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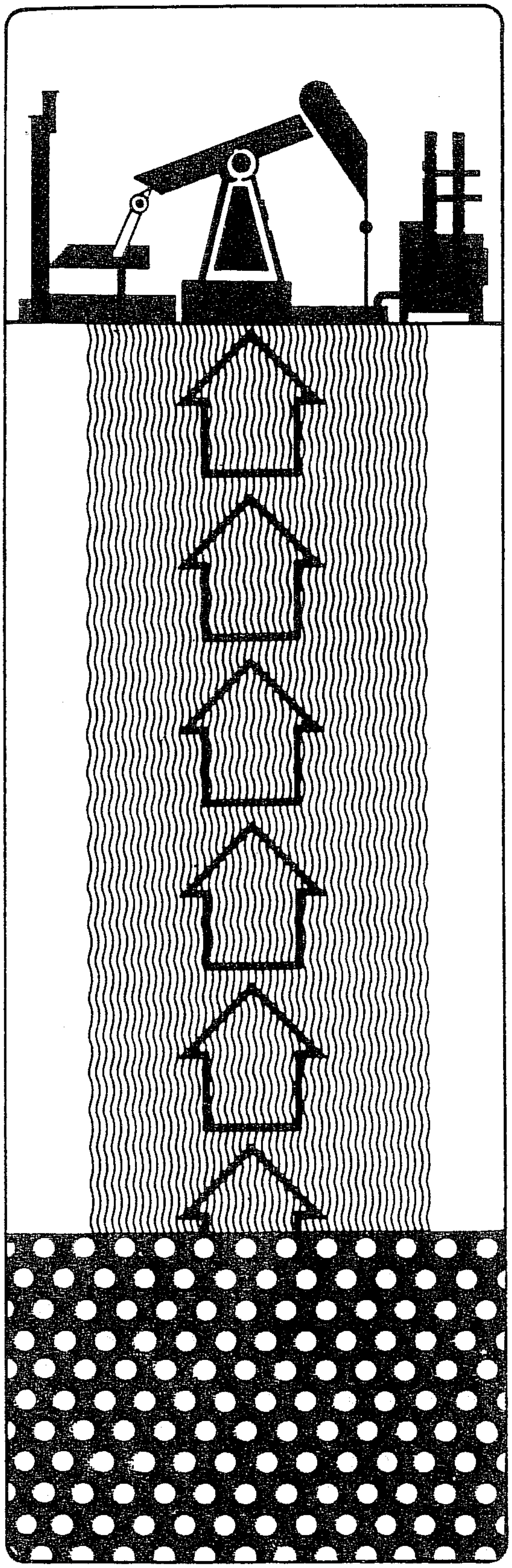

Enhanced Oil Recovery Program Plan

FY 1989

U.S. Department of Energy

Assistant Secretary for Fossil Energy

Deputy Assistant Secretary for Oil, Gas, Shale and Special Technologies

June 1989

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Washington, D.C. 20545

Preface

This program plan reflects many changes in the research agenda of recent years as a result of the "EOR Initiative", which was started in 1987. In the course of developing the EOR Initiative, Fossil Energy (FE) staff interviewed 102 individuals representing 24 organizations. The findings were reviewed by FE's Office of Geoscience Research and DOE's Hydrocarbon Geoscience Coordinating Committee and published in August 1988 as a DOE report. This study has introduced program elements intended to help the oil industry with problems of immediate concern related to lowered world oil price.

In addition, a July 1988 interim report prepared by the Geoscience Institute for Oil and Gas Recovery Research, "Major Program Elements for an Advanced Geoscience Oil and Gas Recovery Research Initiative," has been reviewed in formulating the priorities for future enhanced oil recovery activities. The role of geoscience research is being enhanced both in resource characterization and in the effective development and application of advanced EOR technology.

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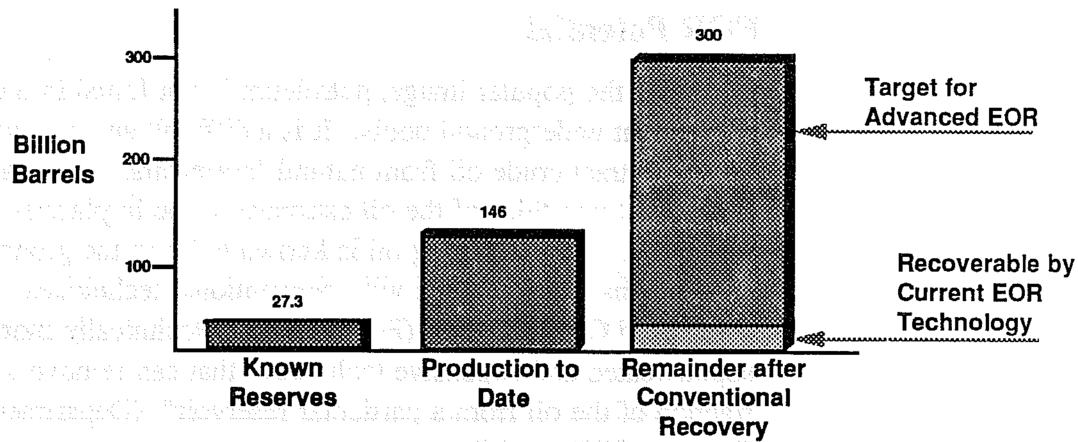
EOR Potential

"Despite the popular image, petroleum is not found in huge, convenient underground pools. It is a difficult and expensive task to extract crude oil from natural 'reservoirs.' Generally, only about one-third of the oil estimated to be in place is recovered. The remaining oil is known to be in the ground, but is to expensive to produce with conventional techniques. 'Enhanced Oil Recovery' (EOR) refers to technically more sophisticated and expensive techniques that can remove a larger fraction of the oil from a particular reservoir" (Department of Energy, 1987b, p. 54)

Conventional techniques include both use of natural forces and the injection of water or natural gas into a reservoir (e.g., waterflooding, repressurization by injection of gas) to produce the oil. Enhanced oil recovery techniques include the injection of heat and/or fluids into reservoirs to achieve a physical or chemical change that will facilitate further oil recovery.

Conventional recovery has left about 300 billion barrels of known oil remaining in the ground in the United States. Potentially, nearly 30 billion barrels could be recovered with EOR techniques now being used, tested or developed by industry (NPC, 1984). The remainder is an inviting target for advanced EOR techniques that might be developed. As technology improves and oil prices increase, recovery of more and more of the oil remaining in the ground will become economic using advanced techniques. For comparison, about 146 billion barrels of oil were produced through 1987, and only 27.3 billion barrels of oil reserves remain to be produced with conventional technology and prevailing economic conditions. (See Figure 1).

