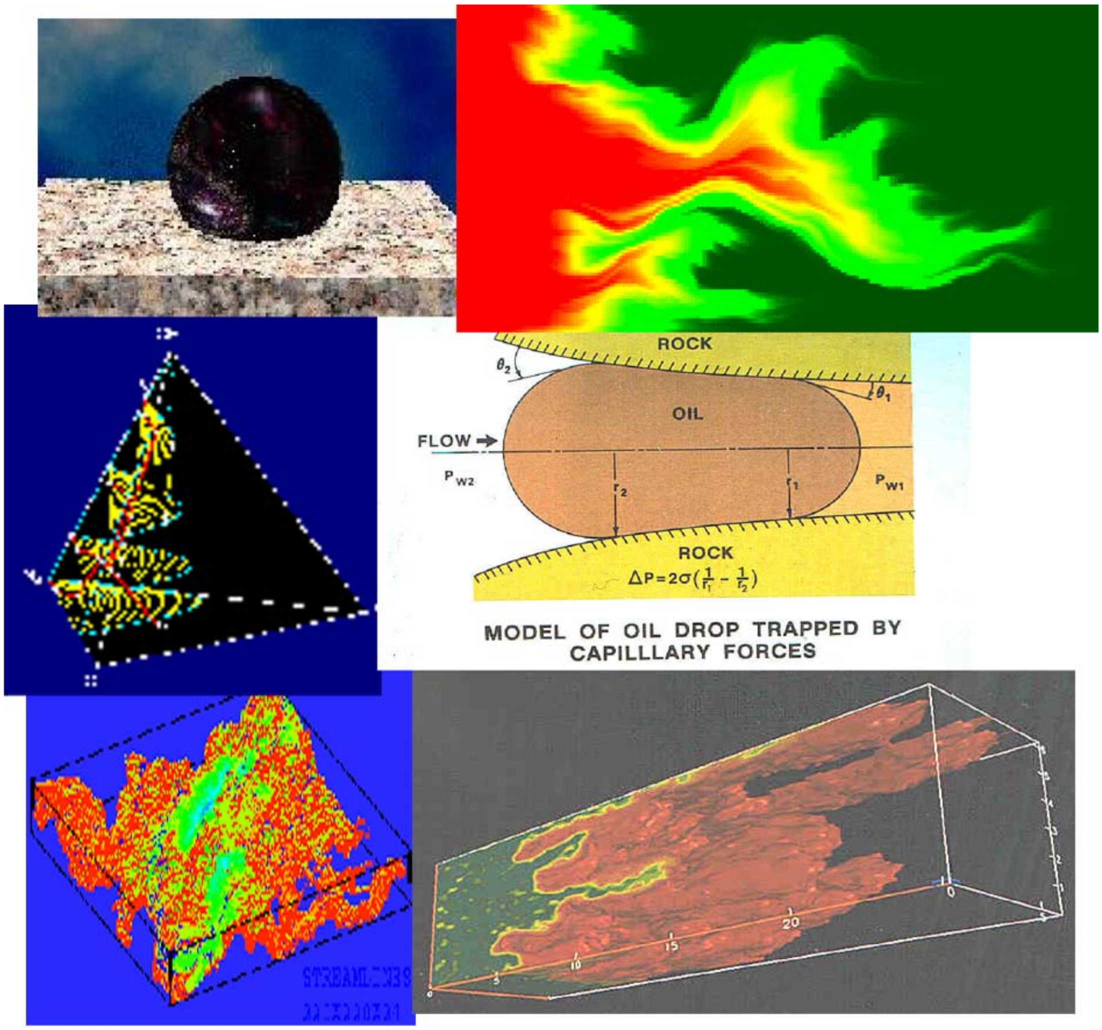
U.S. Department of Energy
Office of Fossil Energy
National Petroleum Technology Office

Reservoir Efficiency Processes
Enhanced Oil Recovery
Production Research



Presented to the National Research Council

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Table of Contents

Acronym List

1-D	One Dimensional
2-D	Two Dimensional
3-D	Three Dimensional
4-D	Four Dimensional
AOR	Advanced Oil Recovery
API	American Petroleum Institute
ASP	Alkaline-Surfactant-Polymer
BETC	Bartlesville Energy Technology Center
BO	Barrels of Oil
BOAST	Black Oil Applied Simulation Tool
BOE	Barrels of Oil Equivalent
BOPD	Barrels of Oil Per Day
CNES	Comprehensive National Energy Strategy
CO_2	Carbon Dioxide
CRADA	Cooperative Research and Development Agreement
DNGOI	1993 Domestic Natural Gas and Oil Initiative
DOE	United States Department of Energy
E&P	Exploration and Production
EIA	Energy Information Administration
EOR	Enhanced Oil Recovery
ERAB	Energy Research Advisory Board
EPACT	Energy Policy Act
ERDA	Energy Research and Development Administration
FE	Office of Fossil Energy
FY	Fiscal Year (October 1 to September 30)
HBCU	Historically Black Colleges and Universities
HO	Heavy Oil
I	Input
IFT	Interfacial Tension
IOGCC	Interstate Oil and Gas Compact Commission
IOR	Improved Oil Recovery
JPT	Journal Petroleum Technology
LO	Light Oil
M&O	Management and Operating

MASTER	Miscible Applied Simulation Techniques for Energy Recovery
MEOR	Microbial Enhanced Oil Recovery
METC	Morgantown Energy Technology Center
MIOR	Microbial Improved Oil Recovery
MMBO	Million Barrels of Oil
MMP	Minimum Miscibility Pressure
N_2	Nitrogen gas
NIPER	Measurement While Drilling
NPC	National Petroleum Council
NPRC	National Petroleum Research Council
NPTO	National Petroleum Technical Office
O	Output
OIP	Oil In Place
OJG	Oil and Gas Journal
OMI	Other Minority Institutions
OOIP	Original Oil In Place
PRDA	Program Research and Development Announcement
PRRC	Petroleum Recovery Research Center
PTTC	Petroleum Technology Transfer Council
SMR	Selective Mobility Reduction
TOR	Tertiary Oil Recovery
TORIS	Total Oil Recovery Information System
UNITAR	United Nations Institute for Training and Research
UTCHEM	University of Texas at Austin, Chemical Flooding Simulator
WAG	Water-Alternate-Gas

General Introduction

The Department of Energy has maintained an active research and development program since its inception in 1918. The program has constantly evolved and adjusted to meet the ever-changing needs of the oil industry. The program has been highly successful and serves today as a vital resource to the nation's research and development program within the oil industry.

Private industry, beginning in the 1930's funded most of the applied research and development activities in the oil industry through the mid-1980s. Most of the major oil companies had research centers and funded major programs for the development of new technologies. These programs resulted in the creation of new technologies that kept the industry strong and competitive. However, the collapse of oil prices in 1986 has resulted in a major restructuring of the industry. The research departments of the major companies have constantly been eroded due to a long period of low oil prices. Today, most of the research departments of the major oil companies no longer exist. This decline in research activity will eventually erode the capabilities of the major companies to compete globally for the discovery and production of oil.

