KFAS

ALTERNATIVE ENERGY SOURCES

Part A

Edited by

Jamal T. Manassah

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Sponsored by

KFAS KUWAIT FOUNDATION for the ADVANCEMENT OF SCIENCES

ACADEMIC PRESS 1981
A Subsidiary of Harcourt Brace Jovanovich, Publishers
NEW YORK LONDON TORONTO SYDNEY SAN FRANCISCO

ACADEMIC PRESS RAPID MANUSCRIPT REPRODUCTION

Proceedings of a Symposium on Alternative Energy Sources, held in Kuwait, February, 1980.
International Symposium Series of the Kuwait Foundation for the Advancement of Sciences (KFAS).

ACADEMIC PRESS, INC.
111 Fifth Avenue, New York, New York 10003

United Kingdom Edition published by
ACADEMIC PRESS, INC. (LONDON) LTD.
24/28 Oval Road, London NW1 7DX

Library of Congress Cataloging in Publication Data

Main entry under title:

Alternative energy sources.

Proceedings of a symposium sponsored by the Kuwait Foundation for the Advancement of Sciences, and held in Kuwait Feb.9-13, 1980.
1. Renewable energy sources–Congresses. 2. Power resources–Congresses. I. Manassah, Jamal T. II. Kuwait foundation for the Advancement of Sciences.
TJ163 15 A46 662 6 80-27710
ISBN 0-12-467101-2 (Cloth)
ISBN 0-12-467121-7 (Paper) Part A

PRINTED IN THE UNITED STATES OF AMERICA

81 82 83 84 9 8 7 6 5 4 3 2 1

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PREFACE

This text has been assembled from the proceedings of the "Alternative Energy Sources Symposium of the International Symposium Series of the Kuwait Foundation for the Advancement of Sciences (KFAS)" that was held in Kuwait in February 1980.

The focus of this symposium was to review and assess those technologies that presently complement and will most likely substitute in the future for oil and gas extracted by conventional techniques. This text includes the state of the art of these technologies as seen by experts in their respective disciplines.

In the coverage of the technologies presented, an attempt has been made to include present developed technologies and those under development. As a consequence, the level of detail in each presentation is appropriate to the developmental stage of the technology under consideration, as assessed by the author. In general, the papers covering proven or nearly proven technologies mostly consist of detailed and or comparative assessments of the diverse engineering schemes without unduly dwelling on basics, while papers addressing technologies under development review the theoretical basis of these technologies in some details. In all instances where meaningful economics are available, numbers are included.

This text also includes review papers of electric storage technology and transportation and energy, topics that, along with conservation, affect most strategic energy planning for the foreseeable future. The text also includes economics methodology and economical development papers that will hopefully allow researchers in the energy field access to the more common tools and approaches of the economic and financial analysts and the international development economists.

During the symposium, participants were also invited to address the following questions in roundtable discussions:

- the role to be played by the Arab countries in the development of alternative energy sources technologies.
- the prioritization to be accorded to each such technology, i.e., to develop a strategy for deciding which technologies should be transferred, adapted, or developed;
- the infrastructure required for the execution of this strategy; and
- the techniques and operational steps to be adopted for implementing this strategy.

The summary of these discussions comprises the subject of a separate publication (Alternate Energy Sources Symposium, Summary Report, Jamal T. Manassah, KFAS).

This text and the symposium would not have been possible without the generous support of KFAS Board of Directors and the personal encouragement of H. H. Sheikh Jaber Al-Ahmed AL-SABAH, Chairman of the Board, Dr. Adnan Al-Aqeel, the Director General, and KFAS member companies. To all these, I am grateful.

Special appreciation is also directed to the KFAS staff for helping me complete this task.

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CONTENTS

ENHANCED OIL RECOVERY

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ABSTRACT

The Enhanced Oil Recovery (EOR) processes are techniques for mobilizing the residual oil that cannot be recovered by water flood, gas injection, or primary production means.

This paper reviews the current status of laboratory experimental studies, theoretical research, and critical field pilot applications for the major types of EOR. Review and technical assessment are presented for the following types of EOR:

- Micellar surfactant polymer floods
- Alkaline floods
- Polymer floods
- Carbon dioxide floods
- Thermal methods, including:

    1. In situ combustion
    2. Combined thermal drive
    3. Steam drive
    4. Steam soaking
    5. Combined methods
    6. Miscible phase flood
    7. Stimulation method

The cost and economic studies that have been made on EOR processes are also reviewed.

