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For the Period
January-December 1992

Bartlesville Project Office
U.S. Department of Energy
Bartlesville, Oklahoma 74005

# One

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UNITED STATES DEPARTMENT OF ENERGY

# Contents

# PUBLICATIONS LIST 66

**Bartlesville Project Office**

Thomas C. Wesson, *Director*

*DOE/BC–92/4/SP*

*January-March 1992*

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### *Quarterly Reports*

**DOE/BC–91/2** **Contracts for Field Projects and Supporting Research on Enhanced Oil Recovery. Progress Review No. 66. Quarter ending March 31, 1991. March 1992. Order No. DE92001006.** Status reports are given for various enhanced oil recovery and gas recovery projects sponsored by the Department of Energy. The field tests and supporting research on enhanced oil recovery include chemical flooding, gas displacement, thermal/heavy oil, resource assessment, geoscience technology, microbial technology, novel technology, and environmental technology.

### *Chemical Flooding*

**NIPER–551** **Treating Paraffin Deposits in Producing Oil. Topical Report. National Institute for Petroleum and Energy Research. January 1992. 48 pp. Order No. DE92001010.** Paraffin deposition has been a problem for operators in many areas since the beginning of petroleum production from wells. An extensive literature search on paraffin problems and methods of control has been carried out, and contact was made with companies which provide chemicals to aid in the treatment of paraffin problems. A discussion of the nature of paraffins and the mechanisms of this deposition is presented. The methods of prevention and treatment of paraffin problems are summarized. Suggested procedures for handling paraffin problems are provided. Suggestions for areas of further research and testing are given.

**NIPER–555** **Modeling of Heavy Organic Deposition. Topical Report. National Institute for Petroleum and Energy Research. January 1992. 36 pp. Order No. DE92001016.** Organic deposition is often a major problem in petroleum production and processing. This problem is manifested by current activities in gas flooding and heavy oil production. The need for understanding the nature of asphaltenes and asphaltics and developing solutions to the deposition problem is well recognized. Prediction technique is crucial to solution development. In the past 5 years, some progress in modeling organic deposition has been made. A state-of-the-art review of methods for modeling organic deposition is presented in this report. Two new models were developed in this work; one based on a thermodynamic equilibrium principle and the other on the colloidal stability theory. These two models are more general and realistic than others previously reported. Because experimental results on the characteristics of asphaltene are inconclusive, it is still not well known whether the asphaltenes in crude oil exist as a true solution or as a colloidal suspension. Further laboratory work which is designed to study the solubility properties of asphaltenes and to provide additional information for model development is proposed. Some experimental tests have been conducted to study the mechanisms of $CO_2$-induced asphaltene precipitation. Coreflooding experiments show that asphaltene precipitation occurs after gas breakthrough. The mechanisms of $CO_2$-induced asphaltene precipitation is believed to occur by hydrocarbon extraction which causes change in oil composition. Oil swelling due to $CO_2$ solubilization does not induce asphaltene precipitation.

**NIPER–563** **Alkaline Flooding Injection Strategy. Topical Report. National Institute for Petroleum and Energy Research. March 1992. 32 pp. Order No. DE92001032.** The objective of this project is to develop improved alkali-surfactant flooding methods, and this includes determining the proper design of injection strategy. Several different injection strategies have been used or suggested for recovering heavy oils with surfactant-enhanced alkaline flooding methods. Oil recovery was compared for four different injection strategies: (1) surfactant followed by polymer; (2) surfactant followed by alkaline polymer; (3) alkaline surfactant followed by polymer; (4) alkali, surfactant and polymer mixed in a single formulation. The effect of alkaline preflush was also studied under two different conditions. All of the oil recovery experiments were conducted under optimal conditions with a viscous, non-acidic oil from Hepler (KS) oil field. The coreflood experiments were conducted with Berea sandstone cores since field core was not available in sufficient quantity for coreflood tests. The Tucker sand of Hepler field is a Class I fluvial dominated deltaic reservoir, as classified by the Department of Energy, which has been selected as the site of a DOE-sponsored field pilot test.

**NIPER–567** **Phase Behavior and Oil Recovery Investigations Using Mixed and Alkaline-Enhanced Surfactant Systems. Topical Report. National Institute for Petroleum and Energy Research. March 1992. 104 pp. Order No. DE92001033.** The results of an evaluation of different mixed surfactant and alkaline-enhanced surfactant systems for enhanced oil recovery are described. Several mixed surfactant systems have been studied to evaluate their oil recovery potential as well as improved adaptability to different ranges of salinity, divalent ion concentrations and temperature. Several combinations of screening methods were used to help identify potential chemical formulations and determine conditions where particular chemical systems can be applied. The effects of different parameters on the behavior of the overall surfactant system were also studied. Several commercially available surfactants were tested as primary components in the mixtures used in the study. These surfactants were formulated with different secondary as well as tertiary components, including ethoxylated and non-ethoxylated sulfonates and sulfates. Improved salinity and hardness tolerance was achieved for some of these chemical systems. The salinity tolerance of these systems were found to be dependent on the molecular weight, surfactant type, and concentration of the surfactant components. Oil displacement experiments in Berea sandstone cores showed considerable improvement in oil recovery potential of these mixed and alkaline-enhanced surfactant systems. Research results have shown the existence of favorable conditions for oil recovery using these two methods. Some of these displacement experiments were conducted with the aid of imaging tools such as NIPER's computer-aided tomography (CT) scanner to determine the pro-

gression of the flood. The effectiveness of the surfactant formulation and the mobility control system were monitored using this technique. Several reservoirs were selected as the focus of the research for the application of these improved chemical fooding methods. These reservoirs included North Burbank (OK) Unit, Hepler (KS) field, and the Government Wells (TX) field. The Burbank reservoir was selected from several Class 1 reservoirs. A database evaluation for this reservoir class was conducted. The Burbank reservoir properties were identified as grouped within the mid-range values for this class. North Burbank retains a significant reserve of unproduced oil and has been identified as a prime candidate for the application of advanced chemical EOR methods.

*Gas Displacement*

**NIPER–559 Improvement in Oil Recovery Using Cosolvents with $CO_2$ Gas Floods. Topical Report. National Institute for Petroleum and Energy Research. January 1992. 32 pp. Order No. DE92001017.** This report presents the results of investigations to improve oil recovery using cosolvents in $CO_2$ gas floods. Laboratory experiments were conducted to evaluate the application and selection of cosolvents as additives to gas displacement processes. A cosolvent used as a miscible additive changed the properties of the supercritical gas phase. Addition of a cosolvent resulted in increased viscosity and density of the gas mixture, and enhanced extraction of oil compounds into the $CO_2$ rich phase. Gas phase properties were measured in an equilibrium cell with a capillary viscometer and a high pressure densitometer. A number of requirements must be considered in the application of a cosolvent. Cosolvent miscibility with $CO_2$, brine solubility, cosolvent volatility and relative quantity of the cosolvent partitioning into the oil phase were factors that must be considered for the successful application of cosolvents. Coreflood experiments were conducted with selected cosolvents to measure oil recovery efficiency. The results indicate lower molecular weight additives, such as propane, are the most effective cosolvents to increase oil recovery.

*Thermal Recovery*

**DOE/BC/14600–17 A Theoretical Analysis of Vertical Flow Equilibrium. Topical Report. University of Southern California. January 1992. 32 pp. Order No. DE92001018.** The assumption of Vertical Flow Equilibrium (VFE) and of parallel flow conditions, in general, is often applied to the modeling of flow and displacement in natural porous media. However, the methodology for the development of the various models is rather intuitive, and no rigorous method is currently available. An asymptotic theory is developed using as parameter the variable $R_L = \frac{L}{H}\sqrt{\frac{k_V}{k_H}}$. It is rigorously shown that present models represent the leading order term of an asymptotic expansion with respect to $1/R_L^2$. Although this was numerically suspected, it is the first time that it is theoretically proved. Based on the general formulation, a series of models are subsequently obtained. In the absence of strong gravity effects, they generalize previous works by Zapata and Lake (1981), Yokoyama and Lake (1981) and Lake and Hirasaki (1981), on immiscible and miscible displacements. In the limit of gravity-segregated flow, conditions are proven for the fluids to be segregated and the Dupuit and Dietz (1953) approximations are derived. Finally, the effects of capillarity and transverse dispersion are discussed.

**DOE/BC/14600–18 Steam Distillation Effect and Oil Quality Change During Steam Injection. Topical Report. Stanford University. January 1992. 60 pp. Order No. DE92001019.** Steam distillation is an important mechanism which reduces residual oil saturation during steam injection. It may be the main recovery mechanisms in steamflooding of light oil reservoirs. As light components are distilled from the residual (initial) oil, the residuum becomes heavier. Mixing of the distilled components with the initial oil results in a lighter produced oil. A general method has been developed to compute steam distillation yield and to quantify oil quality changes during steam injection. The quantitative results are specific because the California crude data bank was used. But general principles were followed and calculations were based on information extracted from the DOE crude oil assay data bank. It was found that steam distillation data from the literature can be correlated with the steam distillation yield obtained from the DOE crude oil assays. The common basis for comparison was the equivalent normal boiling point. Blending of distilled components with the initial oil results in API gravity changes similar to those observed in several laboratory and field operations.

**DOE/BC/14600–19 Transient Foam Flow in Porous Media with CAT Scanner. Topical Report. Stanford University. March 1992. 204 pp. Order No. DE92001022.** Transient behavior is likely to dominate over most of the duration of a foam injection field project. Because of the lack of data, little is presently known about transient foam flow behavior. Foam flow does not follow established models such as the Buckley-Leverett theory, and no general predictive model has been derived. Therefore, both experimental data and a foam flow theory are needed. In this work, foam was injected as a constant mass rate into one-dimensional sandpacks of 1-in. diameter and 24-in. or 48-in. length that had initially been saturated with distilled water. The system was placed in a CAT scanner. Data obtained at room temperature and low pressure at various times include both the pressure and saturation distributions. Pressure profiles showed that the pressure gradient is much greater behind the foam front than ahead of it. Moreover, the pressure gradients keep changing as the foam advances in the sandpack. This behavior differs from Buckley-Leverett theory. The CT scan results demonstrated gas channeling near the front, but eventually the foam blocks all these channels and sweeps the entire cross section after many pre volumes of injection. Three series of experiments were run: (1) surfactant adsorption measurements, (2) gas displacement of surfactant-laden solutions, and (3) foam displacements. The first two series of experiments were made to provide the necessary parameters required to match the foam displacements. To this end, it was necessary to smooth the saturation history data, using a Langmuir-type formula. A theory was proposed based on the principles of the fractional flow curve construction method. This foam theory treats the foam as composed of infinitesimal slugs of gas of varying viscosities. The foam front has the lowest viscosity and foam at the injection end has the highest.

**DOE/BC/14600–20 Visualization Experiments on Steam Injection in Hele-Shaw Cells. Topical Report. University of Southern California. March 1992. 24 pp. Order No. DE92001026.** Flow visualization experiments have been successfully employed in reservoir engineering research for many years. They involve two-dimensional geometries in transparent Hele-Shaw cells and glass micromodels. Although much work has been done on immiscible flows (drainage or imbibition), visualization of steamfloods, which constitute a major part of current enhanced oil recovery methods, has not been attempted to date. In this paper, experimental results are presented on steam injection in a transparent, pyrex glass Hele-Shaw cell. Both synthetic (Dutrex 739) and natural heavy oils were used under a variety of conditions including effects of gravity. The experiments were conducted at low pressure. Results obtained demonstrate the interplay between steam injection, steam condensation, viscous fingering, heat transfer, gravity and steam distillation effects. The experiments revealed that steam fronts are neither smooth nor flat, but undergo constant rearrangements as a result of condensation and injection. These dynamics are substantially different from those in a typical immiscible displacement. The injected steam was generally found to follow the path of the condensed water. The latter set the general displacement pattern, which in the case of heavy oil was highly fingered. Also identified was a rather unusual viscoelastic response of the displaced heavy oils.