DOE's role in the research and development of enhanced oil recovery (EOR) technology has become increasingly important as the industry research activity has continued to decline. DOE's role is expected to become even more vital as the country becomes ever more dependent upon insecure sources of foreign oil. The expertise maintained within DOE and through contractors is needed to maintain a healthy oil and gas industry within the United States and to protect the vital interests of the country.

The purpose of this report is to address issues raised by the National Research Council in the review of DOE activities. The report addresses these specific issues, describes the various EOR technologies, and discusses the benefits of the program that have been accomplished over the years.

Executive Summary

The objective of the Department of Enhanced Oil Recovery (EOR) Program, is to develop technology that is capable of improving oil recovery beyond that recoverable by conventional methods. Conventional primary and secondary recovery operations often leave two-thirds of the oil in the reservoir at the time of abandonment. Enhanced oil recovery (EOR) methods have the potential for recovering much of the remaining oil. However, the challenges are great because the remaining oil is often located in regions of the reservoir that are difficult to access and is also bound tightly into the pores by capillary pressures.

An estimated 200 billion barrels of oil is potentially recoverable by EOR methods. This target resource is particularly valuable to the country because of its size, its location within the United States, and the existence of an infrastructure that permits the application of the technology on a short-term basis.

The DOE research program is highly integrated and cohesive. It is designed to involve academia, government research organizations, and industry. The EOR program is subdivided into the areas of (1) chemical methods, (2) gas flooding, (3) microbial methods, (4) heavy oil recovery, (5) novel methods, and (6) reservoir simulation. Although the research program has a research focus, assistance has also been given to the independent producer in dealing with the day-to-day problems.

Since 1978 DOE has funded around $177,000,000 in these research programs through the year 2000. The DOE has made major contributions to the following areas:

- Development of the alkaline-surfactant-polymer (ASP) process, that is in commercial use today throughout the world. This is a low cost surfactant process that evolved from the earlier work done on the miceller-polymer process.

- Development of cross-linked polymer gel systems for use in controlling injection profiles and for the shut-off of water in producing wells. The research led to the development of commercial products that are being widely used within the industry.

- Evaluation and testing of foams, gels, and thickeners for improving the sweep efficiency in CO_2 flooding.

- Demonstration of the effectiveness of CO_2 flooding for the heavier oils where a miscibility condition is not developed. DOE’s research led to a number of successful CO_2 projects in the heavier oil reservoirs in the United States and in Turkey.

- Assistance to several independent operators in the use of flue gas and nitrogen for repressurization of the reservoir.

- Development of microbial enhanced oil recovery (MEOR) technology for the stimulation of producing wells, the improvement of displacement recovery, and the improvement of sweep efficiency. The process is now used commercially throughout the world for the stimulation of producing wells.

- Evaluation of methods to improve the performance of steam injection projects, including (1) methods for reducing wellbore heat losses, (2) use of cogeneration to reduce the costs for generating steam, (3) and methods for improving sweep efficiency (foams and gels). The early field support of a project in the Cat Canyon Field, California, led to the commercialization of the steamflooding process and to the use of cogeneration.

- Support of a project in the West Hackberry Field, Louisiana, to evaluate in-situ combustion technology for the deeper, light oil reservoirs. Support of this project has been instrumental in the development of in-situ combustion technology for the generation of flue gases in light oil reservoirs.

- Development of reservoir simulators for use by the industry. Major developments include UTCHEM (chemical), BOAST (black oil model), MASTER (gas simulator), and EOR screening models. BOAST is still widely used by industry, with an average of 230 copies being downloaded monthly from the NPTO webpage.

- Development and field-testing of the concepts for the use of horizontal wells in waterflooding and EOR operations. Several successful field tests are in progress and major applications are expected in the future.

An assessment has been made on the benefits of the DOE research program over the years. The impact is known to be large, based upon DOE's role in the critical technologies as noted above. However, a quantitative estimate is difficult to measure because of the diverse technologies employed and the wide array of users. Nevertheless, an estimate has been made using the EOR field data that are published semi-annually by the *Oil and Gas Journal*. The starting point is a calculation that shows the annual value (in 1999 dollars) of the total EOR production conducted in the United States. DOE's contribution was determined to be a certain percent of the total revenues produced by the sale of the EOR production. Using the finding and development costs and the EOR investment costs as a guide, the benefit ratio for DOE's research program was estimated to range from 1-5% of the proceeds from the total gross production. A benefit ratio ranging from 3.7 to 25 was then determined. A benefit ratio of at least 7.3 was selected as a conservative estimate.

FE 1. Briefly describe the selected technologies or projects.

Background

Oil is initially produced as a result of the natural energy that exists in the reservoir at the time of discovery. Reservoirs are initially pressured up and contain oil, dissolved gas, and water. Oil is produced as a result of the difference in pressure in the reservoir and in the wellbore. The most common natural depletion process is the "dissolved gas drive". As the pressure depletes, gas is liberated from the oil and furnishes the energy required to push the oil into the wellbore. Oil producing rates decline with time as the pressure is depleted within the reservoir. The recovery factor is highly variable, but averages around 22% of the initial oil in place (API, 1984).

Secondary recovery methods are frequently implemented at the end of the primary recovery phase to further increase oil recovery from the field. The most commonly used process is waterflooding. The basic principle is to inject water into certain wells and to displace the resident oil into nearby producing wells. The recovery from a waterflood is also highly variable, but averages around 12% of the initial oil in place (API, 1984).

Prior to 1960, reservoirs were traditionally abandoned at the end of primary and secondary recovery operations. Using the above numbers, the average recovery from the typical reservoir is around 34% of the initial oil in place. This means that 66% of the oil is left in the reservoir at the time of abandonment. This remaining oil is difficult to recover. The oil is often contained in isolated portions of the reservoir that are difficult to access and to displace by another fluid. It is also difficult to overcome the capillary pressures that tend to keep the oil contained within the small pores. Figures 1 and 2 depict the oil saturation that typically remains in the pores following primary and secondary recovery operations, respectively.

DOE, together with industry, have worked for many years in the development of processes that can economically recover the large target oil saturation that remains after primary and secondary recovery operations. The challenges are both technical and economic. There is also an urgency to develop cost-effective methods to recover the oil since the wells that are needed to conduct a project are being rapidly plugged and abandoned. It is usually not economic to drill totally new wells in an old field to implement a project for the recovery of the remaining oil.

The term "enhanced oil recovery" (EOR) is most commonly used to designate those processes that can be used to recover the oil that remains after conventional operations. Other terms that have also been used include "tertiary oil recovery" (TOR), "advanced oil recovery" (AOR), and "improved oil recovery" (IOR).

This discussion describes the specific EOR programs that have been evaluated by DOE's research and development program.