This paper also estimates the long-range probable EOR production for the 1985-2000 period.

ISBN 0-12-467101-2

1.0 Introduction

This paper reviews the current status of laboratory experimental studies, theoretical research, and critical field pilot applications for the major types of Enhanced Oil Recovery.

The number of field applications of enhanced oil recovery (EOR) processes are increasing rapidly in response to higher oil prices and the improving technology that results from the extensive Government/Industry Research and Development programs begun in the 1974/75 period.

In 1975, the active Enhanced Oil Recovery projects in the U.S.A. were 156, made up of 106 Thermal Drive (21 Combustion, 54 Steam Soak, and 31 Steam Drive), 13 Micellar Surfactant, 13 Polymer, 1 Caustic, 9 Carbon Dioxide, and 13 Miscible Hydrocarbon.

In 1976, there were 24 Enhanced Oil Recovery projects active in Canada, 51 Thermal Drive projects in Venezuela, and 17 Enhanced Oil Recovery projects in other countries. The number of projects underway in 1979 is not known, but, in the U.S.A. at least, there has been a large increase in the level of activity in all types of Enhanced Oil Recovery compared with 1976.

Cost and economic studies that have been made on Enhanced Oil Recovery processes are also reviewed in this paper. The literature sometimes refers to Enhanced Oil Recovery as Tertiary Oil Recovery. We used the more generally accepted term Enhanced Oil Recovery.

2.0 Definition of Enhanced Oil Recovery (EOR) Processes

After discovery of an oil reservoir; production first takes place during the primary production, or natural depletion phase. Typically, 10 to 30 percent of the oil in situ in the reservoir rocks will be recovered. Natural depletion occurs under the forces of gas and rock expansion as pressure is reduced, gravity drainage, and natural water influx.

Beginning in the 1930s production methods were developed to increase oil recovery. The main technique was water flooding. Gas injection was also developed. A successful water flood may produce 50 to 60 percent of the oil in situ in the reservoir rocks under near ideal conditions. Because of the low mobility ratio of water relative to oil, water floods normally recover more oil than gas injection. The mobility ratio is the permeability of the reservoir to water divided by the viscosity of water, divided by the same term for the oil phase.

Because of non-uniformities in the reservoir sands, or rocks, the water often does not maintain a stable front. Water is lost into channels, into coning, and fingering. The efficiency with which the water flood enters the pores containing oil in every rock volume of the reservoir is called the sweep efficiency. When sweep efficiency approaches 100 percent, oil recovery will normally be in the 50 - 60 percent range. The water continues to flow through the porous rock volume; however, no more oil is produced from the volume. The residual oil is immobile. It may be located in small pores where interfacial tension forces are balanced against the driving force of the water flood. Also, even in channels where water is flowing, there is an equilibrium liquid oil held by the rock capillary forces, or that reaches equilibrium with the water velocities.

Gas injection is generally a more difficult operation because of the high mobility ratio of gas relative to oil or water. This leads to gas breakthrough and channeling with resulting poor sweep efficiency. Thus, many reservoirs cannot benefit from gas injection.

The enhanced oil recovery processes (EOR) are techniques for mobilizing the residual oil that cannot be recovered by water flood, gas injection, or primary production means. Intensive work on EOR began in the 1974/75 period when Research and Development funds were approved by the U.S. Congress, and DOE (Department of Energy) sponsored research programs were initiated. This work is beginning to bear fruit with over one hundred field pilot EOR projects underway or in design, as well as intensive laboratory and theoretical research programs. A recent economic analysis indicates that Government funding at ten times the present level would lead to 4 million BPD EOR production in 1985/90. This study will be reviewed in a later section.

EOR techniques and processes were experimented with starting twenty years ago. The concept of the micellar polymer floods were originated by Marathon and Union Oil companies in the 1960s. Approximately eighty patents have been taken out. The techniques of thermal recovery are part of EOR. Several thermal recovery projects using different processes have been in production since 1960. However, large scale research, both in thermal recovery fundamentals and field applications, is now underway with DOE support. A commercial carbon dioxide flood began in the early 1970s.