Figure 1. U.S. Oil Production, Crude Oil Reserves and Potential for Enhanced Oil Recovery (as of December 1987)

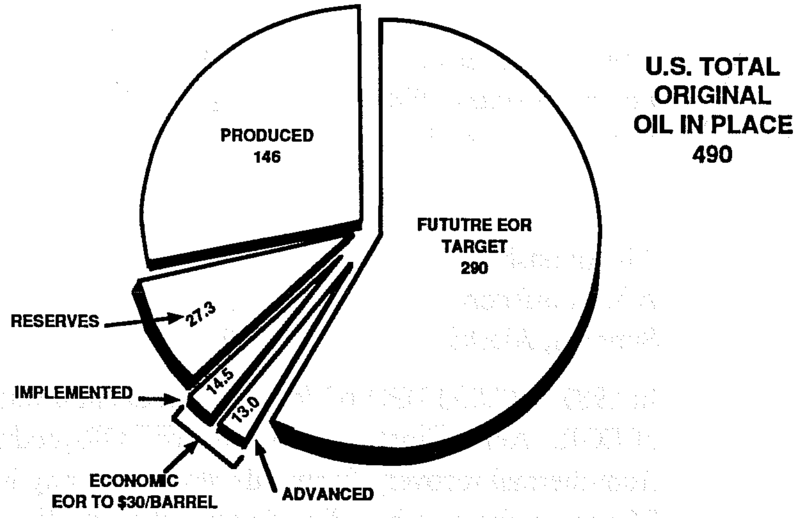


Source: U.S. Department of Energy, 1987b, p.55

The most comprehensive study of EOR potential was done by the National Petroleum Council (NPC) in 1984. It estimated an EOR potential of 14.5 billion barrels using available EOR techniques (implemented EOR) and 27.5 billion barrels using advanced technology. (See Figures 2 and 3.) A "projected (EOR) peak rate of over 1 million barrels per day from the early 1990s to beyond 2005" is possible under the most probable scenario used in the report. However, under the advanced technology case, the potential peak production rate varies from just over 2 million barrels per day to about 2.8 million barrels per day.

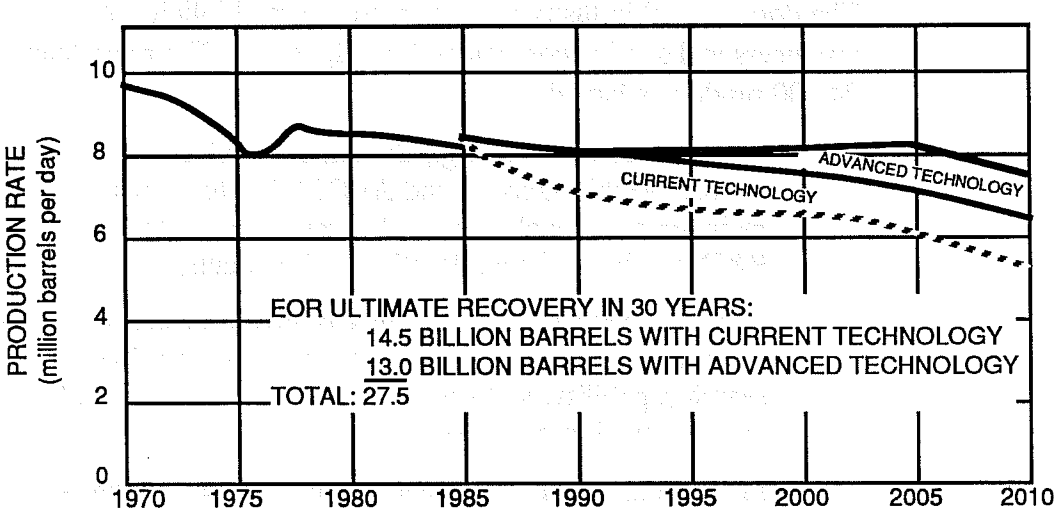
Together, small and large domestic oil companies produced about 8.2 million barrels per day (BPD) in 1988. An approximate breakdown is as follows:

Figure 2. Distribution of Known U.S. Oil in Place (billion barrels)



Source: Department of Energy, 1985, p. 24 updated to reflect data through December 1987.

Figure 3. Projected U.S. Oil Production and Estimated EOR Contribution



Source: Derived from National Petroleum Council, 1984.

	Percent	Millions of Barrels per day
Lower 48 states onshore	63	5.1
Lower 48 states offshore	14	1.2
Subtotal, Lower 48 states	77	6.3
Alaska onshore	22	1.8
Alaska offshore	1	.1
Subtotal, Alaska	23	1.9

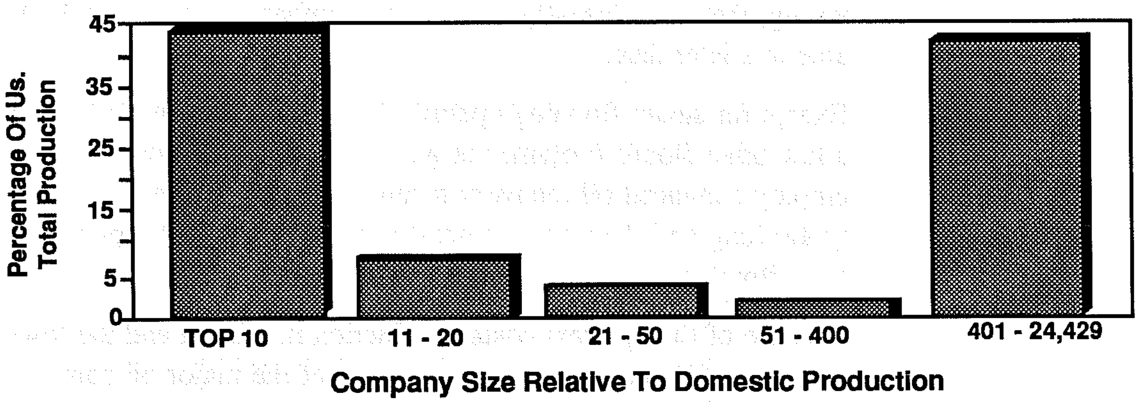
In 1987, 637,000 BPD of domestic production was from the use of EOR. Approximately 73 percent of EOR-produced oil was from thermal recovery (primarily steam flooding in California), 24 percent from carbon dioxide and other gas flooding in the Permian Basin of western Texas and eastern New Mexico, and the balance (3 percent) from chemical floods (primarily polymer).

Structure of Oil Industry

The domestic oil industry is comprised of a multiplicity of producers and service companies (see Figure 4). The more than 24,400 producers include:

- Major oil companies (e.g., Exxon, Shell, Chevron, Amoco, Mobil, Unocal, and ARCO) that have managed to maintain a reasonable level of investment capital and an R&D capability for exploration and production.
- Major oil companies that have had greater investment capital reductions, have sacrificed much of their production research capability, and sustain only technical support of their production operations,
- Major independents that invest in production improvements if the capital requirements are moderate and the benefits can be realized in 1-2 years, and
- Small independents that can put up limited funding only if the return on that investment is immediate.

Figure 4. Distribution of U.S. 1984 Petroleum Production (by Company Size)



Source: EOR Initiative, 1988.

A myriad of service companies and consultants support the producers by performing:

- Drilling and wellbore completion (e.g., casing, perforating, and cementing),
- Stimulation (e.g., fracturing, acidizing, and solvent treatment),
- Well logging and core analysis,
- Disposal of brines, sediments, and wastes,
- Engineering consultation on problem solving and design or modification of production systems,
- Geologic consulting, and
- Servicing of wells for plugging (silts, paraffins, asphalt precipitation, and sand control), corrosion, pump wear, equipment failure, and other problems.

The major oil companies' efforts are directed primarily toward finding and producing large oil fields. Typically, they produce the fields to an economic limit determined by their economic criteria and then sell them to independent oil operators. The independent inherits well log and core data, seismic data, if available, and production histories. However, data interpretation is not provided. The rationale is that if the interpretations were proven wrong, the seller (usually a major oil company) could be held liable at a later date.

Except for steam flooding operations, primarily in California, and a few other floods (polymer or gases), independents do not employ enhanced oil recovery techniques. Payout times are simply too long and the risks too great in view of the high up-front costs involved.

Because of the up-front costs, production in Alaska and the lower 48 states offshore is generally the work of the major oil companies. Independents account for about 70 percent of onshore production in the lower 48 states.

Of the independent operations, an overwhelming majority of the producing wells are stripper wells, i.e., wells that produce less than 10 BPD. The national average production from stipper wells is about 3 BPD. Nevertheless, these wells contribute significantly (15 percent) to national production and account for the bulk of production in many oil-producing states.

