FOSSIL ENERGY

DOE/BC/14893-6
(DE95000147)

INTEGRATION OF ADVANCED GEOSCIENCE AND ENGINEERING TECHNIQUES TO QUANTIFY INTERWELL HETEROGENEITY IN RESERVOIR MODELS

First Annual Report
September 29, 1993 to September 30, 1994

By
F. David Martin
Jill S. Buckley
William W. Weiss
Ahmed Ouenes

May 1995

Performed Under Contract No. DE-AC22-93BC14893

New Mexico Institute of Mining and Technology
Socorro, New Mexico

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

DOE/BC/14893-6
Distribution Category UC-122

INTEGRATION OF ADVANCED GEOSCIENCE AND ENGINEERING TECHNIQUES TO QUANTIFY INTERWELL HETEROGENEITY IN RESERVOIR MODELS

First Annual Report
September 29, 1993 to September 30, 1994

By
F. David Martin
Jill S. Buckley
William W. Weiss
Ahmed Ouenes

May 1995

Work Performed Under Contract No. DE-AC22-93BC14893

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Robert Lemmon, Project Manager
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005

Prepared by
New Mexico Institute of Mining and Technology
New Mexico Petroleum Recovery Research Center
Socorro, New Mexico

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The goal of this project is to provide a more quantitative definition of reservoir heterogeneity. This objective will be accomplished through the integration of geologic, geophysical, and engineering databases into a multidisciplinary understanding of reservoir architecture and associated fluid-rock and fluid-fluid interactions. The intent is to obtain a quantitative reservoir description incorporating outcrop, field, well-to-well, and laboratory core and fluid data of widely varying scales. This interdisciplinary effort will integrate geological and geophysical data with engineering and petrophysical results through reservoir simulation to quantify reservoir architecture and the dynamics of fluid-rock and fluid-fluid interactions. A more accurate reservoir description will allow greater accuracy and confidence during simulation and modeling as steps toward gaining greater recovery efficiency from existing reservoirs.

A field laboratory, the Sulimar Queen Unit, is available for the field research activities that will be conducted. Subcontractors from Stanford University and the University of Texas at Austin (UT) will collaborate in the research and will participate in the design and interpretation of field tests. Dr. Jerry Harris, Associate Professor in the Department of Geophysics at Stanford, will couple crosswell reflection imaging and interwell transmission tomography in a procedure not attempted previously on field data. Dr. Gary Pope, Director of the Center for Petroleum and Geosystems Engineering at the UT, will conduct further research and will design and interpret a single-well wettability tracer test developed in his laboratories but not yet field tested. Several members of the PRRC staff are participating in the development of improved reservoir description by integration of the field and laboratory data as well as in the development of quantitative reservoir models to aid performance predictions.

The three-year project was initiated in September 1993. In the first year, subcontractor agreements with the University of Texas and Stanford University were submitted, modified, and executed. Pecos Petroleum Engineering Inc. in Roswell, NM, was retained as the field site agent.

Preliminary work for the outcrop phase of this study included collecting aerial photos, geologic and topographic maps of the area, and driving the roads in the area to identify Queen outcrops that may be useful for our study. We chose for further work Queen outcrops containing rocks most closely resembling those seen in the Sulimar Queen core. Emphasis is being placed on outcrops having the potential for examination in three dimensions, particularly those with great areal exposure. Several trips were made to the field area, and a few promising outcrops were located.

A report on the diagenesis in the cored interval of Well 1-16 was prepared. Examination of this core demonstrates quite clearly the combination of depositional and diagenetic effects that served to create a hydrocarbon reservoir in the Sulimar Queen Field.

A sample of Sulimar Queen crude oil was obtained for laboratory evaluation of rock/fluid properties. Preliminary wettability testing of this oil sample has been conducted with a series of standard brines of fixed pH and ionic composition for comparison to other crude oils. Other measurements have been made to characterize the oil including density, viscosity, asphaltene content, and elemental analysis. Preliminary tests of adhesion and adsorption of Sulimar Queen oil on glass indicated that adhesion occurred at pH 6 and less for most of the range of ionic strengths investigated. Adsorption results were intermediate to water-wet on silica surfaces for NaCl brines and a synthetic reservoir brine.

As required by the Bureau of Land Management (BLM), a plan of operations for the Unit during the coming year was submitted and approved by the BLM in February 1994. The state production tapes for the

Sulimar Queen Unit were reformatted into a PC-based relational database, well logs were incorporated with the basemap, and the status of all the wells in the Sulimar Queen Unit was updated. The New Mexico Oil Conservation Division witnessed bradenhead tests in all injection wells in April 1994, and results of these tests ensured that all injectors are mechanically sound.

Static reservoir pressures for all wells in the unit were determined in early January 1994. These data serve as background information for the individual well and interwell tests that are scheduled. The PRRC pressure testing equipment and trailer were thoroughly evaluated, necessary replacement parts were ordered, and the equipment was refurbished and installed at the Sulimar Queen Unit for the pressure transient tests that are scheduled. An inverse drillstem test (DST) technique to estimate the flow capacity (permeability-thickness or kh product) has been conducted in the field, and the results indicate that this method can be used satisfactorily to estimate in-situ permeability.