*Microbial Technology*

**DOE/BC/14246–8 Microbial Field Pilot Study. Annual Report. University of Oklahoma. March 1992. 80 pp. Order No. DE92001031.** This report covers progress made during the second year of this project. The objective of this project is to perform a microbial enhanced oil recovery field pilot in the Southeast Vassar Vertz Sand Unit (SEVVSU) in Payne County, Oklahoma. Indigenous, anaerobic, nitrate-reducing bacteria will be stimulated to selectively plug paths which have been preferentially swept by a prior waterflood. This will force future flood water to invade bypassed regions of the reservoir and increase sweep efficiency. Information on reservoir ecology, surface facilities design, operation of the unit, core experiments, modeling of microbial processes,

and reservoir characterization and simulation are presented. To better understand the ecology of the target reservoir, additional analyses of the fluids which support bacteriological growth and the microbiology of the reservoir were performed. The results of the produced and injected water analysis show increasing sulfide concentrations with respect to time. In March 1990, Mesa Limited Partnership sold their interest in the SEVVSU to Sullivan and Company. In April, Sullivan and Company assumed operation of the field. The facilities for the field operation of the pilot were refined and implementation began. Coreflood experiments conducted during the last year were used to define possible mechanisms involved in MEOR. The experiments were performed at SEVVSU temperature using fluids and inoculum from the unit.

**DOE/BC/14663–4** **New Microorganisms and Processes for MEOR. Annual Report. Injectech, Inc. March 1992. 20 pp. Order No. DE92001028.** The study of new microorganisms and processes for microbial enhanced oil recovery has been successful in several key aspects: (1) isolating and characterizing sulfate reducing bacteria from oil field waters which can use the volatile fatty acids found in these waters; (2) showing that these cultures can feed each other in sequential cultures and survive in mixed culture as long as sterile conditions are maintained. When nonsterile conditions are present both organism types are successful but additional microflora develop which are the heterotrophic denitrifying bacteria. These microorganisms appear to be potentially useful in new MEOR processes and are currently being pursued. They are capable of producing large amounts of gas and also form viscosifying agents under conditions which can be maintained in an oil reservoir.

*Geoscience Technology*

**DOE/BC/14473–9** **Demonstration of High-Resolution Inverse VSP for Reservoir Characterization Applications: Task 1 and Task 2. Southwest Research Institute. March 1992. 210 pp. Order No. DE92001030.** Task 1: Three-component downhole sensor planting techniques and instrumentation were developed and evaluated under controlled field conditions for high-resolution inverse VSP measurements. A lightweight (50-lb) commercial three-component VSP probe was modified to contain high-sensitivity, high-frequency accelerometer sensors, and a lightweight (7-lb) pneumatically clamped three-component detector was assembled with high-sensitivity, high-frequency accelerometer sensors and a preamplifier unit. To reduce cross feeding between the channels of the data acquisition system, the pneumatically clamped three-component detector was constructed with shielded circuits in the conductor cable and the electronic unit containing the preamplifiers was located near the accelerometers. Three-component seismic data were successfully recorded using an experimental high-frequency inverse VSP system which included a borehole cylindrical bender source, the modified commercial three-component VSP probe, the lightweight pneumatically clamped three-component detector, and a three-channel data-acquisition system developed for the inverse VSP experiments. The three-component VSP probe and the pneumatically coupled probe readily respond to high-frequency seismic-wave propagation through the formations. These measurements demonstrated that seismic waves in the frequency range of about 500 Hz to 2,500 Hz could be transmitted through the earth using a high-frequency piezoelectric cylindrical bender source and three-component detector probes containing high-frequency accelerometers. A comparison of seismic waveforms obtained with the VSP probe and with the pneumatically coupled detector indicated the presence of strong probe body resonances in the traces acquired using the VSP probe. In comparison, the pneumatically clamped probe signals showed much superior time series and spectral responses to the wideband source pulses than those of the VSP probe.

Task 2: High resolution seismic measurements are now being extended well above the conventional frequency limit of about 150-200 Hz to the Kilohertz frequency range in applications such as interwell seismic imaging, shallow reflection surveys, and reverse VSP. High-resolution measurements demand high-quality data, meaning wideband frequency response, the highest practical signal-to-noise ratio, precision response uncluttered by artifacts related to the detector plants. Artifact-free seismic measurements at frequencies up to about 2,000 Hz are needed if a projected high-resolution limit on the one meter in spatial dimensions is to be realized in reservoir structure delineation, interwell seismic and shallow reverse VSP applications. For this reason, a thorough study of the planting problem was the topic of research for the first year of the project. The development and evaluation of downhole planting techniques and instrumentation under controlled conditions for high-resolution reverse VSP measurements yielded important results which demonstrate that borehole coupled detector probes readily respond to high-frequency seismic wave propagation through the formations. The second year research topic of this project was to conduct high-resolution subsurface seismic experiments to demonstrate the capabilities of the reverse VSP method. Full-scale reverse VSP experiments were conducted at the Western Kentucky petroleum Buckthorn test site near Quincy, Illinois, which is thoroughly documented by well records.

*Resource Assessment*

**DOE/BC/10850–19** **Description of and Users Manual for TUBA: A Computer Code for Generating Two-Dimensional Random Fields Via the Turning Bands Method. Final Report. New Mexico Institute of Mining and Technology. January 1992. 160 pp. Order No. DE92001020.** TUBA is a computer code for the generation of synthetic two-dimensional random fields via the Turning Bands Method. It is primarily used to generate synthetic permeability fields for hydrologic and petroleum engineering applications, but it has applications wherever synthetic random fields are employed. This is version 2.0 of TUBA, a completely redesigned and rewritten code. It generates stationary or non-stationary, isotropic, and point or areal average random fields. Five functional covariance models are available in the code. These are Gaussian, Bessel, Telis, and Generalized Covariance models. The user can supply other forms. The random fields can be generated onto a gridded system (e.g., at the nodes of point centered finite difference model, or the blocks of a block-centered model), or at arbitrary locations in space (e.g., at the Gauss points of a finite element grid). TUBA can be used to generate the field values in local areas at much greater resolution than the original simulated field. The fields can be generated with a normal or a log normal distribution. The size of the simulation is limited only by the virtual memory capabilities of the computer on which it is run. Random fields with over a million nodes have been generated with TUBA on a 386PC running Xenix. The code has been run on 286 and 386 PCs running DOS, on Sun 3s and 4s using Unix, and on Dec VAXs running VMS.

**NIPER–542** **User's Guide and Documentation Manual for "BOAST-VHS for the PC." National Institute for Petroleum and Energy Research. January 1992. 92 pp. Order No. DE92001021.** The recent advancement of computer technology makes reservoir simulations feasible in a personal computer environment. This manual provides a guide for running BOAST-VHS, a black oil reservoir simulator for vertical/horizontal/slant wells, using a PC. In addition to detailed explanations of input data file preparation for simulation runs, special features of BOAST-VHS are described and three sample problems are presented.

**DOE/BC/14251–9** **Reservoir Characterization and Enhanced Oil Recovery Research. Annual Report for the Period September 1988 to August 1989. University of Texas. March 1992. 228 pp. Order No. DE92001029.** Research performed during the reporting period falls into three tasks, each dealing with a different aspect of enhanced oil recovery. The first task was undertaken to develop procedures for accurately modeling reservoirs for use as input to numerical simulation flow models. This section describes how a detailed characterization of an outcrop was used to provide insights into what features are important to fluid flow modeling. The second task deals with scaling-up and modeling chemical and solvent EOR processes. In a sense this task is the natural extension of task 1 and, in fact, one of the subtasks uses many of the same statistical procedures for insight into the effects of viscous fingering and heterogeneity. The final task involves surfactants and their interactions with carbon dioxide and reservoir minerals. This research deals primarily with phenomena observed when aqueous surfactant solutions are injected into oil reservoirs. The reason for injecting surfactant solutions is to render the displacement of oil by carbon dioxide a more efficient process.

# PUBLICATIONS LIST 67

**Bartlesville Project Office**

Thomas C. Wesson, *Director*

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### *General*

**DOE/ID/01570–T158** **Naturally Occurring Radioactive Materials (NORM) in Oil and Gas Industry Equipment and Wastes. A Literature Review. Idaho National Engineering Laboratory. June 1992, 44pp. Order No. DE92001050.** The purpose of this report is to briefly describe issues relating to the contamination of oil and gas industry equipment and wastes with accumulations of naturally occurring radioactive materials (NORM). The report describes the present state of knowledge regarding NORM in the oil and gas industry, including information on known geographic distributions of NORM and observations on concentration levels from various types of equipment and wastes. Environmental fate and effects of NORM radionuclides and potential human impacts are discussed. A review of existing, proposed, and planned state and federal regulations, standards, and guidelines for NORM is provided, along with a brief discussion of the potential economic and technological constraints that regulations and standards governing the disposal of NORM-contaminated wastes could have on domestic oil and gas production. Research and technology transfer needs relating to issues associated with NORM are also summarized.

**NIPER–557** **1990 Annual Report. National Institute for Petroleum and Energy Research. May 1992. 100pp. Order No. DE92001046.** In FY90, IITRI/NIPER was responsible for 14 Base Program projects with total DOE funding of over 4.6 million dollars. Eleven projects received funding under the Office of Fossil Energy's (FE) EOR Heavy and EOR Light Oil Programs and three under FE's Advanced Extraction and Process Technology (AEPT) Program. AEPT has responsibility for advanced research instrumentation and cross-cutting fundamental and exploratory research relating to the evaluation, extraction, processing, and upgrading of oil, gas, shale oil, tar sands, and underground coal gasification resources. The Energy Production Research (EPR) Department conducted research on 12 projects; four each under the categories of Geotechnology, Chemical and Microbial EOR, and Thermal and Gas EOR. The Fuels Research (FR) Department managed one project in the category of Processing and Thermodynamics and one in Fuel Chemistry. The FR Department also manages a Fuel/Engines Section, but no Base Program work is currently performed in this area. Engines work is important to NIPER's total program, however, as it provides information on the changes and overall acceptability of today's transportation fuels and represents an area of rapid growth. The Base Program provides supporting research in most areas outlined in the AORPIP which include: (1) reservoir description methods, tools, instrumentation, and modeling, (2) extraction techniques for secondary and tertiary recovery, (3) petroleum chemistry/processing covering constraints on production and refining problems, and (4) technology transfer. A fifth area, the environment, was not a part of Base Program research during FY90, but expertise developed under previous projects provides environmental support to the DOE and other government agencies under the SGP Program. The overall research program is coordinated through the Bartlesville Project Office (BPO) which is collocated with NIPER and serves as the DOE administrator of the cooperative agreement. That office is delegated the lead assignment for implementing the Office of Fossil Energy's (FE) programs in Enhanced Oil Recovery (EOR) and Advanced Extraction and Process Technology (AEPT) and manages a number of projects executed by (1) NIPER, which utilizes the Federal equipment and facilities at Bartlesville; (2) industrial and research organizations; (3) universities; and (4) National Laboratories.

