezuela, Feb. 19-22, 1985. Paper No. 12—Thermal Processes.

CHAPTER 4

STEAMFLOOD RESEARCH

OBJECTIVE

The ultimate goal of this project is to improve the understanding of the steamflood process in light and heavy oil reservoirs. This understanding is critical to the development of techniques to improve recovery.

This is an ongoing program that began in FY84 and over the years research has been performed in a number of areas. These include: (a) elucidation of the importance of reservoir and process parameters on steamflood oil recovery in light oil reservoirs, (b) development and refinement of techniques for improving the effectiveness of surfactant additives in steamflood applications, (c) study the effect of reservoir and operating parameters on the mobility and blocking characteristics of foam and emulsions in steamflood applications, (d) development of procedures and tools to study the effect of temperature on capillary pressures in consolidated and unconsolidated sands, (e) investigation of the role of wettability on steamflood oil recovery, and (f) development of numerical thermal simulators to study laboratory steamflood processes and shed light on the influence of process parameters on steamflood oil recovery.

The light oil steamflood research is objectively reviewed in this chapter. The research relating to the effects of surfactant additives on steam injection processes are reviewed in chapter 5. The role of temperature on capillary pressure and wettability and its effect on steamflood oil recovery are assessed in chapter 10. The numerical thermal simulator development research is critically reviewed in chapter 8.

The goal of various light oil steamflood research activities are outlined in the methodology section. The research findings are summarized in the research highlight section.

METHODOLOGY

In FY84, the effects of rock and fluid properties on steamflood oil recovery were investigated in fired Berea sandstone cores under simulated field conditions of pressure, temperature and overburden pressures. To accomplish these goals, steamflood experiments were conducted using Berea cores of varying permeability and porosity and crude oils with different concentrations of paraffinic, aromatic, and polar compounds. Several runs were conducted to investigate the effect of rock and fluid properties as well as process parameters on oil recovery. These include: permeability, porosity, crude oil composition, initial water saturation, steam injection rate, steam quality and backpressure. Madden and Sarathi (1985) described the details of experimental procedures. Findings of this investigation are summarized in a subsequent section.

In FY86, a two-dimensional (2-D) elemental physical model was designed, constructed and tested. This was a state-of-the-art high-pressure, high-temperature steamflood model designed to

study the effect of gravity override and channeling in steamflood process. Special packing procedures were developed to obtain reproducible sandpack properties from run to run. Data acquisition and control softwares were developed to aid in the automation of steamflood runs. Madden et al. (1987) and Sarathi et al. (1988) have described the details of the model.

In FY87, light oil steamflood experiments were conducted in the 2-D physical model to investigate the importance of gravity override and steam channeling in light oil steamflood processes and to ascertain crude oil composition changes and their influence on oil recovery. Data obtained in this study were also used to verify the findings of reported light oil steamflood simulation studies. Sarathi et al. (1990) presented the results of this investigation.

In FY88, light oil steamflood experiments were conducted in 2-D model to determine the effect of initial water saturation on oil recovery. The purpose of this investigation was to obtain information on the response of light crudes to steam injection in previously waterflooded reservoirs. This is necessary because of an increasing number of shallow light crude oil fields in the U.S. now being waterflooded are approaching their economic limit and alternative recovery methods must be considered, since waterflood typically leaves behind 40% to 45% of the original oil in the reservoir. Among the alternative recovery methods, steamflooding is particularly attractive because of its success in recovering heavy oils. Details of this investigation are described by Sarathi et al. (1989).

In FY90, light oil steamflood studies were undertaken to determine the effect of wettability on oil recovery. Studies were conducted in previously waterflooded 2-D sandpacks of different wettabilities. The rationale for this study was that oil-wet reservoirs are typically poor waterflood candidates and produce at stripper well status but have a high waterflood residual oil saturation. Further, it is not known to what extent the wettability of porous media affects the produced oil composition, which in turn influences the oil recovery. Details of this investigation are presented by Olsen et al. (1992).

HIGHLIGHTS OF THE RESEARCH

The results of the light oil steamflood experiments in linear Berea cores (FY84 studies) indicated that ultimate oil recovery was independent of initial fluid saturations, injected steam quality, steam injection rate and pressure drop across the cores. However, a high initial water saturation in linear cores has a minimal effect on overall oil recovery causing steam to breakthrough prematurely and prolong the run time. The study also revealed that the chemical nature of the crude affects ultimate oil recovery; the presence of large amounts of polar compounds in the crude lowers the ultimate oil recovery.

The results of various 2-D light oil steamflood studies indicated the following:

1. The recovery efficiency of a light oil steamflood is strongly influenced by the chemical nature of the crude. The paraffinic crudes result in much higher recovery than

nonparaffinic oils of the same API gravity. This presumably is because paraffinic oils contain more easily steam distillable components than nonparaffinic oils.

2. Gravity override effects of steam with light oil are substantial; although not as substantial as with heavy oil.
3. Laboratory linear steamflood experiments may not be representative of field steamflood process. Linear steamfloods always result in high oil recovery compared with 2-D results. Presumably, reduced gravity override effects in the linear steamflood resulted in a more piston-like displacement and greater oil recovery.
4. Overall recovery is affected by the presence of high initial water saturation; steamdrive as a primary oil recovery process recovers more oil than when used as a tertiary process.
5. Presence of high initial water saturation results in fluid channels that alter subsequent flow of steam and oil, leading to premature steam breakthrough and loss of oil production.
6. When a previously waterflooded sandpack is subjected to steam injection greater oil recovery is obtained from an oil-wet sandpack than from an intermediate-wet or water-wet sandpack.
7. Oil saturation after steamflooding is nearly independent of initial sandpack wettability.
8. Sandpack wettability affects the produced effluent composition. Analysis of steamflood effluent composition indicated that due to the preferential removal of lighter ends from water-wet sands by water, the steamflood effluents from the water-wet media contained a higher percentage of intermediate fraction than the effluent from oil-wet media during early time.
9. Steamflooding changes the wettability of oil-wet porous media to a more water-wet state. A direct correlation exists between steam temperature, steam volume, and the degree of alteration of rock surface to a more water-wet condition.

Thus, both linear and 2-D light oil steamflood experiments substantially contributed to the understanding of the steamflood processes in real reservoir and yielded information necessary for the development and/or calibration of numerical models.

CRITIQUE

The NIPER steamflood physical models (both 1-D and 2-D) are unscaled elemental models designed to improve the understanding of certain facets of the steamflood process such as the implications of physico-chemical effects and rock-fluid interactions at high temperature. Since the tests were conducted under somewhat idealized conditions, the data should be carefully interpreted using engineering judgment.

The NIPER 1-D steamflood studies used a porous media that was linear, consolidated and small compared to an actual reservoir. However, since rock properties such as permeability, porosity, grain size distribution, initial oil and water saturation, overburden pressure, reservoir temperature and operating parameters are all representative of the field condition, the results should be qualitatively similar to what can be expected in the field. However, laboratory linear steamflood experiments may not be representative of steamflooding processes conducted in the field. Linear steamfloods always result in higher oil recoveries (as high as 80% OIP) than can be reasonably expected in the field due to the absence of gravity override effects and a more piston-like displacement. Further, since linear models do not permit the incorporation of heterogeneity into the porous media, the effect of heterogeneity on oil recovery is masked. These shortcomings can be overcome by performing steamfloods in a 2-D model. Even though linear models are imperfect tools to obtain an adequate description of steamflood processes, they are useful tools to study physico-chemical phenomena and rock-fluid interactions. For example, NIPER linear model clearly demonstrated that the presence of large amounts of polar compounds can lower the ultimate recovery and as the oil becomes more volatile, the effect of permeability on overall recovery diminishes.

The NIPER 2-D model is also an unscaled elemental model that has a more realistic tool and provides certain insights into the mechanisms of the steam displacement process which might not otherwise have been possible. The model clearly showed that gravity override effects can be substantial in light oil steamflood and fingering and channeling can be severe in the hot condensate zone ahead of steam zone. The model also showed that steam zone does not exhibit fingering and the steam displacement is characterized by underrunning of hot condensate fluid. Since the model permits the incorporation of heterogeneities in the porous media, it allowed the investigation of the influence of heterogeneities on the steamflood process. The model indicated that heterogeneities influence the nature of fluids and temperature distribution in the porous media and might contribute to instabilities of steam-hot condensate front. The results of numerical simulation studies confirmed these observations. The 2-D steamflood oil recoveries and cumulative oil steam ratios were also consistent with simulation results.

The NIPER 2-D model, however, is far from perfect and several deficiencies exist. These deficiencies, though not serious in nature, can affect the results and the data should be interpreted with care. The model is limited by its ability to handle only medium pressure (< 250 psia) steam, and it has a tendency to conduct heat faster along the boundaries (metallic plates) than through the porous medium. This difference in heat transfer rate significantly affects the steamfront stability. On the average, about 25% of the injected enthalpy was retained in the cement lining and insulation and this distorts the steamfront temperature profile. The mechanical backpressure regulator (which since has been replaced by a state of the art electronic backpressure regulator) has a tendency to

stick and unstick resulting in the perturbation of model pressure and channeling of condensed fluid.

In spite of its shortcomings, the 2-D steamflood results were consistent with numerical simulation results and thus serve to verify the simulation results. Since the operation of the 2-D model provided certain insights into the mechanism of the steam displacement process, which might not otherwise have been possible, it is a valuable tool for testing the effect of various reservoir and operating parameters on the steamflood performance and to gather data for the evaluation of a steamflood project.

NIPER's new Titanium steamflood model was designed to operate at up to 550° F and nearly 1,000 psi. This X-ray scannable steamflood model will permit operation at most field conditions corresponding to steamfloods operating in the U.S. The CT scanning will permit dynamic determination of saturation within the model. The steamflood model is part of a new steamflood laboratory that uses NIPER LAB WARDEN as the software for data acquisition/control/analysis/presentation for laboratory automation.

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CHAPTER 5

LABORATORY EVALUATION OF FOAMS AND EMULSIONS FOR STEAM DIVERSION

OBJECTIVE

NIPER's efforts in laboratory research of steamflood foam and emulsion were focused on improving the sweep efficiency, and thus oil production of steamflooding both light and heavy oil reservoirs. One of the major problems encountered in light and heavy oil steamflood operations is the gravity override and movement of the steamfront to the top of the reservoir due to the viscosity and density differential between the steam and the reservoir's oil and water. A second problem is the heterogeneity of the reservoir in that higher permeability zones are preferentially swept. Once steam breaks through, steam will tend to follow the path that has already been steam-swept. This occurs because the steam-swept area of the reservoir has a high gas saturation, thus offering little resistance to the flow of steam. This results in inefficient use of heat cycling leading to hot producing wells.

A great deal of effort has been expended at NIPER and elsewhere to find ways to increase oil recovery by reducing the flow of steam through these high permeability channels and diverting it to previously unswept, often lower permeability zones of the reservoir. Foams and emulsions, along with other techniques such as gelled polymers and ultra fine cement, are used to help block or retard the flow of steam into the gravity override zone or a higher permeability zone and to divert the steam into another part of the reservoir where more of the "by-passed" oil still remains.

METHODOLOGY USED

Two routes were undertaken by NIPER to study steam diversion for improving sweep efficiency. In 1983-86, the use of emulsions was pursued as part of an optional program at NIPER. This research, co-funded by DOE and Energy Associates, evaluated emulsions for steam diversion. Similarly, DOE-funded research on steam-diversion foams generated by co-injection of surfactants and non-condensable gases (nitrogen or air) was carried out.

Industrial interest during the 1980s was high in the area of process optimization for steam-foam field applications, in addition to fundamental studies of foam generation and flow in porous media. Thus, NIPER studies evaluated the sensitivity of high-temperature steam-foam surfactants to the operating conditions. One-dimensional (1-D) and rectangular two-dimensional sandpacks were used to evaluate emulsions and foams as steam diverters.

Emulsion Research

The emulsion research primarily focused on adding surfactants and/or sodium hydroxide to the crude oil in order to generate stable emulsions that would block pore throats. Beginning with

the laboratory screening of surfactants and emulsifiers, corefloods were performed in clean Berea sandstones of 250-500 mD, first at room temperature and then using 250°F hot water. The reduction in permeability was measured versus the volume of emulsion injected. The depth of emulsion penetration and crude oil production from previously unswept areas was measured in both split cores and parallel Berea sandstone cores. Six to 17% improvement in recovery efficiency of oil in place (OIP) was achieved.

Based on the successful results obtained in Berea sandstone, i.e., substantial plugging of cores by emulsions, plans were made for a DOE/Energy Associates jointly-funded field test of emulsions for steam diversion (French and Olsen, 1986). This field test was to have both an applied laboratory section and a field test of emulsions generated externally (on the surface) and generation of emulsions in situ. Both methods were to be compared with the performance of foam treatments that Energy Associates had applied in an adjacent pattern in North Kern River field as steam diverters. Negotiations for funding were within one day of signing by the two parties when the 1986 drop in oil prices occurred and Energy Associates suspended steam injection into the North Kern River field in Kern County, California. Kern River oil dropped to <\$7.50/bbl and several operators suspended steam injection and oil production because the cost of production exceeded the oil price. This ended Energy Associates' long pursuit of obtaining a patent on the use of emulsions for steam diversion supported by a field demonstration. Research groups in Canada have pursued more recent efforts in this direction, i.e. the generation and use of emulsions for profile modification (Farouq Ali and Thomas, 1991).

The NIPER emulsion formulation was evaluated in 1989 in NIPER's 2-D steamflood model where the model was packed with Kern River oil-saturated sand, resaturated with Kern River crude (hot, >275° F) to original field oil saturation level based upon well log analysis. The permeability was measured with the hot crude oil, yielding a permeability of 10 darcies. A steamflood was initiated, and steam broke through to the producing port. Foam based on Chaser 1020 and nitrogen was unsuccessfully used to test in situ foam generation, resulting in very little additional oil being produced. Later studies showed the liquid/vapor ratio was too low for foam generation with this surfactant (steam was too dry). An external emulsion (Kern River oil and sodium hydroxide) was generated as in previous successful tests that used Berea sandstone. No detectable increase in pressure was observed at the injector during injection of the external emulsion. However, an emulsified oil was produced and accounted for an additional 17% of the OOIP. The high permeability sandpack would be representative of steam swept, higher permeability zones of the reservoir. This test, a scale-up from 1.5 in. diameter cores, showed that the field test may have produced additional crude oil if the field test had been undertaken. The formulation of the emulsion needed significant improvement because the mean diameter of the Kern River externally formulated emulsion was only 1.5 microns which was not large enough

diameter to effectively block the pore throats of a 10 darcy sand. The injected emulsion may have had other mechanisms other than blocking pore throats that account for the increased oil production achieved in this test. Future research should be directed at reviewing recent advances in stable macroemulsions and repeating the 2-D steam diversion test under conditions representative of field steamflood conditions.

Foams Research

Foam—a dispersion of surfactant, gas, and liquid—has been shown to be attractive for steam (and other fluids) diversion and/or mobility control. Foam offers a resistance to flow that is orders of magnitude higher than that of any of its components. Laboratory tests and field trials have shown that surfactants reduce the mobility of injected steam by generating foam (Sarathi et al, 1988; Eson & Cooke, 1989; Shallcross et al, 1990; Marsden, 1986; Farouq-Ali & Selby, 1986; Muijs & Keijzer, 1987; Muijs et al, 1988; Lau, 1988; Lau & O'Brien, 1986; Lau & Borchardt, 1989; Dilgren et al, 1978; Dilgren & Owens, 1983; Duerksen et al, 1985; Huang, 1985). The low mobility and blocking characteristics of foam help in diverting injected steam to unswept regions, thus increasing oil recovery. A unique feature of foam is "selective plugging," i.e. its preference for blocking the flow in relatively larger channels and oil-depleted regions. This preferential blocking of mostly gas-swept zones minimizes the undesirable side effects of loss in overall injectivity or the formation of oil/foam emulsions in oil rich zones.