Research has begun on the single-well wettability tracer test and on the crosswell seismic work. The crosswell field test is scheduled for December 1994.

EXECUTIVE SUMMARY

The purpose of this project is to conduct a variety of laboratory and field tests and utilize all the geological, geophysical, and engineering information to develop a mathematical model of the reservoir by the use of global optimization methods. This interdisciplinary effort will integrate advanced geoscience and reservoir engineering concepts to quantify interwell reservoir heterogeneity and the dynamics of fluid-rock and fluid-fluid interactions. The reservoir characterization includes geological methods (outcrop and reservoir rock studies), geophysical methods (interwell acoustic techniques), and other reservoir/hydrologic methodologies including analyses of pressure transient data, core studies, and tracer tests. The field testing is being conducted at the Sulimar Queen Unit with related laboratory testing at the PRRC on samples from the Sulimar site and Queen sandstone outcrops. The aim is to 1) characterize and quantify lithologic heterogeneity, 2) mathematically quantify changes in heterogeneity at various scales, 3) integrate the wide variety of data into a model that is jointly constrained by the interdisciplinary interpretive effort, and 4) help optimize petroleum recovery efficiencies.

Subcontractors from Stanford University and the University of Texas at Austin (UT) are collaborating on the project. Dr. Jerry Harris, Associate Professor in the Department of Geophysics at Stanford, will couple crosswell reflection imaging and interwell transmission tomography in a procedure not attempted previously on field data. Dr. Gary Pope, Director of the Center for Petroleum and Geosystems Engineering at the UT, will conduct further research and will design and interpret a single-well wettability tracer test developed in his laboratories but not yet field tested. Several members of the PRRC staff are participating in the development of improved reservoir description by integration of the field and laboratory data as well as in the development of quantitative reservoir models to aid performance predictions. This report provides results of the first year of the three-year project, initiated in September 1993.

INTRODUCTION

Understanding how heterogeneity between wellbores affects flow through reservoirs and quantifying the effects requires further developments in reservoir characterization. The integration of engineering and petrophysics with geology and geophysics through reservoir simulation is necessary to improve the ability to understand well-to-well type heterogeneity. In particular, there are opportunities to combine techniques such as pressure transient testing and tracers that can be directed at improved understanding of interwell reservoir heterogeneity. Some of these techniques are well known, but they are being expanded to provide new information: for example, a novel technique to look at wettability by the use of tracers. Other technologies are emerging in this area, especially pertaining to some of the geophysical means, such as crosswell tomography, as well as interdisciplinary approaches in reservoir management, and measures to quantify reservoir heterogeneity.

In order to maximize oil production from known reservoirs, an understanding of reservoir structures and the development of measures to characterize heterogeneities are essential. The physical phenomena involved with oil recovery have been relatively well understood for some time. Nevertheless, there have been disappointing gaps between laboratory, field, and computer research and the production of residual oil because of a lack of evaluating these techniques in controlled reservoirs and developing an understanding of the manner in which heterogeneities cause oil to be trapped. The scarcity of detailed reservoir data contributes to this break in continuity. A research field laboratory, available to the proposers of this project, and the synergism resulting from interdisciplinary research activities at a common site, presents a unique opportunity to conduct and validate the research needed for improved reservoir characterization.

DISCUSSION

PROJECT ADMINISTRATION, PLANNING, AND ANALYSIS

During the first year of the project, the project team was formed, and work on the project began. Subcontractor agreements with the University of Texas and Stanford University were prepared, submitted, modified, and executed. Pecos Petroleum Engineering Inc. in Roswell, NM, was retained as the field site agent responsible for the day-to-day management of the field site.

A proposal was submitted to the Reservoir and Recovery Forum to solicit industrial support for this project, and several oil companies have expressed interest. We will be forming an Industry Liaison Committee comprising company representatives from the industrial supporters.

In April 1994, the New Mexico Oil Conservation Division witnessed bradenhead tests in the injection wells that confirmed that all injectors in the Sulimar Queen Unit are mechanically sound. As required by the Bureau of Land Management (BLM), a plan of operations for the Unit during the coming year was submitted and approved by BLM.

Reservoir and production data were reviewed and reformatted as a basis for the site characterization work that will be conducted. A basemap of the field was constructed, the state production tapes for the Sulimar Queen Unit were reformatted into a PC-based relational database, well logs were incorporated with the basemap, and the status of all the wells in the Sulimar Queen Unit was updated. Production plots for each well in the field and for the entire field were prepared: total fluid vs. time, oil cut vs. time, oil rate vs. time, oil cut vs. cumulative oil, and oil rate vs. cumulative oil. All of the plots were copied and converted to a computer-assisted drafting format and were incorporated with the basemap for viewing and plotting purposes.