### *Gas Displacement*

**DOE/MC/26031–6** **Field Verification of $CO_2$-Foam. Second Annual Report. New Mexico Institute of Mining and Technology. April 1992. 68pp. Order No. DE92001041.** In September 1989, the Petroleum Recovery Research Center (PRRC), a division of New Mexico Institute of Mining and Technology, received a grant from the U.S. Department of Energy (DOE) for a project entitled "Field Verification of $CO_2$ Foam." The grant provided for an extension of the PRRC laboratory work to a field testing stage to be performed in collaboration with an oil producer actively conducting a $CO_2$ flood. The objectives of this project are to: 1) conduct reservoir studies, laboratory tests, simulation runs, and field tests to evaluate the use of foam for mobility control or fluid diversion in a New Mexico $CO_2$ flood, and 2) evaluate the concept of $CO_2$-foam in the field by using a reservoir where $CO_2$ flooding is ongoing, characterizing the reservoir, modeling the process, and monitoring performance of the field test. Seven tasks were identified for the successful completion of the project: 1) evaluate and select a field site, 2) develop an initial site-specific plan, 3) conduct laboratory $CO_2$-foam mobility tests, 4) perform reservoir simulations, 5) design the foam slug, 6) implement a field test, and 7) evaluate results. The report summarizes the project plans, the baseline field testing, and the laboratory test results that pertain to surfactant selection. A commercial surfactant was approved for the field test by the Joint Project Advisory Team (JPAT) representatives. The baseline testing is in progress, and surfactant injection is scheduled to commence in the first quarter of 1992. Following three months of a pre-foam surfactant pad to satisfy the adsorption of the reservoir, a rapid cycle of surfactant alternated with $CO_2$ will be injected to generate an 80% quality foam.

**DOE/MC/26253–7** **Scale-Up of Miscible Flood Processes. Annual Report. Stanford University. April 1992. 188pp. Order No. DE92001042.** Results of a wide-ranging investigation of the scaling of the physical mechanisms of miscible floods are reported. Advanced techniques for analysis of crude oils are considered in Chapter 2. Application of supercritical fluid chromatography is demonstrated for characterization of crude oils for equation-of-state calculations of phase equilibrium. Results of measurements of crude oil and phase compositions by gas chromatography and mass spectrometry are also reported. The theory of development of miscibility is considered in detail in Chapter 3.

The theory is extended to four components, and sample solutions for a variety of gas injection systems are presented. The analytical theory shows that miscibility can develop even though standard tie-line extension criteria developed for ternary systems are not satisfied. In addition, the theory includes the first analytical solutions for condensing/vaporizing gas drives. In Chapter 4, methods for simulation of viscous fingering is considered. In addition, extension of the models developed previously to three dimensions is described, as is the inclusion of effects of equilibrium phase behavior. In Chapter 5, the combined effects of capillary and gravity driven crossflow are considered. The experimental results presented show that very high recovery can be achieved by gravity segregation when interfacial tensions are moderately low. We argue that such crossflow mechanisms are important in multicontact miscible floods in heterogeneous reservoirs. In addition, results of flow visualization experiments are presented that illustrate the interplay of crossflow driven by gravity with that driven by viscous forces.

*Thermal*

**DOE/BC/14600–23 Modification of Chemical and Physical Factors in Steamflood to Increase Heavy Oil Recovery. Annual Report. University of Southern California. April 1992. 220pp. Order No. DE92001034.** The study of vapor-liquid flow in porous media continued. Three aspects were addressed: *(i)* The further development of percolation and pore network models for phase change (boiling) in porous media; *(ii)* Visualization of steam injection in Hele-Shaw cells; and *(iii)* Macroscopic modeling of countercurrent steam-water flow in porous media. We analyzed the liquid-to-vapor phase change in single-component fluids in porous media at low superheats. Conditions typical to steam injection in porous media were taken. We examined nucleation, phase equilibria and their stability and the growth of vapor bubbles. Effects of pore structure were emphasized. It was shown that at low superheats, bubble growth can be described as a percolation process. A modification was also proposed in the case of spatial temperature gradients, when solid conduction predominates. Visualization experiments on steam injection in Hele-Shaw continued. Both synthetic and natural heavy oil were used under a variety of conditions, including effects of gravity. The experiments were conducted at low pressures. The results demonstrate the interplay between steam injection, steam condensation, viscous fingering, heat transfer and steam distillation effects. The experiments reveal that steam fronts are neither smooth nor flat, but undergo constant rearrangement as a result of condensation and injection. These dynamics are substantially different from a typical immiscible displacement. The injected steam was found to follow the path of condensed water, which set the general fingering pattern. A viscoelastic response of the displaced heavy oil was also identified.

**DOE/BC/14600–26 Steam Foam Studies in the Presence of Residual Oil. Stanford University. May 1992. 160pp. Order No. DE92001043.** The lack of understanding regarding foam flow in porous media necessitates further research. This paper reports the on-going work at Stanford University aimed at increasing our understanding areas of steam foams. The behavior of steam foam is investigated with a one dimensional (6′ × 2.15″) sandpack under residual oil conditions of approximately 12 percent. The strength of the in-situ generated foam, indicated by pressure drops, is significantly affected by injection procedure, slug size, and steam quality. The surfactant concentration effect is minor in the range studied. In the presence of residual oil the simultaneous injection of steam and surfactant fails to generate foam in the model, even though the same procedure generates a strong foam in the absence of oil. Nevertheless when surfactant is injected as a slug ahead of the steam using a surfactant alternating gas (SAG) procedure, foam is generated. The suggested reason for the success of SAG is the increased phase mixing that results from steam continually having to reestablish a path through a slug of surfactant solution. The minimum slug size required to generate foam by SAG is about 5 percent of the model's pore volume. Above this minimum, increases in slug size or changes in surfactant concentration have little effect in the range studied. The injected steam quality, however, does affect foam strength. Reproducible results show that foam strength improves as the injected steam quality increases. Experimental results imply that a savings in the total mass of surfactant needed for a foam flood may be possible by a SAG procedure that utilizes a sufficiently large slug volume. That is, if the slug volume is above some minimum then a dilute concentration of surfactant may give acceptable foam generation. The converse is not true however as a high concentration of surfactant in a small slug volume is ineffective. The results also indicate that the continual washing away and dilution of surfactant by low quality steam injection is detrimental.

**DOE/BC/14600–27 SUPRI Heavy Oil Research Program. Annual Report. Stanford University. May 1992. 160pp. Order No. DE92001044.** This summarizes the progress made during the 1990-1991 fiscal year. The organization of this report in sections refers to the following projects: Project 1: Flow Properties – The experimental work on the study of end effects in displacement experiments continued. It was found necessary to provide some shielding to the core to avoid artifacts generated by beam hardening. Software has been developed to calculate the saturations of each voxel in the core. The results are quite repeatable. The runs indicate the presence of a strong saturation gradient both during imbition and drainage experiments. The effect of flow rate is more pronounced in drainage than in imbibition. Project 2: In-situ Combustion – Thirteen combustion tube runs were made using four different crudes. In addition to Hamaca and Huntington Beach oil, two crude oils, a 12° API and a 34° API Californian oil were also tested. The metallic additives iron, tin, and zinc improved the combustion efficiency in all cases. Fluctuations in the produced gas compositions were observed in all control runs, but disappeared with the iron and tin additives. Project 3: Steam with Additives – Screening of surfactant in the presence of residual oil has continued. It appears that the injection procedure greatly affects the performance of the process. A new micromodel for foam observations is being built using computer technology. This micromodel will be used to study the effect of oil on the flow behavior of foams at the pore level. A three-dimensional steam injection model allowing measurement of saturation by CT scan has been built. Runs with steam displacing water showed that the model can be operated as planned and that saturation in gas-liquid systems can be measured. Foam runs are now in progress. Results of field and laboratory studies indicate that steam injection into fractured reservoirs has economic potential. Project 4: Formation Evaluation – Much heavy oil exists in low-pressure formations and free surface drainage is an important flow mechanism. There is no information on interpreting well test data for these systems. A finite-difference model is running currently, but is still being tested. This work will continue. Another new project concerns multivariate optimization of production systems to select the best well completion conditions. Peliminary work is presented. Project 5: Field Support – A new project was started to study construction of an ultrasonic wellbore flowmeter. The one tool in modern well testing needing improvement is the downhole flowmeter. Currently, testing of an ultrasonic flowmeter is being done in the laboratory. If successful, this device will be installed in a sonde for downhole field testing.

**DOE/BC/14600–28 Effects of Capillary Heterogeneity on Vapor-Liquid Counterflow in Porous Media. Topical Report. University of Southern California. June 1992. 32pp. Order No. DE92001053.** Based on a continuum description, the effect of capillary heterogeneity, induced by variation in permeability, on the steady state, countercurrent, vapor-liquid flow in porous media is analyzed. It is shown that the heterogeneity acts as a body force, that may enhance or diminish gravity effects on heat pipes. Selection rules that determine the steady states reached in homogeneous, gravity-driven heat pipes are also formulated. It is shown that the "infinite" two-phase zone may terminate by a substantial change in the permeability somewhere in the medium. The two possible sequences, liquid – liquid dominated – dry, or liquid – vapor dominated – dry find applications in geothermal systems. Finally, it is shown that although weak heterogeneity affects only gravity controlled flows, stronger variations in permeability can give rise to significant capillary effects.

*Microbial Enhanced Oil Recovery (MEOR)*

**DOE/BC/14662–7 Quantification of Microbial Products and Their Effectiveness in Enhanced Oil Recovery. Annual Report. University of Oklahoma. June 1992. 148pp. Order No. DE92001048.** The overall goal of this project is to obtain

quantitative information on the amount and rate of microbial growth and product formation, to correlate microbial activity to oil recovery, and to develop mathematical models that predict microbial activity and oil recovery in porous media. During the first phase of this work, the metabolism and nutritional features of halophilic bacteria indigenous to a reservoir selected for a field trial of a microbial selective plugging process were characterized. Also, simple porous systems were designed and used to obtain statistically reliable data on the in situ rates of microbial growth, substrate consumption, and product formation required to test the mathematical prediction of these primary dependent variables. Information on the metabolism and nutritional features of indigenous microbial populations is necessary to develop successful in situ microbially enhanced oil recovery processes. Five bacteria were isolated and characterized from brine samples obtained from the Southeast Vassar Vertz Sand Unit, Payne County, OK. A three-phase, multispecies, one-dimensional model was developed to simulate bacterial transport, growth, and metabolism involved in a microbially enhanced oil recovery process and to predict the change in permeability as a result of in situ microbial activity in porous media. Convection-dispersion equations and microbial growth kinetics were incorporated into the model to characterize and quantify biomass production, product information, and nutrient utilization during the MEOR process. Permeability reduction by the MEOR process was assumed to be due to pore plugging by the retention and growth of bacterial cells. The model was applied to static, unconsolidated sandpacks and sandstone coreflood experiments to simulate microbial movement, metabolite production, and nutrient consumption coupled to microbial growth and to predict the net permeability reduction. Comparison between numerical solutions and experimental results indicated that the model simulated the essential microbial kinetics of these laboratory experiments and can be extended to provide numerical prediction for the purposes of design and evaluation of MEOR field projects.