A steam-foam field trial in Midway-Sunset (CA) field was reported to be successful in increasing sweep efficiency and producing incremental oil (Friedmann, 1991). The steam-foam process has been described by Hirasaki (1989) and references therein. A tabular listing of results of field tests was published (Eson and Cooke, 1989; Olsen (NIPER-436, 1989). Because of high industry interest and reports of early successes, foam research was more actively pursued than emulsions at NIPER and resulted in several publications and presentations. The number of research facilities with high temperature and high pressure steamflood capabilities is small, a fact that places NIPER in a unique position for advancing steam-foam technology. In the past, NIPER's primary goals have been to develop effective methodologies of screening surfactants for their effectiveness in steam-foam field application, to identify and investigate the effects of important variables on the steam-foam process, and to test different surfactants ability to improve the steamfront displacement profile. To achieve such multiple objectives, experiments were performed in an integrated fashion, ranging from foam-height in oil-sand columns to bench-scale 2-D displacement experiments .

HIGHLIGHTS OF THE RESEARCH

A methodology for screening surfactant for steam-foam applications was developed by Strycker, et al. (1986) which consisted of dynamic tests, high temperature-pressure foamability

(HTPF) a bulk foam test, foam drainage rate and mobility control (MC) tests. An important contribution of the methodology was a mathematical method developed to eliminate random errors in the HTPF tests. This method's 10% spread in rate constant determination from the average value compares favorably where other methods had errors of $\pm 40\%$. The correlation found between the two independent methods, i.e., foam stability as measured by the HTPF test and mobility reduction as measured by the MC test, are good initial surfactant screening method for steam-foam applications.

The effects of important variables on the promising steam-foam process were addressed in a paper by Mahmood et al. (NIPER-554, 1991) and also has presented at an American Chemical Society Symposium (Mahmood et al., 1991) and NIPER/DOE symposium (Mahmood et al., 1993, NIPER-667, 669). The primary goal of this research was to identify those parameters to which the steam-foam process is so highly sensitive as to dictate its success or failure.

In this study, surfactant formulations were screened at high temperatures in NIPER's 1-D steamflood model for their effectiveness in providing mobility control and steam diversion under a variety of conditions expected in light-oil steamfloods. The high temperature (430° F) and high pressure conditions were similar to those at Naval Petroleum Reserve No. 3, Teapot Dome, Wyoming. These experiments covered a wide range of surfactant concentrations and types, salt concentrations, steam rates, crude oil types, residual oil saturation levels, nitrogen gas flow rates, and nitrogen gas and surfactant injection schemes (including continuous and slug type). Foam generation and foam stability were found to be significantly influenced by fluctuations in the back pressure. Thus, an electronic backpressure regulator was acquired by NIPER which allowed precise backpressure control and higher reliability. Pressure measurements included two sets of differential pressures and six absolute pressures along the length of the model. Recovery was also monitored to estimate oil saturations.

Figures 5.1 through 5.5 are selected graphs representing the scope of studies conducted in linear sandpacks. Figure 5.1 shows the influence of surfactant losses on rock with each slug of foam. Adsorption of surfactant on the rock surface was high during the first cycle and was nearly satisfied after the second cycle. Although not shown, cycles 4-7, show a pressure buildup curve that duplicates cycle 3 where surfactant adsorption was satisfied. Figure 5.2 shows various surfactant and nitrogen pressure buildup tests (time scale has been greatly condensed) where the liquid to volume ratio (LVR) was varied to estimate maximum pressure response for a given formulation. Figure 5.3A compares the performance of foam in the presence of three different oils, and shows the profound effect of oil composition. Figure 5.3B describes qualitatively the oil desaturation during a steam-foam tests of a 1-D sandpack where the sandpack was

FIGURE 5.1 - This graph shows the influence of surfactant losses on rock on foaming. The first cycle did not show any response until 35% PV of steam injection. Such plots are useful for field design.

FIGURE 5.2 - This test for determining injection strategy shows that the foam bank as indicated by pressure buildup and cost for the field application of surfactant and nitrogen can be estimated from laboratory data. Several smaller slugs may perform as well as continuous injection, yet at a lower cost. This type of test is useful in designing an injection strategy to reduce cost and optimize performance of foam..

FIGURE 5.3 - Foaming performance of three oils is compared in plot (A), suggesting that oil composition could have a profound effect. (B) Oil desaturation plot from two linear steamflood experiments showing the effect of oil composition. Captions are visual observations of the effluent plotted vs. oil saturation with differential pressure generated from foam. Each experiment is plotted at specific oil saturation and emulsified effluent precedes first visual observation of foam in effluent.

FIGURE 5.4. - The effect of steam injection rate on foaming behavior is shown in this figure. The data suggests that both the onset of foaming and the maximum pressure drop are influenced by rate and that a maximum rate is required (perhaps to overcome heat losses) for optimum performance. Rate is one of many important design parameters for field applications.

FIGURE 5.5. - This figure shows the role of a non-condensable gas in foaming performance. Higher N_2 fractions cause higher pressure and fluctuations (possibly due to increased foaming). Finding a proper non-condensable gas fraction is important for an optimum field application.

steamflooded to about 20% oil saturation before the same surfactant and gas were injected (same rate and LVR). Oil saturation was obtained from analysis of the effluent and are not anticipated to be uniformly distributed along the core. The history of the physical appearance of effluents during the two steam-foam tests using two different oils (the heavy oil is 13° API gravity Kern River crude and the light oil is 32° API NPR-3 crude). The pressure response at above 10% oil saturation coincides with the beginning of oil/water emulsion production. By about 8% oil saturation, visible foam was observed in the effluent from the steam-foam test with the heavy crude oil, whereas the oil saturation was <2% when similar foam quality was observed with the light oil. A strong foam was produced near the maximum pressure drop (at 5% oil saturation with the heavy crude) but only a tan emulsion was observed at this 5% oil saturation for the light oil. Both experiments reached the same pressure drop across the core (within five pounds). The onset of emulsification (as evidenced by microscopic observation of effluents) preceded the onset of foaming (as evidenced by a sudden rise in pressure).

Figure 5.4 shows that the onset of foaming and the maximum pressure drop are both influenced by steam injection rate, an important design parameter for field applications. This figure also suggests that a minimum rate is required for foam formation and maximum pressure generation i.e., optimum surfactant performance. Finding a suitable noncondensable gas fraction is also important for an optimum field application, as shown in Fig. 5.5 for a series of pressure buildup (surfactant injection) and pressure falloff tests (no surfactant is injected and nitrogen remains at the same flow rate).

NIPER's experiments have supported results of others which show surfactants as foamers having salinity, temperature, oil saturation and oil composition regions over which a foam can be generated.

Other important findings are as follows:

It was found that foamability increased exponentially with increasing VLR, and a linear relationship was observed between maximum injection pressure (which is related to blocking ability of foam) and the steam-nitrogen ratio. Addition of weak alkaline agents to surfactant had only a modest effect on foaming. Proper formulation and design were deemed to be critical for successful steam-foam treatments.

The MC control tests based on linear corefloods are useful for testing foam generation and mobility reduction capabilities of surfactant, but is an unrealistic model for simulating gravity override problem in the laboratory. To overcome this limitation, NIPER developed a bench-scale 2-D steamflood model for testing the capability of foam to remedy gravity override and mobility control problems. Experiments in 2-D sandpack model involved single layer or two layers of sand with contrasting permeabilities arranged to facilitate gravity override (i.e., the higher permeability layer being on top).

Frontal characteristics during several selected 2-D steamflood tests (with and without foam) are displayed in Figs. 5.6 through 5.9. When coupled with other quantitative tools—such as saturation (Dean Stark analysis of the oil in the sand) and temperature mappings (from thermocouples) as shown in Fig. 5.10 and 5.11—these pictures can be diagnostic aides of what is occurring. Figure 5.6 is an example of gravity override in 2-D model, indicating that gravity override can possibly be a problem in the reservoir even in steamflood recovery of a light oil from a homogeneous sand. Figure 5.7 qualitatively shows the potential of foam for improving front profiles. A surfactant slug followed by N₂ was injected in this test during the steamflood. An example of fingering in 2-D model is shown in Fig. 5.8. Multiple surfactant slugs, N₂, and alkaline emulsion slugs were injected to improve the profile.

Previous photographs showed tests with a single (homogeneous) layer of sand. Figure 5.9 shows a steamflood of a heavy crude from a bi-layer sandpack that has an upper layer of 56-Darcy permeability and a lower layer of 19 Darcies (36% porosity). The oil production curve and temperature profile showed that steam was producing oil (<35% of OOIP) from the high-permeability layer. When the water/oil ratio reached 200 a steam-foam was injected and the top layer started to cool while the bottom layer near the injector (right side) increased in temperature. The model began to produce additional oil resulting in recovery of 60% of the OOIP. The photograph of the sand after completion of the steam-foam test shows significant gravity override at the producing end of the model (left side). Dean Stark analysis of the sand showed an oil saturation in the dark portion of the picture as >45% whereas the lighter portions were <3% for most of the upper layer and <7% for most of the low-permeability, lower layer. The foam diverted steam from the high permeability layer to the lower permeability layer.

34° API NEW LONDON CRUDE
 $k \approx 3.5$ Darcies, $\phi \approx 37.5\%$, $S_{oi} \approx 78\%$
 Ultimate Recovery $\approx 81\%$ of OOIP
 No Surfactant, Steam Only

FIGURE 5.6 - An example of gravity override in a homogeneous sandpack in a 2-D model. Steam is injected on the right side (lower half) and oil and water are produced on the left side (entire side). This was a steamflood test of a light oil without any additives. This picture, taken at the end of the flood by exposing one of the sides of the sandpack, qualitatively shows that gravity override can possibly be a problem in the reservoir with unfavorable conditions. Thin fingers are visible in the photograph.

15° API ROUND MOUNTAIN CRUDE
 $k \approx 4.6$ Darcies, $\phi \approx 34.7\%$, $S_{oi} \approx 71\%$
 Ultimate Recovery $\approx 87\%$ of OOIP
 Incremental Recovery After Surfactant+N₂ $\approx 8\%$ of OOIP
 Steam Injection Started at 0 Hrs.
 5% SD-1020 + 1% NaCl at 15 Hrs.
 N₂ 10cc/min at 16.5 Hrs.

FIGURE 5.7 - An example of a good sweep efficiency in 2-D model. Surfactant slug followed by N₂ were injected after a steamflood. The oil was relatively heavier. This picture qualitatively shows the potential of foam for improving front profiles.

13° API KERN RIVER CRUDE
 $k_{top} \approx 26$ Darcies, $k_{middle} \approx \text{clay}$, $k_{bottom} \approx 10$ Darcies,
 $\phi \approx 43\%$, $S_{oi} \approx 61\%$ (average),
 Ultimate Recovery $\approx 86\%$ of OOIP (average)
 Incremental Recovery After Surfactant & Emulsion $\approx 3+2\% \approx 5\%$ of OOIP
 Steam Injection Started at 0 Hrs.
 1st Slug 0.05 PV of 1% SD-1000 + N₂ 4cc/min at 23 Hrs.
 2nd Slug 0.10 PV of 1% SD-1000 + N₂ 4cc/min at 25.5 Hrs.
 3rd Slug 0.10 PV of 1% SD-1000 + N₂ 4cc/min at 26.2 Hrs.
 N₂ + Steam at 26.5 Hrs.
 4th Slug Alkaline Emulsion 0.35 PV at 28.75 Hrs.
 Highly Emulsified Oil Produced Starting at 31 Hrs.

FIGURE 5.8 - An example of fingering in 2-D model. This was a steamflood test displacing a relatively heavier oil. Multiple surfactant slugs, N₂, and alkaline emulsion slugs were injected to improve the profile.

15° API ROUND MOUNTAIN CRUDE
 $k_{top} \approx 56$ Darcies, $k_{bottom} \approx 19$ Darcies,
 $\phi \approx 36\%$, $S_{oi} \approx 76\%$
 Ultimate Recovery $\approx 60\%$ of OOIP
 Incremental Recovery After Surfactant+N₂ $\approx 4\%$ of OOIP
 Steam Injection Started at 0 Hrs.
 5% SD-1020 + 0.1% brine at 13 Hrs.
 N₂ 3cc/min at 15.5 Hrs.

Figure 5.9 - An example frontal profile in layered 2-D model. This steamflood test in heavy oil was followed by surfactant and N₂ injection. Oil was initially produced only from the top, high permeability zone (note gravity override). After steam breakthrough, foam was injected and the top portion started to cool and oil production resumed this time from the lower permeability section as reflected by increasing temperature on thermocouples. Steam was diverted from the high permeability layer to the low permeability layer.

FIGURE 5.10 - Example of residual oil saturation mapping in 2-D experiments. This oil-wet quartz sandpack containing New London Crude Oil (32° API gravity) was steamflooded after the waterflood. This saturation map supports visual postflood observation of gravity override as shown in Fig. 4.6.

FIGURE 5.11 - Example of temperature mapping in 2-D experiments. This oil-wet quartz sandpack containing New London Crude Oil (32° API gravity) was steamflooded after the waterflood. This temperature map also supports visual postflood observation of gravity override as shown in Fig. 5.6.

The combination of post flood sand analysis for oil saturation (Fig. 5.10), temperature data acquired during the steamflood (Fig. 5.11), history of pressure and effluent analysis are not adequate to describe the steam-foam process. Dynamic saturation changes such as those obtained from X-ray CT of the displacement experiment (Demiral et al., 1992) can yield additional information on dynamic changes in saturation and is the direction that NIPER's steamflood laboratory is proceeding in an effort to gain a better understanding steam diversion with foam.

CRITIQUE

The steam diversion research at NIPER has used the 1-D and 2-D steamflood physical models and a foam susceptibility test designed in-house. For shallow (< 1,500-ft-deep) California steamflood conditions, the 1-D and foam susceptibility test could achieve the temperature and pressure corresponding to field conditions. Thus, the laboratory tests were conducted at a temperature representative of several possible sites where the results of NIPER's laboratory tests on surfactants would be applicable. Due to the pressure limitations of the 2-D model, the operating temperature was lower than most California steamfloods. This does not invalidate the results obtained, but it may not reflect actual field performance. Other surfactants may be better choices at field temperatures and the best surfactant at our operating conditions may not be the best at higher temperature.

The 2-D laboratory tests showed that the emulsion formulation that had been developed and was headed for a field test was inadequate even though additional oil was produced. Continuation of the emulsion research such as has been conducted within the last few years in Canada could generate larger, more stable emulsions that may have been effective in blocking higher permeability sands.

Much of the data derived from steam-foam experiments relied on pressure ($\pm >3$ psi) and temperature ($\pm 1^\circ$ F) measurements and external visual inspection of effluent along with changes in mass balance (additional oil and water produced but only by volumetrics in increments that were >100 mL). From this it was inferred that foam or emulsion was diverting steam. On some experiments noticeable changes in temperature ($\pm >5^\circ$ F) were observed when surfactant/nitrogen was injected.

Many of the deficiencies in experimental operation, temperature and pressure limitations, and data analysis capabilities have been addressed in the construction of a new 2-D titanium steamflood physical model and the accompanying laboratory equipment including software for operation/data collection/analysis/presentation. This X-ray scannable, high-pressure (1,000 psi at ± 0.05 psi), high temperature (520° F with current teflon internal insulation) steamflood model has been described in part (Olsen et al., NIPER-603, 1992). Suitable laboratory space has not been obtained and thus establishment of the capabilities to conduct steam diversion experiments at field conditions is still limited. The X-ray scannability, as well as electrical conductivity measurements, can provide dynamic in situ determination of saturation profiles and help analyze what is occurring in the physical model in real time.