Production Research Program

The focus of DOE's program is to conduct research on methods that have the potential to increase oil recovery beyond that recoverable by conventional methods. The program has both a short-term and long-term focus. A short-term focus is needed to improve oil recovery in those reservoirs that are approaching their economic life. Besides increasing oil production, this maintains the infrastructure, and access to the reservoir. A longer-term focus is given to those processes that have especially high potential but which require a more lengthy time to develop.

The program is highly integrated and cohesive. It is designed to involve academia, government research organizations (includes National Laboratories, Other Federal agencies, and state agencies) and industry (includes large integrated companies, independent operators, service companies, and industry organizations). The academia sections consist of major universities, petroleum research centers, Historically Black Colleges and Universities and Other Minority Institutions (HBCU/OMI). The various programs are funded in the Reservoir Efficiency Processes of the Oil Exploration and Production Program. However, all of these programs will be referred to subsequently as enhanced oil recovery (EOR) projects.

The production research program is targeted for reservoirs that contain around 200 billion barrels of oil that are potentially recoverable by EOR methods. Although the program has a research focus, assistance is also provided to the independent producer in dealing with the day-to-day problems. This program is subdivided in the areas of (1) chemical methods, (2) gas flooding, (3) microbial methods, (4) heavy oil recovery, (5) novel methods, and (6) reservoir simulation. Each area addresses one or more specific portions of the resource base.

Chemical Methods.

Chemical methods include the use of surfactants, alkaline-enhanced chemicals, and polymers and gels. Each of these processes is described below:

The micellar-polymer flood is a process designed to recover oil by reducing the interfacial tension that exists between the in-place crude oil and the injected water. The micellar fluid is comprised largely of surfactants and water. The micellar fluid has the capability of mobilizing and displacing the oil at the leading edge as a result of the reduced interfacial tensions that develop upon contact with the resident crude oil. The micellar fluid is also capable of being propagated through the reservoir as a result of its miscibility with the driving water. These capabilities permit the use of a small, water-driven chemical slug to recover a significant amount of oil. Polymers are added to a portion of the drive water to protect the chemical slug from early dissipation by the driving water phase. Figure 3 depicts the various banks that occur in the reservoir in the micellar-polymer flooding process.

DOE funded a significant amount of research during the 1980s to develop the process. This emphasis was given because of the potential of the process to recover a significant amount of oil from the nation's shallow to mid-depth reservoirs. Competing processes were not available for this resource base.

The general industry experience has indicated that the process is capable of recovering a significant amount of oil (up to 28%), especially with the later-generation surfactants. However, the economics have proved to be unfavorable at the prevailing crude oil prices due to excessive chemical losses and to the adverse effects of reservoir heterogeneities.

The alkaline-surfactant-polymer (ASP) process evolved from the early studies on micellar-polymer flooding. This process is based upon the generation of surfactants that occurs when certain crude oils that contain organic acids react with alkaline solutions. Such surfactants, when enhanced by additional surfactants, have the capability of mobilizing additional oil. Polymer is added to protect the chemical slug from early dissipation by the driving water phase. The principal advantage of this process is its low cost. However, the process is adversely affected by contact with water or rock that contains high salinity and hardness. The process has been successfully used in recent years in the Minnelusa reservoirs of Wyoming, the Sho-Vel-Tum Field in Oklahoma, and the Daqing and Karamay Fields in China.

Polymer flooding was originally developed to increase oil recovery by improving the sweep efficiency of the injected water. This was made possible by the addition of extremely high molecular weight polymers to the water being injected into the reservoir. The most commonly used polymers (polyacrylamides) act both to increase the viscosity of the water and also to reduce the permeability of the rock. A large number of polymer floods have been conducted. Many of these were in the Minnelusa reservoirs in Wyoming. A review of 31 projects in the Minnelusa reservoirs indicated an average recovery of 7.5% of the initial oil in place at a cost of $1.69 per barrel of incremental oil (Green, 1998). In spite of the successes, polymer flooding is not commonly used today in the United States because of the low incremental recovery achieved. However, polymer flooding is being extensively used in the Daqing Field in China (Demin, 1998).

Profile improvement methods have been commonly used in recent years for the improvement of sweep efficiency in waterflooding and in EOR projects. These treatments are accomplished by the use of crosslinked polymers and chemical gels to reduce the permeability of the more permeable zones. Such treatments can then divert the subsequently injected fluid into the less permeable intervals. DOE has funded a number of studies designed to improve the capabilities of using polymer for profile control. Sydansk (1998) discusses the results of 1400 polymer gel treatments conducted by Marathon Oil Company over a 12-year period.

Water shut-off methods have also been developed to reduce the amount of water that is being produced. Crosslinked polymers and chemical gels are also used for this kind of application. ARCO and Chevron have indicated that water shut off projects have saved the U. S. oil industry about $142,000,000 on projects conducted since 1995. This amount of savings would fund the Reservoir Efficiency Processes research program for over 20 years (at $7,000,000 per year).

Gas Flooding.

The various gases that have been used in reservoir applications include carbon dioxide, enriched natural gas, flue gas, and nitrogen. The first two gases are often used to improve oil recovery by developing miscibility with the in-place crude oil. Carbon dioxide is the most commonly used gas because of its availability at low cost and because of its versatility. Enriched gas is less commonly used in the United States because of a strong demand for the intermediates (e.g., ethane, propane, butane) required to develop miscibility. Flue gas and nitrogen are used principally for maintaining reservoir pressure, although a miscible displacement condition can be developed in some of the deeper, hotter reservoirs. The DOE program has focused principally on the use of carbon dioxide.

Carbon dioxide flooding is the most commonly used gas flooding process in the United States. Moritis (2000) indicates that about 190,000 barrels of oil per day are being produced in the United States as a result of applying carbon dioxide flooding. Most of the production comes from the Permian Basin reservoirs located in Texas and New Mexico. The process is applied by injecting a large slug of carbon dioxide followed ultimately by drive water. Water is often injected along with the carbon dioxide to maximize the reservoir sweep efficiency. Figure 4 depicts the carbon dioxide flooding process and shows the tendency to channel due to the contrasts in permeability (k). The process is most commonly applied where a miscible displacement condition can be developed. This condition is desired because of the greater oil recovery that can be achieved. Miscibility can often be established in reservoirs containing a light oil and located at depths greater than 3000 ft.

One of the major challenges arises from the large differences in the density and viscosity of carbon dioxide relative to the in-place crude oil. The injected carbon dioxide tends to break through prematurely into the producing wells due to a combination of channeling through the more permeability zones and to gravity override. The result can be a lower-than-expected oil recovery. The most common method to deal with this problem is the alternate injection of water and gas (referred to as a WAG process). Although the WAG process improves sweep efficiency, the displacement efficiency in the contacted areas may be decreased due to the shielding of the oil by water. DOE research efforts have focused on alternative methods to improve the sweep efficiency of carbon dioxide. These methods include the use of foams, chemical gels, and direct carbon dioxide thickening agents.