Program Structure

Eight major studies on petroleum recovery research are helping shape the nation's petroleum research programs:

- Enhanced Oil Recovery--a National Petroleum Council Report, 1984,
- Geoscience for Energy Security--an Energy Research Advisory Board report to the Secretary of Energy, 1987,
- Energy Security--a Department of Energy (DOE) report to the President, 1987,
- Factors Affecting U.S. Oil and Gas Outlook--a National Petroleum Council report, 1987,

- Future Directions in Advanced Exploratory Research Related to Oil, Gas, Shale, and Tar Sand Resources--a National Research council report, 1987,
- Geoscience Research for Oil and Gas Discovery and Recovery--a DOE report, 1987.
- The "EOR Initiative"--a Fossil Energy staff study, August, 1988, and
- Integrating R&D Efforts--a National Petroleum Council Report, 1988.

These reports provide solid evidence of the need for an aggressive R&D program to increase the recovery of domestic oil. They also highlight the need to integrate the development of advanced technologies with private sector initiatives and to obtain an industry perspective on future research needs.

In recognition of recent events impacting the oil industry and the above-mentioned studies, the Secretary of Energy:

- Established the Office of Geoscience Research, which reports directly to the Assistant Secretary for Fossil Energy, to coordinate geoscience activities within Fossil Energy.
- Established the Hydrocarbon Geoscience Research Coordinating Committee, which reports to the Under Secretary and has representatives from all DOE offices engaged in geoscience research, to coordinate all geoscience-related research and activities within DOE which report to the Under Secretary and with other federal agencies.

The EOR Initiative recommends a significant increase in reservoir characterization efforts. Reservoir engineering is also critical to understanding the interactions between reservoirs and injected fluids. Therefore, a balance of the two is essential.

This document is structured so that the two major components of the program, reservoir characterization research and advanced EOR technology development are described individually; but they are indivisible parts of the program that complement each other. The reservoir characterization component is enhanced in FY 1989 as a result of a Congressional mandate to allocate $5 million to research devoted to openly competitive cost-shared geoscience research as well as the result of the recently completed "EOR Initiative" which emphasizes the importance of shorter term oil recovery activities directed at independents, declining oil fields and stripper wells. The advanced EOR Process Development component represents the continuation of that part of the EOR program which is based on long range, fundamental EOR aspects of oil recovery.

In general, this structure corresponds well with the National Petroleum Council's study on EOR in which production contribution is divided into "implemented" and "advanced" technologies and is depicted in Figures 2 and 3.

Program Goal

The EOR program is directed to the research and development of new reservoir understanding and extraction technologies for the recovery of oil from our large, currently unrecoverable petroleum resources.

The overall goal of the EOR program is twofold:

- To foster geoscience research with emphasis on reservoir characterization for more efficient extraction of oil, mobile and immobile.
- To foster the development of advanced, environmentally acceptable enhanced oil recovery processes. These would include thermal, chemical, miscible gas and novel approaches to hydrocarbon extraction.

Necessary program implementation steps include basic and applied R&D, proof-of-concept activities and first-of-a-kind field tests. Effective program efforts will require the singular and/or joint participation of the oil producing sector, universities, DOE national laboratories and oil producing states as well as federal research capabilities.

The EOR program goal and research activities rest on the premise that critical information, not otherwise available, will enable the private sector to develop and apply advanced technology.

Special efforts are being made to provide program results to not only large producers with active research arms, but also to the large community of independent operators who produce about 40 percent of the total oil recovered, but are too small to conduct needed research.

Specific technical objectives for the EOR program are presented in Section IV, Program Strategy.

II. Technology Description

All oil bearing reservoirs are subjected to a standard pattern of development--first, exploration to determine if hydrocarbons exist; second, the drilling to confirm the exploratory findings; and finally, commercial development of production.

Our concern is with the production phase only and, at that, the latter stages of the production cycle. The production phase of a reservoir is also subjected to three stages--first, the "primary" production, which is due almost entirely to natural pressure existing within the oil bearing reservoir; second, the waterflooding or pressure maintenance measures to provide additional energy for the expulsion of additional oil, known as "secondary" production; and finally, the application of special, relatively sophisticated and expensive methods to wring out the "tertiary" oil. There are a variety of enhanced oil recovery (EOR) methods such as chemical and gas miscible methods for the recovery of light oil and steamflooding and fireflooding for the recovery of heavy oil, to be discussed later.

Reservoir Characterization

The Office of Fossil Energy is placing increased attention on a broader scope of oil recovery challenges that can be grouped in three principal resource categories:

- Mobile Oil in Subtle Traps. This oil remains under conditions of natural reservoir pressure in existing fields and can be the lowest cost addition to domestic reserves if it can be located efficiently. However, some of this oil is in "traps" or "reservoir envelopes", isolated by fluid barriers, which will require additional and more sophisticated geological research to be located. Once found, it will likely be producible by in-fill drilling and improved drilling technology.

- Mobile Unswept Oil. This movable oil is left in the reservoir after the natural pressure has been diminished. The oil has been bypassed, or "unswept", by conventional secondary water or gas flooding because of barriers to fluid flow. A large amount of the mobile unswept oil is a target for advanced recovery techniques, but improved geoscientific knowledge and techniques are necessary before petroleum engineers can accurately predict its location. Sufficient data for rough estimates exist for only 10 states, but in those states, more than 80 billion barrels of mobile, unswept oil may exist. Texas, alone, may have at least 25 billion barrels of oil in this category.

- Immobile Oil. This oil is trapped in the reservoir rock by a variety of chemical and physical forces and cannot be moved by typical water or gas flooding processes. The most challenging and, in all likelihood, most expensive petroleum target, immobile oil has traditionally been the main focus of the Energy Department's enhanced oil recovery research. Approximately 15 different EOR techniques, including the addition of chemicals and gases, have been attempted in more than 800 fields, but many have failed to perform as predicted because reservoir variations and flow paths are inadequately understood. Therefore, better understanding of reservoir characteristics, especially of how the reservoir rock was deposited and subsequently altered, is important to the successful use of advanced EOR techniques, and should increase our ability to locate and recover this immobile oil.

In all three categories, the research requirements are exactly the same: improved geoscientific understanding of the depositional, diagenetic and tectonic history of the petroliferous basin and of the resulting reservoirs on a well-to-well scale. If the technology for describing and predicting the performance of these geological reservoirs were at hand, the location of subtle traps and mobile unswept oil would be more straightforward and the design of tertiary recovery processes would become more a result of engineering and less of the art it is now. Figures 5 and 6 show examples of potential reservoir structures and potential geometries within oil bearing rocks and how they may affect oil recovery.

Inherent in this research program is increased attention on developing the tools and techniques needed to define more accurately the architecture of oil-bearing reservoirs. Improvements are needed in the analyses of key reservoir data, such as pressure and production data, well logs and rock samples. Improvements are also needed in instrumentation used to determine reservoir properties (for example, seismic tomography, 3-D reflection seismology, underground imaging also known as geotomography, etc.) as well as in logging tools, monitoring methods for tracing the movement of underground fluid fronts, techniques for assessing outcrops of reservoir forming strata, and diagnostic equipment tailored to advanced reservoir modeling.

Figures 7 and 8 show the magnitude of mobile oil that can be left unrecovered and the average recovery efficiency as a function of reservoir genesis and drive mechanisms. Obviously, the potential for improvement is very large.