NIPER has acquired high-temperature (950° F) and high-pressure (9,000 psi) stirred 5 gallon reactor that could be used for surfactant research at conditions corresponding to steam applications similar to Venezuela or Canada (650° F and 1,000 psi) or to those corresponding to deeper ($> 3,000$ ft) U.S. steamfloods or cyclic steam applications. Both the thermal stability and kinetics of the reactions of surfactants with reservoir oil and rock could be studied using this equipment. The software developed for the titanium steamflood model could be adapted for this severe service application.

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CHAPTER 6

LABORATORY AUTOMATION

OBJECTIVE AND BACKGROUND

NIPER's research objective in developing laboratory automation software has been several fold. Safety, efficiency, and the quality of the research were the main impetus behind automating the thermal oil production research laboratory. The previous laboratory automation of thermal lab (developed in 1983-85) was a IBM PC-based data acquisition system that used Keithley interface boards. The software (written in BASIC) was not interactive or user-friendly. There were no warning or error recovery systems. As a result, data loss was a common occurrence. Most instruments were manually controlled because there were no control features. New software programs were developed in 1992-93 to make the system user friendly and usable by other laboratories and pilot plants for data acquisition/control/analysis/presentation.

METHODOLOGY USED

The initial computer programs developed in 1983-85 were designed for data collection from thermocouples and pressure transducers on NIPER's 1-D and 2-D steamflood models. The BASIC code interfacing Keithley cards installed on an IBM-AT computer served the thermal group from 1984 through 1990. Some of its limitations were no user's guide, no logic flow diagrams, (these were not considered a priority when the program was initially written), inability to save a file when the electrical power was shut off, data files were tabular data, and the program contained no alarms for out of range data, thus requiring constant manual supervision of data collection and experimental equipment. Attempts were made in 1988-1989 to modify the program, but the complexity of the code to accommodate new features of electronic instrument (especially controllers) and the need for better data analysis prompted NIPER to reexamine our approach for achieving the stated goals of automation and data acquisition. NIPER's response was to construct two software packages to operate on Macintosh® computers. One is a stand-alone application named "NIPER LAB WARDEN" and the other is an add-on to LabVIEW® 2 named "NIPER GENERAL PURPOSE AUTOMATION". The following is a brief description of the programs.

HIGHLIGHTS OF THE RESEARCH

NIPER Lab Warden

NIPER LAB WARDEN program was initially written on an Apple Macintosh II (nu-bus) computer using LabVIEW 2®, an objected-oriented language from National Instruments. Use of LabVIEW as an operating platform makes it possible to run these programs on IBM-compatible and Sun workstations. Only a different version of LabVIEW software compatible to one of those machines will be required. This computer program controls instruments, collect-analyzes data,

and provides a functional and adaptable software program for operating a laboratory conducting experiments at extreme conditions of pressure and temperature such as those found in a steamflooding laboratory. This software was developed to provide interactive computer control of a wide variety of instruments, control devices typical of those found in laboratories and to handle emergency situations safely.

This program allows real-time (on-the-fly) configuration (setting, adjustments) with built-in help messages and cues. Users only need to provide the drivers for communicating with their own instruments. A driver program can be thought of as a mediator/translator between a computer and an instrument, each trying to communicate in a different language. Many instruments use standard driver protocols, and standard driver programs come with the LabVIEW 2 package or are available from third party consulting/software development companies. To ease the task of writing a driver program, a template is provided that serves as the starting point. Examples of several standard driver programs are also included. A driver program can be written or modified, on the average, in a few hours.

This software was written as a general software program that could be readily adapted by other users to their specific laboratory or pilot plant application. One of the reasons for this easy adaptability is the use of objected-oriented computer language which permits easier and faster adaptation than typical line code languages such as FORTRAN. These object-oriented programs can be written in one of many graphical languages (such as LabVIEW) to look more like logic flow, diagrams or electrical circuitry rather than typical syntax line codes. With suitable compilers, these objected-oriented graphical languages can incorporate other languages. For example, LabVIEW and Prograph® can execute C++ or THINK C® line code. The program and the logic behind the setup (structure) of the program are presented in general terms. One of the real advantages of object-oriented programming is the ability to configure a system (laboratory or pilot plant) from the operational schematics. For example, the operation of a solenoid valve (open or closed) can be easily programmed. This operational schematic of a valve can then be duplicated as needed and installed in more complicated circuits such as those for pressure sensors, flow rate meters, pumps, etc. NIPER LAB WARDEN has the feel and look of typical Macintosh applications such as Microsoft Word® or Microsoft Excel®, and makes running sophisticated laboratory automation programs easier. Typical features are the ability to launch various applications, change the setting of various experimental parameters, edit experimental data during run-time, and plot it in other graphical applications of user's choice, send and receive textual and sound alert messages, and control a remote laboratory operation over a network.

NIPER General Purpose Automation

This software is an add-on to the LabVIEW® 2, (Mahmood and Olsen, 1992; Kodosky, MacCriskin, and Rymar, 1991). NIPER General Purpose Automation software eliminates the

need of any programming. User's can directly configure it for most automation needs in run-time by following a few simple steps as described in an Operators Manual (Tyagi et al., 1992). It is useful for laboratories and prototype pilot plants where instrumentation requirements change frequently. The application of this software to NIPER's thermal lab is described in Olsen et al. (1992).

NIPER's automation software consists of the following three main interactive sections: data acquisition, instrument control, and interactive graphics.

All three of these facilities are fully integrated, such that while the user interacts with one, the others continue to process in the background. Facilities can be alternated manually or automatically on the basis of event priority. For example, the data acquisition panel may be activated during the actual scanning of data from pumps, pressure transducers, etc. to display the acquired data and report any errors. Then the interactive graphics can be called up to display the data graphically. Finally, the control panel may be activated to give a visual picture of the process. Events may be assigned priorities so that higher priority messages can automatically be switched to the interactive panel. The following is a brief description of each of the three facilities.

Instrument Control

The control panel for this facility is shown in Figure. 6.1 and is described in a recent report (Mahmood et al., 1993). The process control facility allows the user to operate the remote-sensing instruments such as pumps, controllers, balances, temperature sensors, pressure sensors, fluid flow controllers, and alarms through the computer panel. The facility has a built-in logic that checks the validity of user's commands and disallows them if illogical; e.g., it would not allow the user to run a pump if the outflow valve is closed, reducing the chances of avoidable accidents and failures. Another safety feature built into the facility is the continuous monitoring of the test progress by material balance in which the injected and discharged fluids are continuously weighed and compared, and by rate-of-change calculations in which changes in certain parameters (such as pressure) are detected. If a discrepancy beyond the user's acceptable limits is found, user is warned of possible leaks or other mishaps in the system. When a situation falls outside the user-defined ranges, and no response from the user is received, the safety feature automatically turns the system off.

Data Acquisition

The interface for the data acquisition facility is shown in Fig. 6.2. It has three features: (1) let user manipulate current and/or previous data interactively, e.g., analyze, compare, plot,

FIGURE 6.1 - The instrument control panel in DOE/NIPER General Purpose Automation Software Program.

FIGURE 6.2 · A main panel (screen) in DOE/NIPER General Purpose Automation software program.

curve-fit and print; (2) warn user for system errors and out-of-range measured values; and (3) allow user to re-configure system set-up; e.g., connect or disconnect instruments, define allowable ranges outside of which warning is issued and system is shut down, select interval between scans, and emergency shutdown sequence, etc. The title bar contains nine buttons which allow user to select between features. By pointing and clicking on the buttons in the title bar (see Fig. 6.2), user may switch between features. Some of these sub-windows open a new window, allowing the user to make selections. Since these sub-windows have lower priority, they do not interfere with other activities, i.e., data acquisition and control functions continue in the background.

Interactive Graphics

The 3-D graphic display as shown in Figure 6.3 is an example of LabVIEW's data export and communication capability with other applications. Every time a new data set was scanned, the graphic facility in NIPER's automation software automatically opened a Microsoft Excel file containing this chart. The chart was updated with new data. The chart was then automatically

FIGURE 6.3 - A sample snapshot of automatic 3-D visualization of data in Microsoft Excel, DeltaGraph Professional, and Spyglass Transform can also be similarly used.

rotated with different attributes such as at different angles, aspect ratios, etc. Then, the chart was closed, and the control was transferred to the LabVIEW 2. All the while, LabVIEW 2 continued to operate in the background acquiring (or waiting for) new data and checking for error and safety messages.

Microsoft Excel is one of many applications that has been integrated with LabVIEW 2. In fact, any application that supports the Microsoft System 7's feature of Dynamic Data Exchange (DDE) can be integrated; i.e., it can link, subscribe and publish to or from other files. Also, any application that allows macro-expansion (sometimes called scripting) is a good candidate for integration. Some of the commercial applications that have these capabilities are Microsoft Excel, DeltaGraph Professional™, and Spyglass Transform™. Spyglass Transform can display diffused-color surreal graphics by filling in interpolated data points along with the actual data in a multidimensional spatial field.

CRITIQUE

The new laboratory automation system benefits from the new advances in automation technology and in object oriented software. The software is easily expandable and adaptable to

allow for changes in operation or design such as those encountered in laboratory or pilot plant operations. The NIPER software incorporating commercial programs offers real-time data acquisition/processing, graphics, and video display capabilities, along with run-time editing and adjustment of data-acquisition process. The software offers instrument control via most standard protocols (i.e., IEEE-488.2 and RS-232 Series, wave and pulse signals). It has extensive warning and error recovery facilities and sends sound and text warnings to any authorized user on the network and receives the reply. If no authorized user responds or no corrective action is taken in due time, the software acts on a built-in logic to safely handle the situation. This built-in logic can easily be modified by authorized users during run-time. The software has been developed with versatility in mind and can be readily adapted to a wide variety of pilot plant/laboratory configurations with relatively minor changes to equipment configuration and logic diagrams in the software.

Software of this magnitude needs extensive testing with both actual and simulated data. Most of the advanced features, such as sending and receiving sound and text warnings over the network and automatic shut down logic, were only briefly tested.

Although the thermal group has been without an operating steamflood laboratory, a series of low-temperature simulations of hardware and software have been conducted. These included the use of DOE summer interns to read an operating guide, followed by a 2-hour training session before startup and tests of systems hardware and software. This test used an inexperienced operator with a minimum of training to operate the system. Interns were instructed to turn any value(s) or electrically disconnect any valve or electronic part (pressure regulator, valve, balance, oven, etc.) on the steamflood model (random selection) and test the systems ability to respond and safely shut down operations. The system has accommodated and passed all low-temperature tests. Once the steamflood laboratory is completed, a more extensive series of tests will be undertaken. Then, it should be registered with National Instruments for a wider distribution than is likely with a DOE report or SPE publication. In a finished form, it can be an efficient useful tool for automation of processes in laboratories and pilot plants.

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CHAPTER 7

ENVIRONMENTAL ISSUES OF RELEVANCE TO THERMAL EOR PROCESSES

OBJECTIVE

The purpose of this research was to review and summarize environmental regulations and rules that are applicable to thermal EOR industry.

This research was performed in FY91 as part of Task 1 of Project BE11B—Compilation of Steamflood Operators Guide. This task was designed to support DOE in near-term technology transfer to independent operators by publishing a handbook detailing information required to evaluate, design and implement steam injection processes in the field. The task was completed in FY92.

METHODOLOGY USED

Various federal, state, and private organization environmental publications were reviewed, and the laws and regulations relevant to thermal EOR operations were abstracted and summarized. The procedures for obtaining an environmental permit was outlined.

HIGHLIGHTS OF THE RESEARCH

The environmental requirements for candidate domestic thermal EOR projects were identified, defined, and evaluated in terms of federal and state regulatory viewpoints. Various federal, state, and local environmental agencies were contacted and the desired information obtained. After data from these sources were extracted, screened, analyzed and summarized, conclusions were determined as follows:

- (1) The major issues of environmental significance regarding thermal EOR projects are the impact on ambient air quality, ground water quality, and process water availability.
- (2) Noise emissions from steam-injection operations, are not generally considered to be a potential environmental concern.
- (3) In order to develop an environmental compliance strategy, field specific details need to be gathered and analyzed in the environmental areas of solids and liquids waste handling procedures, land use and disturbances, and ecological impact.
- (4) The mitigation measures to be employed at each thermal EOR facility are strictly site specific; thus, requiring an assessment of short-term and long-term environmental impacts before the start of the project.

CRITIQUE

Development of the Nation's heavy oil resources by thermal techniques is subject to environmental regulations and economic factors that have varying degrees of impact . This study attempted to analyze the requirements of various environmental legislation, standards, and criteria

enacted and enforced at the federal and state levels, and it examined their relative impacts on thermal processes. In addition, the potential environmental deterioration likely to be generated by steam injection processes and the nature and types of pollutants that are likely to be discharged during the life of the projects were outlined. Remedial steps which are necessary to comply with the environmental legislation, standards, and criteria were discussed.

The study placed major emphasis on federal environmental laws and only briefly outlined the state laws. In the U.S., thermal operations are concentrated in California, where standards are considerably more stringent than those required by federal regulations. The California standards are enforced very rigidly. The study failed to discuss fully the California regulations and their impact, both in California and the rest of the U.S., on the thermal recovery process. Because of their strict enforcement within California and their strong influence on regulations adopted in the rest of the U.S., the industry generally agrees that California regulations are the most significant challenge to the continued growth of thermal EOR processes in the U.S. This fact was not emphasized.

In all fairness, however, considering the complexity and vastness of the subject matter, the researchers have succeeded in succinctly presenting the subject. This view has been echoed by the editors of the *Journal of Petroleum Technology* (JPT) who selected an article based on this research as the article of the month and stated: "I'll give him kudos for handling a maze of information and putting it into an understandable and readable format." It is recommended that a more in-depth analysis of California and Texas state and county environmental laws and regulations be conducted and that their full impact on the thermal process be documented.

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CHAPTER 8

THERMAL SIMULATOR DEVELOPMENT AND EVALUATION

OBJECTIVE

The objective of this project is to conduct research related to numerical thermal simulation. This includes development and validation of a personal computer-based numerical thermal simulator and evaluation of thermal predictive models developed under a DOE sponsored program.

This is an ongoing program that began in FY88. In FY92, the scope of this program was expanded to include field scale simulation studies to assess the thermal oil recovery potential of heavy oil resources outside California. The objective is to assist DOE in its technology transfer effort in identifying targets where thermal techniques are likely to be successful and to encourage independents to implement this proven technology.

The numerical thermal simulator development research is objectively reviewed in this chapter and the recommendation for future course of action is made. The applicability of steamflood in heavy oil reservoirs outside California is assessed in a subsequent chapter.

STEAMFLOOD SIMULATOR DEVELOPMENT AND VALIDATION

METHODOLOGY

Highlights of the Research

The primary objectives of this modeling research were three-fold:

1. To develop a predictive simulator that can rigorously model the complex phenomena that occurs during the steamflooding of light and heavy oil bearing reservoirs;
2. To develop a model that can easily be modified by a researcher to better predict the performance of specific experiments;
3. To provide independent operators and others a personal computer-based thermal simulator that can be used as a preliminary engineering design tool.

The main objective of this research was achieved with the development and testing of a compositional steamflood simulator on a personal computer. The major features of the developed model are listed in Table 8.1. The simulator is capable of being run in one- or two-dimensions and permit both areal and vertical cross-sectional simulation. The simulator can be used to simulate both laboratory and pilot steamflood studies and permit the simulation of hot water and steam injection operations. The model cannot be used to simulate a cyclic steam injection operation.