OUTCROP STUDIES

The Queen Formation crops out in south-central Eddy County, New Mexico. The goals of the outcrop portion of this study are 1) to ascertain if the Queen in outcrop is similar enough to the Queen in the subsurface to serve as a reservoir analogue, and 2) if so, to examine outcrops and characterize their lateral, vertical, and areal heterogeneity. Preliminary work for the outcrop phase of this study included collecting aerial photos, geologic and topographic maps of the area, and driving the roads in the area to identify Queen outcrops that may be useful for our study. We chose for further work Queen outcrops containing rocks most closely resembling those seen in the Sulimar Queen core. Emphasis was placed on outcrops having the potential for examination in three dimensions, particularly those with great areal exposure. Several suitable outcrops have been located; most are either in Rocky Arroyo to the northwest of Carlsbad, NM, or on the Queen Plateau southwest of Carlsbad.

Exposures along and adjacent to Rocky Arroyo (T-21-S, R-24-E) were chosen for the first detailed outcrop studies. There are several miles of Queen Formation that crop out in this area, primarily along the walls of Rocky Arroyo and the surrounding hills. The Queen section in this area contains the Shattuck sandstone, which is one of the productive units in the subsurface, along with over- and underlying dolomites; the contact with the overlying Seven Rivers Formation is well-exposed in this area. The Queen outcrops are relatively easily accessed by road—another reason for making Rocky Arroyo our first area of focus.

During the field work, we accomplished a number of objectives: 1) detailed measured sections were made of Queen outcrops at a number of locations to aid in distinguishing between various depositional units, which also might serve as flow units, 2) measurements of outcrop permeability were performed using a field minipermeameter loaned by TEMCO, Inc., and 3) rock samples were collected for further petrographic and petrophysical analyses.

Permeability in all samples is fairly low, ranging between 7 and 108 md, which is consistent with permeability measurements made on reservoir core samples. Generally, rocks with low permeabilities are of two types: finely laminated siltstones and shales, or massively-bedded and tightly cemented fine-grained sandstones. The permeability distribution does appear to be a function of depositional environment. Qualitative observations suggest that the sandstone units deposited in subaqueous environments show higher permeabilities than those deposited as eolian dunes, and the permeability heterogeneities are higher within units than between units.

A number of samples were collected from some of the measured sections for further permeability measurements and detailed study in the laboratory. Some of these samples will be thin-sectioned for petrographic study. This will enable us to determine if the Queen found in outcrop will serve as a suitable substitute for reservoir rocks in wettability studies and for detailed studies of rock heterogeneity. Depositional and diagenetic history of the Queen in the study area will also be determined from thin section examination.

It was believed that by making detailed measured sections at a number of locations in the area, it might be possible to determine the lateral extent of various units we noted within the Shattuck. Preliminary analysis of our data does indicate that most units are fairly continuous throughout the area of study, although they may vary in thickness. In a few areas we were actually able to study the rocks in three dimensions at a given outcrop, noting any changes in lithology and/or permeability in two directions laterally, as well as vertically.

The outcrop study of the Queen Formation in Eddy County will provide more quantitative information on the dimensions and geometries of the sand bodies, possible presence of barriers to fluid flow that might cause compartmentalization, distribution of permeability and porosity in three dimensions, and factors controlling their distributions.

DIAGENESIS STUDIES

Preserved reservoir core material is available from the Sulimar Queen Well #1-16 that the PRRC had drilled in 1990. Core obtained from the well consists of cyclically interbedded halite, anhydrite, sandstones, and siltstones deposited on the northwestern shelf of the Permian Basin during Guadalupian (Permian) time. Thin sections were made from this core material to investigate diagenesis in the cored interval of this well. Eighteen samples representing four of the major lithologies were examined, with emphasis being placed on the oil-bearing sandstone intervals.

Diagenesis of the Shattuck Member of the Queen Formation within the Sulimar Queen Field is very similar to that of other sandstone units within the Permian basin, and is in many ways analogous to modern-day diagenesis in the sabkha areas of the Persian Gulf. The core examined in this study records a transgressive event that, either through a lowering of sea level or increased clastic supply, produced a succession of lithologies ranging from fine-grained, probably subaqueously-deposited sands upwards into dolomite capped by interbedded evaporites and redbeds. Diagenetic minerals within the sequence include anhydrite, gypsum, halite, quartz, dolomite, feldspar, and rutile.

Early diagenetic events generally occluded primary porosity through precipitation of evaporite minerals, authigenic feldspar, and authigenic quartz; whereas, later events increased both porosity and permeability through dissolution of grains and cement. Oil emplacement may have actually occurred prior to optimum timing, as secondary porosity apparently increased following hydrocarbon migration into the reservoir. Examination of this core demonstrates quite clearly the combination of depositional and diagenetic effects that served to create a hydrocarbon reservoir in the Sulimar Queen Field.

WETTABILITY STUDIES

Wettability of combinations of crude oil, brine, and rock depends, in part, on the compositions of each of these three phases. Other factors that can influence wetting include spacial arrangement of these phases and the temperature and pressure during the long periods of aging in the reservoir. Of particular importance are the compositions of the interfacial regions, pore lining mineralogy and surface active components of crude oil and their equilibria with the brine phase.