3.0 The Types of Enhanced Oil Recovery (EOR)

Current research and development, field pilot applications, and full scale projects, are going on in the following areas of EOR:

3.1 Micellar Surfactant Polymer Floods

These processes are based on a sequence of flooding operations: (1) the salinity of the reservoir in situ water (connate water) is adjusted by a fresh or low salinity preflush water flood. (2) This flooding is followed by the injection of a carefully designed and controlled chemical slug made up of surfactants and cosurfactants, such as sulfonates and long chain alcohols; as example, amyl alcohol. The action of this slug will be discussed in detail later on. Essentially, a microemulsion is formed between the oil, water, and chemical flood, in which the interfacial tension forces previously holding the oil immobile are reduced essentially to zero (ultralow). The velocity forces of the flood, plus buoyancy forces now able to act, force the oil to flow toward the producing well. (3) Following this slug, a large slug of polymers mixed in water with careful quality control to assure high viscosity are injected. The polymers increase the viscosity of the water flood and reduce the mobility ratio. This enables the flood to penetrate into smaller pores and increase sweep efficiency. It also may bridge larger pores where channeling would occur with water alone. The higher pressure drops required to flow the high viscosity fluid helps to mobilize the oil water emulsions. The polymer slug is tapered with the concentration of polymer normally decreasing with time in a logarithmic fashion. (4) Chase water flood then follows for a sufficient number of pore volumes to remove all residual oil mobilized.

3.2 Alkaline Flood

Because of the expense of the chemicals required for the micellar-polymer flood, a lot of research is devoted to finding cheaper chemical floods. The alkaline flood using sodium hydroxide and adjusted salinities is now under study in the laboratory and in the pilot flood stage.

3.3 Polymer Flood

Polymer floods are generally viewed as a way of improving water floods. The increased viscosity of the water/polymer mixture reduces the mobility ratio; thereby, increasing sweep efficiency and pressure drop in the reservoir. The polymers also serve to bridge channels and fissures; thus, reducing water loss and improving efficiency. Polymer flooding would not be expected to reduce residual oil saturation after conventional water flooding to the low levels that are hoped for in micellar surfactant polymer flooding.

3.4 Carbon Dioxide Flood

Extensive research studies are underway to determine how a CO_2 flood works and where it can be profitably applied. There are already commercial applications. When operating at reservoir temperatures where carbon dioxide is supercritical, the flood proceeds by miscible displacement. The oil and carbon dioxide mix to give a supercritical mixture which has very low surface tension and flows readily. This requires pressure levels in the reservoir that will create the supercritical gas. However, care must be taken to prevent parting of the formation. Recent experiments in low temperature reservoirs indicate that the carbon dioxide is effective in its liquid phase.

3.5 Thermal Methods

Several successful thermal methods are now in operation. The different techniques are being studied in pilot floods and fundamental research is underway. There is a need to determine where the thermal techniques are best applied. The main techniques now in use are described below.

3.5.1 In Situ Combustion

The air is injected under pressure into injection wells optimally located with respect to several producers. A down hole heater raises temperature at the sand face to approximately 600 — 700°F. The oil ignites in the immediate vicinity of the well. By controlling the rate of air injection and the pressures, the heat generated is transferred as temperature gradients throughout the surrounding area. Applications are normally in fields with low API gravity and very high viscosities. As the temperature is raised in the area, the viscosity decreases. The burning front moves oil under thermal gradient to the wells. Down hole heaters are often placed in the producing wells to maintain the temperature of the oil that arrives.

3.5.2 Combined Thermal Drive

Here water is injected periodically, while in situ combustion goes on. The water is converted to superheated steam in the burned rock section. It then passes through the fire front, and, after reaching the lower temperature areas in front of the fire front, it condenses to water forming a hot water flood which gives improved efficiency to the entire process.

3.5.3 Steam Drive

Steam generating plants are provided at the surface and high pressure supersaturated steam is injected. The producing wells are located nearby and benefit from the hot oil. Later, water breaks through and a cycling process combining thermal and water flood effects may be established.

3.5.4 Steam Soaking

The steam generator is moved to a producing oil well. Steam is injected in the oil well itself for a period of days. The well is shut in and allowed to stabilize. The well is then opened up and is produced for a period of time or until its production stops. The steam injection process is then repeated.

3.5.5 Combined Methods

There are many combinations of thermal drive; as example, in situ combustion in the lower part of the zone with water injection in the upper part. Other gases like nitrogen or carbon dioxide may be injected.

