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**ANISOTROPY AND SPATIAL VARIATION OF RELATIVE
PERMEABILITY AND LITHOLOGIC CHARACTER OF
TENSLEEP SANDSTONE RESERVOIRS IN THE
BIGHORN AND WIND RIVER BASINS,
WYOMING**

D.O.E. Contract No. DE-AC22-93BC14897

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First Quarterly Technical Progress Report

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Objectives

This multidisciplinary study is designed to provide improvements in advanced reservoir characterization techniques. This goal is to be accomplished through: (1) an examination of the spatial variation and anisotropy of relative permeability in the Tensleep Sandstone reservoirs of Wyoming; (2) the placement of that variation and anisotropy into paleogeographic, depositional, and diagenetic frameworks; (3) the development of pore-system imagery techniques for the calculation of relative permeability; and (4) reservoir simulations testing the impact of relative permeability anisotropy and spatial variation on Tensleep Sandstone reservoir enhanced oil recovery.

Concurrent efforts are aimed at understanding the spatial and dynamic alteration in sandstone reservoirs that is caused by rock-fluid interaction during CO₂ enhanced oil recovery processes. The work focuses on quantifying the interrelationship of fluid-rock interaction with lithologic characterization in terms of changes in relative permeability, wettability, and pore structure, and with fluid characterization in terms of changes in chemical composition and fluid properties. This work will establish new criteria for the susceptibility of Tensleep Sandstone reservoirs to formation alteration that results in a change in relative permeability and wellbore scale damage. This task will be accomplished by flow experiments using core material; examination of regional trends in water chemistry; examination of local water chemistry trends on the scale of a field; and chemical modeling of the reservoir and experimental systems in order to scale-up the experiments to reservoir conditions.

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Progress Summary

Work has begun on each of the three technical tasks and the fourth administrative task, Project Management. The effort has focused on acquisition of the necessary databases, acquisition and construction of the relative permeability apparatus, initial development of the design for the CO₂ flood experiments, and assembly of the necessary scientific and administrative staff. The contract effort has been strengthened by the creation of the Institute for Energy Research (IER) at the University of Wyoming. The University Trustees gave their approval for the Institute in October 1993. The IER is a research and instructional organization devoted to basic and applied research in oil and gas exploration and production. Dr. Ron C. Surdam, Professor of Geology and a coinvestigator on this contract is the Director of the Institute. The Institute will provide administrative infrastructure and office space for the staff working under this contract. The Institute provides an advanced working environment for engineers, geologists, geochemists, and mathematicians.

TASK 1.0 — REGIONAL FRAMEWORKS. This research will associate spatial distributions and anisotropy of relative permeability with the depositional subfacies and zones of diagenetic alteration found within the Tensleep Sandstone. The associations between depositional lithofacies, diagenetic alteration, and pore geometry will strongly link relative permeability with the distinct and measurable dimensions of lithofacies and authigenic mineral facies. Effects of the depositional processes and burial diagenesis will be investigated.

The Institute for Energy Research has obtained the Dwight's historical database for the Bighorn and Wind River Basins. This information serves as a basis for base maps of the Tensleep. A decision to purchase the production

database is pending. Work is in progress in sorting and loading the relevant data into OGCI's PRODUCTION ANALYST software. This will be one of the principle systems used to analyze and output the regional frameworks. Both the program and the database are in place. Partial listings of Tensleep Formation cores from two core repositories have been obtained. Core examination will begin after the first of the year. The September 15, 1993 contract starting date precluded extensive field work until early summer, 1994. A reconnaissance of the western side of the Bighorn Mountains and the northeastern Owl Creek Mountains was performed. The Tensleep is extensively exposed along the ranges, typically in steeply dipping hogbacks and excised canyons along the Bighorn Mountains and as barrier cliffs in the Owl Creek Mountains. In anticipation of the summer field sampling program, a gasoline powered, small-diameter coring device was constructed. This device will be used in conjunction with other IER projects.