The simulation was validated by comparing the simulator results with the published data. Since a complete set of data for a reservoir undergoing steamflooding is seldom available and the treatment of the phase behavior and other thermodynamic and transport properties of the fluid

TABLE 8.1 - Model features

• A two-dimensional semi-implicit finite difference simulator
• Describes the flow of three phases and four components (water and three hydrocarbon components)
• Gravity and capillary pressure phenomena are included
• Heat transfer in the porous medium is by conduction and convection
• Temperature dependent relative permeabilities
• Constant or variable porosity and permeability
• Interphase mass transfer is governed by pressure and temperature dependent equilibrium ratios
• Both regular and irregular grid block sizes can be specified
• Automatic time-step control feature
• Block centered grid system
• Sequential solution scheme
• Direct matrix solver
• Rock and fluid properties are functions of pressure, temperature and composition

differ from model to model, an exact comparison of results from this simulator with results of other models is impossible. Therefore, the validation of this simulator was made by investigating the behavior of the variables qualitatively. The results from the model showed qualitatively similar behavior as the published results. Sensitivity studies were performed over a range of parameters to document the capability of the simulator. While these sensitivity studies were by no means complete, they did provide some insight into the relative importance and effect of various parameters on the steamflood process. Table 8.2 summarizes the results of the numerical simulation sensitivity studies.

TABLE 8.2 - Summary of Sensitivity Study

Sensitivity Case	Conclusions
Porosity	Major effect due to difference in oil-in-place.
Absolute permeability	Negligible effect.
Rock heat capacity	Minor effect; changes heat front advance rate.
Initial oil saturation	Major effect.
Irreducible water saturation	Minor effect; changes initial oil production rate.
Relative permeability	Major effect.
Critical gas saturation	Minor effect; alters initial oil production rate.
Oil viscosity	Major effect on recovery.
Oil volatility	Major effect on recovery.
Steam injection rate	Major effect; overall recovery suffers at lower injection rate.
Steam quality	Major effect.
Backpressure	Major effect; affects oil production rate and recovery.
Time-step size	Major effect; large time-step size affects the stability of the simulator.

Model Limitations

Because of the Implicit Pressure-Explicit Saturation (IMPES) formulation, the current version of the steamflood simulator is time-step sensitive and exhibits conditional stability. Numerical stability of the simulator depends on the type of formulation (IMPES or fully implicit) and truncation errors. Although all discrete approximations are subject to truncation errors, time-step values that are too large will result in larger truncation errors. Thus, while all simulators to a certain extent are affected by time-step size limitation, the effect is much more severe on IMPES type simulators that solve problems involving rapid saturation changes or high flow rate such as the steamflood process.

The stability of this simulator can be improved by limiting the time-step size. However, the model running time increases markedly with smaller time-steps. Only a fully implicit model is capable of overcoming time-step limitations and yield stable solutions. Memory requirements and the complexity of the steamflood model drastically increases with the use of fully implicit formulation and direct solution technique. Because of DOS memory constraints, it is not possible to code and test a fully implicit compositional simulator on an IBM-AT type personal computer.

Since the development of this model, faster personal computers and compilers that make use of DOS extenders to overcome DOS memory limitations have become common place. Efforts should be made in the future to improve model stability and performance by reformulating the model and taking advantage of the hardware and operating system advancements.

Details of the model development and validation have been published by Sarathi (NIPER-495, 1991).

Critique

The steam injection technique has proven to be an effective means of recovering light and heavy oil. Because of high costs associated with steam injection projects, forecasts of reservoir response to steam are critical to an engineering evaluation of proposed or ongoing projects. Numerical thermal simulators are routinely being used to forecast future reservoir performance and formulate operations strategy. Thermal simulators are also used to interpret laboratory experiments and study the impact of certain variables on the processes which are too difficult or expensive to determine experimentally.

Although a number of vendors market reliable and sophisticated thermal simulators, they are very expensive, require expensive hardware and highly skilled manpower to run, and are beyond the means of most independent operators and consultants. Hence, a need exists for an easy-to-use public domain thermal simulator capable of running on an inexpensive hardware such as a personal computer which can be used by independent operators as a preliminary engineering design tool. This research is an attempt in that direction.

Development of an easy-to-use thermal simulator capable of running on an inexpensive personal computer poses many challenges to the developer. Models describing the field behavior of the steam injection process must account for the complex physico-chemical phenomena occurring in or in the vicinity of steam zone. Accurate representation of physico-chemical phenomena such as the thermodynamic equilibria processes lead to more complicated mathematical models than those used in conventional black oil models. Computational instability is much more severe in thermal simulation than in black oil reservoir simulation. An acceptable level of computational stability can only be achieved in thermal simulation by minimizing the dimensions of the grid blocks and by specifying smaller time-steps. However, this leads to excessive computer memory and computing time. Inexpensive personal computers are limited by their memory capacity and are also slower than their expensive cousins. These limitations severely limit the type of thermal simulation that can be performed on an inexpensive personal computer. Stability of computational processes has always been a source of frustration for engineers performing thermal simulation on an IBM-AT type personal computer.

Despite the hardware limitations and the complexity of the process, the researchers have succeeded in developing a numerical simulator that allows steamflood performance prediction. The developed model contains all of the essential features necessary for the preliminary design of a pilot steamflood and laboratory history match. The simulator can be used to evaluate the effect of areal sweep as well as the gravity controlled vertical sweeps on steamflood recovery. Since the developed model is two-dimensional, it cannot be used to predict the flow in the vertical (third) direction. Flow in the vertical direction must be accounted for if the reservoir thickness is large in relation to the areal extent or if pronounced heterogeneity exists in the vertical direction (for example, if there is high stratification). Since in thick reservoirs subject to steam injection, gravity drainage of oil is the major producing mechanism, this simulator cannot be used to predict correctly the steamflood performance in such reservoirs.

The NIPER model employs a central difference scheme to replace the first derivatives in the flow equations. This was done to minimize the numerical dispersion and to have a reasonably sharp saturation front. In processes such as steamflood, where there is a rapid saturation change and the viscous forces dominate the capillary forces, numerical dispersions can significantly alter the calculated saturation distribution and result in an optimistic production. Numerical dispersion, however, contributes to the computational stability of the model. Reservoir simulators such as the NIPER thermal simulator, which employs a central difference scheme to minimize the numerical dispersion, are extremely vulnerable to minute numerical disturbances and this vulnerability in most cases leads to computational instability and destruction of the computational process.

Computational instability can be avoided by employing a one-sided (forward or backward) difference scheme to replace the first derivatives in the flow equation. The one-sided difference

scheme achieves the numerical stability by introducing large numerical dispersions. As pointed out earlier, computational schemes prone to numerical dispersions are not desirable in simulating thermal processes. Computational stability can be ensured through the use of fully implicit formulation. However, fully implicit formulation requires about eight times more computing time per time-step than an IMPES type formulation and much larger storage requirements. Even with a fully implicit formulation, smaller time-steps are required in steamflood simulation because of the flow direction reversals.

Previous discussion underscores the difficulties that a modeler faces in the development of a thermal numerical simulator. Given the hardware and operation system limitations that existed at the time of the development of the model, it could be argued that it is not possible to develop and test a steamflood simulator on an 'AT' type personal computer capable of predicting field performance to the accuracy sought by the industry.

Steamflood Software Evaluation

This is a support research activity designed to assist DOE in its technology transfer effort. The objective of this research is three-fold: (1) Evaluate thermal EOR softwares developed under a DOE-funded project or those acquired by DOE and if found valid and useful, place it in public domain; (2) develop user's manual; and (3) assist DOE in answering software related inquiries from the users.

As part of this research, the semianalytical steamflood predictive model developed by Stanford University for DOE was evaluated. Also, the suitability of this model to predict field performance and its usefulness as a steamflood screening and design tool were assessed. The code was modified to remove major inconsistencies and logical errors before evaluation. A report detailing the assessment was written and delivered to DOE (Sarathi, NIPER-566, 1991).

In FY93, it is planned to evaluate a steamflood predictive model developed by the industry (Mobil Exploration and Production Company) and to make recommendations to DOE about its usefulness as a steamflood design tool.

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CHAPTER 9

MICROMODEL DEVELOPMENT

OBJECTIVE

NIPER's research on micromodels was aimed at developing a new technique that allows a direct view of the physical/chemical phenomena involved in fluid transport and oil droplet mobilization within the microscopic pores of the porous media. The ultimate objective was to enable researchers to obtain pore-level understanding of various oil recovery processes and phenomena through a direct observation.

METHODOLOGY USED

This research was initiated with a literature search/review by Sarathi (1986) and was then pursued by Mahmood and Maerefat (1988) and Mahmood (1990). The work reported includes both work performed within the thermal EOR group and that under the imaging group.

The technique involves sandwiching two millimeter thick and about an inch long rock slabs in a glass/metal casing which has built-in input and output ports. Fluids are slightly dyed with food colors. A powerful light source, a highly sensitive video camera, a video processor, and a modified microscope are required. Although the clarity is somewhat compromised by the low light conditions, the fluids are clearly distinguishable. The relative thick sample used in this technique allowed fluid to flow through 3-dimensional pore structure with realistic pore size and shape, and hence is a significant advancement over the traditional micromodels.

Historical Perspective

It is now well known that the microstructure of a porous matrix has a great influence on its physical properties, such as acoustic, electrical, mechanical, thermal and hydraulic properties. The shape, size, orientation, connectiveness, and wetting characteristics of the rock grains influence the transport of various fluids through porous media. A detailed understanding of the role of microstructure on fluid distribution and flow is useful in many phases of petroleum operations.

Current techniques of studying microstructure are either destructive (such as serial sectioning) or invasive (such as epoxy pore casting), thus alter rock's wettability. They are not able to image dynamic behavior (i.e., any movement). CAT SCAN or NMRI (X-ray or nuclear magnetic-resonance computed axial tomography) do not yet offer enough resolution or speed to discern interfacial phenomena.

To bridge this gap, a non-destructive imaging technique was developed at NIPER in FY88. It uses 2-3 mm rock slabs to study microscopic behavior. The idea was inspired by an earlier industry-wide project in the mid 1950's spanning over six years, which became the basis of multiphase fluid distribution theories. A set of color photographs was published (Chatenever,

1957) at the conclusion of this project. The rock specimen used in this project was polished thinly (to less than one millimeter) in order to transmit light through the specimen.

Later publications postulated that a minimum of 2-mm thickness is required for realistic pore level flow. Thinner than 2 mm slabs are likely to encounter flow by-passing through the rock/frame adjoining boundaries and pore discontinuity problems. Transmission of enough light through a 2-mm rock slab appeared to be a formidable task. However, we pursued in anticipation that translucent fluids may refract enough light to allow imaging through the rock.

Experimental Technique

The essential details of this technique are previously documented (Mahmood and Maerefat, 1988). A 2-3 mm thick and 1" diameter slab is cut from a core and is encapsulated between two transparent glass plates. The metallic frame that holds this rock/glass assembly has holes drilled in it that allow fluid injection and production in and out of the rock slab. The inner glass surfaces are pre-coated with transparent silicon rubber to provide a good seal between the flat rock surfaces and the assembly. The fluids are confined to the rock by rubber gaskets and silicon rubber fillings. This whole assembly (named rock-slab micromodel) is then mounted on a standard transmitted-light microscope equipped with imaging capabilities.

Fluids are injected using syringe pumps. The micromodel is visually scanned—as well as video-recorded—before, during, and after fluid injection. Both static and dynamic behavior are recorded. The video is previewed and dubbed with captions and sound narratives to describe the high velocity events occurring in the pores of the rock. The video imaging is preferred over still photography because of the following two reasons: (1) High velocity events can not be depicted with still photography as adequately as with a video. (2) Technical difficulty and high cost are involved in mass reproduction of numerous high quality photographs needed to describe a single dynamic event.

HIGHLIGHTS OF THE RESEARCH

A videotape and accompanying document were prepared as a partial deliverable for the Project BE12, Imaging Techniques Applied to the Study of Fluids in Porous Media. This 10-minute video shows fluids and their movements in the pores of 3-mm thick Berea and Bentheimer rock slabs. The experiments were performed with all three phases—oil, water, and gas—flowing simultaneously and in various combinations. The images shown in this video were selected as sample observations to show this technique's potential. Along with the video, a document very much like this one was annexed to provide further detail. A sample reproduction from this video is shown in Fig. 9.1. The gray-scale copying of color images renders a heavy toll on the clarity of the busy pictures, but the interfaces can still be discerned.

FIGURE 9.1 A visual illustration of the pore-level dynamic behavior of foam flow in rock-slab micromodel. This figure illustrates the following: (1) The foam flow is in the form of coalescence-and-reformation of bubbles as shown by bubbles B and C. Bubble B collapsed and is no longer visible in the lower photograph, which instead shows a new bubble formed (Bubble C). Certain locations (such as the pore-throat adjacent to bubble A) act as foam generators because of their specific geometry. (2) Foam in porous media exists in form of discrete bubbles and not as web-like structure. (3) The size of the foam bubbles ranges from filling the entire pore space to only a small fraction of pore space. The time-lapse between the two photographs is only 1/16th of a second.

Often the events occurring at pore-level were too complex or too fast to be captured with our equipment, but certain conditions allowed adequate descriptions. For example, foaming and emulsification were two phenomena amenable to images with reasonable clarity. It is important to note that the limitation previously mentioned are imposed mainly by imaging difficulties; an operator looking into the pores at run-time (through the microscope) has a much better view of the rock, fluids, and fluid movements.

Some of the observations for which the rock-slab micromodel is uniquely qualified (because of its realistic pore geometry) versus the conventional micromodels are as follows: It can now be said with certainty that foaming is possible in typical reservoir rocks, contrary to a theoretical study raising some doubts about it (Dietz et al, 1985). Similarly, it can be concluded that individual foam bubbles cannot propagate very far in the rock, because they expand (due to pressure decrease at the producing end and coalescing) and get trapped. The breakup and regeneration of foam lamellae at certain locations because of specific geometry is the dominant mechanism in foam flow through rocks. In the presence of oil, foaming is largely inhibited.

The following are some of the observations from analyzing a few hours of video tape recordings out of more than 100 hours of collection:

1. This innovative technique has enormous potential for providing a better understanding of the complex microscopic behavior of fluid flow through rocks.
2. Monochromatic images offer high resolution under low light conditions, but are not effective for discerning complex, multiphase fluids in porous media. Color images are required in imaging multiple fluids in porous media.
3. During secondary drainage (oil re-injection), oil flows in the form of discrete bubbles because water encroachment cuts-off the bubbles.
4. Turbulence is frequently observed at microscopic level at injection rates corresponding to the front velocity of 1-10 ft/day. Oil bubbles also spin along their own major axis.
5. At lower rates when capillary forces dominate the flow, oil transport, at least in part, is in the form of a snap-off/coalesce sequence.
6. The bubbles are several-fold smaller than the pores at the start of oil injection. As the oil throughput increases, some of these bubbles coalesce and consequently become trapped due to the restrictive pore morphology.
7. The pressure field often fluctuates because of the non-continuous advancement of oil (non-wetting fluid). Large bubbles advance and retract at a fixed general location.
8. Surfactants can effectively generate in situ foam even in the presence of residual oil. Foam lamellae are either held stationary or flow as small bubbles.
9. Multiphase flow is sometimes in form of emulsions—its role in the flow mechanism varying from subdued to prominent.

CRITIQUE

The major contribution of this work is development of the methodology of micromodel construction, imaging and image processing. Several other groups having read and discussed our initial research on micromodels have greatly expanded the technology to higher pressure (BP Research) and to chemical systems with lower interfacial tension (New Mexico Petroleum Recovery Research Institute). Both funding and other priorities prevented the development of these capabilities and the momentum generated was lost and picked up by other researchers. NIPER's use has been to study chemical, microbial, foam and emulsion systems to recover oil, as well as waterflood and gas floods through the use of micromodels.

Rock-slab micromodels do not always guarantee observation of realistic behavior, but they come closer than any other technique in doing so. There are many instances, especially for those recovery processes not dominated by viscous forces, in which rock-slab models can provide information not otherwise possible from other laboratory tests.

The micromodel research has resulted in the creation of two super-VHS tapes of fluid displacement. Copies of these tapes have been requested by several researchers throughout the world. However, due to the low priority as a project, the completion of the tapes for public distribution with accompanying textual material, audio and printed, has not been completed. The tapes show visually fluid displacement at the pore level, effect of wettability, pore size, pore geometry, network paths for several different oil displacement processes.