Research conducted at DOE has also determined that carbon dioxide flooding is often effective in improving the recovery in the more viscous oil reservoirs where a classical miscible displacement process cannot be established. The increased recovery is attributed to the beneficial effects of the carbon dioxide in reducing the viscosity of the oil and increasing the oil saturation through swelling. These findings have led to a number of applications of carbon dioxide flooding in the lower gravity, heavier crude oils. Future applications are also expected.

DOE has also assisted the small operator in the use of flue gas, natural gas, and nitrogen for improving the oil recovery through reservoir repressuring. Several projects have been implemented.

Microbial Enhanced Oil Recovery (MEOR)

The MEOR process operates by the action of microbes to ferment a hydrocarbon and produce a byproduct that is useful in the recovery of oil. Ideally, microbes could function on the use of crude oil alone. However, experience has shown that nutrients such as molasses, phosphate, or nitrate must be co-injected to nurture the process to insure good production of the byproduct chemicals. Injection of trace minerals may also be required. DOE has been a leader in the development of the technology in recent years.

The MEOR process is being evaluated for the following different applications:

- Microbial Well Stimulation. This process is now being applied on a commercial basis throughout the world. The major applications have been in the heavier oil reservoirs that are dealing with problems associated with paraffin and asphaltene deposits. The major areas of application include Venezuela, China, and Indonesia.

- Microbial Enhanced Waterflooding. This process, which requires the transport of nutrients over a long distance within the reservoir, is still in the development phase. DOE has tested this process in the Delaware-Childers and Chelsea Fields in Oklahoma.

- Profile Control and Sweep Improvement. This process uses microbes that produce polymers, biomass, and slimes for the selective plugging of the more permeable zones. This process is also still in the development phases. However, a successful DOE-sponsored project is in progress in the North Blowhorn Creek Field, Alabama (Brown, 2000).

The MEOR process has two distinct advantages: (1) microbes do not consume large amounts of energy, and (2) the use of microbes is not dependent on the price of crude oil as many of the other EOR processes. Because microbial growth occurs at exponential rates, it should be possible to produce large amounts of useful products rapidly from inexpensive and renewable resources. Thus, MEOR processes have the potential to be more cost-effective than other EOR processes. Recent studies have also shown that several microbially produced biosurfactants have interfacial tension activities that compare very favorably with chemically made biosurfactants. The ability to produce effective surfactants at a low price may make it possible to recover a significant amount of oil that currently exists at a residual oil saturation.

DOE is currently supporting several MEOR projects that have high potential. These include a (1) a project to make surfactant from waste products, (2) a project to make microbes more tolerant to a wide range of reservoir conditions, and (3) a project to achieve mobility control and sweep improvement.

Heavy Oil Recovery.

The recovery of heavy oil is usually accomplished by the introduction of heat into the reservoir. The major EOR processes that have been traditionally used include steam injection and in-situ combustion. This discussion will focus on these two applications. However, it is important to note that an increasing amount of the heavy oil is being produced by cold production methods under primary recovery conditions. In Canada, success has been achieved by the co-production of heavy oil and sand. In Venezuela, the practice is to produce the heavy oil through long, horizontal wells where sand production is excluded.

Steamflooding is the dominant EOR process in the United States. Moritis (2000) indicates that about 418,000 barrels of oil are produced daily as a result of steam flooding. The process is conducted by injecting a high quality steam into a reservoir that is relatively shallow, permeable, thick, and which contains a moderately viscous oil. The dominant mechanism is a reduction in the viscosity of the oil. Figure 5 depicts the various banks that build up in the reservoir as a result of steam injection. The total recovery from the combined primary depletion and steamflooding is usually 50% or more of the initial oil in place (Green, 1998).

The major problem in the process is the tendency of the steam to override the oil bank due to the differences in the gravity of steam and oil. DOE has supported several projects designed to develop methods to improve the distribution of steam within the reservoir. Field tests in California using foams and chemical gels have been encouraging.

In-Situ Combustion is a process that introduces heat into the reservoir by the burning of a portion of the oil. The combustion process is initiated by the injection of air and the use of a downhole ignition device. The combustion front is thereafter sustained and propagated through the reservoir by the continuous injection of air. Water is often injected along with the air to improve the process efficiency. The injected water transfers some of the heat behind the combustion front to the rock immediately ahead of the combustion front. The major problems have traditionally been the premature breakthrough of the combustion front and severe operating problems. Figure 6 depicts the in-situ combustion process and shows the tendency for gravity override. Recent studies have suggested ways that the process can be improved by using horizontal wells along with gravity drainage concepts. Many of the early projects were not successful. However, there have been some successful demonstrations of the technology in recent years.

An emerging technology is the application of the in-situ combustion process in deep, light oil reservoirs. These applications are designed to improve oil recovery by the generation of flue gases in the reservoir. The process was implemented in several fields in North Dakota and South Dakota to repressure the reservoir. A DOE-supported project in the West Hackberry Field in Louisiana was successful (Gillham, 1998). Air was injected at the top of a steeply dipping reservoir to produce a flue gas, which in-turn displaced oil downward under gravity-stabilized conditions.

Novel Methods

Novel methods are those that do not fit within the conventional EOR processes. These methods are usually determined to have potential as a viable EOR but which are largely unproven. The various processes that fit into this category include downhole electric heating, microwave heating, seismic wave stimulation, and wettability reversal. DOE will sometimes support some of the projects within this category based upon the merits of the process. The following are interesting progects that are now being supported by DOE.

Seismic wave stimulation is a novel process that is receiving increased attention within the industry. The premise is that high-energy seismic waves can re-distribute the oil droplets in a high water saturation environment to create a mobile oil phase. The seismic waves may be transmitted to the reservoir by large sized surface vibro-seismic devices or by downhole wellbore devices that generate the energy close to the reservoir. The Russians have been developing this process for nearly 40 years and have conducted numerous field tests. Several U.S.-based groups have been refining the technology and are now conducting field tests. DOE is now supporting The Los Alamos National Laboratory in conducting a cooperative program with industry to develop and evaluate the technology in the field. The field tests have been encouraging, but many questions still remain.

Wettability reversal is a novel process that is now being studied at two institutions. Wettability is determined principally by the constituents that are contained in the crude oil. Recovery is determined principally by the constituents that are contained in the crude oil. Recovery is usually lower in reservoirs that are oil-wet. The ultimate goal in these studies is to evaluate methods whereby the wettability can be changed from an oil-wet to a water-wet condition. One project is studying the basic charactistics of wettability, and the second project is evaluating the idea of injecting an optimally-designed dilulte brine to reverse the wettabillity. These projects could have a huge benefit in improving oil recovery if successful.

Simulation

Reservoir simulators have proven to be useful in the design and prediction of performance from EOR projects. Good progress has been made in the development of EOR models over the past 10 years. In-spite of the progress, additional research is needed to develop the state-of-the-art models that are needed to better design and to predict field performance.

Several DOE-supported projects are now in progress to improve the hardware and software capabilities of reservoir simulators. These projects include both the sophisticated models as well as the scaled-down versions that may be suitable for independent operators. An improved capability to handle horizontal wells is also being developed.