TASK 2.0 — RELATIVE PERMEABILITY MEASUREMENTS. The focus of this task is to obtain quantitative laboratory data on the magnitude and variability of relative permeability anisotropy and spatial variation of the dominant reservoir and boundary surface lithologies of the Tensleep Sandstone. Existing data will be collected, compiled, and placed within the regional frameworks constructed in Task 1.0. Laboratory measurements will be performed in the Petroleum Engineering Department at the University of Wyoming. Relative permeability will be measured using the unsteady-state technique. An additional objective of this study is to provide algorithms for calculating relative permeability from quantitative pore imagery data.

The major engineering effort has been the configuration of a laboratory apparatus capable of making the necessary measurements for the research contract. Along with this effort, we have reviewed published material on relative permeability determination and selected the technique to be used in this study.

For relative permeability laboratory experiments, we have decided to use the unsteady-state technique, commonly referred to as the JBN method

(Johnson, Bossler, and Naumann, 1959). Numerous more recent studies have also been based upon the fundamental JBN process. Jones and Roszelle (1978) presented graphical techniques for extrapolating both saturation and relative permeability from the same linear displacement curve. And Willhite (1986) incorporated these methods into a commonly used textbook on waterflooding. The use of JBN allows us to compare our laboratory measurements with previously published work. In particular, Morrow (1973, 1991) has recorded impressive quantities of two-phase flow experiments. Dr. Morrow has joined the faculty here at University of Wyoming, and we will be interacting directly in the laboratory. The effects of wettability of relative permeability measurements are particularly important (Anderson, 1987). The interaction with Dr. Morrow will be extremely useful for this relative permeability anisotropy research.

We have decided to build a new apparatus, modeled after an active apparatus used by Dr. Morrow, and have ordered the necessary equipment. Also on order is an assortment of tubing, valves, and connections, and a critical item, a constant-rate fluid pump. Past experience with unsteady-state relative permeability tests has indicated that the flow rate must be maintained at a precisely constant level, irrespective of pressure and temperature. The pump on order has a temperature control confinement, and is specified to maintain constant rate to 0.1% up to 10,000 psi on a single syringe displacement piston. Construction will begin in the second quarter of this contract.

Relative permeability computed from our laboratory displacement experiments will allow comparison of our results with previously published results. However, the investigation of anisotropy will not necessarily require actual relative permeability calculations. Laboratory data directly provides measurements of fractional (water-cut) flow only, which can then interpreted to yield relative permeability data. By using the JBN technique in this investigation, we will be able to look for anisotropy effects with more than just

relative permeability. Raw laboratory data will be in terms of pore volume injected versus average core saturation. It can be shown that variations in relative permeability are necessarily a result of variations in the first derivative of a pore-volume-versus-saturation curve. In this way, a minimum number of assumptions and calculations will be needed to examine relative permeability anisotropy.

TASK 3.0. CO₂ FLOOD — FORMATION ALTERATION AND WELLBORE DAMAGE. The work of this task is to establish criteria for susceptibility of Tensleep reservoirs to formation alteration resulting in a change in absolute or relative permeability and/or possible wellbore scale damage during CO₂ enhanced oil recovery. This advanced reservoir characterization technology will be used to optimize recovery efficiencies. This task includes: (a) flow experiments on core material to examine the effects of CO₂ flooding on the alteration of the fluid and rock system; (b) examination of regional trends in water chemistry; (c) examination of local water chemistry trends on the scale of a field; and (d) chemical modeling of both the reservoir and experimental systems in order to scale-up the experiments to reservoir conditions.

The task leader and principal author of this task, Dr. L. K. Smith, has taken a position at a petroleum industry research laboratory. Dr. Dunn will assume the duties of the task leader for Task 3.0. In order to retain Dr. Smith's expertise and familiarity with the program, we are attempting to retain Dr. Smith as an additional Industry Advisor/Mentor. This would allow her continued participation and guidance of this task.