Figure 5. Potential Geometrics of Oil-Bearing Reservoir Compartments Depending Upon Original Depositional System

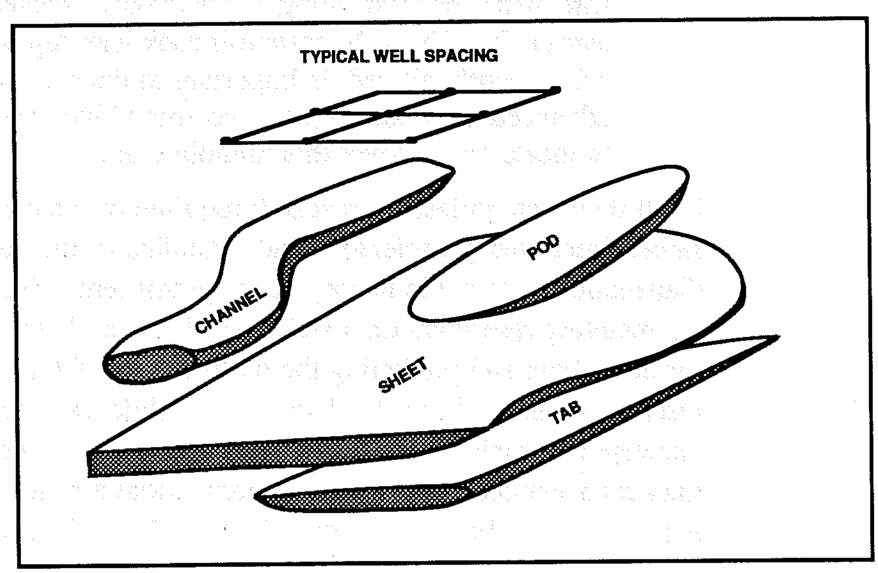


Figure 6. Schematic Illustration of the Geometries within Each Bed and How They May Affect Fluid Displacement

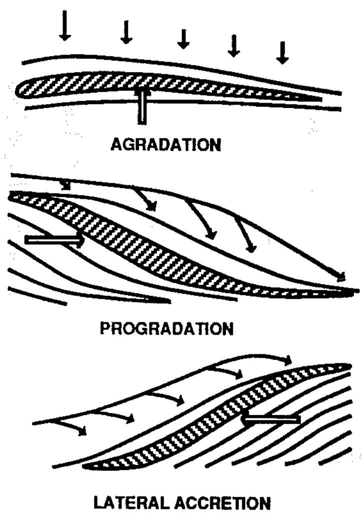


Figure 7. Unrecovered Mobile Oil as a Function of Reservoir Genesis Based on a Sample of 450 Texas Oil Reservoirs

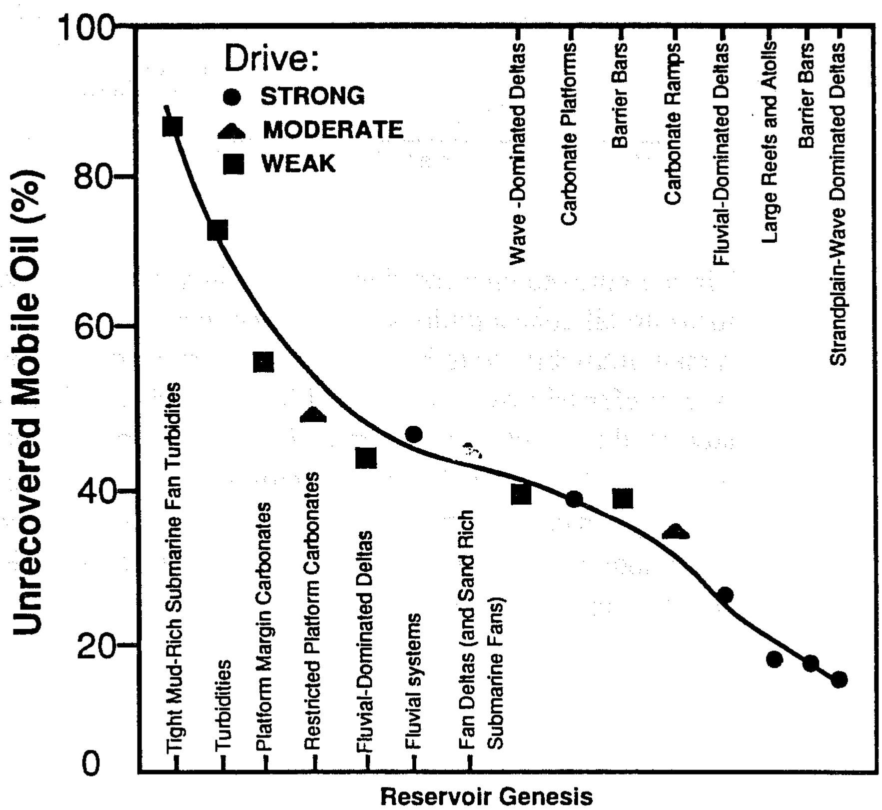
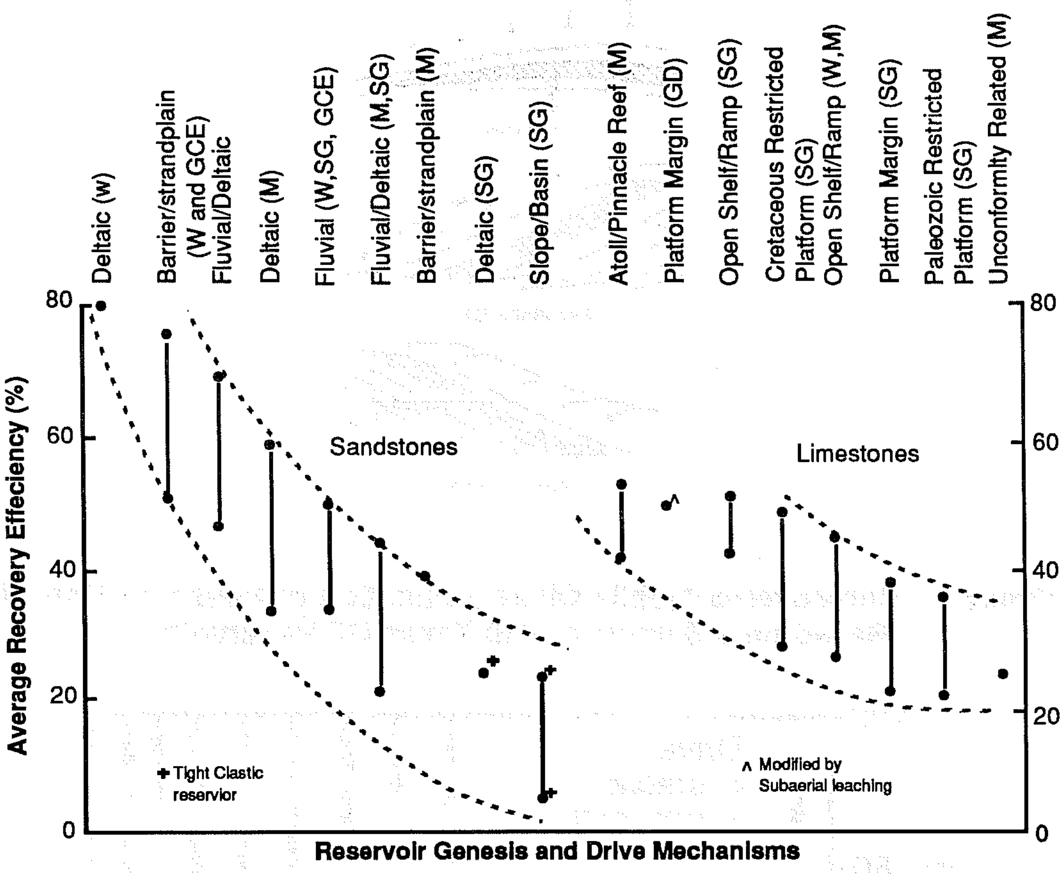