Figure 1
Oil Remaining After Primary Recovery

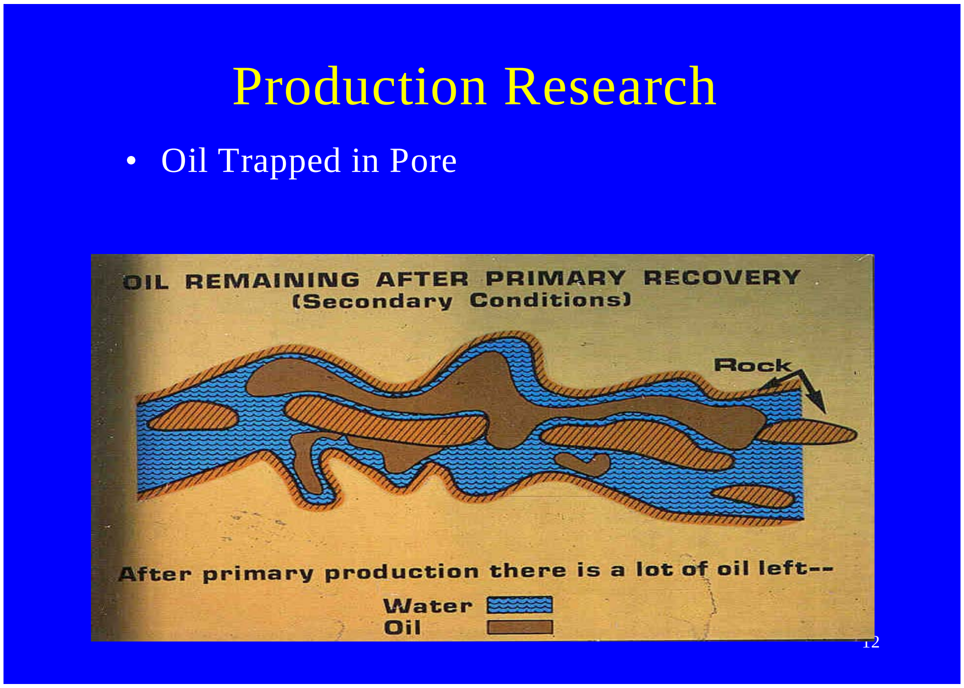


Figure 2
Oil Remaining After Secondary Recovery

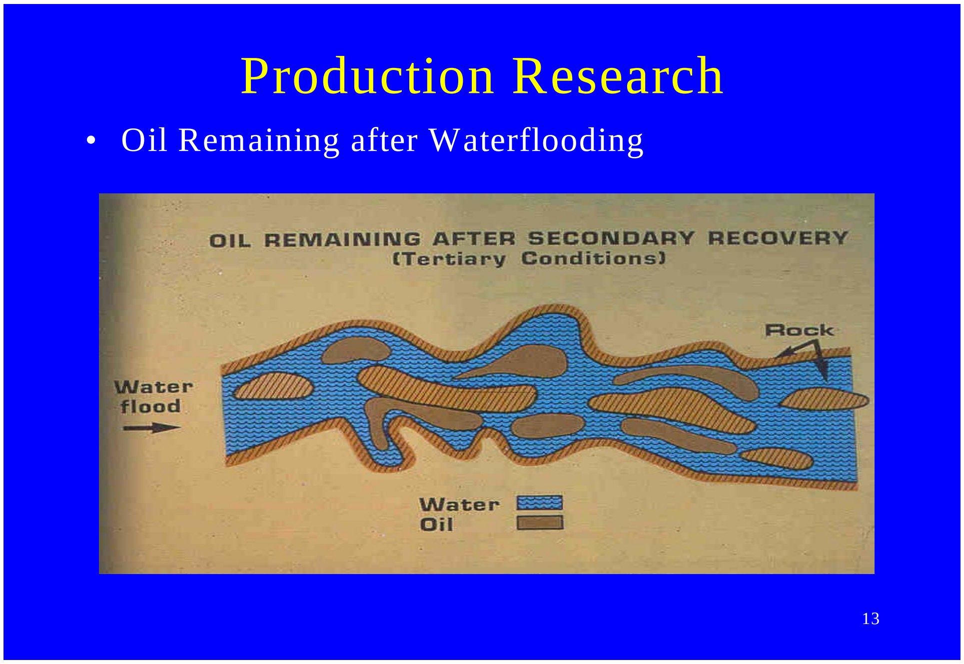


Figure 3
Depiction of Micellar-Polymer Flooding

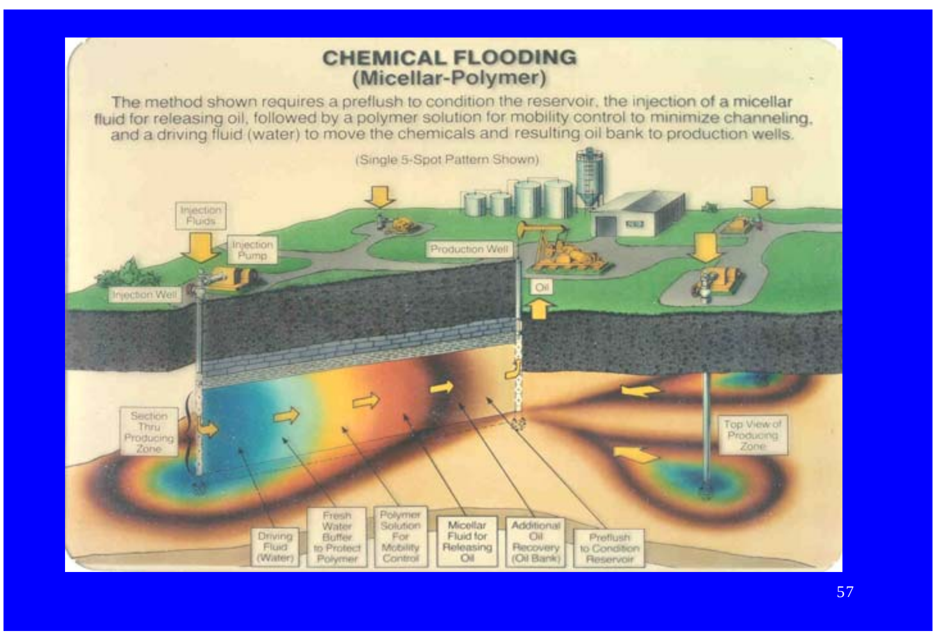


Figure 4
Depiction of Carbon Dioxide Flooding

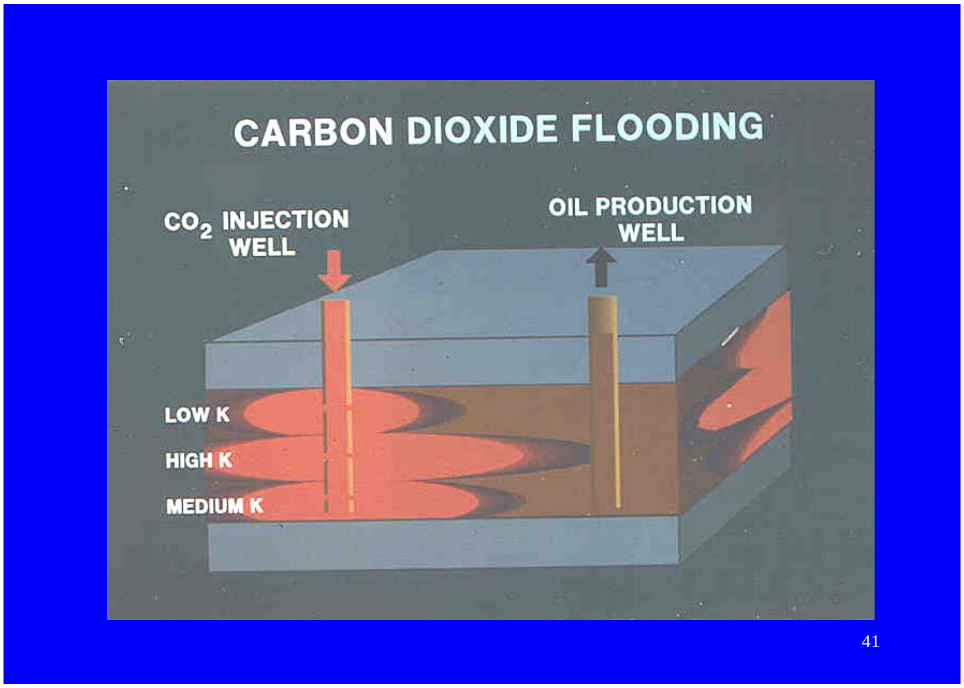


Figure 5
Depiction of Steamflooding Process

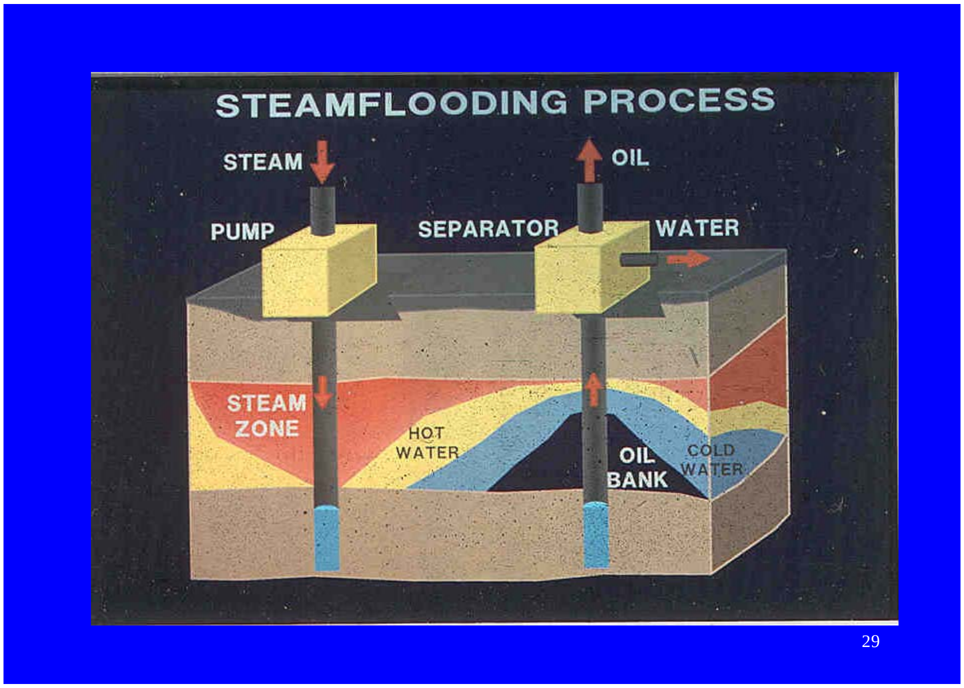
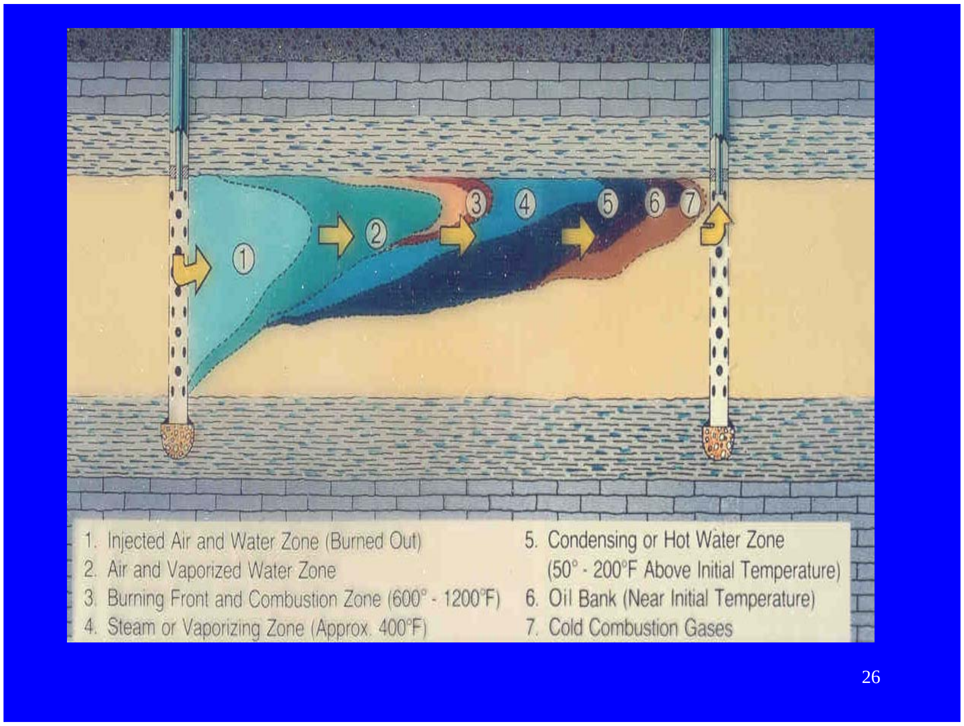


Figure 6

Depiction of In-Situ Combustion Process



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FE 2. For each of the identified technologies, what factors (such as policy issues, changes of Administration, or OPEC actions) influenced the annual DOE R&D funding allocations for each technology (both increases and decreases)?

The following information quoted is from the U.S. Department of Energy Fossil Energy Programs submissions the Office of Management and Budget (OMB) and Appropriations Committees.

FY 1979

'The EOR program is being significantly redirected in FY 1979. The new emphasis will be on longer range, higher risk, advanced technology development. Past programs that were basically commercialization oriented will be phased out in FY 1979.'

FY 1981

'As with the FY 1980 budget, no direct funding is included here for field pilot tests or commercial demonstrations. It is anticipated that these types of projects will be undertaken by private industry because of the administration's pricing incentives. Small field experiments will continue, however, as an essential part of the R&D program which allows problems to be detected and identifies areas where additional R&D is needed.'