The sample images shown in Fig. 9.1 were captured and processed using standard off-the-shelf consumer video products; a camcorder and a VCR, both of super-VHS format. The only specialty component was an analog video processor that allowed signal improvement (enhancement/noise reduction), color control (tint, intensity, brightness, black pedestal, and white level), and chroma/lumin inversion. The video processor was instrumental in transforming the marginal images to a usable form, but it degraded the images considerably because of its VHS format that has only half the resolution of the other super-VHS video equipment.

The quality of images can be substantially improved with top-of-the-line commercial video equipment, such as a 3-chip RGB camera, a 3/4" or larger tape-size video deck with advanced editing capabilities, and a super-VHS video processor. The image quality can also be improved by using more appropriate microscope objectives, a brighter light source, and contrast enhancement accessories (such as Hoffman's modulation contrast system).

Although the image quality can be substantially improved, questions can be raised about the effect of scale difference on flow behavior of any micromodel (including rock-slab). The enclosing plates may have a non-matching wettability compared to the rock; a difference which ought to be carefully deciphered in the planning and analysis of experiments. The so-called "end effects," caused by the capillary discontinuity at the external boundaries, also have the potential

of masking the true behavior. Choosing suitable flow rates and other experimental conditions to minimize such problems is a formidable task.

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CHAPTER 10

CAPILLARY PRESSURE AND WETTABILITY STUDIES

OBJECTIVE

Capillary pressure and wettability are rock-fluid properties that influence oil recovery. For some time it has been known that temperature affects both capillary pressure and wettability. The effect of elevated temperature on capillary pressure has been previously studied (Sinnokrot et al., 1971; Sanyal et al., 1973; O'Kandan et al., 1974; Samaroo and Guerrero, 1981). These studies indicate an increase in irreducible water saturation with elevated temperature and this should correspond with increased oil recovery, but no systematic study has been performed. The shift in capillary pressure (towards increased wetting phase saturation) has been postulated to arise from a wettability change in the core to a more water-wet state. Knowledge of the effect of temperature on capillary pressure and wettability of a reservoir is a critical requirement for accurately predicting oil recovery by steam or hot water. Changes in these factors often accounted for alteration of the oil-water relative permeability curves in simulation studies to make performance and prediction coincide.

NIPER pursued research to investigate the effect of elevated temperature on capillary pressure and wettability in well characterized cores and fluids to document the results. A number of methods of determining capillary pressure and wettability depend upon using a centrifuge techniques. The use of centrifuge techniques for consolidated cores is widely used. Since most thermal oil production is from friable or unconsolidated porous media and there was no known reproducible centrifuge technique for determining capillary pressure and wettability, NIPER undertook development of a centrifuge technique that could accommodate unconsolidated sands.

METHODOLOGY USED

The capillary pressure and wettability measurements were made using the USBM centrifuge method (Donaldson et al., 1969). The centrifuge was altered to conduct experiments at elevated temperature without the loss of vapors. Both consolidated cores and unconsolidated sandpacks were used. The methodology used to conduct the capillary pressure and wettability studies are described in detail by Olsen et al. (1991) and Olsen (NIPER-552, 1991).

The calculation of capillary pressure or wettability indices from centrifuge data has long been a problem. NIPER undertook comparison of the mathematical approaches to calculation of capillary pressure from raw centrifuge data (Sarathi, in NIPER-320, p. 158; NIPER-400, p 232-236; Olsen et al., 1991).

To obtain consolidated cores and unconsolidated sandpacks of different wettability a series of treatments of water-wet porous media were undertaken. Early efforts focused on treating cores with crude oil or crude oil components such as asphaltene or polar fractions that had been separated

from the crude oil. Cores were soaked for extended periods of time to alter the wettability (Crocker and Marchin, NIPER-184, 1986; Crocker and Marchin, 1988). These techniques required significant aging time (weeks to months) and the wettability of the surface was stable at only low temperature. Chemical methods of treating water-wet surfaces were pursued initially as liquid phase treatments (soaking or pumping a wettability alteration chemical through the core) or later as gas phase treatments. The liquid phase silylating procedure to alter wettability used siloxane (Donaldson et al., 1969) or silanes with various side chains length diluted with an organic solvent (Olsen and Crocker, 1991). The vapor phase silylating procedures used consolidated Berea sandstone plugs and unconsolidated quartz or crushed Berea sandstone silylated with bis(dimethylamino)dimethyl silane at 650° F (Olsen, and Crocker, 1991).

NIPER also pursued analyzing the effect on wettability of various surfactants at elevated temperature. This research was undertaken to investigate the effects of surfactants (such as those used in steam-foam) on reservoir wettability.

HIGHLIGHTS OF THE RESEARCH

NIPER's TEOR group conducted several studies over a 3-year period resulting in several papers in the area of capillary pressure and wettability and the effect they have on thermal oil production. These studies could essentially be divided into four major areas of interest. These areas are: (1) development of centrifuge techniques to measure capillary pressure in unconsolidated porous media at elevated temperature (construction of high temperature centrifuge, design of pressure cells, development of methodology for making unconsolidated sandpacks for use in centrifuge studies, and data analysis); (2) techniques to convert water-wet to oil-wet porous media (liquid-phase oil-wetting procedures and vapor-phase oil-wetting procedures); (3) study the effect of various oils and oil components on capillary pressure and wettability and the influence of temperature on these properties; and (4) elevated temperature capillary pressure and wettability measurements (stability of porous media that had been converted to oil-wet, effect of surfactants on wettability at elevated temperature and the effect of steam on wettability in the presence and absence of oil).

DEVELOPMENT OF CENTRIFUGE TECHNIQUES FOR HIGH-TEMPERATURE UNCONSOLIDATED SANDS

NIPER retrofitted a centrifuge for operating at temperatures up to 350° F and conducted capillary pressure measurements at different temperatures as shown in Fig. 10.1. The studies found that irreducible wetting phase saturations increased with increasing temperature for a wide variety of fluid systems indicating that oil production should increase with increasing temperature.

FIGURE 10.1. - Capillary pressure curves for nitrogen/brine/Berea sandstone.

A packing procedure and holder were designed and constructed which allows centrifuge studies of capillary pressure and wettability to be determined on unconsolidated sands (Olsen et al., 1991). This allows determination of rock-fluid properties with temperature in a centrifuge on heavy oil from unconsolidated formations.

CONVERSION OF WATER-WET POROUS MEDIA TO OIL-WET

Most quarried rock, such as Berea sandstone, is water-wet but petroleum reservoir rock ranges from water-wet to strongly oil-wet. The USBM method (Donaldson et al., 1969) uses the ratio of the areas under the imbibition and drainage capillary pressure curves to calculate a wettability index (W), where $W = \log(A_1/A_2)$ and where A_1 and A_2 are areas under the oil and brine-drive capillary pressure curves, respectively. The USBM wettability index typically ranges from -1.0 (highly oil-wet) to +1.0 (highly water-wet) for most reservoir rock. It is possible to exceed these values if the area under one capillary pressure curve is much greater than the other.

To synthesize an oil-wet version of Berea sandstone, crude oils and fractions of crude oils were used to alter the surface (Crocker and Marchin, 1986; 1988). The wettability values for some of the systems are shown in Fig. 10.2, which indicates more water-wet with higher temperature. These oil treated oil-wet surfaces reverted to water-wet at temperatures below 200° F. Both liquid

FIGURE 10.2. - Comparison of wettability values at various temperatures.

phase and gas phase reactions with organic reagents were used to prepare oil-wet surfaces on glass, consolidated and unconsolidated porous media (Olsen and Crocker, 1991). The thermal and hydrolytic stability of the surfaces treated with liquid-phase (less stable) and vapor-phase (more stable) silylating procedures are shown in Table 10.1 and have been used at NIPER to convert water-wet porous media to oil-wet porous media for many research groups.

Elevated Temperature Capillary Pressure and Wettability Study

The elevated temperature capillary pressure and wettability study by Olsen et al. (1991) showed that irreducible water saturations in capillary pressure measurements and the wettability values both increase (i.e., cores became more water-wet) with increasing temperature irrespective of the initial wettability. One important contribution of this study was the new computer program and calculation method for capillary pressure measurement. The program was based on extending Rajan's method (Rajan, 1986). The calculation methods are also described in by Olsen (1989).

Light Oil Steamflooding Wettability Study

Table 10.2 shows the effect of temperature on the wettability index on some water-wet and oil-wet porous media. Increasing the temperature of the system caused conversion to more water-wet conditions (Olsen, 1991). The effect of wettability is also shown in Fig. 10.3. It also shows oil desaturation resulting from waterflood followed by steamflood to displace a light oil from strongly water-wet, intermediate oil-wet, and strongly oil-wet sands. These studies showed that waterflooded oil-wet light oil reservoirs might be more economical targets for steamflooding

TABLE 10.1 - Changes in wettability of silylated Berea sandstone and Quartz sands

Silylation treatment	None	Liquid-Phase		Vapor-Phase
		Si(C ₈ H ₁₇) ₃	Si(CH ₃) ₃	Bidentate Si(CH ₃) ₂
Untreated (Berea Sandstone)	+0.48 ¹			
Silylated (Initial)		-0.82 ²	-0.78 ¹	-0.66 ³
After 48 hr at water reflux	+0.51 ³	+0.32 ³	+0.47 ³	-0.45 ³
After 8 hr steam from 285° to 335° F				-0.29 ³
After 8 hr steam from 335° to 365° F				+0.09 ³
1-D steamflood at 350° steam injection end of oil saturated core after 10 hrs of steaming				-0.42
1-D steamflood at 350° production end of oil saturated core after 10 hrs of steaming				-0.52
Untreated Quartz sand	+0.53 ³			
Silylated Quartz sand (Initial)				-0.39 ³
After 8 hr steam from 335° to 365° F				-0.21 ³

¹ Average of 3 tests. ² Average of 2 tests. ³ Average of 6 tests.

TABLE 10.2. - Wettability increase with temperature for various systems

	75° F		150° F		250° F	
	O/W	W/W	O/W	W/W	O/W	W/W
Wettabilities of consolidated Berea sandstone cores						
Brine/mineral oil	-0.51	+0.75	-0.30	+0.92		
Brine/New London	-0.66	+0.40	-0.47	+0.78	-0.14	+0.95
Wettabilities of unconsolidated quartz sand						
Brine/New London	-0.39	+0.53	-0.21	+0.75	+0.27	+1.06
Wettabilities of unconsolidated Berea sandstone cores						
Unextracted New London crude	-0.45	+0.52	-0.15	+0.85	+0.03	
		+0.18				+0.81
Brine/mineral oil		+0.60		+0.87		+1.21

FIGURE 10.3. - Comparison of oil production from 2-D models, waterflood followed by a steamflood, in oil-wet, intermediate-wet, and water-wet quartz sandpacks.

compared to previously waterflooded water-wet light oil reservoirs. This is due to the fact that the initial oil saturation at the start of steamflood and the oil recovery rate during the steamflood are much higher in the oil-wet cases than in the water-wet case.

CRITIQUE

This research made some significant contributions: Methodology of preparing unconsolidated sandpacks for use in capillary pressure and wettability determinations at elevated temperature using centrifuge techniques; methodology for preparing oil-wet surfaces that can withstand elevated temperature; calculation technique for converting centrifuge data into capillary pressure curves for high permeability porous media; correlation of the effect of temperature on the changes in wettability, becoming more water-wet with increasing temperature for both hot water and steam displacements.

Concurrently with NIPER's efforts, numerous laboratories were conducting research in capillary pressure and wettability determinations. A series of literature reviews was published by Anderson (1987) and the problems of reproducibility and extraction of data from centrifuge methods that NIPER encountered early in the study are highlighted. Much of the technique of reproducibility encountered in high permeability sandpacks was reduced by taking care of the small details of packing, in allowing long enough time between measurements for the system to stabilize,

in using very small finely graduated centrifuge tubes, and running duplicate samples. Further refinement of the technology was implemented on another NIPER centrifuge. Video recording of the readings while the centrifuge was spinning added to the reproducibility of data because points that were out of line could be verified by reviewing the video tape and rereading the meniscus of the volume of fluid displaced. This often helped to smooth raw data and improved performance. Both the speed of the centrifuge and the upper temperature at which the centrifuge could be operated with external heating jackets was at the lower limit of where steamfloods are conducted. A centrifuge that could handle high temperature, higher rotating speeds, and larger sample (core) size could add to the capabilities of these determinations.

The gas phase silylation of porous media was used to prepare high temperature stable oil-wet surfaces on glass slides, glass beads, sand, cores and plugs. These have been used both by the thermal group at NIPER and by other research groups at NIPER and other institutions where both samples have been supplied or a detailed description of the silylation technique has been supplied so that others could prepare oil-wet surfaces.

NIPER was fortunate to have Jesus Betancourt as visiting INTEVEP engineer in FY90. He worked on some of the computer programming to overcome the limitations in solving the data reduction problem as part of his training in thermal EOR. The final computer program and part of the report was submitted by Betancourt in Spanish to INTEVEP as part of the account of his training.

The question of correlating centrifuge data (determined from high-temperature centrifuge runs) with high-temperature two-phase relative permeability data obtained on the same core has been pursued in part by Shimbo (1990). The results parallel those of the thermal group, however, the X-ray CT scans of cores to determine saturation throughout the core as conducted by NIPER in the relative permeability group (Honarpour et al., 1990; Maloney et al., 1990) question whether the effluent analysis conducted in both centrifuge and in corefloods accurately reflect what is happening in the porous media and the value of some of the relative permeability curves derived from effluent analysis.

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CHAPTER 11

FIELD RELATED RESEARCH PROJECTS

OBJECTIVES

The principal objective of this research was to assist DOE in its technology transfer effort by identifying heavy oil reservoirs outside California that are amenable to steamflooding and encouraging independent operators to try out this technology. Another objective was to support DOE's NPR-1 and NPR-3 steamflood operation by providing laboratory and technical support to field personnel.

METHODOLOGY

Assessment of Steamflood Potential of Heavy Oil Reservoirs of Arkansas

A recent study conducted by NIPER as part of SGP37 (Olsen et al., NIPER-521, 1991), identified several heavy oil fields in Arkansas, Louisiana and Texas. These heavy oil resources represent significant future sources of domestic liquid fuel and can make a substantial contribution to domestic crude oil if and when developed. Steam injection is the most efficient way to produce these resources. Thermal technique, however, is not universally applicable to heavy oil fields and the technical and economic success of the process is reservoir dependent. Hence, heavy oil reservoirs must be individually evaluated and the applicability of steam injection process established. Thermal simulation is the most cost-effective way to determine the applicability of steam injection process in the targeted reservoir.

Reservoir simulation, like formation evaluation, is a highly specialized area of petroleum engineering and entails the service of experienced engineers to interpret the results. The small to medium-size independent operators who own most of the heavy oil leases in the U.S. lack the necessary technical expertise, tools and resources needed to conduct simulation studies and assess the viability of steam injection processes in their reservoir.

To preserve access to the resource in such reservoirs and assist DOE in transferring steamflood technology to independents, steamflood simulation of selected Gulf Coast States heavy oil reservoirs was undertaken. In FY92, the steamflood potential of Arkansas heavy oil reservoirs was assessed and specific recommendations as to the viability of the process in these reservoirs was made. In FY93, the steamflood potential of Texas Gulf Coast heavy oil reservoirs will be assessed.

APPROACH

The NIPER heavy oil data base was reviewed to identify and collect preliminary data on heavy oil reservoirs in the Nacatoch formation of Arkansas. Published screening criteria were utilized to screen these reservoirs and select reservoirs for further scrutiny. DOE's steamflood

predictive models were used to predict the steamflood performance of these reservoirs and select the best candidates for further study. Although several prospects satisfied the performance criteria, time and manpower constraints precluded the in-depth performance analysis of all of the prospects. Hence, based on the steamflood predictive model performance prediction and data availability, the Charivari Creek field was selected for further study.