Although studies are often intended to restore cores to reservoir wetting conditions, it is not really possible to duplicate conditions existing in the reservoir. Even if it were possible to overcome the geochemical hurdles, with fluid samples representative of the reservoir, unoxidized pore surface mineralogy, and the correct conditions of temperature and saturation, the aging times in laboratory experiments can never approach the geologic expanses of time during which reservoir wettability was established. Instead, the approach in this work is to investigate crude oil/brine/rock (COBR) interactions under a variety of conditions and, by comparison with other COBR systems, to make some estimate of the reservoir wetting. Studies of interactions, in order of increasing complexity, include 1) the oil/brine and solid/brine interfacial properties, 2) oil/brine/solid interactions observed on flat surfaces, and 3) oil/brine/solid interactions in porous media. Work during the first year of this project has concentrated on characterization of the crude oil, and on interactions in the first two categories.

Crude Oil Properties

A sample of Sulimar Queen crude oil was obtained in January 1994. Physical properties of the crude oil sample are listed in Table 1. Elemental ratios of the oil and of asphaltene precipitates, resulting from mixing with both n-pentane and n-heptane, are given in Table 2. The elemental ratio of H to C of 1.825 indicates that the Sulimar Queen is fairly paraffinic in composition, although there is also a significant amount of asphaltenic material. The sample, as received, is below the cloud point of the oil, and wax crystals can be observed microscopically.

Table 1. Physical Properties of Sulimar Queen Crude Oil

Viscosity at 25°C	7.06 cp
Density at 25°C	0.8381 g/ml
API Gravity	36°
Asphaltenes precipitated with 40:1	
n-pentane	4.071%
n-heptane	1.44%

Table 2. Elemental Analysis of Sulimar Queen Oil and Asphaltenes

Atomic ratio	crude oil	40:1 n-pentane asphaltenes	5:1 n-pentane asphaltenes	40:1 n-heptane asphaltenes
H/C	1.825	1.153	1.201	1.136
N/C	0.001	0.004	0.004	0.004
S/C	0.004	0.015	0.015	0.014
O/C	0.009	0.014	0.015	0.015

Oil/Brine Interfacial Tension

The crude oil/brine interfacial tension (IFT) reflects the concentration of surface active oil components at the interface. Some of these components are organic acids and bases which can exist as charged species when they are in contact with brine; interfacial tension can be further decreased depending on the interfacial charge.[1] The du Nouy ring method was used to measure IFT for NaCl brines of 0.1 and 1.0 *M* concentrations, with pH buffered from 4 to 9.5. The measurements, shown in Fig. 1, are for unequilibrated fluids.

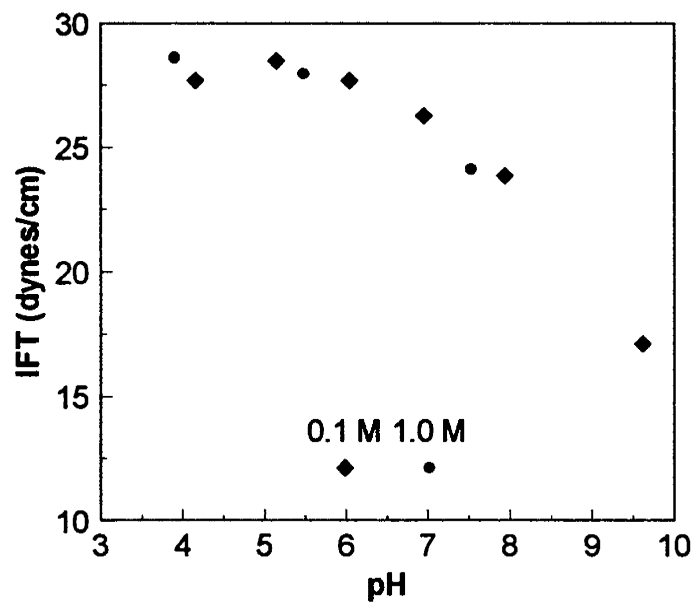

Fig. 1. IFT between Sulimar Queen crude oil and NaCl brines.

Fluid/Fluid/Solid Interactions—Flat Surfaces

Interactions between oil and water on flat surfaces are observed in two kinds of tests, distinguished primarily by the length of time allowed for crude oil contact with the solid. For either test, the solid is equilibrated with brine for at least a week before contact with oil. A short exposure of oil to solid is observed in the *adhesion* test. In this test, an oil drop is formed under the brine phase, then it is pressed against the solid for several minutes. Finally, the drop volume is reduced. Results, either adhesion of the oil drop to the surface, or either adhesion of the oil drop to the surface, or removal of oil back into the buret (referred_to as non-adhesion), can vary for a particular oil and solid surface, depending on the brine composition and temperature. When this test was performed with the Sulimar Queen oil and buffered NaCl brines at 25°C on glass microscope slides, the results, shown in Fig. 2, were comparable to many other crude oils studied by this method. Adhesion was observed at low pH (< 5 or 6) and non-adhesion at higher pH. For the lowest ionic strength, 0.01M, transitional behavior was observed up to a pH between 8 and 9.