*Geoscience*

**NIPER–575** **Integrated Geological-Engineering Model of Patrick Draw Field and Examples of Similarities and Differences Among Various Shoreline Barrier Systems. National Institute for Petroleum and Energy Research. April 1992. 160pp. Order No. DE92001037.** The Reservoir Assessment and Characterization Research Program at NIPER employs an interdisciplinary approach that focuses on the high priority reservoir class of shoreline barrier deposits to: (1) determine the problems specific to this class of reservoirs by identifying the reservoir heterogeneities that influence the movement and trapping of fluids; and (2) develop methods to characterize effectively this class of reservoirs to predict residual oil saturation (ROS) on interwell scales and improve prediction of the flow patterns of injected and produced fluids. Accurate descriptions of the spatial distribution of critical reservoir parameters (e.g. permeability, porosity, pore geometry, mineralogy, and oil saturation) are essential for designing and implementing processes to improve sweep efficiency and thereby increase oil recovery. The methodologies and models developed in this program will, in the near- to mid-term, assist producers in the implementation of effective reservoir management strategies such as location of infill wells and selection of optimum enhanced oil recovery methods to maximize oil production from their reservoirs.

**NIPER–581** **Three-Phase Relative Permeabilities and Other Characteristics of 260-mD Fired Berea. Topical Report. National Institute for Petroleum and Energy Research. April 1992. 36pp. Order No. DE92001036.** A laboratory investigation was conducted to determine relative permeabilities and other characteristics of a 260-mD fired Berea sandstone. The mineralogical and physical characteristics of the sample were characterized by XRD tests, thin section analyses, mercury injection tests, and centrifuge capillary pressure and wettability tests. Two-phase oil/water relative permeabilities were measured under several stress conditions. Resistivity characteristics of the sample were also evaluated during several of the oil/water tests. Oil/gas and gas/water relative permeabilities were measured during steady-state tests. Three-phase steady-state oil/gas/water tests were performed for six DDI saturation trajectories (decreasing brine and oil saturations, increasing gas saturation) in which the sample was not cleaned between saturation trajectories. Oil/water relative permeability results for two different confining-stress conditions were similar. The relative permeability results for unstressed 260-Md Berea samples, however, were different from those of the stressed samples.

**NIPER–582** **Imaging Techniques Applied to the Study of Fluids in Porous Media. National Institute for Petroleum and Energy Research. June 1992. 22 pp. Order No. DE92001047.** Improved imaging techniques were used to study the dynamics of fluid flow and trapping at various scales in porous media. Two-phase and three-phase floods were performed and monitored by computer tomography (CT) scanning and/or nuclear magnetic resonance imaging (NMRI) microscopy. Permeability-porosity correlations obtained from image analysis were combined with porosity distributions from CT scanning to generate spatial permeability distributions within the core which were used in simulations of two-phase floods. Simulation-derived saturation distributions of two-phase processes showed very good agreement with the CT measured values. The improvements in the imaging capabilities allowed the expansion of the use of the imaging facility to support other base programs and projects for industrial clients. A videotape, which highlights the potential applications of the thin slab micromodel technology for the pore level study of fluids, has been produced, as an instrument for technology transfer.

**NIPER–589** **Petrographic Correlation and Mathematical Analysis of Log Signatures for Clay Identification. National Institute for Petroleum and Energy Research, April 1992. 20pp. Order No. DE92001038.** This report presents the results of correlation of log signature with information on distribution of the types and volumes of clays in the sandstone pore spaces determined from detailed CT-scan, XRD, SEM and thin section analyses of core samples from three sandstone reservoirs. The log signatures are then analyzed to determine if suitable mathematical/statistical parameter(s) could be calculated from the logs for identification of types and volumes of clays in sandstone reservoirs. Because of differences in cementation and consequent changes in pore throat size distribution, two sandstones having the same amount of identical clay types may have very different production characteristics. These sandstones can be easily identified from a clay volume, density plot.

**DOE/BC/14448–9** **Reservoir Heterogeneity in Carter Sandstone, North Blowhorn Creek Unit and Vicinity, Black Warrior Basin, Alabama. Geological Survey of Alabama. May 1992, 108 pp. Order No. DE92001045.** Additional oil remains to be produced from the Black Warrior foreland basin using improved recovery strategies, and characterizing reservoir heterogeneity provides information necessary to utilize these strategies effectively. This report characterizes heterogeneity in the Upper Mississippian (Chesterian) Carter sandstone reservoir in North Blowhorn Creek oil unit, the most productive oil reservoir in the Black Warrior basin of Alabama. Sandstone-body geometry and depositional sequences determined from subsurface cross sections and cores indicate that the Carter sandstone in North Blowhorn Creek oil unit represents a spit system that was preserved as part of a muddy, delta-destructive strand plain. The Carter sandstone is not a homogeneous reservoir, but consists of a series of shingled, southeast dipping clinoformal lenses that decrease in size toward the southeastern terminus of the reservoir body. Near the downdip margin of the reservoir, amalgamated shoreface and foreshore sandstone lenses join to form a single flow unit that is continuous along the axis of the reservoir body. Updip lenses of reservoir sandstone are separated by shale and merge into nonreservoir, backshore siltstone and shale. As a result of this facies anisotrophy, fluids may be transmitted more easily along the axis on the sandstone body than perpendicular to the axis. Because the localized, lensoid nature of Carter sandstone reservoirs differs greatly from the widespread beach-barrier, sandstone bodies have formed the basis of previous sandstone-heterogeneity studies, results of this study provide a template for recognizing heterogeneity that will be useful for implementing improved-recovery strategies, not only for oil reservoirs in the Black Warrior basin, but in other sedimentary basins as well.

*Resource Assessment Technology*

**NIPER–573** **Development of General Inflow Performance Relationships (IPR's) for Slanted and Horizontal Wells Producing Heterogeneous Solution-Gas Drive Reservoirs. Topical Report. National Institute for Petroleum and Energy Research. April 1992. 36pp. Order No. DE92001035.** Since 1968, the Vogel equation has been used extensively and successfully for analyzing the inflow performance relationship (IPR) of flowing vertical wells producing by solution-gas drive. Oil well productivity can be rapidly estimated by using the Vogel IPR curve and well outflow performance. With recent interests in horizontal well technology, several empirical IPRs for solution-gas drive horizontal and slanted wells have been developed under homogeneous reservoir conditions. This report presents the development of IPRs for horizontal and slanted wells by using a special vertical/horizontal/slanted well reservoir simulator under six different reservoir and well parameters: ratio of vertical to horizontal permeability, wellbore eccentricity, stratification, perforated length, formation thickness, and heterogeneous permeability. The pressure and gas saturation distributions around the wellbore are examined. The fundamental physical behavior of inflow performance for horizontal wells is described.

**NIPER–583** **Enhanced Oil Recovery Projects Data Base. Topical Report. National Institute for Petroleum and Energy Research. April 1992. 416pp. Order No. DE92001035.** A comprehensive enhanced recovery (EOR) project data base is maintained and updated at the Bartlesville Project Office of the Department of Energy. This data base provides an information resource that is used to analyze the advancement and application of EOR technology. The data base has extensive information on 1,388 EOR projects in 569 different oil fields from 1949 until the present, and over 90% of that information is contained in tables and graphs of this report. The projects are presented by EOR process, and an index by location is provided.

*Fundamental Petroleum Chemistry*

**NIPER–570** **Hydrodenitrogenation: An Increasingly Important Part of Catalytic Hydroprocessing Interlocking of Thermodynamics and Kinetics. Topical Report. April 1992. 36pp. Order No. DE92001040.** This report outlines a new use of thermodynamic property data. The Gibbs energies of reaction obtained from thermodynamic property measurements are used to estimate, with some success, relative reactivities for aromatic organonitrogen compounds. Calculated relative rates of reaction reproduce literature values within one power of ten. The relative rates of reaction are shown to be directly proportional to the concentration of hydrogenated species formed during hydrodenitrogenation (HDN). The production of completely saturated ring systems (overhydrogenation) in HDN reactions using conventional hydroprocessing is explained solely in terms of the thermodynamics in operation in the system. The results obtained show that the order of relative reactivity obtained is strongly dependent on the reaction temperature and hydrogen pressure. This strong dependence can account for some apparent contradictions when kinetic studies reported in the literature are compared. The results for a study of the hydroprocessing of a straight-run gas oil are reproduced in this report. The formation of anilines and the increase in indole concentration above that in the original gas oil sample are explained via the thermodynamics operating in the system.

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### *Quarterly Reports*

**DOE/BC–91/3** **Contracts for Field Projects and Supporting Research on Enhanced Oil Recovery. Progress Review No. 67. Quarter ending June 30, 1991. May 1992. 206 pp. Order No. DE92001008.** Status reports are given for various enhanced oil recovery and gas recovery projects sponsored by the Department of Energy. The field tests and supporting research on enhanced oil recovery include chemical flooding, gas displacement, thermal/heavy oil, resource assessment, geoscience technology, microbial technology, novel technology, and environmental technology.

### *Chemical Flooding*

**DOE/BC/14447–15** **Fluid Diversion and Sweep Improvement with Chemical Gels in Oil Recovery Processes. Final Report. New Mexico Institute of Mining and Technology. September 1992. 184 pp. Order No. DE92001061.** The report describes progress made during the third and final year of the project. Four gels were the focus of experimental work: (1) resorcinol-formaldehyde, (2) colloidal silica, (3) $Cr^{3+}$ (chloride)-xanthan, and (4) $Cr^{3+}$ (acetate)-polyacrylamide. All experiments were performed at 41 °C. During injection of gelants that contained $Cr^{3+}$, chromium propagation was significantly more rapid when the counterion was acetate rather than chloride. For a given counterion, chromium propagation was much more rapid in Berea sandstone cores than in Indiana limestone cores. It is doubtful that unbuffered chromium-chloride gelants can propagate through carbonate reservoirs. During core experiments, the strongest gels reduced the permeability of all cores to about the same value (in low microdarcy range). For weaker gels (i.e., those leaving a significant permeability), residual resistance factors decreased with increased rock permeability in Berea sandstone. Tracer studies indicated that strong gels occupied most of the pore space, while weaker gels occupied a small fraction of pore space. Experiments revealed that gelation in the porous rock was often far less complete than that in a bottle. For unbuffered gelants in porous rocks, the pH at which gelation occurs may be determined by rock mineralogy than by the pH at which gelation occurs may be determined more by rock mineralogy than by the pH of the injected gelant. Thus, the buffering action of reservoir rocks must be considered when evaluating gel performance in the laboratory.

### *Gas Displacement*

**DOE/BC/92001027** **Predicted Optimal Well Geometries for a Carbon Dioxide Flood In A West Texas Field Unit. Morgantown Energy Technology Center. July 1992. 44 pp. Order No. DE92001027.** Tertiary production due to carbon dioxide flooding in a waterflooded, 240-acre (1-$km^2$) pattern in a west Texas field unit was modeled with a black-oil, pseudo-miscible simulator. This pattern was a small portion of a stratified sandstone formation with an average thickness and permeability of 25 ft (7.6m) and 32 md ($10^{-3}$ $um^2$), respectively. It consisted of two sands that were separated by a shale barrier. This barrier did not completely prevent flow in the vertical direction, but it did reduce the vertical transmissibility between the two sands. The vertical permeability was equal to approximately 90% of the horizontal permeability throughout the formation. After simulating primary recovery and secondary recovery using an inverted five-spot pattern, many different tertiary well geometries, consisting of vertical and/or horizontal injectors and producers, were considered.