The Charivari Creek is a fluvial-deltaic heavy oil reservoir with a thin low-permeability zone and high water saturation. This is typical of many Gulf Coast heavy oil reservoirs. The selection of this marginal heavy oil reservoir permitted the evaluation of the feasibility of steam injection process in an unconventional heavy oil reservoir and compiles analysis of various injection/production strategies (Tham et al., 1991).

An operator in this reservoir supplied copies of geological and reservoir data. The information was reviewed and the missing information estimated. These data were input into a commercial steamflood simulator (Computer Modeling Groups 'STARS' simulator), and the steam injection performance of the reservoir was evaluated for various injection/production scenarios. No detailed economic analysis of the process was performed; however, an economic analysis, based on California development and operation costs, was performed to gain insight into the economics of conducting steam injection operation in a less-than-ideal heavy oil reservoir. The simulation results were then analyzed and specific conclusions were made.

The study showed that a marginal heavy oil reservoir (i.e., reservoir characterized by low permeability, thin pay and low initial oil saturation) such as the Charivari Creek will respond favorably to steamdrive, but not to cyclic steaming. Steam stimulation, however, is necessary to improve steam injectivity during subsequent steamdrive. Further, in such marginal reservoirs, conventional steamdrive (i.e., steam injection using vertical wells) is unlikely to be economical and nonconventional methods must be utilized. It was found that the use of horizontal well steamdrive technology holds greater potential for economic oil recovery in such reservoirs. Details of the findings can be found in the report by Sarkar and Sarathi (1993).

Critique

This research made some significant contributions. This study showed that it is economically feasible to steamflood heavy oil reservoirs that do not meet the classic definition of steamflood recovery prospects, namely—A shallow massive unconsolidated reservoir with high initial oil saturation. The Charavari Creek reservoir in Arkansas is typical of many Gulf Coast states heavy oil reservoirs. Thin pay, low-permeability and low initial oil saturations are the hallmark of these reservoirs. The study showed that even though these reservoirs are steamfloodable, steamflood operations using vertical wells are likely to be uneconomical. The study showed that the steamflood economics can, however, be improved using a horizontal producer and vertical

injector. This enabled NIPER to develop guidelines for conducting steamfloods in marginal heavy oil reservoirs with unusual characteristics. This is the major contribution of this research effort.

Naval Petroleum Reserve-3 (NPR-3) Steamflood Operation-Support Research

This is a support research activity designed to provide technical support for NPR-3 steamflood operations. As part of this research, the steamflood operations currently being conducted in the Upper and Lower Shannon sandstones in Teapot Dome field, Wyoming, were reviewed and the problems affecting the economics of the project were identified. These problems were prioritized, analyzed and remedial actions were recommended to address these problems.

Major problems affecting the Shannon steamflood operations included: (1) premature steam breakthrough, (2) hot wells, (3) high operating costs, (4) heat management, (5) low capture efficiency of the mobilized oil, and (6) operation of a steamflood in an adverse geologic formation. Suggestions for a systematic approach to improve operations were recommended (Olsen, 1992). Some of the suggested remedies are currently being implemented. NIPER analyzed one steamflood pattern and the reservoir geology to help improve the performance of the steamflood (Jackson et al., 1992).

The NPR-3 steamflood operation is an unusual EOR project in that the project is being conducted in a reservoir that defies conventional steamflood screening criteria. Shannon field is a shallow, very heterogeneous, low permeability light oil reservoir and is highly faulted and fractured. Such reservoirs are normally considered unsuitable for steamflood operations. Shannon steamflood operations, however, demonstrated that by employing multidiscipline approach to design, and by accommodating the reservoir characteristic, it is feasible to steamflood economically a less than ideal reservoir. To publicize this fact and demonstrate how the productive life of many shallow, tight, pressure depleted, and highly heterogeneous light oil reservoirs can be extended by thermal methods, a paper documenting the NPR-3 steam injection operations was written and presented at the 1993 International Thermal Operations Symposium (Olsen et al., 1993).

The publication of this document directly supports the DOE's technology transfer efforts in three ways: (1) It provides a detailed project specific information, (2) it analyzed an unusual operation and defined key elements that make steam injection operations successful in nonconventional reservoirs, and (3) publicized a record of success to a targeted audience and thereby gave impetus to operators to try out this proven technology in unusual reservoirs.

Naval Petroleum Reserve No. 1 (NPR-1) Steamflood Operation-Support Research

Laboratory research to select a surfactant for use as a steam diverter was undertaken in FY90 in support of the steamflood pilot being conducted in the shallow oil zone at NPR-1, Elk Hill Field, Kern County, California. Research was suspended concurrently with the decision by DOE to suspend the pilot.

Although no satisfactory surfactant was found (Olsen et al., NIPER-605) for the steamflood in the Shallow Oil Zone (SOZ) at NPR-1, the 2-D steamfloods with SOZ crushed core and oil were informative. Under the laboratory conditions (150 psi backpressure corresponding to a saturated steam temperature of 355° F) which was at lower temperature than field injection temperature (due to pressure limitations of 2-D model). Under these milder laboratory conditions, scale deposition, and swelling and mobilization of clays were observed. These caused severe production problems (similar to those concurrently encountered in the field) and occurred as soon as steam broke through to the producer. In floods where a waterflood preceded a steamflood, oil recovery during the waterflood was nearly as good as a steamflood because no production problems were encountered. Steamflood following a waterflood recovered only slightly more oil than either waterflood or steamflood alone. These laboratory tests indicated that waterflooding the 27° gravity oil was efficient. The mineralogy of the SOZ sand and its high divalent ion concentration and 550° F operating temperature were not amenable to steamflooding or foam generation for steam diversion using the surfactants studied.

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CHAPTER 12

FEASIBILITY STUDY OF INCREASING DOMESTIC HEAVY OIL PRODUCTION

OBJECTIVE

The objectives of this nationwide heavy oil feasibility study were (1) to investigate from secondary data the known heavy oil resources; (2) to screen this resource for potential production by thermal enhanced oil recovery (TEOR) or other EOR techniques; and (3) to evaluate constraints (oil price, production cost, refining, transportation, environmental, etc.) that might impede the development and expansion of domestic heavy oil production.

BACKGROUND

This feasibility study of increasing domestic heavy oil production was conducted as a multi-year supplemental government project (SGP37). The studies conducted under SGP37 analyzed among other things why heavy oil was successful in California in spite of low oil prices and stringent environmental regulations, whether there is the potential for heavy oil to make a significant difference in other areas of the U.S., and what it will take for this to occur. The results of this study were published in a number of regional geological heavy oil reports, as well as heavy oil refining and transportation reports. In order to get a more accurate picture of the volume of heavy oil in a region and the difficulty in its production, constraints imposed by the reservoir geology, oil quality, location and the transportation and refining capability in any given region were analyzed. A heavy oil reservoir database was developed as part of this study.

Heavy oil is defined as having gas-free viscosity of >100 and $<10,000$ MPas (centipoise, cP) inclusive at original reservoir temperature or a density of 943 kg/m^3 (20° API gravity) to $1,000 \text{ kg/m}^3$ (10° API gravity) inclusive at 15.6° C (60° F). (Group, 1981). Heavy oil production in California has increased from 20% of the state's total oil production in the early 1940s to 70% in the late 1980s reaching 675,977 BOPD in 1989. Concurrently, light oil production in the major regions of California, Los Angeles, Coastal and San Joaquin Valley, has peaked and then declined throughout the past 50 years (see Figs. 12.1 and 12.2). This reflects the general production decline pattern of the rest of the United States. California is the largest heavy oil producer in the United States, producing 87% of all the heavy oil produced in the country (Olsen, NIPER-606, 1992). California is also the largest producer of TEOR produced oil, producing 99% of all the country's thermally produced oil (Moritis, 1992).

METHODOLOGY

An overview of the Nation's heavy oil resources (see map as Fig. 12.3) and constraints to production and processing was prepared using secondary sources of information, including

FIGURE 12.1. - California oil production since 1940 showing the percent of total oil that is heavy oil.

FIGURE 12.2 - Total oil production by region within California.

FIGURE 12.3 - U.S. heavy oil fields.

geological theses, state production and geological reports, trade journal articles, SPE reviews of EOR projects, published heavy oil reservoir databases, and other unpublished in-house databases. Regional geological studies, resource assessments, analyses of constraints (refining, transportation, environmental, etc.) were conducted and resulted in a series of publications assessing the feasibility of increasing domestic heavy oil production. A major product, in addition to the reports, was a new, documented heavy oil reservoir database.

As background for NIPER's heavy oil reservoir database, it should be noted that previous studies by Interstate Oil Compact (1984), the United States Geological Survey (USGS, Crysdale and Schenk, 1990), and others (Dietzman, Carrales and Jirik, 1965; Nehring, Hess and Kaminski, 1983; Bureau of Mines circular 8352, 1967; Dowd, Kuuskraa and Godec, 1988; and Kujawa, 1981) have resulted in printed heavy oil reservoir databases. NIPER constructed an electronic copy of the USGS database and sent copies to USGS and DOE as one of the first tasks in this project. However, these databases have usually been limited in scope due to high minimum limits being set on Original-Oil-in-Place (OOIP), as much as 20 million barrels of oil was the minimum cutoff for inclusion of reservoirs in some databases. NIPER's original heavy oil reservoir database includes reservoirs with > 1 million barrels OOIP and was derived from secondary information (not direct operator contact). Other information has been gathered along the way on even smaller heavy oil reservoirs, as well as on many reservoirs in the 20° to 25° API range, without any OOIP limits. Another limitation of some previous heavy oil reservoir databases was that they were not developed using reservoir data but rather field data. This was especially true for oil production, since many heavy oil reservoirs are produced as commingled production with light

oil that made allocation at the reservoir level difficult. This also makes oil-in-place determinations difficult, resulting in a lack of definition of the remaining heavy oil resource. NIPER's database was developed as a reservoir level database, including estimates of production. NIPER's database development used a "fill in all the holes best engineering estimate of values" approach on key unreported reservoir parameters. Only one value was assigned to reservoir parameters such as API, permeability, and porosity rather than listing ranges or leaving the value blank. Ranges of values are maintained in a related database file for reference. The result is a sortable, reservoir level database with a higher degree of resource and reservoir parameter accuracy. No database accurately reflects all reservoir and production parameters, but the database is an improvement in that it incorporates limited geologic parameters.

HIGHLIGHTS OF RESEARCH

The heavy oil feasibility study can basically be broken down into four major areas. Results of this research include a series of regional geological reports, refinery and transportation reports, a projection of future heavy oil development, and a heavy oil reservoir database.

Regional Geological Studies

The regional geological studies that were conducted and their resulting papers included the Midcontinent area (Oklahoma, Kansas, and Missouri), the Permian Basin, the Appalachian Basin, Wyoming and the Rocky Mountain states, and Alaska. Additional geological report(s) on the Mississippi Embayment are being prepared. The following are results of the regional geological reports:

(1) The Midcontinent (Kansas, Missouri and Oklahoma) study (NIPER-560) showed that a substantial amount of heavy oil was predominantly in Pennsylvanian age, shallow, consolidated, tight, fluvial dominated sandstone deposits that would be difficult to produce in an economically profitable and environmentally safe manner with TEOR. The original 1960 and 1970s publications and leasing of this area in the early years of TEOR development were based on consideration of the sandstones as blanket type deposits because of the widespread location of the occurrence of heavy oil. These were gross overestimates of the resource and the economically recoverable oil is only a small fraction of the resource. Thirty years of field tests in the area showed that most thermal oil recovery methods recover more oil than primary production but the only potentially economic projects are those in unconsolidated sands. The unconsolidated sands in the Midcontinent are located on the north side of the Arbuckle mountains in south-central Oklahoma. This is the only sight of current thermal oil production. Heavy oil is present in the carbonates of Central and Western Kansas but the volume of the resource has not been determined and since there has been little success in thermal recovery of heavy oil from carbonates, there was no reason to pursue determination for the volume of the resource. If heavy oil were brought into the area, the refineries

could not handle significant amounts because the refineries are typically small sweet light oil refineries.

(2) The Permian Basin and Appalachian report (NIPER-584) showed small amounts of heavy oil in consolidated reservoirs and with the exception of a few select refineries processing imported blended crude (heavy oil diluted with light oil), the refineries are light oil processors. The reports recommended no further research on heavy oil in these areas.

(3) The Rocky Mountain states (NIPER-619) showed fairly substantial amounts of deep, hot, paraffinic heavy oil that may be waterfloodable and not require thermal recovery methods for production. However, the Rocky Mountain states lack heavy oil refining capacity, and any substantial increase in production would require additional refining capacity in the area and/or transport to the Midwest.

(4) The Alaska report (NIPER-610) showed the potential for large amounts of heavy oil but it would be difficult to produce by TEOR without damage to the permafrost and when transport costs to California heavy oil refineries are added the economics may not justify development. There is heavy oil being produced on the North Slope on primary production, but future development of large scale heavy oil production may occur only after smaller lighter oil reservoirs are developed. In a free market economy, the cost of oil production and transport to California, where Alaskan oil would have to compete with California heavy, makes little economic sense. Heavy oil will be imported before much of Alaska's heavy oil is developed because of the high production and transportation costs.

(5) The report on the feasibility of heavy oil production along the Gulf Coast is being prepared. This area encompasses Southern Arkansas, Northern Louisiana and East Texas as one area, South Texas and then the remaining U.S. Gulf Coast. This area has heavy oil, but most of the reservoirs are thinner and smaller as compared to those in California, but they are more like California heavy oil reservoirs (friable or unconsolidated) than any of the other heavy oil reservoirs in the lower 48 states. Many of these reservoirs have previously been overlooked as there was plentiful light oil reservoirs in the area. As light oil production declines, more operators may consider producing heavy oil. However, the cost of producing heavy oil is more than producing light oil. This resource is located in the area with the Nation's largest refining capacity, including capacity for heavy oil processing. The heavy oil is paraffinic, which is projected to be easily produced by TEOR and has a higher market value than the more asphaltic California heavy oil. This area has the potential for being a future major heavy oil producing area.

Refinery and Transportation Studies

The refinery and transportation studies that were conducted and the resulting papers included a refinery paper at the national level, the heavy oil production projections reports, which served as

the basis for another report that was contracted to Bonner and Moore, and the California refinery reports. The following are offered as general background for the reports:

The original refinery report—Olsen and Ramzel, November 1991, examined the Nation's refining capacity and crude oil transportation system relative to regional heavy oil resources. Attention was given to the heavy oil processing capability of the regional refineries and the regional transportation systems. The report examined crude oil imports relative to domestic production, production and refinery capacity trends, and production market, refinery and transportation margins and technical constraints of heavy oil relative to light oil. This report was also published in FUEL (Olsen and Ramzel, 1992) and indicated that there were downstream problems in increasing domestic heavy oil production.

Projections of Future Heavy Oil Development

Projections report—(NIPER-606), based on NIPER's documented regional heavy oil production and heavy oil resource levels, made heavy oil production projections through the year 2010, including time frames and locations of production, on a low-level, middle level and high-level production case basis. This data was used as input in a national heavy oil refining impact study conducted by Bonner and Moore. The high case used National Energy Strategy (NES) production projections for advanced thermal EOR technology. Based on the analysis of U.S. heavy oil resources, oil quality, the pipeline network and existing refining capability, NIPER made projections as to volumes, locations and possible time frames for expansion of the heavy oil industry in the U.S. Current heavy oil production in the U.S. is about 750,000 BOPD. NIPER approached making projections of future heavy oil by backing into numbers from the high volume case (930,000 BOPD additional heavy oil) are projected by Brasher et al. (1992), which supports some of the details of the production and research programs proposed in the 1991/1992 National Energy Strategy. More realistic volumes of 500,000 BOPD (same volume as current thermal heavy oil production in California, which has taken 30 years to develop) and 300,000 BOPD (an achievable volume but will require great effort) were considered.