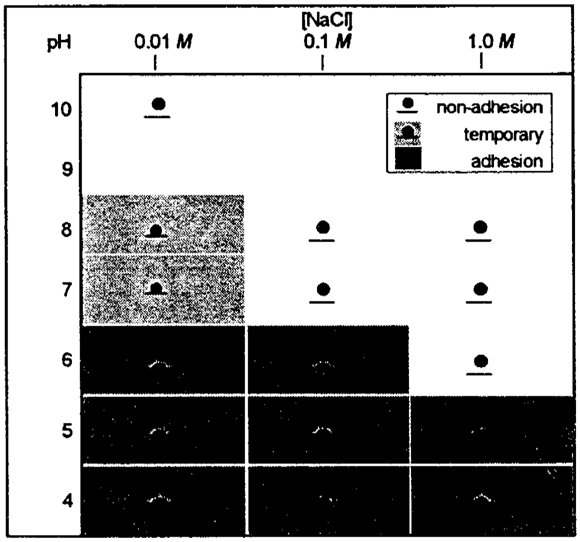

Fig. 2. Adhesion of Sulimar Queen crude oil at room temperature.

The composition of Sulimar Queen synthetic reservoir brine is given in Table 3. When this composition was tested, non-adhesion was observed both at 25°C and 32°C, the reservoir temperature.

Table 3. Composition of Sulimar Queen Synthetic Reservoir Brine

$NaHCO_3$	282 mg/L
Na_2SO_4	4,303 mg/L
$CaCl_2 \cdot 6H_2O$	7,776 mg/L
$MgCl_2 \cdot 6H_2O$	74,612 mg/L
NaCl	262,314 mg/L
TDS	307,712 mg/L
Ionic Strength	5.8 *M*
pH	6.2

Longer exposure of oil to solid is observed in an *adsorption* test.[2] The wetted glass slides are submerged in crude oil and aged for periods that can be as short as a few hours or as long as a month or more. After aging, the bulk oil is washed off the surface with toluene, and contact angles are measured between decane and distilled water in both water-advancing and water-receding directions. Before exposure to oil, the surfaces are strongly water-wet and contact angles are zero degrees. After exposure to the Sulimar Queen crude at 80°C for periods as long as three weeks, the water advancing contact angles vary from about 20 degrees to almost 100 degrees depending on the brine with which the surface was initially in contact, as shown in Fig. 3. Most of the receding angles were low, as observed for other crude oils. The advancing angles were lower than those observed for many other oils, especially for brines of intermediate pH.

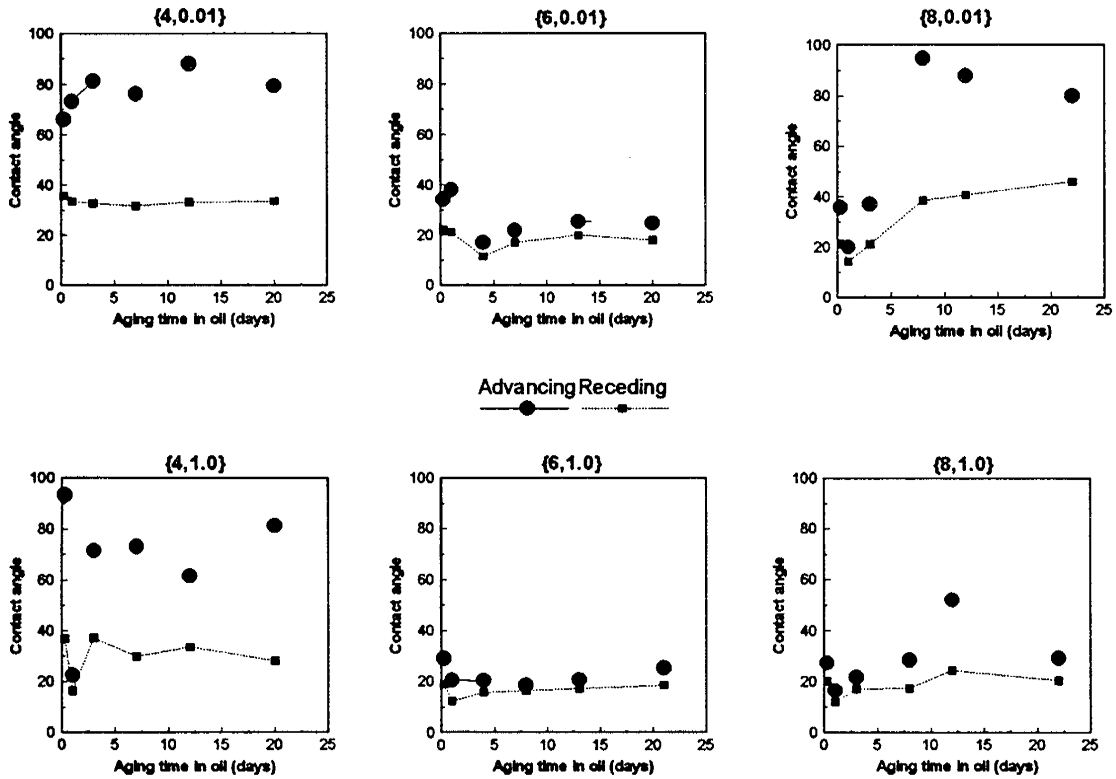

Fig. 3. Adsorption of Sulimar Queen crude oil on glass slides treated with NaCl brines.

Adsorption from Sulimar Queen crude at 32°C onto glass slides that were pretreated with the synthetic reservoir brine is shown in Fig. 4. Contact angles again remained fairly water-wet over the 3 weeks of aging in crude oil.