**DOE/BC/92001066** **The Validation of Horizontal Well Models Using A Physical Model of Heat Flow In An Anisotropic Conductor. Morgantown Energy Technology Center. August 1992. 32 pp. Order No. DE92001066.** Two recently proposed models of fluid flow in an anisotropic media yield different expressions for horizontal well productivity because of their representation of the wellbore. The model developed by Babu and Odeh used a point source/sink for the wellbore, while Peaceman's model implemented an isobaric boundary along the surface of the wellbore. Babu and Odeh's model predicted elliptical isobars, even in the immediate vicinity of the wellbore. Peaceman's model predicted a rapid transition from circular to elliptical isobars as the distance from the wellbore increased. Both models were mathematically correct and seemed plausible, but only one could have been accurate with respect to the actual system. Therefore, the more appropriate model to use in reservoir simulation was determined experimentally. The temperature-induced flow of heat from an anisotropic conductor into a circular heat sink is analogous to the pressure-induced flow of fluids from an anisotropic porous medium into a circular wellbore, since the governing differential equations for both processes are identical in form. Heat transfer experiments were, therefore, used to model this fluid flow problem. Three types of experiments were conducted: unsteady-state heat transfer from a high-conductivity source into an anisotropic medium, steady-state heat transfer from an isothermal elliptical boundary to a high-conductivity circular heat sink, and steady-state heat transfer from a circular high conductivity heat source to an isothermal elliptical boundary. These boundary conditions were in agreement with both mathematical models. Since the anisotropic conductor, a thermoplastic copolymer, was coated with a thin layer of wax which melted at 308 K, the 308 K isotherm was easily detected as the boundary between the wet and the dry portions of the wax. The position and shape of this isotherm corresponded to the position and shape of an isobar in a porous medium. The results clearly indicated that a transition from circular to elliptical isopotentials occurred, in agreement with Peaceman's model. It is, therefore, more appropriate to model a wellbore as an isopotential when studying near-wellbore problems, such as the calculation of well productivity.

### *Thermal Recovery*

**NIPER–584** **Feasibility Study of Heavy Oil Recovery in the Appalachian, Black Warrior, Illinois, and Michigan Basins. National Institute for Petroleum and Energy Research. July 1992. 52 pp. Order No. DE92001055.** This report is one of a series of publications assessing the feasibility of increasing domestic heavy oil production. Each report covers select areas of the United

States. The Appalachian, Black Warrior, Illinois, and Michigan basins cover most of the depositional basins in the Midwest and Eastern United States. These basins produce sweet, paraffinic light oil and are considered minor heavy oil (10° to 20° API gravity or 100 to 10,000 cP viscosity) producers. Heavy oil occurs in both carbonate and sandstone reservoirs of Paleozoic Age along the perimeters of the basins in the same sediments where light oil occurs. The oil is heavy because escape of light ends, water washing of the oil, and biodegradation of the oil have occurred over millions of years. The Appalachian, Black Warrior, Illinois, and Michigan basins' heavy oil fields have prodcued some 450,000 bbl of heavy oil of an estimated 14,000,000 bbl originally in place. The basins have been long-term, major light-oil-producing areas and are served by an extensive pipeline network connected to refineries designed to process light sweet, and with few exceptions, limited volumes of sour or heavy crude oils. Since the light oil is principally paraffinic, it commands a higher price than the asphaltic heavy crude oils of California. The heavy oil that is refined in the Midwest and Eastern United States is imported and refined at select refineries. Imports of crude of all grades accounts for 37 to >95% of the oil refined in these areas. Because of the nature of the resource, the Appalachian, Black Warrior, Illinois and Michigan basins are not expected to become major heavy oil producing areas. The crude oil collection system will continue to degrade as light oil production declines. Smaller refineries will close because of lack of local, sweet light oil, economies of scale and environmental constraints on operations and product quality. Major refineries will refine increasing volumes of imported higher-sulfur, lower-gravity crude oil from Canada and Venezuela. Select East Coast refineries will process increasing volumes of light Mideast crude. The demand for crude oil will increase pipeline and tanker transport of crude to select large refineries to meet the areas' liquid fuels needs.

**NIPER–587 Trends in Heavy Oil Production and Refining in California. National Institute for Petroleum and Energy Research. July 1992. 28 pp. Order No. DE92001056.** This report is one of a series of publications assessing the feasibility of increasing domestic heavy oil production and summarizing trends in oil production and refining in California. 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. In each of the three principal petroleum producing districts (Los Angeles Basin, Coastal Region, and San Joaquin Valley) oil production has peaked and then declined at different times throughout the past 30 years. Thermal production of heavy oil has contributed to making California the largest producer of oil by enhanced oil recovery processes in spite of low oil prices for heavy oil and stringent environmental regulation. Opening of Naval Petroleum Reserve No. 1, Elk Hills (CA) field in 1976, brought about a major new source of light oil at a time when light oil production had greatly declined. Although California is a major petroleum-consuming state, in 1989 the state used 13.3 billion gallons of gasoline or 11.5% of U.S. demand but it contributed substantially to the Nation's energy production and refining capability. California is the recipient and refines most of Alaska's 1.7 million barrel per day oil production. With California production, Alaskan oil, and imports brought into California for refining, California has an excess of oil and refined products and is a net exporter to other states. The local surplus of oil inhibits exploitation of California heavy oil resources even though the heavy oil resources exist. Transportation, refining, and competition in the market limit full development of California heavy oil resources.

**DOE/BC/14600–29 In Situ Combustion With Metallic Additives – SUPRI TR 87. Stanford University. July 1992. 68 pp. Order No. DE92001057.** In situ combustion is the most energy efficient of the thermal oil recovery methods. In this process, a portion of a reservoir's oil is burned in situ as fuel to drive the recovery process. In light oil reservoirs, too little fuel may be deposited leading to high air injection requirements and unfavorable economics. This study has been designed to attack these problems. Water soluble metallic additives are investigated as agents to modify fuel deposition and combustion performance. In previous papers by Shallcross (1989) and De los Rios et al (1988), results were reported from kinetic experiments run on Huntington Beach (CA) and Hamaca (Venezuela) crude oils. In these experiments, mixtures of sand, crude oil, and aqueous metallic salts were oxidized. While the presence of copper, nickel and cadmium had little or no effect, iron and tin increased oxidation rates and oxygen consumption. This report describes seven combustion tube runs using two crude oils and two metallic additives. The oils are 12° and 34° API, both from Cymric (CA). The metallic additives tested are iron nitrate ($Fe(NO_3)_3 9H_2O$) and zinc nitrate ($Zn(NO_3)_2 6H_2O$). Iron and tin additives improved the combustion efficiency in all cases. Fluctuations in the produced gas compositions were observed in all control runs, but nearly disappeared with the iron and tin additives. The combustion front velocities were also increased by iron and tin. Changes were also observed in the apparent hydrogen to carbon (H/C) ratio of the fuel, heat of combustion, air requirements, and amount of fuel deposited. Iron and tin caused increases in fuel concentration while causing a decrease in air requirement. The increase in fuel concentration while causing a decrease in air requirement. The increase in fuel concentration varied between the oils, however; tin and iron were consistently more effective than zinc. A particularly interesting result occurred with the Cymric light oil. In the control runs, a sustained combustion front was not achieved, while in the iron additive runs, stable, sustained combustion was achieved. Iron and tin salts are suitable additives to increase fuel deposition when that is needed. Additives suitable for use as a fuel recycling agent have not yet been found.

**DOE/BC/14600–32 Visualization of Foam/Oil In A New, High-Resolution, Sandstone Replica Micromodel – SUPRI TR 86. Stanford University. August 1992. 36 pp. Order No. DE92001067.** A new micromodel construction procedure has been developed as a tool to better understand and model pore-level events in porous media. The construction procedure allows for the almost exact two-dimensional replication of any porous medium of interest. For the case presented here, a Berea sandstone was chosen. Starting with a thin section of the porous medium of interest, a two-dimensional replica of the flow path is etched into a silicon wafer to a prescribed depth. Bonding the etched pattern to a flat glass plate isolates the flow path and allows the pore level flow events to be studied. The high resolution micromodels constructed with the new procedure were used to study wettability. A crude oil was injected into the micromodel, partially filling it. The oil was then produced under two different displacement schemes. First, a slug of surfactant was used. Second, foam generated in situ, far from the oil bank, was used to displace the oil. Qualitative observations indicate significant differences at the interface between the oil and the displacing phase. When slug surfactant injection is used, the oil appears to wet the surface. The oil displacement process is efficient due to a large fractional production of oil from the large pores before the surfactant breaks through. When in situ foam is the displacing phase, the foam is observed to break near the oil interface. The liquid phase in the foam becomes the wetting phase. It is observed to reside in the small pores and to coat most of the grain surfaces. Displacement of oil under this injection scheme is inefficient due to transfer of the surfactant along grain edges and subsequent early breakthrough of the surfactant.

**DOE/BC/14600–33 A Three-Dimensional Laboratory Steam Injection Model Allowing In Situ Saturation Measurements – SUPRI TR 83. Stanford University. August 1992. 92 pp. Order No. DE92001059.** The CT imaging technique together with temperature and pressure measurements were used to follow the steam propagation during steam and steam foam injection experiments in a three-dimensional (3-D) laboratory steam injection mold. During the design period, the advantages and disadvantages of different geometries were examined to find out which could best represent radial and gravity override flows and also fit the dimensions of the scanning field of the CT scanner. As a result of this analysis a 3-D rectangular box with dimensions $20 \times 20 \times 7.5$ cm was constructed. This box simulates one quarter of a five-spot pattern. Aluminum, Teflon™ and Fiberfax™ were chosen as supporting and insulating materials. Teflon™ was placed between the porous medium and the aluminum shell so that the rate of heat transfer in the porous medium would be much faster than that in the aluminum during a steam injection run. During experiments, steam was injected continuously at a constant rate into the water-saturated model and CT scans were taken at six different cross sections of the model. Pressure and temperature data were collected with time at three different levels in the model. CT pictures and 3-D temperature distributions were compared and analyzed in terms of observed steam zone at each section. To do that, CT numbers within the scan section were used to determine the steam and water zones, and with the aid of x-ray pictures the position and propagation of the steam zone was determined. In addition, using the 3-D temperature distribution measurements at the same

times, steam displacement fronts could be drawn at the scan section locations. These pictures and drawings were used to compare the results obtained from classical temperature-pressure monitoring and from CT scans.

**DOE/BC/92001058 Report on Variation of Electrical Conductivity During Steam Injection in Unconsolidated Sand Saturated With A Salt Solution. Lawrence Livermore National Laboratory. July 1992. 52 pp. Order No. DE92001058.** The spatial and temporal variation of electrical conductivity in saturated sands during steam injection has been measured and modeled. Experiments consisted of introducing steam into one end of a tube filled with a sand saturated with a slightly saline solution. Measurements of electrical conductivity were then made every 10 seconds at 10 locations along the tube using a four-electrode technique. After injection, a steam condensation front forms ahead of the steam front that separates the mixed-phase steam zone from the liquid zone. Conductivity measurements at a specific position in the tube throughout time show that the electrical conductivity starts at a constant value, decreases before the steam front arrives and then, immediately prior to the steam front arrival, goes through a maximum before dropping by a factor of about 25. These variations can be explained by (1) a dilution of the interstitial solution ahead of the steam front thereby causing the initial drop in conductivity, (2) an increase in temperature of the solution immediately prior to the arrival of the steam front causing the conductivity maximum, and (3) a drop in conductivity due to the combined effects of a decrease in saturation and dilution of the residual liquid in the two-phase zone. Mathematical solutions of a set of differential equations that take into consideration all of these effects are presented. These solutions reproduce the significant features of the conductivity data, and help to explain the physical phenomenon. The study suggests that the measurements of changes in the subsurface conductivity field during steam injection operations may indicate the location of ionic concentration, temperature, and steam-saturation fields.