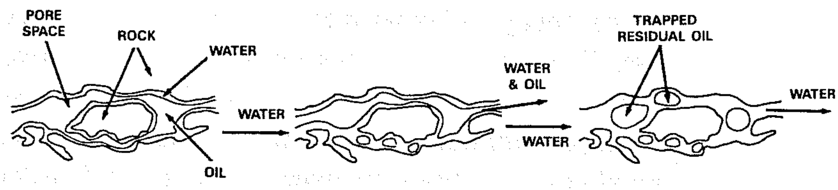
Figure 8. Recovery Efficiency vs. Reservoir Genesis and Drive Mechanism for Major Clastic and Carbonate Reservoirs in Texas



These improvements can then be used in specific reservoirs to measure oil concentrations, to deterine what is causing it to remain immobile or to be bypassed, and to predict the most likely or preferred flow pattern resulting from the application of an advanced production technique. These are also the first steps towards bolstering an integrated geoscience/engineering petroleum recovery program. A reasonable goal is to provide the basic understanding and advanced geoscientific technology necessary to increase oil recovery from the current 32 percent to 50 percent over the next 30 to 40 years.

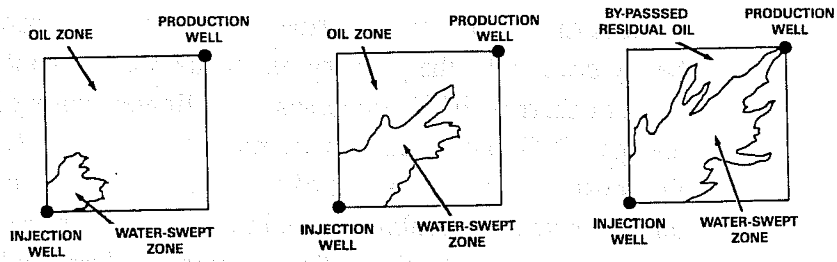
Figure 9. Reasons for Low Ultimate Recovery

EXAMPLE OF MICROSCOPIC TRAPPING



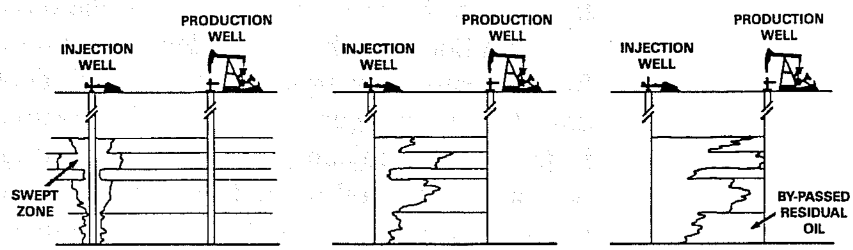
1. OIL IS ORIGINALLY IN A CONTINUOUS PHASE IN THE PORE SPACE.
2. AS WATER ENTERS THE PORE, THROUGH NATURAL WATER DRIVE OR SECONDARY WATER FLOODING, OIL IS PUSHED OUT . . .
3. UNTIL THE OIL PHASE BREAKS DOWN INTO DISCRETE DROPLETS DUE TO INTERFACIAL TENSION. THEN, ONLY WATER WILL FLOW; THE OIL IS TRAPPED.

EXAMPLE OF AREAL BY-PASSING



1. AS WATER IS INJECTED, IT PUSHES OIL TOWARD THE PRODUCTION WELL.
2. AS THE FLOOD CONTINUES, THE WATER-SWEPT ZONE GROWS, BUT DIFFERENCES IN MOBILITY OF OIL AND WATER AND HETEROGENEITIES IN THE RESERVOIR CAUSE "FINGERING" . . .
3. UNTIL A CONTINUOUS PATH OF WATER DEVELOPS. THEN, ONLY WATER CAN BE PRODUCED: OIL IN THE UNSWEPT ZONE CANNOT BE RECOVERED BY CONVENTIONAL MEANS.

EXAMPLE OF VERTICAL BY-PASSING



1. AS WATER OR STEAM IS INJECTED, IT DISPLACES OIL TOWARD THE PRODUCTION WELL.
2. AS THE FLOOD CONTINUES, THE SWEPT ZONE GROWS BUT DIFFERENCES IN GRAVITY AND RESERVOIR HETEROGENEITIES CAUSE "FINGERING" AND "OVERRIDE" . . .
3. UNTIL A CONTINUOUS PATH CONNECTS THE INJECTOR AND PRODUCER, AFTER WHICH THE INJECTION FLUID FAILS TO CONTACT ADDITIONAL OIL.

Source: U.S. Department of Energy, 1985, p. 13.

Enhanced Oil Recovery Technology

Conventional oil recovery leaves nearly two thirds of discovered oil in a reservoir. Microscopic (capillary) forces, wettability, heterogeneity and other reservoir characteristics account for the loss. The technical reasons for low ultimate recovery are illustrated in Figure 9. In general, EOR involves the injection of a substance into a reservoir to mobilize and displace the oil remaining after conventional recovery. The injected materials and specific process designs depend on the characteristics of the crude oil and the reservoir. EOR processes are generally grouped according to whether the oil is heavy (i.e., highly viscous and having high specific gravity) or light (i.e., less viscous and having lower specific gravity).

EOR is discussed here in terms of four types of processes. For heavy crude oils, the primary mechanism is the application of heat, or thermal EOR processes. For lighter crude oils, chemical and gas EOR processes may be more applicable. Recovery of the most significant portion of the residual oil will probably require substantial breakthroughs in understanding the factors governing oil production. This research is discussed in terms of novel concepts. All these processes are described below:

- Thermal EOR Processes: The primary EOR mechanism for recoverying heavy crude oil is the application of heat. Steam flooding and in-situ combustion supply heat to the reservoir, reducing the viscosity of the heavy oil and allowing it to be driven more easily to the producing well. In steam flooding, the heat is derived from steam injected from the surface or produced at reservoir depth by a downhole stream generator. Heat for in-situ combustion is derived from injecting air or oxygen and igniting a portion of the crude oil in the formation. Another method that uses steam involves alternately injecting steam into and producing oil from the same well (also know as cyclic steam or huff and puff).
- Chemical EOR Processes: Chemical EOR includes polymer flooding, surfactant- (or micellar-) polymer flooding, alkaline flooding and combinations of the three.

Polymer flooding is the addition of polymeric thickening agents to increase the viscosity (and thus reduce the mobility) of the injected water. The polymer-thickened water is more efficient in displacing oil than the plain water used in conventional waterflooding and results in improved sweep efficiency.

Micellar-polymer flooding is the injection of surface-active agents (surfactants), usually in the form of micro-emulsions, to displace oil by reducing interfacial tension and forming an oil bank that can be driven to the producing well. Polymer-thickened water is generally used to control the movement of the micellar solution in the resevoir.

Alkaline flooding, applicable only to certain crude oils, involves injection of alkaline fluids. The alkaline fluids first react in situ with the residual oil to form surfactants, which then displace more oil. The injected alkaline fluids are usually followed by polymer flooding. Although alkaline flooding is a chemical process, it may be applicable to both light and heavy oils.