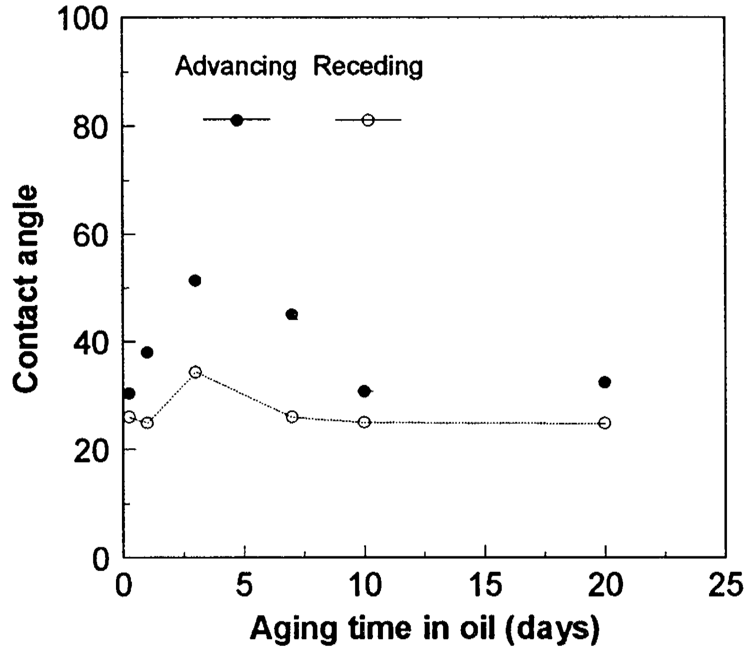

Fig. 4. Adsorption from Sulimar Queen crude oil onto glass pretreated with synthetic reservoir brine.

All of the observations with Sulimar Queen crude oil and glass surfaces (shown in previous work to be reasonable approximations for silica) suggest that this is not an oil that has a great propensity to alter wettability. Additional work with other kinds of flat surfaces and with porous media is needed, of course, to make these observations more general.

HYDROLOGIC AND TRACER RESEARCH (University of Texas)

Preliminary design calculations for a single-well wettability tracer test (SWWTT) were conducted. These calculations considered the behavior of both reactant and the product tracers, producing cuts, and bottomhole pressures under two different wetting conditions: strongly water-wet and strongly oil-wet conditions, as characterized by different relative permeabilities, capillary pressures, and residual phase saturations. For these simulations, we have considered both a homogeneous reservoir and a two-layer reservoir, using radial geometry and the average reservoir and fluid properties of the Sulimar Queen formation, producing at 94% water-cut. No fluid drift was considered, and capacitance was neglected.

As expected, these preliminary simulations show distinct and characteristic behavior of the tracers, producing cuts, and bottomhole pressures under different wetting conditions. However, many more questions remain before an optimal SWWTT design can be obtained; for example,

- End-point relative permeabilities and fluid saturations to be obtained from preserved core studies of the Sulimar Queen reservoir are very important since relative permeability is a wettability-dependent property.

- Wettability studies currently in progress at the PRRC (Task 2), part of which will focus on estimation of wettability in the area to be contacted by the SWWTT, alteration of wetting using reservoir core and fluids, and variation of wetting with geology and fluid saturation history.

- The maximum injection and withdrawal rates possible from the well from which the SWWTT will be conducted, since they will impact the total duration of the test and sampling-related issues.

We expect the issue on the maximum injection and production rates to be resolved with the completion of the single-well, pump-in, pump-out tracer test using sodium thiocyanate. This test is planned for December. We have also conducted some preliminary calculations to estimate the amount of tracer and the total duration of this test.

GEOPHYSICAL RESEARCH (Stanford University)

Crosswell imaging, as performed to date, has two separate and distinct steps: 1) traveltime inversion for velocity and 2) reflection imaging of amplitudes. Traveltime inversion normally uses rectangular pixels as velocity basis functions, whereas reflection imaging uses a 1-D stratified velocity model. Our goal in this project is to combine these two steps in an iterative manner that results in a more consistent model for both velocity and reflection amplitudes.

The objective of our traveltime inversion research is to develop a parameterization for seismic velocity that is consistent with the model required for amplitude reflection mapping. To this end, we have developed a nodal model wherein the velocity is determined on an irregularly spaced grid of nodes. The code has been written and tested on synthetic data. We plan to test existing field data this next quarter. The final phase of this particular effort is to develop a pre-processor to adaptively select the location of the nodes on the basis of heterogeneity or ray coverage, or other consideration.

FIELD TESTS

All of the field tests conducted for this project will be conducted at the Sulimar Queen Unit, operated by Tech Oilfield Research Corporation. Well locations at the primary test area are shown in Fig. 5. Most of the tests will be conducted in Well 1-16, a new producing well, and in Well 1-3, an old injector.

Static reservoir pressures for all wells in the unit were determined in early January 1994. These data serve as background information for the individual well and interwell tests that are scheduled. The PRRC pressure testing equipment and trailer were thoroughly evaluated, and necessary replacement parts were ordered. This equipment was refurbished and installed at the Sulimar Queen Unit for the pressure transient tests that are scheduled.