**DOE/BC/92001062 A Pore-Level Scenario for the Development of Mixed-Wettability in Oil Reservoirs. Lawrence Berkeley Laboratory, University of California. September 1992. 60 pp. Order No. DE92001062.** Understanding the role of thin films in porous media is vital if wettability is to be elucidated at the pore level. The type and thickness of films coating pore walls determines reservoir wettability and whether or not reservoir rock can be altered from its initial state of wettability. Pore shape, especially pore wall curvature, is an important factor in determining wetting-film thicknesses. Yet, pore shape and the physics of thin wetting films are generally neglected in models of flow in porous rocks. This paper incorporates thin-film forces into a collection of star-shaped capillary tubes model to describe the geological development of mixed-wettability in reservoir rock. Here, mixed-wettability refers to continuous and distinct oil and water-wetting surfaces coexisting in the porous medium. The proposed model emphasizes the remarkable role of thin films. New pore-level fluid configurations arise that are quite unexpected. For example, efficient water displacement of oil (i.e., low residual oil saturation) characteristic of mixed-wettability porous media is ascribed to interconnected oil lenses or rivulets which bridge the walls adjacent to a pore corner. Predicted residual oil saturations are approximately 35% less in mixed-wet rock compared to completely water-wet rock. Calculated capillary pressure curves mimic those of mixed-wet porous media in the primary drainage of water, imbibition of water, and secondary drainage modes. Amott-Harvey indices range from $-0.18$ to 0.36, also in good agreement with experimental values.

*Geoscience Technology*

**DOE/BC/92001051 Kinetic Modeling of Petroleum Formation in the Maracaibo Basin: Final Report. Lawrence Livermore National Laboratory and INTEVEP. July 1992. 136 pp. Order No. DE92001051.** The purpose of this project is to develop and test improved kinetic models of petroleum generation and cracking, pore pressure buildup, and fluid expulsion. The work was performed jointly and laboratory experiments were conducted at both Lawrence Livermore National Laboratory (LLNL) and INTEVEP to obtain the reaction rate and product composition information needed to develop chemical kinetic models. Experiments at INTEVEP included hydrous pyrolysis and characterization of oils by gas and liquid chromatography. Experiments at LLNL included programmed pyrolysis in open and self-purging reactors, sometime including on-line gas analysis by tandem mass spectrometry, and characterization of oils by gas chromatography and nuclear magnetic resonance. Global hydrocarbon generation kinetics were derived using an activation energy distribution model. These were combined with thermal histories of 80 wells to calculate global maturation across the Maracaibo basin. The thermal histories were intially derived at INTEVEP and were modified slightly at LLNL based on comparison of observed vitrinite reflectance profiles and those calculated from the LLNL EASY%Ro vitrinite reflectance model. Calculated $T_{max}$ and H/C ratios of the residual kerogen agreed well with observed values, and the calculated fraction of kerogen converted agreed well with the API gravity and sulfur content of oil in Cretaceous reservoirs. In parallel, a formalism was developed for calculating pore pressures and fluid expulsion. This formalism was first incorporated into PYROL, the detailed LLNL pyrolysis parameters model. The pore pressure-fluid expulsion formalism was tested initially using kinetic parameters for the Green River formation and preliminary kinetic parameters for a generic marine source rock. Although the approach appeared promising, the PYROL code was difficult to modify and use, so a more easily used and flexible code, PMOD was developed. PMOD enables the user to develop interactively a pyrolysis mechanism that satisfies elemental balance and to automatically calculate many geochemical indicators.

**DOE/BC/14443–12 A Field Laboratory for Improved Oil Recovery. Final Report. University of Houston. 108 pp. Order No. DE92001063.** The purpose of this project was to develop a field laboratory for research in improved oil recovery using a Gulf Coast reservoir in Texas. The participants (1) made a field site selection and conducted a high-resolution seismic survey in the demonstration field, (2) obtained characteristics of the reservoir, (3) developed an evaluation of local flood efficiency in different parts of the demonstration reservoir, (4) used diverse methodology to evaluate the potential recovery of the remaining oil in the test reservoir, (5) developed crosswell seismic tomography, and (6) will transfer the learned technologies to oil operators through publications and workshops. The report describes each of the tasks performed.

**DOE/BC/14657–7 Measuring and Predicting Reservoir Heterogeneity in Complex Deposystems. Annual Report for the Period September 20, 1990-September 20, 1991. West Virginia University, Appalachian Oil and Natural Gas Research Consortium. August 1992. 160 pp. Order No. DE92001068.** The Lower Mississippian Big Injun sandstone, a major oil producer in the western half of West Virginia, consists of several sandstones that overstep each other from east to west. In Granny Creek field, Roane and Clay counties, the Big Injun can be subdivided into three informal units, designated A, B, and C from top to bottom, based on the bulk density log. Furthermore, the lower C unit can be divided into ascending C1, C2 and C3 subunits that overstep each other to the west. An unconformity between the A unit and the overlying Greenbrier Limestone represents an erosional episode that has progressively eliminated the A, B and C2 units eastward across Granny Creek field. The distribution of Big Injun oil fields in south central West Virginia is influenced by geologic structure. Oil fields have been developed on the flanks of anticlines and synclines in the area, and can be observed to wrap around the nose of the Parkersburg Syncline and the northeastward plunging nose of the Warfield Anticline. Seismic data collected across Granny Creek field have good resolution in the Greenbrier-Big Injun interval and strengthen stratigraphic and structural interpretations based on geophysical logs and drillers' data. Examination of cores and thin sections has led to preliminary interpretations of depositional environments for the Big Injun. These include distributary-mouth bars with associated distal, bar crest and back bar environments in a marine-deltaic system, and channel, point bar and chute environments in a fluvial system. Overall, the Big Injun is a medium-grained sublitharenite in which initially high porosity has been modified by compaction and diagenesis. Chlorite grain coatings helped to preserve original porosity, whereas illite promoted pressure solution during compaction, resulting in a loss of porosity. Diagenetic effects within specific environments are being evaluated to determine if environmental interpretations can be used to predict porosity preservations.

**DOE/BC/14471–11 Analysis of Reservoir Heterogeneities Due to Shallowing-Upward Cycles in Carbonate Rocks of the Pennsylvanian Wahoo Limestone of Northeastern Alaska. University of Alaska. Annual Report for the Period September 1989-September 1990. September 1992. 76 pp. Order No. DE92001064.** The primary objective of this project was to develop an integrated database to characterize reservoir heterogeneities resulting from numerous small-scale shallowing-upward cycles (parasequences) comprising the Pennsylvanian Wahoo Limestone. The Wahoo Limestone is the upper part of an extensive carbonate platform sequence of the Carboniferous Lisburne Group that is widely exposed in the Brooks Range and is a widespread hydrocarbon reservoir unit in the subsurface of the North Slope of the Alaska. A major goal is to determine lateral and vertical variations in the complex mosaic of carbonate facies comprising the Wahoo Limestone. This report presents the preliminary results of research in carbonate petrology, biostratigraphy, and diagenesis during the year. It includes a summary of some petrographic data which has been entered into a computerized database; a discussion of biostratgraphic data, particularly conodont biofacies analyses; an overview of diagenetic studies; and a section of the regional geological framework studies. The database allows tests of which parameters, such as ooids, can be used to recognize and understand the carbonate petrology of the shallowing-upward cycles. The cycles have been interpreted in terms of depositional environments and sea-level fluctuations and used to develop detailed facies models. Conodont biostratigraphy is providing an independent means of correlation and age dating. Conodont biofacies analyses are being related to paleoenvironments as determined by carbonate facies analysis. Analyses of diagenesis have allowed recognition of a number of subaerial exposure surfaces that are another important means of correlation and will figure importantly in developing seal level curves. Regional studies provide an understanding of lateral facies relationships and how position on a southward-facing carbonate ramp affects the nature of carbonate shallowing-upward cycles.

**DOE/BC/14471–12 Analysis of Reservoir Heterogeneities Due to Shallowing-Upward Cycles In Carbonate Rocks of the Pennsylvanian Wahoo Limestone of Northeastern Alaska. University of Alaska. Annual Report for the Period October 1990-September 1991. September 1992. 76 pp. Order No. DE92001065.** This is the second annual report of the project to develop an integrated database to characterize reservoir heterogeneities resulting from numerous small-scale shallowing-upward cycles (parasequences) comprising the carboniferous Pennsylvanian Wahoo Limestone. The Wahoo Limestone is the upper formation of an extensive carbonate platform sequence of the Carboniferous Lisburn Group which is widely exposed in the Brooks Range and is a widespread hydrocarbon reservoir unit in the subsurface of the North Slope of Alaska. A principal goal is to determine lateral and vertical variations in the complex mosaic of carbonate facies comprising the Wahoo Limestone. The report presents preliminary results of research in carbonate petrology, biostratigraphy, and diagensis during the year. It includes a summary of regional geological framework studies, a discussion of conodont analyses, an overview of diagenetic studies, a brief description of progress in computerized database development, and appendices containing some of the new data on petrographic analyses, conodont analyses, and locality and sample information. Regional studies provide an understanding of lateral facies relationships and describe how position on a southward-facing carbonate ramp affect the nature of carbonate parasequences (shallowing-upward cycles). In order to understand the overall basin history and its relationship to the stratigraphic and structural framework, the research considers the rock units adjacent to the Wahoo Limestone, the underlying Alapah Limestone and overlying Echooka Formation. Conodont biostratigraphy is providing an independent means of correlation and age dating. Conodont biofacies analyses are being related to paleoenvironments as determined by carbonate facies analysis. Analyses of diagenesis have allowed recognition of a number of subaerial exposure surfaces which are another important means of correlation and will figure importantly in developing sea-level curves. The computerized database allows tests of which parameters, such as ooids, can be used to recognize and understand the carbonate petrology of the parasequences/shallowing-upward cycles. The cycles have been interpreted in terms of depositional environments and sea-level fluctuations and have been used to develop detailed facies models.

*Resource Assessment*

**DOE/BC/14476–10 Characterization of Reservoir Rocks and Fluids By Surface Electromagnetic Transient Methods. Blackhawk Geosciences Inc. Annual Report for 1990-1991. September 1992. 76 pp. Order No. DE92001060.** The objectives of this research were to improve the interpretations of transient electromagnetic (TEM) measurements over two-dimensional subsurface structures. TEM is a surface electromagnetic method employed in fossil energy reservoir exploration and characterization. Electrical measurements find application in (1) assisting in fossil energy exploration, mainly in areas where seismic methods yield inadequate data quality, such as volcanic-covered terrain, permafrost areas, and the Rocky Mountain Overthrust; (2) mapping contacts between hydrocarbon and brines in shallow producing horizons; and (3) monitoring enhanced oil recovery processes which cause zones of lower resistivity. The work under this contract consisted of three tasks: (1) Selection of a test site and acquisition of a high-density, 3-component data set over the test site; (2) Development of finite element modeling algorithms for computing 3-D EM fields over 2-D subsurface structures; and (3) Development of TEM 2-D subsurface imaging method.

# PUBLICATIONS LIST 69

**Bartlesville Project Office**

Thomas C. Wesson, *Director*

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### *Quarterly Reports*

**DOE/BC–91/4** **Contracts for Field Projects and Supporting Research on Enhanced Oil Recovery. Progress Review No. 68. Quarter ending September 30, 1991. November 1992. 188 pp. Order No. DE92001052.** Status reports are given for various enhanced oil recovery and gas recovery projects sponsored by the Department of Energy. The field tests and supporting research on enhanced oil recovery include chemical flooding, gas displacement, thermal/heavy oil, resource assessment, geoscience technology, microbial technology, novel technology, and environmental technology.