FY 1985

'Over the past 30 years, private industry has researched various EOR techniques with mixed results. Because of the complexities of subsurface behavior of injected fluids and chemicals, none of the EOR processes are very well understood. As was noted, current EOR production is only 400 thousand barrels per day with most of it coming from the relatively simple thermal recovery methods applied to heavy oil resources. The industrial research effort has been aimed at resource-specific targets and is primarily designed to solve immediate problems related to petroleum exploration, development, and production. By improving the understanding and performance predictability of processes, EOR can be made more attractive to the industry. Fundamental research envisioned under the EOR program expects to look at the problem as a whole and will attempt to provide solutions to discrete research requirements which can then become the necessary building blocks for innovative process development by the industry. The focus of the EOR program is thus based on obtaining a clearer understanding of the scientific processes through long-range technology base research.'

FY 1987

'One of the most comprehensive reports on the future of EOR in the United States was recently completed by the National Petroleum Council (NPC) at the request of the Secretary. They study points out that only 27% of all the oil discovered in the United States was produced (130 billion barrels) and that only 6% remains to be produced with conventional technologies (28 billion barrels). This leaves 323 billion barrels or 67% of the otherwise unrecoverable oil as the target for EOR. This oil remains out there, not waiting to be discovered but in places we know, in fields that are opened, but trapped in geology and by forces that are still beyond the grasp of today's production technology.'

'The NPC study recommends a number of research areas in EOR and states in the transmittal letter to the Secretary that "only through continued process research and field testing with both industry and government support, can the large volume of hydrocarbons discussed in the report be produced." Using today's EOR know how, the NPC report concludes that 14.5 billion barrels—the equivalent of about half our current recoverable reserves—could be added to the domestic crude oil supply. Further, NPC concludes that advances in technology could double that amount. This still leaves more than 300 billion barrels of oil in the ground.'

'Because of the present world energy situation and restructuring of the oil industry, exploration for new reserves has dropped off, particularly in the domestic arena. But even in the recent past when exploration was at a peak, reserves were being added at a rate far below that previously experienced, and the average size of reservoirs discovered was found to be declining rapidly. Overall, domestic production has been on the decline for 15 years with some states experiencing serious economic consequences, because of drastic reductions in production. This only emphasizes the importance of relying on existing, but currently unrecoverable, oil resources and new technologies to recover that oil. Also, from a purely strategic point of view, EOR can help fill the oil supply shortfall after the strategic reserve runs out and before synthetic fuels make measurable impact on oil supply.'

'Fundamental research envisioned under the EOR program expects to look at the problem as a whole and will attempt to provide solutions to discrete research requirements which can then become the necessary building blocks for innovative process development by the industry. The focus of the EOR program is thus based on obtaining a clearer understanding of the scientific processes through long-range technology base research.'

'The U.S. does have considerable heavy oil (approximately 100 billion barrels) and tar sand resources (54 billion barrels) but our neighbors to the north and south have orders of magnitude larger in-place resources. Canada has an estimated 1.2 trillion barrels contained in their tar sands and Venezuela has 1 to 4 trillion barrels in their heavy oil deposits. Mexico is still determining the magnitude of their petroleum deposits (both heavy and light oil) but they are known to be vast. It is therefore important from a strategic standpoint to develop efficient, effective and economic recovery technologies for these resources. The fact that Canada, Venezuela and Mexico have mutual interests in recovery research affords us the opportunity to leverage our resources through cooperative research efforts. We do in fact have active and mutually beneficial agreements in place with these countries and are task sharing research on defined critical needs.'

FY 1991

'Regarding private sector participation, private sector input is solicited during the program planning process through a variety of mechanisms, including advisory groups, workshops and peer reviews. In the program execution phase, substantial emphasis is placed on program evaluation to assure that intended benefits are realized and on cost-sharing and teaming with other R&D performers to facilitate the transfer of technology to the private sector and to reduce federal expenditures. Inherent in this approach is an attempt to attract research performers that have a long-term, market-based commitment to an are of research and to the ultimate application of the research results. In general, industry, trade and consortia representatives, individual states, and even foreign entities will be more willing to co-invest money in potential high payoff R&D as risks and uncertainties are reduced and market opportunities and return-on-investment are more evident, and thus cost-sharing frequently becomes more attractive as R&D approaches the proof-of-concept stage.'

'One of the primary goals of all the applied research areas in FE is to effectively transfer technology from Federal and university laboratories to the U.S. private industry. The earlier the U.S. industry and/or their trade and consortia representatives (EPRI, GRI, etal.) are involved, and the more directly that the research agenda is guided by the companies' own economic self-interest, the more effective the transfer is likely to be.'

FY 1993

'The overriding goal of the National Energy Strategy (NES) is to reduce the nation's vulnerability to sharp future fluctuations in oil supply. This will require efforts on two broad fronts: measures to increase oil supply and measures to reduce oil demand. Increased supply is the focus of the Enhanced Oil Recovery (EOR) program. Accordingly, the program emphasizes activities that facilitate domestic oil recovery efficiency. The result, as estimated in the National Energy Strategy, could be an additional 3.2 million barrels per day by 2010.'

'The EOR light oil program approach, based on the National Energy Strategy, and the Oil Program Implementation Plan, is to support research that will improve the economic producibility of the domestic oil resource. The target resource is the huge amount of oil left behind in reservoirs after conventional extraction processes have reached their economic limit. The target oil is of two types: (a) oil that is mobile when water-flood recovery technology is utilized and which is not produced because of variations in fluid flow in complex reservoirs (heterogeneity); and (b) oil that is not mobile when water-flood recovery technology is utilized because of a variety of physical and chemical forces. All reservoirs contain both kinds of oil, but some represent more significant targets for future recovery than others. Previously, low oil prices have led to an increasing rate of reservoir abandonment because many are no longer economical to produce. Once abandoned, the oil remaining is not likely ever to be produced. The increasing rate of abandonment has added urgency to the effort. Thus, the light oil program has initiated a near-term goal to identify the most urgent of the high potential reservoirs, and to preserve access to them through targeted technology transfer of the best available processes. In parallel, the mid-term focus of the program is on improving out knowledge of reservoir architecture and its impact on fluid flow, and, using this knowledge, to improve the technical, economic, and environmental performance of advanced extraction processes for those same reservoirs.'

'The requested level of effort in the EOR heavy oil program will allow continuation of limited near-term producibility field tests and mid-term advanced EOR and horizontal well field trials initiated in 1992, and maintenance of core laboratory level advanced extraction research and technical support. At the same time, the heavy oil program will benefit by anticipated studies in advanced upgrading and crude processing technology being explored within the AEPT program which is now more closely integrated with the EOR program. Further work on recovering our heaviest oils from tar sands reservoirs will be deferred to allow program focus on the recovery of more valuable lighter oils.'