3.5.6 Miscible Phase Floods

Research is underway to lower the cost of enhanced oil recovery floods. A miscible phase theoretically can be established with a wide variety of gases and a given oil. The liquid banks of condensed gases will have miscible effects with the oil. Therefore, research is underway on the use of lower grade gases than carbon dioxide, such as, gas mixtures of hydrogen sulfide, carbon dioxide, methane, and others, such as flue gases. These are forms of enriched gas injection.

3.5.7 Stimulation Methods

Stimulation Methods enhance recovery of oil from the producing wells themselves and their surrounding regions. Examples are the foam fracturing techniques and the polymer gel treatment of wells in which water zones are bridged off by polymeric action.

4.0 Micellar Surfactant-Polymer Floods

4.1 Entrapment and Mobilization Correlating Parameters

Systematic research is underway on the entrapment and mobilization of residual oil by Morrow, et al. (1). The three problems under study are:

1. The mechanisms of entrapment and mobilization.

2. Development of correlations of the Capillary Number (the ratio of viscous to capillary forces) and the Bond Number (ratio of gravity to capillary forces).

3. Correction of well bore in situ residual oil saturations to the values actually in the reservoir.

Entrapment mechanisms determine the proportion of oil that is recovered from the wet zone. The fraction that can be produced is one main criteria of an EOR process. The conventional methods of determining residual oil by resistivity logs or laboratory core water flooding are not accurate enough for evaluating the formation for an EOR process. The region around the well bore normally has been stripped of residual oil because high pressure gradients during production enable the viscous forces to overcome the capillary retaining forces.

Entrapment and mobilization mechanisms control recovery by causing low flow rates, and preventing ultralow interfacial tension. The ratios of viscous to capillary forces are high when interfacial tensions are very low. Development of a continuously mobile oil bank means that entrapped oil must be mobilized to form a continuous bank which gathers low residual oil as it advances. Interfacial tension exists between the micellar bank and the oil, and between the micellar fluid and the aqueous polymer bank used to push the micellar fluid. Any entrapment of oil by the micellar bank, or of the micellar fluid by the polymer bank, would cause the process to fail. Figure 1 shows conditions of entrapment and mobilization.

An important finding about the displacement mechanisms when interfacial tensions are ultralow and flood flow rates are typically low is that buoyancy forces may have an important influence.

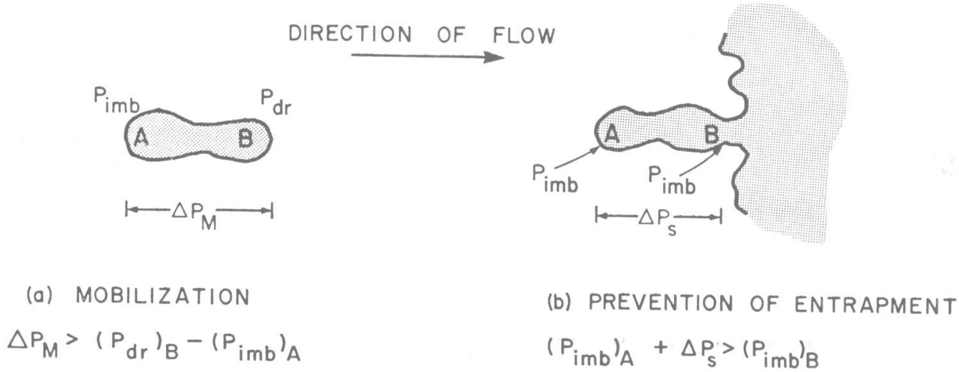
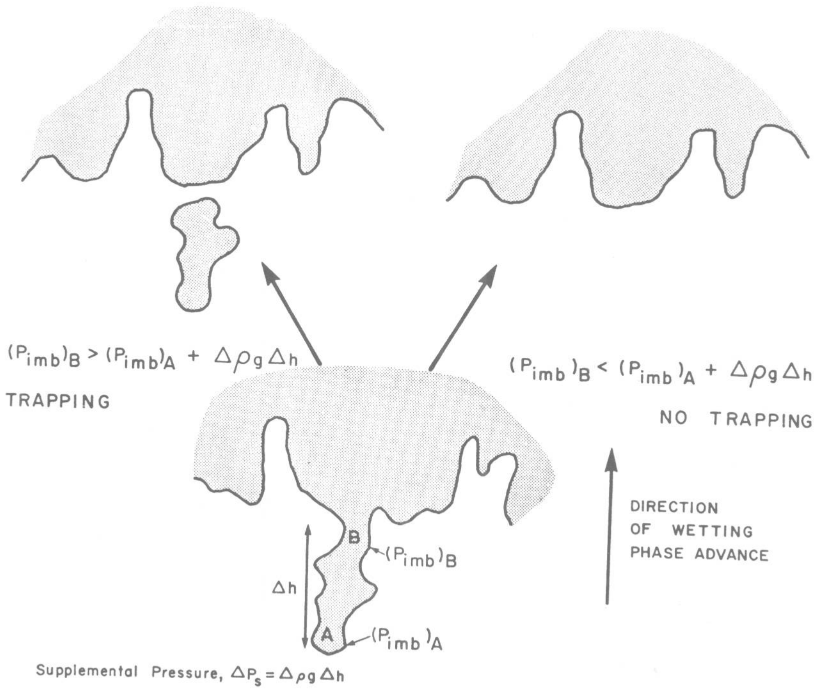