An inverse drillstem test (DST) technique was investigated to enable the estimation of flow capacity (permeability-thickness or kh product). Permeability data are needed to characterize the Sulimar Queen reservoir, and estimating permeability from pressure buildup tests using an automatic acoustic fluid level device to monitor bottomhole pressure has not been satisfactory. Because of low bottomhole pressures and low permeabilities, buildup periods of more than a week would be required to collect satisfactory test data.

In addition, most of the wells at the Sulimar Queen Unit are temporarily abandoned and many do not have pumping equipment. Therefore, the inverse DST, similar to "slug testing" used by hydrologists, was explored as a suitable means of providing the required permeability data.

In a conventional DST, a packer is set to relieve the prospective producing formation of static mud pressure, a valve is opened to permit formation fluids to enter the drill pipe, and the valve is closed to allow pressure buildup. In an inverse DST, the pressure change is monitored when the casing or tubing of a shut-in well is loaded with water and during the pressure decline period after the loading is ceased.

Inverse DSTs were conducted at the Sulimar Queen Unit in Injection Well 1-2 and Producing Well 1-16. This well pair will be used for the interwell tracer test and for the crosswell imaging test. A truck was used at Well 1-16 to load the wellbore with fresh water, and loading the tubing at Well 1-2 was accomplished with an available fresh water line. An automatic acoustic fluid level device was used to record the bottomhole pressures when the inverse DST tests were conducted. Well 1-16 is a shut-in pumping well where loading was down the annulus and pressure was measured via fluid levels.

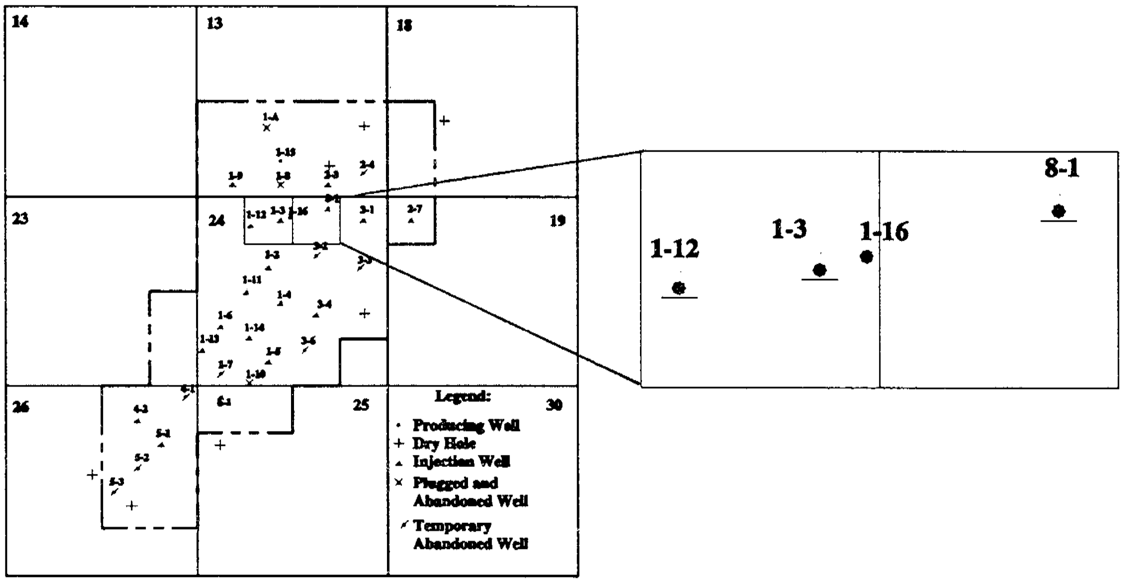

Fig. 5. Well locations and test area in Sulimar Queen Unit.

The procedures for analyzing results from the inverse DST test have been discussed in a previous report.[3] From the tests that have been conducted, it appears that the inverse-DST method can be satisfactorily used to estimate permeability. The optimum procedure for loading the wells was evaluated and the proper setting for pressure tolerance and power source filtering of the pressure-time recording equipment were defined. The pressure history during the inverse DST in Well 1-2 is shown in Fig. 6, and the semilog plot used for type curve matching is shown in Fig. 7. Results from Well 1-2 provided a permeability estimate of 5.7 md with a skin of 2.7. Well 1-16 was tested without wellhead pressure, and permeability was estimated to be 4.5 md with a 2.6 skin. Core analysis data[4] collected in 1990 suggest the permeability in the productive interval might be in the 10-23 md range, with the median core permeability of about 3 md. Thus, the permeabilities obtained with the inverse DST method seem to be reasonable estimates.