- Gas EOR Processes: In light oil reservoirs not suitable for chemical flooding, flooding by gases, usually carbon dioxide, is augmented by injecting additives such as water or nitrogen. Under high pressure, carbon dioxide acts as a solvent to strip lighter components of the crude oil, to swell and mix partially with the oil and to reduce the oil's viscosity, ultimately building an oil bank that can be pushed to producing wells by other gases or water. Other gases such as nitrogen, flue gas or hydrocarbons (as well as combinations of the above) could also be injected to push or strip the oil under certain conditions.
- Novel EOR Concepts: Novel EOR includes unconventional high-risk research that could lead to a breakthrough. For example, in microbial EOR (MEOR), microbes are used to generate surfactants and/or polymers or gases to displace the crude oil. Microbes may also be able to change crude oil by reducing its viscosity or interfacial tension, making it easier to recover.

Light oil mining involves the direct extraction of crude oil through mining and boring, usually coupled with gravity drainage. Horizontally drilled holes used for improved drainage efficiency or in conjunction with other EOR techniques are now under study. Light oil steamflooding is also a possibility. Conventionally, steam stimulation is considered only for heavy oil, but some light oil reservoirs may benefit from steam injection.

All these enhanced recovery technologies are fundamental to realizing the vast potential of the nation's oil resources, but they differ significantly in stage of development and applicability.

III. Technology Status And Research Needs

Enhanced oil recovery operations in the United States contribute about 7 percent of domestic production, which corresponds to about 12 percent of crude oil imports.

Improvements in enhanced oil recovery technologies to justifiy their greater use are essential to sustaining domestic oil production at a level that does not strategically compromise the United States. Much of the estimated 200 billion barrels of unrecovered light oil and 100 billion barrels of unrecovered heavy oil can be produced only by using EOR. In the past, DOE has focused on laboratory-scale research, depending on industry for the full spectrum of applied research. With the possible exception of the top ten oil companies, the industry has severely cut back on research facilities, equipment and staff. All have reduced research activities. Scientific and engineering support is focused on improving performance of operations already in place. It is no longer reasonable to assume that industry will provide the full spectrum of applied research.

Few, if any, new major finds can be expected in the lower 48 states. Yet after conventional techniques have been used, approximately two-thirds of the original oil in place will remain in these known reservoirs--an estimated 300 billion barrels. Of this potential resource, much exists in high enough concentrations to be recovered without applying EOR measures (i.e., the injection of heat, gases, or chemicals). To recover it, however, its location and the cause for its not having been recovered must be determined. This oil was bypassed because the reservoirs are not homogeneous.

High concentrations of oil remaining in the reservoirs not contacted because of heterogeneities can be displaced easily, if located. This mobile oil represents a relatively low-cost near-term target for additional recovery.

Considerations must also be given to improved recovery through better engineering design of both primary and secondary operations. Significant, predictable improvements in primary and secondary recovery can come only through a better understanding of the reservoir being produced.

One major concern of the U.S. petroleum industry is the very large number of stripper wells in operation (460,429 in 1987) which, on the average, produce only 2.7 barrels of oil per day -- hardly enough to pay for operating expenses at the currently low oil prices. Yet, in the aggregate total, stripper oil production is not insignificant -- 450 million barrels per year, over 20% of lower 48 production.

Many independents, who operate most of the stripper wells, were forced to shut-in the wells as uneconomical, hoping to restore production when oil prices rise. But the shut-in time is limited. There are environmental concerns that the oil may contaminate fresh water aquifers when the oil bearing zone is not pumped off. Also, both the reservoir and equipment suffer from lying dormant due to corrosion, scale deposits, stratification of fluids and precipitation of hydrocarbons and salts. Once the stripper is plugged and abandoned, it cannot be redrilled economically and access to the remaining target oil in those reservoirs is cut off from future application of advanced technologies. It is therefore in the national interest to prolong the lifetime of the strippers to the extent possible, as it is beneficial to the operators and the states afflicted with the declining oil fields.

Reservoir Characterization

Reservoir characterization is an essential element of any oil recovery operation. Whether it is locating mobile oil, enhancing stripper well production, or developing efficient and effective EOR technologies, an understanding of the reservoir and its response to fluid injection and production is essential. The in-ability to define reservoir interaction with injected fluids is one of the greatest deterrents to oil recovery in mature fields.

Reservoir characterization has two important facets: 1) defining the structure, of the reservoir, its geometry and composition, and 2) determining how these aspects govern the flow of fluids. Characterization, then, requires interfacing disciplines in geoscience and reservoir engineering.

The geoscientist must help identify what heterogeneities exist and where they are located. The engineer must determine which of this myriad of parameters are critical and how they affect fluid movement. The desired objective is to have a geological model and a three-dimensional simulation capability to predict the effectiveness of a given recovery strategy or process with a high degree of confidence.

The state-of-the-art technology is such that there is room for improvement in projecting reservoir heterogeneties between wells. By drawing on available data (core, log, well test data, seismic data, and performance history) a knowledge of depositional processes and diagenesis (the chemical and physical changes of sedimentary deposits), and applying geostatistical techniques, a geoscientist can with a fair amount of effort define reservoir anatomy. This effort is both time consuming and expensive. It takes about one man-year of effort or more to evaluate a single reservoir. Better diagnostics and computational tools are needed. Neither these comprehensive reservoir evaluations nor the development of diagnostics and computational tools can be done by the independent operators because they lack the resources and sophistication required for the task.

The complexity of reservoirs is illustrated in Figure 5 and 6, which show potential geometries of oil bearing zones dependent upon the original depositional systems. These may, of course, be further complicated by faulting, vertical and horizontal permeability variation, directional permeability, diagenesis and many other factors.

One optimistic note in dealing with this very complex set of problems is that reservoir classification is possible. Reservoirs with similar depositional histories and diagenesis should have similar types of heterogeneities and/or anisotropy (directional properties). If so, lessons learned in Texas, for example, may have application in other states. Likewise, lessons learned in Louisiana sandstones may be used in similar depositional environments elsewhere. And here lies the importance of reservoir characterization and classification.

Advanced Oil Recovery Process Development

Thermal EOR Process

Thermal recovery processes include stream drive, cyclical steam injection and in-situ combustion. All are well-known commercial technologies. With steam processes, more than 455,000 barrels of heavy crude oil are recovered per day, primarily in California. In steam flooding, however, the overriding of steam above crude oil due to gravity differences reduces recovery efficiency. The number of in-situ combustion projects has declined over the past decade, with recovery at only about 10,000 barrels per day. Research to improve thermal recovery efficiency by using additives is required. Specifically, research should focus on:

- Identifying the recovery mechanism and range of applications for additives in the steam drive process,
- Analyzing the benefits of using enriched air in in-situ combustion and
- Analyzing the benefits of using horizontal injection and production wells for thermal processes.

Chemical EOR Processes

Chemical flooding is the least developed of the three principal EOR processes (chemical, gas and thermal), but it has significant potential for large recoveries. In polymer flooding, incremental recovery has been small due to the lack of an effective displacement agent. Alkaline flooding experiments to date are inconclusive; the costs are relatively low, but applicability is limited to certain acidic crude oils. Micellar-polymer flooding has been tested in various settings, but results are positive only in shallow, homogeneous, low-temperature, low-salinity reservoirs. In general, its highly unpredictable performance and high costs are discouraging. Many producers have reduced or terminated their micellar-polymer programs.

Improved process predictability and increased recovery efficiency are of the highest priority. As understanding of the process increases and predictions become more accurate, improved control (through more refined process designs and materials) should increase recovery efficiency and extend the range of application to reservoirs with higher temperatures, higher salinity levels and greater shale content. The research should be followed by laboratory and small-scale field testing and analysis. The process should be continual, with analysis of one set of R&D results leading to the formulation and testing of new hypotheses and more advanced technology, until process predictability and recovery efficiency goals are met.