An impact study (NIPER-620) gives the results of additional heavy oil production (projected costs of additional refining capacity, units) for the U.S. refining industry. A linear program model of the U.S. refining industry was produced and analyzed domestic and imported crude, and the refining capacity necessary to meet projected demand between 1990 and the year 2010. The study concluded that a significant increase in oil imports from the Mideast would occur. If domestic heavy oil were developed as projected in NIPER-606, then some of these imports would be displaced. To refine this domestic heavy oil would require an investment of 7 billion dollars in refining units between 1990 and 2010. This investment level is small compared to that required to be in compliance with amendments to the 1900 Clean Air Act.

California refinery report—Heavy oil (10° to 20° API gravity) production in California has increased from 20% of the state's total oil production in the early 1940s to 70% in the late 1980s. Oil production in Los Angeles Basin, Coastal Region, and San Joaquin Valley has peaked and then declined at different times throughout the past 50 years. California produces 99% of U.S. thermally produced oil in spite of low prices for heavy oil and stringent environmental regulations. California is the largest gasoline market in the United States, but with Alaskan oil, imports brought into California for refining, and the state's own production, a local surplus of oil exists that inhibits higher utilization of California heavy oil resources. Transportation, refining, and competitive factors in the market limit full development of California heavy oil resources.

The refinery reports can be summarized as follows: (1) The original refinery report detailed the Nation's heavy oil refining capacity relative to the major heavy oil resource areas of California, the Gulf Coast states, and Wyoming, finding 50% of this capacity to be in the Gulf Coast area, a substantial portion in California, and very little in the Rocky Mountain area. The report detailed the reasons that heavy oil is more difficult to process than light oil in refineries as well as current and potential future problems with both heavy oil and light oil in the transportation network. It discussed the current and forecasted ready availability of foreign light oil supplies to the Nation's refineries as the Nation's production declines significantly. It emphasized the importance of domestic producer and refinery incentives for increasing the level of heavy oil use in the U.S. (2) The Projections report supplied the domestic heavy oil production scenarios to the Bonner and Moore report which found that both the low and high heavy oil production scenarios, using both low sulfur and high sulfur Gulf Coast heavy oil, would cost approximately \$7 billion to implement with about half of the cost attributed to the Clean Air Act Amendment and half to incremental refinery capacity additions. (3) The California refinery report found that independents and non-vertically and horizontally integrated major oil companies (i.e., those whose production does not equal their processing and marketing capabilities) were at an extreme economic disadvantage relative to fully integrated major oil companies. The reasons for California's current oversupply of crude oil (especially heavy oil), the consequences of this oversupply to California's heavy oil producers, and the oil pricing mechanisms at work in California were discussed.

Within these projections, California has the greatest resource, but expansion is limited by an over supplied oil market. Alaska has the second greatest resource, but production and transportation are very expensive relative to other sources. The U.S. Gulf Coast states have the third largest domestic heavy oil resource. Wyoming has heavy oil in deeper formations that have only partially been developed on wide spacing with primary and limited secondary production. The Rocky Mountain states have no significant refining capacity to process heavy oil. The Midcontinent and Appalachian Basin heavy oil resources are limited by the geology of the resource

and economic extraction has not been proven by the last 30 years of pilot tests from these principally consolidated sandstones.

Future Gulf Coast heavy oil will come from Tertiary Age unconsolidated or friable sandstones. These are younger sands (4.6 to 67 million years in age). The Gulf Coast heavy oil, except for selected areas, has not been fully developed because there has been ample light oil in the region. The unconsolidated Gulf Coast reservoirs are more like California heavy oil reservoirs than any other areas of the U.S. however, they are typically thinner, less massive sands with more shale laminations because the sands were deposited as fluvial or fluvial-deltaic systems. This region has light oil available for diluting heavy oil for pipeline transport, and it has refining capability to process heavy oil. Production scenarios were built to fulfill production targets. A production volume of 930,000 BOPD of additional domestic heavy oil (NES, 1991) was the upper limit. To be able to refine an additional 930,000 BOPD of domestic heavy oil, the Bonner and Moore study indicated that an investment of 7 billion dollars was required for refining units. Nearly the same dollar investment is required for 300,000 or 500,000 BOPD of additional heavy oil as is required for 930,000 BOPD. This figure includes only refining equipment costs—incidental costs are excluded. The low investment level of 7 billion was explained as resulting from the displacement of imports whose refining infrastructure already exists or is scheduled as part of the expansion between 1990 and 2010 to accommodate increasing imports, and included only equipment costs, not secondary costs such as installation, etc. The increased domestic heavy oil would displace imported medium high-sulfur crude oil, probably Arab medium (31.1° API gravity, 2.5% S) and Arab heavy (27.6° API gravity, 2.84% S). The low cost of refining construction is also due to the U.S. Gulf Coast heavy oil which is for the most part lower in sulfur and is more paraffinic. Most of the future Gulf Coast heavy oil that will be produced is anticipated to be - 18° API gravity and <2% sulfur.

Heavy Oil Reservoir Database

In order to obtain a more accurate picture of the true volume of heavy oil in a region, the difficulty in producing the oil, and its transportability and refinability in any given region, a heavy oil reservoir database was developed. The result is a sortable, reservoir level database with a higher degree of resource and reservoir parameter accuracy. In addition, this database has been documented on a "cell by cell" basis using the Microsoft Foxbase relational database program which is easily converted into Lotus 1,2,3 spreadsheet format.

The following are the results of the heavy oil reservoir database work: (1) A concerted effort was made to generate an accurate, documented National heavy oil resource database at the reservoir level. Reservoir and resource development economics were not, as a rule, considered during the database development. However, they were considered in the geological reports and in subsequent evaluations using the DOE TORIS system to analyze the feasibility of EOR with a variety of

processes in each reservoir. (2) Outside of California, numerous reservoirs in other databases were discovered to be carrying various amounts of light oil production as heavy oil production. Usually, this was due to commingled production and/or not describing the reservoir on a "true reservoir" basis. (3) Within California, numerous heavy oil reservoirs were "rediscovered" because previous databases had used production listings as their "backbone." Thus, when a reservoir ceased to produce or when development of the reservoir was not undertaken for whatever reason, the reservoir ceased to exist in various databases or files. A concerted effort was made to "reconcile" production terminology with reservoir data.

CRITIQUE

This project started as an assessment of the Midcontinent (Kansas, Oklahoma, and Missouri) heavy oil producing area and based on the presentation and publication of the status report, (Olsen, NIPER-487, 1990). The project was subsequently expanded to include the continental U.S. and Alaska. The second status report on the heavy oil was published, Feasibility Study of Heavy Oil Recovery in the Lower 48 States, (Olsen et al., NIPER-521, 1991). The major points in that status report have been substantiated by additional research. One of the often overlooked parts of the status report are the appendices of the report that contained a geologic screening guide, environmental guide, refinery database, and reservoir database using the USGS (Crysdale and Schenk, 1990) heavy oil database that was converted to electronic copy and submitted to DOE and USGS. In addition, a heavy oil reservoir database and some heavy oil refining studies were undertaken and produced as part of this extended study. As a whole, this project has generated a remarkable amount of interest and several professional papers and presentations. The study is important and strategically useful information for the U.S. Department of Energy. Technology transfer has been a major objective of this project. Encouraging development of the heavy oil resources that are more amenable to production such as the Gulf Coast States Tertiary Age deposits and discouraging attempts to recovery oil from other areas that have proven to be difficult to produce economic heavy oil such as the consolidated formations of the Midcontinent. Papers and presentations resulting from this research have attempted to highlight the lessons learned through research and the last 30 plus years from thermal heavy oil production experience. This project has also tried to convey problems that exist on the downstream side of heavy oil production. Extraction of heavy oil is capital intensive. Each barrel of heavy oil costs more to produce than a comparable barrel of light oil, but yields a lower value product (as compared to refining light oil) when refined. The margin on production and refining heavy oil are marginal at low world oil prices.

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CHAPTER 13

TECHNOLOGY TRANSFER OF NIPER THERMAL EOR RESEARCH RESULTS

TECHNOLOGY TRANSFER EFFORTS

The basic objective of DOE-sponsored research at NIPER is to advance the state-of-the-art for EOR technology and to transfer the research results to the petroleum industry. Presentations and publications are among the key vehicles used by NIPER to transfer its research findings and practical applications to industry and academia. As part of technology transfer efforts, NIPER's thermal oil production researchers over the years have conveyed the research results to the petroleum production community at large as follows:

1. Participating and presenting the results in professional meetings.
2. Publishing the results in peer reviewed professional journals.
3. Publishing articles of practical significance in trade publications.
4. Publishing and distributing NIPER research reports.
5. Preparing briefs on technology as requested by DOE.
6. Sponsoring meetings and symposiums on specific oil production technologies.
7. Presenting short introduction covering EOR to students and visitors.
8. Cooperation with industry.

The effectiveness of these technology transfer mechanisms was gauged by tracking citations of these publications by other researchers, and by the number of requests for these reports by the research community.

Judging from the number of requests received from the industry and academia for its research reports and the citation of its research findings in professional publications, it is apparent the Thermal Research Group at NIPER has largely succeeded in fulfilling DOE's basic technology transfer objectives. This is best illustrated by the following selected examples. These examples best characterize NIPER's contribution towards the advancement of thermal EOR technology and its approach to technology transfer efforts. NIPER thermal EOR research presentations and publications are listed at the end of this chapter.

A. Conference Presentations and Journal Publications

1. Effectiveness of Screening Tests as Predictive Model for Steamflood Additives, SPE Reservoir Engineering, November 1987, pp. 543-548.

This paper describes equipment set up and procedures for screening surfactants at steamflood conditions for use as mobility control agent. A new correlation was presented for predicting the effectiveness of a surfactant as a steamflood mobility control agent. This correlation was often cited by researchers involved in screening and selecting surfactants for use in steamflood application.

2. Laboratory Investigation of Surfactant Additives to Steam for the Recovery of Heavy Oil. Paper presented at the Southwest Regional ACS meeting, Houston, TX, Nov. 19-21, 1986.

This paper was one of the first to elucidate the mechanism of oil recovery by steam-foam and the first to document that the ability of a surfactant to foam in the presence of a crude oil depends upon the oil saturation and for each surfactant there exists a critical oil saturation above which the surfactant will not foam. This paper also pointed out that the ability of a surfactant to foam is very much dependent upon the oil composition. Thus, a surfactant that foams in the presence of one crude may or may not foam in the presence of another crude oil. Thus, in steam-foam applications, the surfactant crude oil compatibility must be considered in the selection of a surfactant.

3. Light Oil Steamflooding: A Laboratory Study, SPE Reservoir Engineering, May 1990, pp. 177-184.

This paper was one of the first to describe the features of a high pressure 2-D sandpack physical model that has a high degree of instrumentation and its usefulness in studying the problems associated with steamflood such as gravity segregation, poor areal and vertical sweep efficiencies, and fingering of steam through zones of high permeability. This is the first paper in the Petroleum Engineering literature to present the response of light crudes to steam injection and the problems associated with the process. This paper was also the pioneer in presenting detailed compositional analysis of produced fluids as a function of time and the first to present actual measurement of saturation distribution and composition of residual oil at various locations in the model. This study also demonstrated for the first time that light oil steamfloods are typified by an early production response to steam injection and that recovery efficiencies are strongly influenced by the chemical nature of the crude. Crudes with identical API gravity, but differing chemical composition will respond differently to steam and hence estimation of steam injection oil recovery using API gravity based correlations are likely to be in error.

4. Effects of Elevated Temperatures on Capillary Pressure and Wettability. Presented at the 5th UNITAR/UNDP International Conf. on Heavy Crudes and Tar Sands, Caracas, Venezuela, Feb. 17-23, 1991. Conference Proceedings, v. 3, pp. 199-207.

This is a pioneer work documenting the effect of temperature on capillary pressure and wettability and describes procedures and techniques for determining capillary pressure and wettability of unconsolidated cores as function of temperature. This paper was also the first in the Petroleum Engineering literature to present the changes in wettability of cores subjected to steamflood as a function of time and demonstrated that steamflood

performance differs significantly from one another in water-wet, intermediate wet, and oil-wet porous media.

5. Environmental Aspects of Thermal Oil Recovery. J. Pet. Tech., v. 43, No. 6, June 1991, pp. 662-721.

This is the first paper in the Petroleum Engineering literature to address major environmental issues of significance to thermal oil production and discuss the steps to develop an environmental compliance strategy. In this study, an attempt was made to identify and define the environmental requirements for candidate thermal EOR project and evaluated from federal, state and local regulatory viewpoints. The potential environmental deterioration likely to be generated by a thermal project were identified and the mitigation measures to be employed at each thermal EOR site outlined. This paper was highly acclaimed by the industry for its thoroughness and timeliness and selected as one of the best papers of the year by the editors of the *Journal of Petroleum Technology*.

6. Case History of Steam Injection Operations at Naval Petroleum Reserve No. 3, Teapot Dome Field, Wyoming: A Shallow Heterogeneous Light Oil Reservoir. Presented at the SPE International Thermal Operations Symposium, Bakersfield, CA, Feb. 8-10, 1993.

This work is a prime example of NIPER's technology transfer effort as outlined in DOE's Oil Research Program Implementation Plan. This paper publicizes the successful implementation of an advanced technology in a reservoir considered not amenable to steamflooding. It was shown that in spite of unfavorable reservoir characteristics, steam injection projects can be successfully implemented in shallow, fractured light oil reservoirs using a multi-disciplinary approach to planning and design. By analyzing and publicizing this field test and providing reservoir specific performance and economic data, this paper resolved the technological and economic uncertainties surrounding steamflood projects in marginal reservoirs. Thus, this work fulfilled one of the objectives of the Oil Research Program Implementation Plan in that it provided guidance to the successful implementation of a proven oil recovery technique in marginal reservoirs and prolongs the access to these oil resources.

B. NIPER Reports

1. Practical Aspects of Steam Injection Processes—A Handbook for Independent Operators, NIPER-580, August 1992. This highly popular report, designed to help DOE in transferring steam injection technology to independent operators, explores the concepts behind steam injection processes and discusses the information required to evaluate, design, and implement these steam as a recovery aid in the field. This report places major emphasis on steam injection field practices, problems and solutions thus fulfilling the need for a non-mathematical field-oriented thermal EOR monograph. The popularity of

this report among field engineers and academia indicates the success of this technology transfer effort. More than 600 copies of this report have been distributed within the first 6 months of printing and the report has been adopted as a thermal EOR text by the Universities in the U.S.A. and Canada.

2. Using Micromodels to Study Steam Displacement Processes in Porous Media. NIPER-180, October 1986. This NIPER review report on micromodeling was considered a classical work on micromodel and is an often cited reference by researchers planning to develop newer models. This report reviewed the history of micromodels and offers guidance as to the usefulness and limitations of micromodels as a research tool. It identifies factors that must be considered in the construction of newer models. This report was well received by researchers from both industry and academia. Several dozen copies of this report were distributed and requests for copies of the report continue to be received even after 7 years.
3. Feasibility Study of Heavy Oil in the Midcontinent Region (Kansas, Missouri, Oklahoma), NIPER-560, October 1992. This feasibility study showed that contrary to previous publications the heavy oil resource of the tri-state area of western Missouri, southeast Kansas and northeast Oklahoma did not contain billions of barrels of heavy oil. The study showed that economic recovery of heavy oil in the area was severely limited by the reservoir rather than geology of the oil recovery process. The paper highlighted the importance of determining the internal architecture of these fluvial deltaic Pennsylvanian Age reservoirs. Lessons learned from the thirty years of field tests in the area showed that economic heavy oil can be recovered from unconsolidated or easily friable sands such as those of south central Oklahoma. Transportation and refining were additional constraints to heavy oil development in the region.
4. Feasibility of Heavy Oil Recovery in the Lower 48 States, NIPER-521, January 1991. This study summarized the heavy oil deposits, production history, environmental constraints, refining and transportation constraints and identified opportunities for increasing the Nation's heavy oil production. More than 1,400 heavy oil reservoirs are in the lower 48 states but only those of California have been significantly developed. A reservoir database, proposed changes to developing a reservoir database, reservoir screening protocol, environmental screening protocol, geological evaluation protocol and engineering evaluation protocol were presented. Heavy oil reservoirs could be divided into two categories, consolidated or unconsolidated, and most heavy oil in the U.S. is trapped in either fluvial-deltaic or turbidite sandstone deposits. The largest impediment to heavy oil development is oil price and this is directly related to what a refiner is willing to pay. Heavy oil is not only more difficult and costly to produce but also to transport and

to refine. Refining heavy oil yields less high value product and significant low value product as compared to light oil and refiners post oil prices accordingly.