Drs. Smith and Dunn met with the research staff at the Marathon Oil Company Petroleum Technology Center in Littleton, Colorado in order to initiate the experimental design phase of Task 3.0. The first experiment is scheduled to commence in May, 1994. The design is being iteratively constructed and reviewed by the task leader, advisor/mentors and the research staff at Marathon's facility. The regional water database construction is initially using data available through the Wyoming Geological Survey.

TASK 4.0 — PROJECT MANAGEMENT & TECHNICAL TRANSFER. This task incorporates the efforts to achieve a high level of success in this interdisciplinary project. This administrative task provides for effective coordination and integration of the project's research tasks. The program manager is responsible for ensuring the task workers meet on a frequent and regular basis to exchange information and discuss results. The program manager is responsible for the coordination and timely reporting of results to its Industry Advisor/Mentors, the Department of Energy, and the scientific and engineering communities.

Administrative duties performed include the preparation of the Once After Award documents required by the Department of Energy (Management Plan, Cost Plan, Work Plan, Travel Plan, Milestone Schedule Log and Plan, etc.), and the creation of an Associate Research Scientist position. The position was necessary to accommodate the redistribution of responsibilities as a result of Dr. Smith's departure. Currently, the position is open. The University of Wyoming is an Equal Opportunity/Affirmative Action Employer. An engineering undergraduate has been hired to help assemble, test, and run the relative permeability apparatus. An engineering graduate student will arrive sometime prior to the beginning of the 1994 fall semester to work on Task 2.0. An undergraduate geology student will be hired after the holidays to help assemble the data for Task 1.0. An Office Technician has been hired (half time) to perform accounting and general office duties. This small administrative staff will be in place December 28. The Project Director has been in contact with each of the Industry Advisor/Mentors.

THE INSTITUTE FOR ENERGY RESEARCH. The Institute for Energy Research (IER) at the University of Wyoming is a multidisciplinary organization devoted to basic and applied research in oil and gas exploration and production. The goals of the IER are to develop innovative conceptual and technological solutions to problems related to exploration for and production of energy resources, to enhance applied energy research in the State of Wyoming, and to create a context for graduate education in the area of energy research at the University of Wyoming, particularly with respect to interdisciplinary

research efforts. The IER was created in response to state and national initiatives for research and development in domestic hydrocarbon exploration and production. The Institute has current contracts and grants providing nearly three million dollars in yearly funding. The mission of the Institute includes the development, support, and maintenance of an infrastructure at the University of Wyoming for energy research. Some examples of ongoing programs are: development of hydrocarbon production techniques that minimize formation damage and improve recovery technology; improvement of exploitation strategies through reservoir characterization; development of exploration methodologies that enhance the predictive modeling of hydrocarbon maturation, migration, and trapping; construction of new technologies necessary to detect, delineate, and exploit unconventional oil and gas accumulations; and development of numeric models for the analysis of basin development, petroleum accumulation, and hydrocarbon production.

Most importantly, all of these tasks bear directly on the future economic health and well-being of the energy industry in the State of Wyoming. The Institute will be the focal point for information on energy resource evaluation and development in Rocky Mountain basins.

The Institute will provide major support for energy research in Wyoming by expanding the funding base by continuing to seek additional federal funding, nonfederal nonprofit funds, and industrial partnerships; will assist in establishing the University of Wyoming as a state-wide center for both the development of new energy related technology, and the exchange of ideas and information; and will fulfill a domestic research and technology-development void left by ever-increasing industrial focus on foreign energy resources.

Success in delineating new domestic energy reserves is critically important to the Wyoming State economy because the state government receipts are directly tied to the hydrocarbon industry's production. As a consequence, Wyoming's future is directly related to the health of the mineral

industry, or to the rate at which new energy resources are discovered and added to the state's reserves. The IER at the University of Wyoming was created so that a well qualified, motivated, multidisciplinary team can begin to solve the energy problems facing our state — converting energy resources to commercial reserves through reducing exploration risk and increasing profitability.

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