Gas EOR Processes

Injection of miscible and immiscible gas into a reservoir accounts for 20 percent of commercial enhanced oil recovery production in the United States. In west Texas carbonate reservoirs, carbon dioxide flooding has been sufficiently successful to justify building carbon dioxide supply pipelines of several hundred miles. However, the predictability and recovery efficiency of the process remain limited. Problems include uncertainties about the displacement mechanisms and the tendency for carbon dioxide to override and finger through crude oil, resulting in poor sweep efficiency. In sandstone reservoirs, typically with considerably lower residual oil saturation, carbon dioxide flooding is even less predictable. Research in gas flooding offers an opportunity to improve understanding of factors controlling miscible gas flooding, improve process predictability and increase the overall gas flooding recovery efficiency. Current and predicted production levels from gas flooding are a small portion of domestic needs. However, screening models (used in selecting EOR processes for specific reservoirs) indicate that miscible gas flooding is applicable to many U.S. reservoirs. Gas flooding is currently focused in the Permian Basin in west Texas and Florida. The miscible gas processes applied there use state-of-the-art techniques that recover less than one half the original oil in place.

The miscible gas research that is required should increase understanding of:

- The primary mechanisms of miscible gas flooding, including gas phase behavior in mobilizing and transporting the oil,
- Mechanisms to improve horizontal and vertical sweep efficiencies and
- Methods for predicting and increasing recovery efficiency.

Although the use of miscible carbon dioxide is predominant in field applications, the use of nitrogen is expected to increase in the near future, particularly in deeper reservoirs, and immiscible carbon dioxide and nitrogen applications with chemical additives are expected to increase. Research is needed for a better understanding of the miscibility mechanisms of nitrogen/light oil systems.

Novel EOR Concepts

Novel EOR methods are long-term, high-risk technologies whose technical feasibility is not yet proved. Comprehensive study and research are required to establish the feasibility of truly novel high pay-off concepts. The following processes are in the feasibility assessment stage:

- MEOR,
- Oil Mining,
- Horizontal well bores and
- Light oil stream drive.

Although preliminary laboratory and engineering work indicates that they may be effective, countinuing research is necessary to demonstrate and apply the technologies in the field.

MEOR is limited first by the viability of bacteria in a reservoir environment characterized by hostile temperature, pressure and chemical conditions. Another limitation is bacterial capacity to produce adequate types and volumes of biosurfactants and biopolymers. Industry and government need to continue their exploratory work and conduct verifiable field testing of promising microbes.

Oil mining has nontechnical as well as technical constraints which must be circumvented if this technique is to be successfully used. Engineering data are scarce because industry is reluctant to commit to field application. This reluctance is based on the large front-end investments needed for project implementation. It is compounded by questions of whether the target formation is mineable, has a collectable gravity flow of oil and is free of unsolvable safety problems related to underground operations. Adequate screening criteria are critically needed to select target sites and determine the resource potential.

Recent advances in horizontal drilling technology have made it an attractive technique for inclusion in various EOR schemes. Horizontal holes provide several benefits for both production and injection strategies. Work in this area would include numerical simulation of lateral well bores employing EOR techniques, development of tools and techniques to drill horizontally on a routine basis and development of logging tools and testing procedures.

Steam drive has not been widely applied to light oil reservoirs because other recovery techniques are often more suitable. There are also difficulties with depth and pressure and the economics of generating steam. Researchers, however, point out the certain advantages of using steam in light oil reservoirs, which should be investigated and field tested.

IV. Program Strategy

Historically, the Fossil Energy oil and gas programs have focused on the long-term aspects of resource recovery: on fundamental research to provide a technology base that can help industry design efficient methods to recover oil from reservoirs after conventional methods have been applied. Current consensus is that conditions have now changed dramatically within the oil industry and the research community and that government's program should change accordingly.

The change has broadened the FE/EOR program to one that considers near-, mid-, and long-term measures to enhance the domestic oil production capability. It considers oil recovery in a broader context to include oil that does not require the extraordinary measures associated with EOR, i.e., the application of heat, gases, or chemicals. It is also directed especially towards the needs of some 24,000 independent operators who produce about 40 percent of the total oil recovered yet are unable to conduct the needed research themselves.

The basic premise underlying the current EOR program strategy is that future U.S. oil production, particularly in the lower 48 producing states, will come about not through major new discoveries, but by learning how to produce economically more of the oil that has already been found -- the two-thirds, or about 300 billion barrels that remains in reservoirs following conventional production. The key to producing this remaining oil is a better understanding of the geology of the host reservoir and the targeted application of enhanced oil recovery techniques.

The new approach would bring together oil producing states, oil producers (major and independents), service companies, universities and national laboratories. A series of near-, mid-, and long-term research strategies will be implemented to include the characterization of reservoirs in existing fields on a geologic rather than a geographic basis, field trials and other efforts (to better engineer and identify bypassed mobile oil in these fields) and a technology transfer effort to analyze, document and disseminate the information in a form usable by the industry.

The beneficiaries of the program, regardless of its size and timing are numerous: the U.S. public in general, through increased energy security and improved trade balance; the producing states, through enhanced local economics; operators, especially the small and mid-size independents who will apply the results, and; service companies and consultants who will be the major avenues of technology transfer.

The best source of information on declining oil fields lies with state agencies. They have vast amounts of data, but the form of the data does not lend itself to analysis and interpretation. A first-order goal should be to help states that have sufficiently large volumes of unrecovered oil to begin selective processing of the information that they have. More and better data will, in effect, reduce development costs, particularly for the independents, and increase production. In addition, the resulting data base and underlying analyses will provide the basis for formulating specific R&D and engineering projects by focusing on reservoir and field types with the greatest potential.

Basic implementation strategy of the current EOR program consists of the following elements:

- Establish a balance and integrate near-, mid-, and long-term research. Applying state-of-the-art technology to immediate problems would parallel efforts to advance technology where it is most needed. Information obtained in the near-term would be structured to benefit long-term efforts.

- Leverage the existing infrastructure to the fullest extent. This effort would include coordination with the U.S. Geological Survey and other federal agencies and use of state agencies, universities, and other research institutions with programs in place to focus efforts on problems peculiar to regional and local resources. Involving the universities would provide needed direction to their research and help maintain a strong technical resource.

- Integrate the oil producers, consultants, and service companies into the research to ensure effective technology transfer. They would help identify research opportunities and shape the research efforts so that information generated and technology developed could be applied expeditiously.
- Use the national laboratories as problem-solving team members, when feasible, in areas where they have demonstrated expertise. Their experience in developing sophisticiated diagnostics and in rock mechanics, their superior computer capability, and their other special skills would be used in concert with universities and state agencies in addressing the problems defined by industry.
- Encourage collaborative and cooperative research programs/projects with participation and funding by industry, universities, and state and federal agencies.
- Coordinate with existing and future geoscience and EOR research activities in which the federal government participates under the auspices of oil producing states and other research institutions.
- Initiate more active technology transfer programs to bring to bear the latest technology and "lessons learned" about oil recovery. This effort would include establishing needed geological/engineering reservoir data bases, developing area-specific plans for recovery, and integrating results into usable information on recovery methods and results that will serve as guidelines to industry.