5. Estimates of Future Regional Heavy Oil Production at Three Production Rates—Background Information for Assessing Effects on the U.S. Refining Industry, NIPER-606, April 1993. This report is one of a series of publications considering the feasibility of increasing domestic heavy oil (10° to 20° API gravity) production being conducted for the U.S. Department of Energy. The report included projections of future heavy oil production at three production levels: 900,000; 500,000; and 300,000 BOPD above the current 1992 heavy oil production level of 750,000 BOPD. These free market scenario projections include time frames and locations. A second managed market scenario's production projections were created to examine which heavy oil areas would be developed if significant changes in the U.S. petroleum industry occurred. The production data helps to define the possible constraints (impact) of increased heavy oil production on the U.S. refining industry.
6. Projections of the U.S. Refining Industry from 1990 to 2010 and the Impact of Expansion of Domestic Heavy Oil Development on the U.S. Refining Industry, NIPER-620, February 1993. This report analyzes the U.S. refining industry and estimates the impact by region of projected increases of 300,000 and 900,000 BOPD of additional domestic heavy oil on the U.S. refining industry. Projections are made for the rate of decline in U.S. oil production during this time frame and the volume and origin of the imports necessary to meet demand. The cost of accommodating this increased domestic heavy oil production is estimated at 7 billion dollars. The development of domestic heavy oil not only reduces the U.S. trade imbalance but provides jobs and investment opportunities in the U.S. while lessening our dependence on foreign crude.
7. As a result of NIPER thermal research, a U.S. Patent, entitled "EOR Using Flash Driven Steamflood" (U.S. Patent No. 4,957,164), was issued to NIPER.

As part of the technology transfer and in cooperation with industry, the NIPER thermal group participated in several activities in addition to the publications and presentations listed.

As part of the NIPER optional program where DOE and industry cost-shared research during FY83 to 86, research was conducted on the use of emulsions to divert steam. This DOE/Energy Associates sponsored research resulted in several papers and a field test of the technology that was developed and planned. Due to the drop in oil prices in 1986, steam injection into the target field was suspended as well as the industrial support. In addition to SPE papers, a summary of the research was also presented as part of expert testimony on behalf of Energy Associates in U.S. Federal Tax Court, Los Angeles, CA, Oct. 14, 1989. Energy Associates were pursuing patent coverage of the technology developed.

DOE and the Venezuelan Ministry of Energy and Mines (MEM) have an agreement to promote balanced exchange of energy technologies and to conduct joint projects in the areas of petroleum, solar energy, geothermal energy, hydroelectric energy and coal. Annex IV of this agreement on Enhanced Oil Recovery Thermal Processes has been the most active. Biennial technology exchanges have been conducted between DOE and MEM with three tasks each being conducted over 18 months by each participant. NIPER, Stanford University and Lawrence Livermore National Laboratory conduct research on behalf of DOE. Research during FY93 currently covers tasks 57-63. The results from the research is published as a series of reports entitled DOE Supporting Technology for Enhanced Oil Recovery, EOR Thermal Processes. The exchange minimizes duplication of efforts, promotes acceleration of the research and promotes cooperation among participating researchers.

DOE and NIPER sponsored a Symposium on the Field Application of Foam for Oil Production February 11-12, 1993, in Bakersfield, CA. Seventy-two participants from six countries discussed the application of foam in steam, carbon dioxide, gas flooding and stimulation. The symposium prompted open exchange of the pros and cons of foam application and a preprint (NIPER-667) and proceedings (NIPER-669) including results of panel discussion were published.

NIPER cooperated with DOE at Naval Petroleum and Oil Shale Reserves, Colorado, Utah and Wyoming and their contractor, F. D. Services, to research and publish a SPE paper (SPE 25786) on the light oil steamflood being conducted in the shallow Shannon sandstone in the Teapot Dome Field, Wyoming NPR No. 3. This review of operations, problems and economics was prepared to document the case history of an unusual or marginal EOR project and demonstrate how the productive life of many shallow, light oil reservoirs may be extended by application of thermal EOR.

NIPER researched and wrote environmental papers (Sarathi, 1991; Johnson et al., 1991) describing regulations and thermal operations.

The most requested publication has been "Practical Aspects of Steam Injection Processes—A Handbook for Independent Operators" (Sarathi and Olsen, NIPER-580, 1992), which is being used as a text in several petroleum engineering school and reference book for practicing thermal operators.

Based on the results of project SGP37, which identified the Tertiary Age, unconsolidated sand heavy oil reservoirs as one of the future heavy oil-producing areas of the U.S.; a more detailed assessment of the feasibility of producing this heavy oil was made by Sarkar and Sarathi (1993). The simulation study analyzed various heavy oil production scenarios and estimated economics of operation.

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CHAPTER 14

CONCLUSIONS AND RECOMMENDATIONS FOR TEOR RESEARCH AT NIPER

CONCLUSIONS

This report provides a comprehensive overview of NIPER's TEOR research activities and outlines the extent to which the program has succeeded in advancing technology and addressing the needs of industry.

The TEOR research at NIPER evolved with the EPR Department over the 10-year period and during this time frame the group performed both long-range, high-risk research and research oriented towards fulfilling DOE's near-term objectives, including support of DOE's light oil steamfloods at NPR-1 and NPR-3. NIPER's thermal research efforts are divided into two areas: (1) heavy oil research and (2) light oil research.

During the past 10 years, NIPER addressed the needs of the industry by conducting research in several areas including elucidation of the mechanisms of steam oil recovery; effect of steam temperature on wettability modification; quantification of the temperature dependency of capillary pressures; development of techniques to measure capillary pressure of unconsolidated cores at steamflood conditions; elucidation of the mechanism of steam diversion with foam; development and evaluation of analytical and numerical thermal oil recovery models; field-scale simulation studies to assess the steamflood potential of non-California heavy oil reservoirs; domestic heavy oil data base development; domestic heavy oil resource and refinery capacity assessment; TEOR environmental impact assessment; and laboratory automation software development and testing.

The Thermal Research Group also developed several state-of-the-art laboratory and investigative tools to study TEOR processes. These include: two-dimensional steamflood assembly to investigate the gravity override phenomena and evaluation of additives to improve sweep efficiency under reservoir conditions; novel centrifuge technique to determine the capillary pressure and wettability of unconsolidated and consolidate cores at steamflood conditions; screening facilities to evaluate the adsorption of surfactants in rocks, partitioning of surfactants into oil, and the foaming ability of surfactant in the presence of crude oils.

The major accomplishments of NIPER's thermal research programs include:

- (1) Compilation of a steamflood handbook that introduces newcomers to the fundamentals of steamflooding technology and design, engineering, and equipment requirements for a successful steamflooding project. The handbook was compiled as an effort to transfer steamflood technology to the independent operators. This publication was widely acclaimed and well received by both the industry and academia. More than 600 copies of this report were distributed, and major universities in the U.S. and Canada have adopted this handbook as a text for a course in TEOR.

- (2) In a separate technology transfer activity, a report detailing the environmental regulations of importance to TEOR operations and the procedures for obtaining environmental permits was written. This publication received high marks from industry for its timeliness and thoroughness.
- (3) Reviewed heavy oil resources in the United States and assessed the feasibility of producing heavy oil. Particular emphasis was placed on identifying and quantifying areas where potential heavy oil could be produced in the future to slow the rate of increase in importing oil.
- (4) Assessed the limitations of existing refineries to accept potential increases in domestic heavy oil. This assessment was used to evaluate various production and refining scenarios and the cost for developing the refining capacity to handle the increasing U.S. heavy oil production.
- (5) Conducted field scale simulation studies assessing the feasibility of steamflooding in the Arkansas and Texas Gulf Coast heavy oil reservoirs. This was an attempt to demonstrate to operators (especially independents) the feasibility of applying steamflood technology to recover oil from these reservoirs.
- (6) Wrote a report detailing the usefulness and limitations of micromodels as a steamflood research tool and identified factors that must be considered in the construction of newer models. This report written in 1986, was considered a classical work on micromodels and is an often cited reference by researchers planning to develop newer micromodels.
- (7) Demonstrated the feasibility of observing oil displacement and two-phase flow phenomena in realistic pseudo 3-dimensional micromodels.
- (8) Developed correlations for the prediction of the effectiveness of a surfactant as a steamflood mobility control agent. These correlations are often cited by researchers involved in screening and selecting surfactants for use in steamflood applications.
- (9) Investigated the mechanism of oil recovery by steam-foam and was the first to document that the ability of a surfactant to foam in the presence of a crude oil depends on the oil saturation and for each surfactant there exists a critical oil saturation above which the surfactant will not foam. The NIPER Thermal Research Group was also the first to document that the ability of a surfactant to foam is very much dependent upon the oil composition. Thus, a surfactant that foams in the presence of one crude may or may not foam in the presence of another crude oil.
- (10) The NIPER Thermal Research Group was one of the first to describe the features of a high-pressure, high-temperature 2-D sandpack physical model and its usefulness in studying the problems associated with steamflooding such as gravity segregation, poor areal and vertical sweep efficiencies, and fingering of steam through zones of high

permeability. NIPER was also the pioneer in demonstrating the effect of oil composition on light oil steamflood recovery. NIPER demonstrated that crudes with identical API gravity, but differing chemical composition, will respond differently to steam, and estimations of steam injection oil recovery based on empirical API gravity based correlations are likely to be in error.

- (11) Investigated and measured the changes in the wettability of cores subjected to steamflooding as a function of time and temperature, and demonstrated for the first time that steamflood performance differs significantly in water-wet, intermediate-wet, and oil-wet porous media.
- (12) As part of the ongoing communication with industry, NIPER's Thermal Research Group hosted a symposium on field applications of foam and, in cooperation with the NPR-3, presented to industry the case history of the NPR-3 steamflood operation.

We believe that these and other research accomplishments and the popularity of NIPER Thermal Research Group's publications and presentations among the industry and academia researchers are indicators that the group largely succeeded in its research efforts and accomplished its set of goals fulfilling DOE's objectives, namely advancing the technology and transferring the results to industry.

The U.S. produces more oil by thermal methods than any other nation in the world and in 1991 produced 460,691 bbl/day (Moritis, 1992). The U.S. thermal oil production accounts for 39% of all thermally produced oil in the world and exceeds the combined TEOR production of Canada and Venezuela. The U.S. thermal oil production is twice that of Venezuela, the second largest producer of thermal oil in the world. The worldwide steamflood oil production by country (excluding China and Russia) is shown in Table 14.1.

TABLE 14.1
1991 Daily World Oil Production by Steam (After Moritis, 1992)

Country	Daily production bbl/day
U.S.A.	460,500
Venezuela	234,200
Canada	106,800
Indonesia	180,000

Thermal oil production technology has developed rapidly in the U.S. since the 1950s and along the way, domestic thermal oil producers and service companies have developed techniques and tools that are unique to thermal operations. U.S. thermal operations are the envy of the world, and other nations often seek assistance from U.S. operators and service companies to implement new projects and to trouble-shoot existing operations. Even though thermal oil production has been commercially practiced in the U.S. for over 30 years, the technology is far from being mature, and several problem areas exist and must be addressed to improve the process efficiency. Tham et al. (1991) has discussed these problems in considerable details.

Due to the current poor economic conditions in the U.S. oil patch, most major U.S. thermal operators and service companies have drastically reduced their thermal EOR related research activities and closed or are closing down their research facilities. Increasingly, more and more major U.S. thermal operators are curtailing their TEOR activities and selling their producing thermal properties to smaller independents. These smaller operators lack the expertise and personnel to keep their operations at peak efficiency and need help. Further, it is likely that TEOR operations will expand outside California, especially in the Gulf Coast states. Unlike California, Gulf Coast heavy oil reservoirs are not as massive, and implementation of thermal projects in these reservoirs requires cost-effective technology and careful planning for economic operation even though the oil quality may be higher. Technical support from DOE to these operators is crucial in developing these resources and minimizing the import of foreign crudes.

To pick up the research slack left by major companies and support new players who lack TEOR related technology, DOE should continue to support funding TEOR related research. NIPER, with its experienced staff, is uniquely qualified to fill the vacuum created by the curtailment of industry research.

The NIPER Thermal Oil Production Research Group has considerable experience in conducting TEOR related research. The NIPER staff has made significant contributions to the advancement of TEOR technology over the years and are recognized and respected by their industry peers. NIPER's thermal oil production related research publications are well received, as evidenced by the number of requests received for NIPER publications at regional and national meetings. NIPER's EOR staff experience encompasses every facet of thermal oil production technology and ranges from fundamental laboratory studies on oil displacement mechanisms to the analysis of the design and operation of field projects. Thus, by virtue of its past experience, developed expertise, and standing with industry, NIPER thermal staff members are uniquely positioned to perform future thermal oil production related research for DOE.

Recommendations for Future TEOR Research at NIPER

As pointed out previously, the U.S. is the world's largest producer of thermally enhanced oil and the global thermal technology leader. Industry and service companies responsible for the

Nation's technology lead have drastically curtailed their research efforts in recent years due to declining oil prices. To maintain the Nation's technology lead in TEOR, it is vital that DOE continue funding TEOR research.

Suggestions for future TEOR research at NIPER are detailed in Table 14.2. All recommended research are near-term activities except laboratory research which is mid-term in nature. All near-term activities are oriented to the individual problems and designed to support DOE in its technology transfer effort.

Laboratory research is also problem oriented research and will be undertaken to hold the door open for potential breakthrough that could significantly reduce costs or increased recovery efficiency. Laboratory research will also provide opportunities to follow-up technical leads and refine findings of academia into means for improving the producibility of oil from difficult reservoir settings. For the laboratory program discussed funds must be appropriated at a level to meet space requirements for efficient laboratory operations and to satisfy the stringent environmental, safety, and health requirements of an management and operating (M & O) contract operation. Laboratory research will be performed at reservoir and steamflood conditions and preferably will be targeted to specific reservoirs.

REFERENCES

- Moritis, G. EOR Increases 24% Worldwide; Claims 10% of U.S. Production, *Oil & Gas J.*, v. 90, No. 16, Apr. 20, 1992, pp. 51-79.
- Tham, M. K. et. al. Research Needs to Maximize Economic Producibility of the Domestic Oil Resource. DOE Report NIPER-527, October 1991.

TABLE 14.2
SUGGESTED TOPICS FOR FUTURE NIPER THERMAL RESEARCH

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- (1) Use field as laboratory and conduct research to optimize field operations.
 - (2) Establish a laboratory to study phase splitting problems in steam distribution lines.
 - (3) Revise steam injection process handbook.
 - (4) Conduct a steamflood reservoir management practice study to optimize recovery.
 - (5) Investigate novel recovery techniques to produce heavy oil.
 - (6) Identify target reservoirs and support DOE and independents in implementing thermal projects.
 - (7) Review DOE cost-shared projects in heavy oil reservoir.
 - (8) Conduct steam-foam related studies and recommend ways to improve the economics of the process.
 - (9) Analyze current thermal EOR reservoir management practices and develop guidelines.
 - (10) Conduct studies related to thermal EOR environmental problems.
 - (11) Conduct research to recover oil by thermal methods from non-sandstone reservoirs.
 - (12) Conduct research related to rock-fluid interactions during steam injection.
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