Illustration of change in trapping mechanism caused by hydrostatic contribution to imbibition capillary pressure



Conditions required for (a) mobilization of a trapped blob, (b) prevention of entrapment of a potential blob

Figure 1

A basic criteria of successful EOR processes is that residual oil can be recovered if the flowing phase causes viscous forces acting on the residual oil to exceed the capillary retaining forces. The ratio of viscous to capillary forces is, therefore, a key correlating parameter for evaluation of an EOR flooding process. The capillary number (N_{CA}) is expressed in the following equation:

$$N_{CA} = \frac{v\mu}{\sigma}$$

v = fluid velocity normal to a unit area of rock

μ = viscosity of displacing fluid (poise)

σ = interfacial tension (dyne/cm)

Capillary number is significant in trapping which occurs in the sequential banks of the micellar fluid process.

Taber established critical values of viscosities to capillary forces to produce residual oil from a given rock sample. This value appears to be an intrinsic property of the rock. For economic recovery of the oil, Taber's values must be exceeded by a factor of 10. However, because of practical and economic limitations on the pressure gradients that may be established across a rock unit, and the distance between injection and producing wells, it was realized that ultralow interfacial tensions, about 1/100 of a dyne/cm, are needed to mobilize the rock's residual oil.

The viscous forces in the flowing media can mobilize the residual oil freed by ultralow interfacial tension of the bank. They are proportional to the interstitial velocity of the flowing phase. To establish a given pressure drop, a given fluid velocity is required. Velocity is inversely proportional to the relative permeability of the flowing phase. Oil blocking the largest pore spaces will be displaced first. A large increase in permeability to the flowing phase occurs for a relatively small decrease in residual saturation. This effect is detrimental to oil recovery because local viscous forces are reduced while the oil remaining in smaller pores is harder to mobilize. This area of effective permeability under reduced residual oil conditions is yet unknown and is an important area of research for determining economic EOR floods. In one case when continuously displacing oil at a high capillary number, oil was produced as a clay stabilized emulsion with structural damage to the sandstone giving permeability loss and high residual oil saturations.

Since accurate values of residual oil saturation are essential for the economic evaluation of EOR processes, in situ saturations found by logging techniques in the well must be corrected for the high flow rates suffered in the well bore. The relationships of capillary number and permeabilities to the flowing phase for EOR target reservoir rocks must be determined. This research work is going on.

EOR mechanisms depend not only on the quantity of in situ residual oil, but also on its microscopic distribution within the pore spaces. There is very little qualitative information on the structural detail of residual oil.

With normal oil/water interfacial tensions, the capillary forces retaining residual oil far exceed the buoyancy forces. It is now believed that with ultralow interfacial tensions in surfactant flooding, the buoyancy forces become effective both on trapping and mobilization.

Experiments show that residual oil saturations remaining after water flooding range from less than 10 percent to more than 50 percent in rocks which may be similar in porosity and permeability. Thus, it becomes necessary to go beyond these two conventional reservoir engineering terms to develop appropriate correlations for estimating EOR project success. Therefore, a systematic investigation including particle shapes, size, size distribution, heterogeneities, change in fluid properties, and initial water saturation is underway.

The trapping mechanism is influenced by:

1. The geometry of the pore network.
2. Relative fluid properties, such as, interfacial tension, density difference, viscosity ratio, and phase behavior.
3. Fluid/rock interfacial properties which effect wetting, applied pressure gradient, and gravity.