Program Elements

The thrust of the EOR program is to foster improved understanding and assessment of our petroleum reservoirs and effective implementation of existing and advanced oil recovery efforts. Program components are designed to meet the EOR research needs as described in the previous section. The following is a brief description of each element and its objective:

- Reservoir and Resource Research: To improve understanding of the 300 billion barrels of remaining oil in place through fundamental studies of the major reservoir characteristics (e.g., engineering and geological parameters) affecting all EOR processes, determination of oil saturation in the areas where EOR fluids can be injected, micro- and macroscopic heterogeneities that cause channeling around areas of saturation and analytical and instrumentation techniques for quantitative reservoir description to improve sweep efficiency.
- Analysis and Evaluation: To develop an analytical procedure, based on sound engineering and scientific practices, as well as field experience, for EOR process indentification, application and performance prediction of individual projects. Included in this activity is the Tertiary Oil Recovery Information System (TORIS), an analytical system that contains cost-shared field test information, predictive models and reservoir/geological engineering information on major domestic oil fields, a historical EOR project data base and a comprehensive data base of crude oil properties.
- Thermal EOR Processes: To improve existing technology for steam flooding and in-situ combustion, primarily with research on higher sweep efficiency in heavy oil reservoirs. Advanced thermal EOR could add 4 billion barrels of cumulative oil production (NPC, 1984).
- Chemical EOR Processes: To foster fundamental research in micellar-polymer and alkaline processes, leading to advanced technologies. Advanced chemical EOR could add 8.5 billion barrels of cumulative oil production (NPC, 1984).
- Gas EOR Processes: To extend application of miscible gas flooding to the more varied carbonate and sandstone reservoir categories. Advanced gas EOR could add 5.5 billion barrels of cumulative oil production (NPC, 1984).
- Novel EOR Concepts: To identify effective concepts, assess the feasibility of novel EOR concepts, and where feasible, define their technological and R&D requirements. In particular, to determine the optimum operation-

al requirements for microbial EOR and its applicability and/or recovery potential through laboratory and field/pilot scale research, determine the utility of novel drilling technology for particular reservoir application and to evaluate novel recompletion and well diagnostic technology for declining wells.

- Technology Transfer: To initiate a more active technology transfer which would put emphasis on independent producers, declining fields and stripper wells. This would be accomplished through a series of custom-designed seminars in the most affected areas of the country and by acquainting the independent operators with the DOE comprehensive data bases and other research results which can be directly applicable.

Table 1 summarizes the EOR budget for fiscal years 1988 and 1989.

Table 1. Enhanced Oil Recovery Budget (thousand dollars)

Activity	FY 1988 Appropriation	FY 1989 Appropriation
Heavy Oil	$ 3,700	$ 4,245
Light Oil	9,894	16,738
Total	$13,594	$20,983

V. Program Management

Organization

Management of the EOR program is shared by Fossil Energy headquarters and DOE's Bartlesville Project Office (BPO). At headquarters, the Office of the Deputy Assistant Secretary for Oil, Gas, Shale and Special Technologies is responsible for overall program planning and establishment of program goals and strategies, for status information and for evaluation of program accomplishments. The Office of Geoscience Research reviews the EOR research program, as part of its coordination role for all geoscience programs both within and outside the department. BPO is responsible for developing an implementation plan to achieve these program goals and for managing this implementation. Data base, technology transfer and outside-sponsored research procurement and management are handled by BPO. Administrative support is provided to BPO by the Pittsburgh Energy Technology Center.

Cooperation with States

A new element of the overall program strategy is the development of memoranda of understanding (MOUs) with states interested in EOR research. The MOU has already proved to be a valuable tool in supporting research and technology transfer efforts with the states. It is also seen as an important means of affecting action in support of state initiatives that are consistent with DOE program objectives and policy. Through early coordinated planning, the MOUs allow DOE and individual states an opportunity to leverage their limited research funding and eliminate unnecessary duplicative efforts. Any funding support provided under the MOU is 50/50 cost shared. Task sharing and information exchange can also take place. There are MOUs being developed or implemented with Alabama, Alaska, California, Illinois, Indiana, Kansas, Louisiana, New Mexico, Oklahoma, Texas and Utah.

Other External Relations

Much emphasis has been placed on developing outside input and review and in maintaining external relations. During FY 1984, for example, program staff worked closely with the NPC enhanced oil recovery research group. This collaboration resulted in an expanded reservoir data base, validated process models and a consolidated overall approach.

The Interstate Oil Compact Commission and BPO collaborated in FY 1987 to make TORIS useful to the oil-producing states. Similar collaboration with public and private organizations (e.g., the Gas Research Institute, Texas Bureau of Economic Geology, The Geoscience Research Institute) will continue.

The technology R&D program elements (chemical, thermal, gas, microbial, geoscience and novel concepts) make extensive use of industry participation, review panels and workshops. The panels and workshops add information and insight into program development, state-of-the-art assessment and program direction. Their input is particularly valuable in determing whether continuing research is necessary. A formal peer review of heavy oil projects was held in FY 1986 and for light oil projects in FY 1987.

The EOR program also initiated and intends to expand the industry/National Laboratory cooperative research program. The major purpose of the initiative is to transfer weapons lab technology that is applicable to oil recovery, e.g. software and hardware developed in the defense programs such as transmitters, receivers and interpretation methods for sending signals in earth for the purpose of monitoring nuclear explosions or tracking submarines. In EOR, adaptation of these technologies can be very useful for the determination of reservoir heterogenities and the measurement of fluid saturations, using sonic or electromagnetic signals between wells and within the formation of interest (also known as geotomography).

During 1987, Fossil Energy staff met with 102 individuals representing 24 organizations to draft a new research agenda for enchanced oil recovery--the "EOR Initiative." This report was reviewed by Fossil Energy's Office of Geoscience Research and DOE's Hydrocarbon Geoscience Coordinating Committee. Much of the research agenda presented there is already included in this EOR program plan. In addition, the "EOR Initiative" has been an important factor in formulating the priorities for future enhanced oil recovery budget requests.

VI. International Activities

Many countries are involved in enhanced oil recovery R&D--Australia, Brazil, Canada, China, German, France, India, Italy, Mexico, Norway, the United Kingdom, the USSR, Venezuela and Yogoslavia. In addition, research in EOR is conducted under the auspices of the International Energy Agency (IEA)--an organization of non-OPEC energy-consuming nations.

Supporting the EOR R&D program, FE has entered into bilateral technical agreements with several of these nations as well as with the IEA. The agreements provide for information exchange on a task-sharing basis (i.e., there is no flow of funds across national borders, and there are little or no additional costs to DOE). However, research is sometimes done in the United States with funding from another country.

Canada and Venezuela are our long-standing partners in EOR. Both nations have vast heavy oil and tar sand resources. Like the United States, both are interested in research focusing on heavy oil recovery techniques.

Joint projects include reservoir characterization, microbial enhanced oil recovery, standardized data bases, subsidence due to fluid withdrawal, tracking thermal fronts (geotomography) and training petroleum engineers.

Technical cooperation with the U.K. Department of Energy and with Italy involves the development of advanced numerical simulators that will be tested on field data for EOR projects.

A recent cooperative effort involves Norway. Norway and the United States will work together to develop a sensitive technique for tracing fluid flows in reservoirs, with the potential of determining oil saturation in the flooded area.

Fossil Energy cooperates with several nations under the umbrella of the IEA. Projects include joint research in chemical flooding, miscible gas displacement and thermal recovery. All are conducted on a task-shared basis, with no additional cost to the EOR program.

The following activities are planned:

- Set up meetings of the Joint Steering Committee for cooperation with Venezuela,
- Review the status of cooperation with Mexico and determine whether to initiate a new agreement beyond 1989 with the Mexican Petroleum Institute; if positive, determine the new areas for cooperation,
- Draft two project agreements for cooperation with Norway, coordinate, obtain appropriate approvals and initiate joint research,
- Draft final report on cooperation with UK DOE on discrepancy analysis of EOR project performance,
- Organize and conduct a meeting of the International Energy Agency Executive Committee, an EOR workship and a one day symposium devoted to reservoir characterization, and
- Conduct the Second International Reservoir Characterization Conference.

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