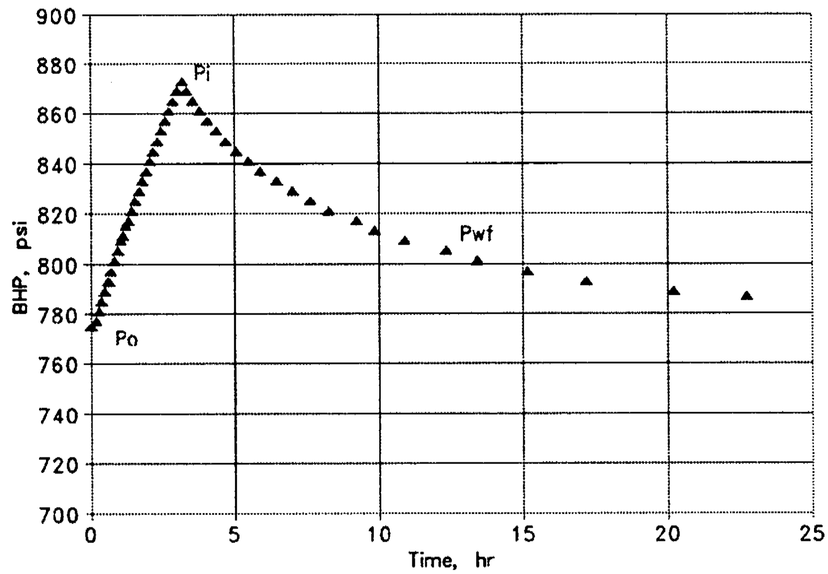

Fig. 6. Well 1-2 inverse-DST history.

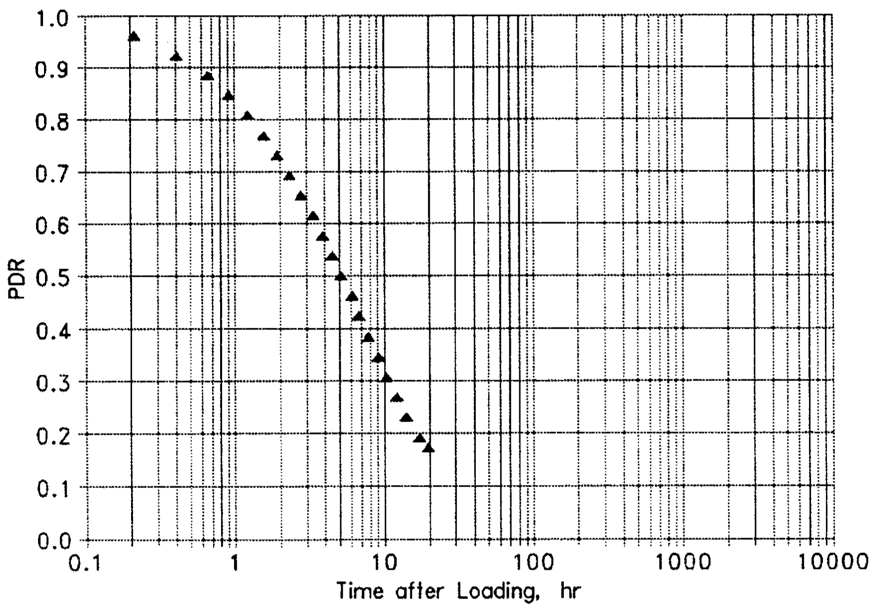

Fig. 7. Well 1-2 semi-log type curve.

FUTURE RESEARCH PLANS

Wettability studies will focus on tests of reservoir core. Horizontal plugs of the preserved reservoir core will be cut and various cleaning and restoration procedures applied.

In the geophysical research area, development of the inversion/imaging algorithm will continue. Our major effort over the next few months will be to plan and carry out the crosswell field experiment at the Sulimar Queen site. The field contractor, TomoSeis, has submitted a cost estimate for acquisition and standard turnaround processing. Stanford will do "research" processing over the next year. The TomoSeis estimate is to be revised to include a small set of well logs and well deviation surveys. The interwell seismic field work is scheduled for mid-December, the field experiment should be completed in four days or less.

New signal transmitting cable and transducers were ordered for the PRRC pressure testing equipment. It is anticipated that the multi-well pressure testing will be done in the first quarter of 1995. The single-well pump-in/pump-out tracer test is planned for December 1994, and the interwell tracer tests for heterogeneity characterization will be scheduled for early 1995. The in-situ wettability field test will be scheduled after the single-well and interwell tracer tests are completed.

REFERENCES

1. Buckley, J.S.: "Chemistry of the Crude Oil/Brine Interface," presented at the 1994 International Symposium on Reservoir Wettability and Its Effect on Oil Recovery, Laramie, WY, Sept. 21-23.

2. Liu, Y. and Buckley, J.S.: "Wetting Alteration by Adsorption from Crude Oil," paper SPE 28970 to be presented at the 1995 International Symposium on Oilfield Chemistry, San Antonio, Feb. 14-17.

3. Martin, F.D., Buckley, J.S., Weiss, W.W., and Ouenes, A.: Quarterly Progress Report: "Integration of Advanced Geoscience and Engineering Techniques to Quantify Inter-Well Heterogeneity," Contract No. DE-AC22-93BC14893, July 1994.

4. Martin, F.D. and Weiss, W.W.: "Planning Phase for the New Mexico Improved Oil Recovery Project," final report, Contract No. DE-FG07-89ID12872, June 1991.

☆U.S. GOVERNMENT PRINTING OFFICE: 1995 - 660-029/20023