### *General*

**NIPER–596** **General-Purpose Automation Programming: A Case Study on Using a Graphic Language. Topical Report. National Institute for Petroleum and Energy Research. October 1992. 48 pp. Order No. DE92001071.** As part of an ongoing effort to transfer technology to the petroleum industry and other engineering, science and manufacturing areas, this report conveys background information and the benefits of data acquisition/control/analysis/presentation software to operate a high-temperature, high-pressure steamflood laboratory. The National Institute for Petroleum and Energy Research developed the background and extensive applications by using National Instruments™ LabVIEW®, an object-oriented programming software, as the programming platform. The software was developed to automate the thermal lab, but was designed in such a way that the program would be general and could be configured to any laboratory automation during the run time. This modular program has been constructed so that application, with minor modification, can be used in other laboratory, pilot plant or commercial operations for data acquisition/control/analysis/presentation.

### *Gas Displacement*

**NIPER–632** **Application of Polymer Gels for Profile Modification and Sweep Improvement of Gas Flooding. Topical Report. National Institute for Petroleum and Energy Research. December 1992. 36 pp. Order No. DE93000106.** This study included evaluation of several different candidates for their potential as gelled polymer treatments for in situ profile modification. Crosslinking of one gel system (melamine resinxanthan polymer) was activated in the pH range of 4 to 5. This method depended upon $CO_2$ contacting reservoir brines to form carbonic acid. For a $CO_2$ gas flood, brines contacted by $CO_2$ will have a lower pH than the reservoir brine. The primary disadvantages of the melamine resin-gel system were the high sensitivity of the gel to shear and the inability of the gel to reheal because the resin degraded after the resin activation in acidic brines. Another gel system was evaluated which was a blend of hydroxypropyl cellulose (HPC) and sodium dodecyl sulfate (SDS). A gel was formed by increasing the salinity of the polymer/surfactant blend. This gel had the advantage of not requiring a crosslinking agent such as a heavy metal compound and did not require any specific solution pH to form a gel. However, because the gel formed immediately upon increasing salinity, the gel could be placed only a short distance from the point of injection. This gel system did not appear to be a practical method for profile modification because of the inability for deep penetration and placement of the HPC/SDS solutions in the reservoir. Also, brine injection following gel placement produced an increase in the sandpack permeability. This demonstrated that the gel was not stable to subsequent brine flooding.

### *Thermal Recovery*

**NIPER–580** **Practical Aspects of Steam Injection Processes, A Handbook for Independent Operators. National Institute for Petroleum and Energy Research. October 1992. 448 pp. Order No. DE92001070.** This handbook explores the concept behind steam injection processes and discusses the information required to evaluate, design, and implement these processes in the field. The emphasis is on operational aspects and those factors that affect the technology and economics of oil recovery by steam. The intended purpose of this handbook is twofold: (1) to provide operators with a ready reference, a starting point when searching for information to engineer a steam injection project; and (2) to provide a bibliographic source on the subjects discussed in the handbook. This handbook is not, however, a "troubleshooter" manual on field problems. The first four chapters describe the screening criteria, engineering, and economics of steam injection operation as well as discussion of the steam injection fundamentals. The next four chapters begin by considering the treatment of the water used to generate steam and discuss in considerable detail the design, operation and problems of steam generations, distribution and steam quality determination. The subsurface aspects of steamflood operations are addressed in chapters 9 through 12. These include thermal well completion and cementing practices, insulated tubulars, and lifting equipment. The next two chapters are devoted to subsurface operational problems encountered with the use of steam. Briefly described in chapters 15 and 16 are the steam injection process surface production facilities, problems and practices. Chapter 17 discusses the importance of monitoring in a steam injection project. The environmental laws and issues of importance to steam injection operation are outlined in chapter 18.

**DOE/BC/14600–36** **Chemical Composition Profiles During Alkaline Flooding at Different Temperatures and Extended Residence Times. Topical Report. University of Southern California. December 1992. 152 pp. Order No. DE93000107.** The objective of this work was to investigate whether or not caustic effectively sweeps the major portion of the reservoir efficiently during an alkaline flood process. It was also the objective of this work to study the state of final equilibrium during a caustic flood through determination of the pH and chemical composition profiles along the porous medium. For this purpose, a long porous medium which provided extended residence times was required. It was necessary to set up the porous medium such that the

changes in the pH and chemical composition of the solution could be monitored. Four Berea sandstone cores (8" in length and 1" in diameter) placed in series provided the desired length and the opportunity for sampling in-between cores. This enabled establishment of pH and chemical composition profiles. The experiments were run at temperatures up to 180°C, and the flow rates varied from 4.8 to 0.2 ft/d. The samples were analyzed for pH and for Si and Al concentrations. The results show that caustic consumption is insignificant for temperatures up to 100°C. Above 100°C consumption increases and is accompanied by a significant decrease in pH. The sharp decline in pH also coincides with a sharp decline in concentration of silica in solution. The results also show that alumina is removed from the solution and solubility of alumina ultimately reaches zero. Sharp silica and pH declines take place even in the absence of any alumina in solution. As a result, removal of silica from solution is attributed to the irreversible caustic/rock interaction. This interaction is in the form of chemisorption reactions in which silica is adsorbed onto the rock surface consuming hydroxyl ion. Once these reactions are satisfied, caustic breakthrough occurs at a high pH. However, significant pore volumes of caustic must be injected for completion of the chemisorption.

**DOE/BC/14600–37 Characterization of Surfactants in the Presence of Oil for Steam Foam Application–SUPRI TR 88. Stanford University Petroleum Research Institute. December 1992. 60 pp. Order No. DE93000108.** A one-dimensional sandpack (6 ft. × 2.15 in.) model is used to investigate the behavior of four anionic sulfonate surfactants of varying chemical structure with steam. The study is performed with a crude oil at residual oil saturation of about 12% of pore volume. The observed pressure drops across the various sections of the pack are used to study the behavior of the surfactant. The surfactants tested vary in chain length, aromatic structure and number of ionic charges. A linear toluene sulfonate produced the highest strength foam in presence of the oil at residual saturations, as compared to the alpha olefin sulfonates. This is in contrast to the behavior of the surfactants in the absence of oil, where the alpha olefin sulfonates perform better. The reason for this change in behavior is the relative propagation rate of the foams produced by the surfactants. This conclusion is based on the observation that increase in propagation rate decreases the detrimental effect of oil, while the propagation rate is of little significance without oil. The disulfonate performed better in the presence of oil. The improvement in the performance is embedded in the propagation rate of these surfactants, as the rate of propagation in this case is also high. But the true mechanism of improvement in the strength of the foam instead of deterioration needs further study.

*Resource Assessment Technology*

**DOE/BC/14403–3 Characterization of Oil and Gas Reservoir Heterogeneity. Final Report. The University of Texas at Austin. October 1992. 232 pp. Order No. DE92001072.** Research described in this report addresses the internal architecture of two specific reservoir types: restricted-platform carbonates and fluvial-deltaic sandstones. Together, these two reservoir types contain more than two-thirds of the unrecovered mobile oil remaining in Texas. The approach followed in this study was to develop a strong understanding of the styles of heterogeneity of these reservoir types based on a detailed outcrop description and a translation of these findings into optimized recovery strategies in select subsurface analogs. Research targeted Grayburg Formation restricted-platform carbonate outcrops along the Algerita Escarpment and in Stone Canyon in southeastern New Mexico and Ferron deltaic sandstones in central Utah as analogs for the North Foster (Grayburg) and Lake Creek (Wilcox) units, respectively. In both settings, sequence-stratigraphic style profoundly influenced between-well archiectural fabric and permeability structure. It is concluded that reservoirs of different depositional origins can therefore be categorized into a "heterogeneity matrix" based on varying intensity of vertical and lateral heterogeneity. The utility of the matrix is that it allows prediction of the nature and location of remaining mobile oil. Highly stratified reservoirs such as the Grayburg, for example, will contain a large proportion of vertically bypassed oil; thus, an appropriate recovery strategy will be waterflood optimization and profile modification. Laterally heterogeneous reservoirs such as deltaic distributary systems would benefit from targeted infill drilling (possibly with horizontal wells) and improved areal sweep efficiency. Potential for advanced recovery of remaining mobile oil through heterogeneity-based advanced secondary recovery strategies in Texas is projected to be an incremental 16 Bbbl. In the Lower 48 States this target may be as much as 45 Bbbl. at low to moderate oil prices over the near- to mid-term.

**NIPER–611 CT Imaging of Surfactant-Enhanced Oil Recovery Experiments. Topical Report. National Institute for Petroleum and Energy Research. December 1992. 32 pp. Order No. DE93000103.** Four CT-monitored corefloods were conducted, and oil saturation distributions were calculated at various stages of the experiments. Results suggested that this technique could add significant information toward interpretation and evaluation of surfactant/polymer EOR recovery methods. CT-monitored tracer tests provided information about flow properties in the core samples. Non-uniform fluid advance could be observed, even in core that appeared uniform by visual inspection. Porosity distribution maps based on CT density calculations also showed the presence of different porosity layers that affected fluid movement through the cores. Several types of CT-monitored corefloods were conducted. Comparisons were made for CT-monitored corefloods using chemical systems that were highly successful in reducing residual oil saturations in laboratory experiments and less successful systems. Changes were made in surfactant formulation and in concentration of the mobility control polymer. Use of a poor mobility control agent failed to move oil that was not initially displaced by the injected surfactant solution, even when a "good" surfactant system was used. Use of a less favorable surfactant system with adequate mobility control could produce as much oil as the use of a good surfactant system with inadequate mobility control. The role of mobility control, therefore, becomes a critical parameter for successful application of chemical EOR. Continuation of efforts to use CT imaging in connection with chemical EOR evaluation is recommended.

*Thermodynamics*

**NIPER–623 Thermodynamic Modeling for Organic Solid Precipitation. Topical Report. National Institute for Petroleum and Energy Research. December 1992. 32 pp. Order No. DE93000104.** A generalized predictive model which is based on thermodynamic principle for solid-liquid phase equilibrium has been developed for organic solid precipitation. The model takes into account the effects of temperature, composition, and activity coefficient on the solubility of wax and asphaltenes in organic solutions. The solid-liquid equilibrium K-value is expressed as a function of the heat of melting, melting point temperature, solubility parameter, and the molar volume of each component in the solution. All these parameters have been correlated with molecular weight. Thus, the model can be applied to crude oil systems. The model has been tested with experimental data for wax formation and asphaltene precipitation. The predicted wax appearance temperature is very close to the measured temperature. The model not only can match the measured asphaltene solubility data but also can be used to predict the solubility of asphaltene in organic solvents or crude oils. The model assumes that asphaltenes are dissolved in oil in a true liquid state, not in colloidal suspension, and the precipitation-dissolution process is reversible by changing thermodynamic conditions. The model is thermodynamically consistent and has no ambiguous assumptions.

*Fundamental Petroleum Chemistry*

**NIPER–598 The Thermodynamic Properties of 4, 5, 9, 10-Tetrahydropyrene and 1, 2, 3, 6, 7, 8-Hexahydropyrene. Topical Report. National Institute for Petroleum and Energy Research. December 1992. 64 pp. Order No. DE93000102.** Measurements leading to the calculation of the ideal-gas thermodynamic properties are reported for 4, 5, 9, 10-tetrahydropyrene and 1, 2, 3, 6, 7, 8-hexahydropyrene. Experimental methods included combustion calorimetry, adiabatic heat-capacity calorimetry, vibrating-tube densitometry, comparative ebulliometry, inclined-piston gauge manometry, and differential-scanning calorimetry (d.s.c.). Critical properties were estimated for both materials based on the measurement results. Entropies, enthalpies, and Gibbs energies of formation were derived for the ideal gases for selected temperatures between 380 K and 700 K. The property-measurement results reported here for 4, 5, 9, 10-tetrahydropyrene and 1, 2, 3, 6, 7,

8-hexahydropyrene are the first for these important intermediates in the pyrene/$H_2$ hydrogenation reaction network.

*Microbial Technology*

**NIPER–629 Modeling and Laboratory Investigations of Microbial Oil Recovery Mechanisms in Porous Media. Topical Report. National Institute for Petroleum and Energy Research. December 1992. 36 pp. Order No. DE93000105.** Simulation and experimental results on the transport of microbes and nutrients in one-dimensional cores are presented, and the development of a three-dimensional, three-phase, multiple-component numerical model to describe the microbial transport and oil recovery in porous media is described. The change of rock's wettability and associated relative permeability values after microbial treatments were accounted for in the model for additional oil recovery. Porosity and permeability reductions because of cell clogging have been considered and the production of gas by microbial metabolism has been incorporated. Governing equations for microbial and nutrient transport are coupled with continuity and flow equations under conditions appropriate for a black oil reservoir. From our concepts of the hydrodynamics, physics, chemistry and microbiology of microbial oil recovery (MEOR) processes, microbial parameters incorporated into the microbial transport model include: (1) microbial growth and decay; (2) microbial deposition; (3) chemotaxis; (4) diffusion; (5) convective dispersion; (6) tumbling; and (7) nutrient consumption. Laboratory experiments were conducted to obtain actual data for the simulator regarding microbial growth and decay, nutrient consumption, microbial deposition, convective dispersion, and diffusion. Unsteady-state relative permeability measurements using microbial formulations were made to determine the effects of microbial metabolites on fractional fluid flow in porous media. Mechanisms considered important for oil recovery include changes in microscopic properties such as interfacial tension, wettability, and adsorption that govern oil mobilization and affect fractional flow and relative permeability. Computer tomography studies demonstrated that gas production by microorganisms in porous media can reduce residual oil saturation in porous media.

**DOE/BC/14665–8 A Study of the Interactions Between Microorganisms, Microbial By-Products, and Oil-Bearing Formation Materials. Final Report. Mississippi State University. December 1992.** The results of this investigation support the concept that microorganisms indigenous to subterranean oil reservoirs enhance oil recovery. Studies were conducted to test this concept under the most realistic conditions possible in the laboratory. Specifically, cores from oil reservoirs were used in coreflood experiments. This way, microorganisms, formation materials, oil, and water were in as close to their natural state as possible. Simulated production water containing supplemental nutrients then were allowed to flow through these cores. No supplemental nutrients were added to the water flowing through the control cores. One test core and one control core were prepared from cores obtained from five different reservoirs. The following results were obtained when supplemental nitrogen and phosphorous sources were added to the injection water: (1) oil was released from the test cores; (2) there was an increase in the number of microorganisms present in the core effluent; (3) the production of acid by the microflora resulted in the dissolution of large amounts of carbonate material and the development of new channels; (4) some plugging of the more porous zones occurred; (5) gas was produced in some cases; and (6) the addition of trace amounts of ethanol to the injection water greatly enhanced the release of oil and the dissolution of carbonate in the formation material.

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# DELTAIC-RESERVOIRS WORKSHOP
# Norman, Oklahoma, March 23-24, 1993

A workshop on "Fluvial-Dominated Deltaic Reservoirs in the Southern Midcontinent," co-sponsored by the Oklahoma Geological Survey and the Bartlesville Project Office of the U.S. Department of Energy, will be held March 23-24, 1993, at the University of Oklahoma in Norman.

The workshop will present current and ongoing research and studies dealing with types of deltaic reservoirs, depositional settings, diagenetic history, reservoir characterization, and enhanced oil recovery. The workshop is designed to transfer technical information that will aid in the identification and characterization of oil and gas plays, and thus improve our ability to search for and produce our petroleum resources. Provisional titles and speakers are listed below:

## March 23

**Distinction, or Indistinction, of Fluvial-Dominated Deltaic Reservoirs,** by John W. Shelton, MASERA Corp., Tulsa

**Types of Deltaic Reservoirs—A Comparison,** by Glenn S. Visher, Geological Services & Ventures, Inc., Tulsa

**Pennsylvanian Deltaic-Channel Reservoirs in Oklahoma,** by Robert Northcutt, Oklahoma City, and Kenneth S. Johnson, Oklahoma Geological Survey

**Evolution of Fluvial Influence on Deltaic Sedimentation, Atokan and Desmoinesian of Arkoma Basin,** by David Houseknecht, U.S. Geological Survey, Reston

**The Morrowan Reservoirs: A Complex Fluvio-Deltaic Depositional System,** by Zuhair Al-Shaieb, J. Puckette, and A. Abdalla, Oklahoma State University

**The GYPSY Field-Research Program in Integrated Reservoir Characterization,** by Daniel J. O'Meara, University of Oklahoma

**Integrate Reservoir Description Using Outcrop Studies: Example from the Bartlesville Sandstone, Northeast Oklahoma,** by Dennis Kerr, G. Martinez, I. Azof, and M. Kelkar, University of Tulsa

**Mine-Assisted Secondary Recovery of Oil in the Bartlesville Sand in the Cushing Field, Northeastern Oklahoma,** by Maynard F. Ayler, Oil Mining Co., Golden, CO

**Geometry, Depositional Environment, and Exploration of the Pennsylvanian Red Fork Sandstone,** by Richard D. Fritz and Christopher L. Johnson, MASERA Corp., Tulsa

**Integrated Perspective of the Depositional Environment, Reservoir Geometry, Characterization, and Performance of the Upper Morrow Buckhaults Sandstone in the Farnsworth Unit, Ochiltree County, Texas,** by Richard H. McKay, UNOCAL, Oklahoma City, and Jesse T. Noah, UNOCAL, Houston

## March 24

**On the Seismic Characterization/Classification of Deltas,** by John D. Pigott, University of Oklahoma

**Deltaic Facies: Problems, Practices, and Pitfalls,** by James R. Chaplin, Oklahoma Geological Survey

**Reservoir Characterization and Economic Potential of the Marmaton (Desmoinesian) Sand, Roger Mills County, Oklahoma,** by Douglas W. Johnson, and Shahveer P. Kapadia, Grace Petroleum Corp., Oklahoma City

**Sequence Stratigraphy, Delta Models, and Fluvial-Deltaic Facies Tracts in the Pennsylvanian Cyclothemic Deposits of North-Central Texas,** by Arthur W. Cleaves, Oklahoma State University

**River-Dominated Deltaic Reservoirs of the Desmoinesian in Southeast Kansas,** by Anthony W. Walton, University of Kansas

**Reservoir Geochemistry—Concepts, Applications, and Results,** by Paul Philp and Andrew Bishop, University of Oklahoma

**General Reservoir and Production Characteristics for Fluvial-Deltaic-Dominated Reservoirs,** by Ming Ming Chang, Min K. Tham, and Susan R. Jackson, NIPER, Bartlesville

**Heterogeneities Related to Deltaic Depositional Processes and Their Effect on Waterflood-Recovery Efficiency,** by Susan R. Jackson, Min K. Tham, and Ming Ming Chang, NIPER, Bartlesville

**Understanding Reservoir Depositional Environments Contributes to Optimize Oil Recovery—Muskogee Oilfield, a Classical Example,** by Jorge M. Perez, E.C. Donaldson, and S.W. Poston, Texas A&M University

## Poster Session, March 24

**Fluvial-Deltaic Facies Sequences in the Lower Deese Group, Ardmore Basin,** by Patricia C. Billingsley, Sanjay Banerjee, R. Douglas Elmore, and Patrick K. Sutherland, University of Oklahoma

**Improved Recovery Alternatives for the Alamo SW Field: A Tight Distal-Deltaic-Sand Reservoir,** by Roy Knapp, James Forgotson, Tim Collins, Amaldo Ganuzio, and John Gosling, University of Oklahoma

**Mine-Assisted Secondary Recovery of Oil in the Bartlesville Sand in the Cushing Field, Northeastern Oklahoma,** by Maynard F. Ayler, Oil Mining Co., Golden, CO

**Integrated Reservoir Management to Maximize Oil Recovery from a Fluvial Reservoir, A Case Study of the Sooner Unit, Colorado,** by Mark A. Sippel and Ronald W. Pritchett, Research & Engineering Consultants, Inc., Englewood, CO, and Bob A. Hardage, Texas Bureau of Economic Geology

**Heterogeneity in Delta-Destructive Oil Reservoirs: Deposition and Diagenesis of Carter Sandstone (Upper Mississippian), Black Warrior Basin, Alabama,** by Jack C. Pashin and Ralph L. Kugler, Geological Survey of Alabama

**Surface Geochemical Hydrocarbon Signature of the Eastern Colorado and Western Kansas Morrow Formation,** by Daniel C. Hitzman, James D. Tucker, and Brooks A. Rountree, Geo-Microbial Technologies, Inc., Ochelata, OK

**Reservoir Characterization of Pennsylvanian Sandstones, Nelson Lease, Savonberg Field, Allen County, Kansas,** by Tim Phares, Tony Walton, and Lanny Schoeling, University of Kansas

**Stratigraphic Characterization from Integrated Core and Well-Log Data of some Selected Pennsylvanian Sandstone-Producing Reservoirs—Conoco 33-5 Well, Conoco Test Borehole Facility, Kay County, Oklahoma,** by James R. Chaplin, Oklahoma Geological Survey

**Electrofrac Heatflood Process Demonstration in Peru Sand—A Fluvial-Dominated Deltaic Reservoir,** by Shapour Vossoughi, University of Kansas, and Erich Sarapuu and R.H. Crowther, Electrofrac Corp., Kansas City

**Cherokee Group (Pennsylvanian) Production in Oklahoma: Data from Fluvial-Dominated Deltaic Reservoirs,** by David P. Brown and Mary K. Grasmick, Geological Information Systems, and Robert A. Northcutt, Oklahoma City

**Detrital Ore Minerals and Their Significance, Basal Atoka Formation, Northern Arkoma Basin, Arkansas,** by Lisa K. Meeks, Arkansas Tech University, and Walter L. Manger, University of Arkansas

**Use of Stratamodel Software for Reservoir Characterization of GYPSY Field,** by Daniel J. O'Meara and Dirk Seifert, University of Oklahoma

**Seismic Exploration for Fluvial-Deltaic Sands in Oklahoma,** by Raymon L. Brown, Oklahoma Geological Survey, and Ron Everett, Geobyte Images, Inc., Oklahoma City

**Fluvio-Estuarine Facies in the Douglas Group (Virgilian) of Kansas,** by Allen W. Archer, Kansas State University, Howard R. Feldman, Kansas Geological Survey, and William Lanier, Emporia State University

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Advance registration (prior to February 26) is $50, which includes two lunches and a copy of the proceedings. Late and on-site registration will be $65 per person. Lodging will be available on the OU campus or at local motels.

For more information, contact Kenneth S. Johnson, General Chairman, Oklahoma Geological Survey, University of Oklahoma, 100 E. Boyd, Room N-131, Norman, OK 73019; phone (405) 325-3031, fax (405) 325-7069. For registration forms, contact Linda Nero or Tammie Creel at the same address and phone.

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