FY 1995

'In addition, immediate expansion of disciplined lab research and evaluation of past advanced field trials directed to incremental recovery potentials in large, promising Class 1 and 2 reservoirs will be initiated in accordance with DNGOI priorities. This will include expanded adaptation and transfer to industry of DOE nation laboratory high performance computational technology developed for defense purposes. Likewise, exploration and production environmental research efforts will expand its focus on assessing oil field risks and fostering streamlining of necessary environmental regulation. Research efforts in the base program will continue to foster improvement in recovery technology in producing light and heavy oil reservoirs. Fundamental geotechnical studies and Oil Recovery Technology Partnership efforts previously supported primarily in the former Advanced Extraction and Process Technology program will be continued.'

FY 1999

'The vision of the program is for our domestic oil resource to reach its full potential in contributing to the Nation's national energy security, economic growth, environmental quality and science and technology leadership. The United States remains the world leader in oil technologies; advanced U.S. technologies are sold and used worldwide. A customer-driven, public-private partnership is recognized as a key contributor to the development of technologies, regulatory streamlining, and policies that support increased oil supplies.'

'Extensive stakeholder involvement in the development and ongoing assessment of coordinated oil programs is consistent with requirements of the Government Performance and Results Act (GPRA) of 1993. The purpose of the Act is to reduce waste and inefficiency and increase customer satisfaction in Federal programs.'

'DOE's RD&D acts as a catalyst for increasing domestic oil production. In turn, this supports the reliability and affordability of energy supplies and the stability of energy markets, providing an essential foundation for U.S. energy security, contributes positively to the U.S. balance of trade, increases economic activity and creates high-paying jobs.'

'The RLE work focuses on coordinating oil technology activities in research, development, and demonstration of advanced technologies for extraction of hydrocarbons from known (discovered) oil reservoirs. The activities provide improved technology and/or more efficient methods to recover more of the 351 billion barrels of discovered but unproduced domestic oil resource. The goals are to increase recovery of oil from Federal lands, to conduct research to develop and demonstrate tools and methodologies that permit oil operators to recover hydrocarbons from known reservoirs not producible by current technology, and support university research in extraction technologies and recovery-process modeling to ensure a supply of well-trained workers. The objective is to develop scientific breakthroughs with are applicable to the industry and that benefit the nation's economy and protect our environmental heritage. Fundamental and applied geotechnical studies and the industry driven Natural Gas and Oil Recovery Technology Partnership efforts will also be continued.'

FE 3. For each of the technologies identified, list and briefly describe any products that resulted for DOE's R&D investment that are currently finding commercial or research application in an area other than the original project or program.

Chemical Methods

Perhaps the industry which has benefited the most from enhanced oil recovery technology has been the environmental restoration industry or more specifically those environmental programs dealing with groundwater remediation or clean up. Essentially all of the current groundwater clean-up programs throughout the industry are based upon technologies designed and proven in the oil field. Both petroleum and hydrology industries are designed to extract fluids from subsurface reservoirs or aquifers based upon geologic interpretation. The following enhanced oil recovery technologies have all been applied successfully in the groundwater remediation industry.

One of the key parameters of enhanced oil recovery is mobility control and is generally related to moving the oil through areas of the reservoir where the oil does not normally want to flow. The oil will follow the path of least resistance and therefore will flow along the more permeable areas of the reservoir both laterally and vertically. This causes the oil in the less permeable areas to be bypassed during secondary recovery such as a water flood. In an effort to prevent this from happening, polymers are added to the injection water to reduce the flow through the high permeability zones and direct the water from the flood into the less permeable zones where the trapped oil resides. This process has been proven to work, but is somewhat expensive and DOE has been working on research to develop low cost polymers for improved oil recovery. Consider a subsurface aquifer which has become contaminated and in which the contaminated groundwater plume is moving or approaching a non-contaminated drinking water source. In order to prevent the contamination from flowing preferentially along high permeability strata, polymers are injected into the path of the approaching groundwater plume to force the water to flow through the less permeable strata thereby reducing the rate of approach. This technique had been used many times in groundwater clean-up programs to confine or restrict the flow of the plume until a more thorough clean up approach can be implemented. In most cases the same polymers which have been developed for the petroleum industry are used for this application in the groundwater industry where costs are not always the deciding factor.

Reservoir Simulation

The DOE enhanced oil recovery program was at the forefront of reservoir simulation technology and led numerous research projects focused on the flow behavior in heterogeneous reservoirs. With the advent of personal computers and software programs designed to model the movement or flow of fluids through a porous medium, geologists and engineers can now more accurately predict the outcome of oil recovery programs. This same simulation technology has been adapted to the groundwater industry for essentially the same reasons. The same technology which allows the most accurate depiction of the subsurface reservoir for oil recovery also works extremely well for the recovery of contaminated groundwater from aquifers. The computer program, UTCHEM, developed at the University of Texas at Austin and funded by DOE has been used extensively for modeling ground water contaminates. UTCHEM's versatility allows components of high or low solubility in water to be tracked accurately.

Microbial EOR

The DOE has been involved in numerous projects to investigate the feasibility of utilizing microbial populations for enhanced oil recovery. This process called "Microbially Enhanced Oil Recovery" or MEOR has sought to develop technology which would allow the microbes or bacteria to alter the permeability of an oil reservoir in order to divert more of the water from a flood into the less permeable portions of the reservoir to recover some of the bypassed oil. Microbes are also used in several other ways such as removing paraffin or wax buildup from the perforations around the wellbore. The environmental industry has adopted much of the knowledge gained from these programs and has applied the same processes to clean up activities. Because much of the contamination in groundwater is from petroleum-based materials, the same microbial technologies are being used for groundwater remediation. An important aspect of any groundwater clean up program is the identification and remediation of the source material such as contaminated soil from a leaking underground storage tank. The most common and least expensive form of cleanup technology for both soil and groundwater contaminated with organic compounds is bioremediation.

Microbial EOR contributed to the clean-up of the Persian Gulf after Desert Storm. Microbes were introduced into the oil slicks in the Persian Gulf and aided in the rapid dispersion of the oil. Microbial EOR has been used for surface and near surface clean-up of areas around producing wells and around fuel storage areas on air force bases.

Thermal Methods

The petroleum industry has been utilizing steam injection for enhanced oil recovery from heavy oil fields for several years. DOE has been involved with several research projects to determine the most efficient steam flooding processes and optimize the effective limits to steam flood applications. There have been several advances in steam flooding technology and a significant amount of heavy oil is produced in this manner. Recent groundwater remediation programs have begun to utilize steam injection and flooding of contaminated aquifers in order to accelerate the clean-up process. The ability of steam to reduce the viscosity of materials and enhance the flow capability of these fluids has been applied to the cleanup of aquifers where the steam acts to increase the mobility of the contaminant.

Gas Flooding Methods

The injection of certain gases such as CO_2 for enhanced oil recovery has been included as part of many of DOE's field demonstration programs. In addition to CO_2, other gases have been tested such as nitrogen, flue gas, and air. Because of the dangers of the oxygen in air becoming an explosive mixture when combined with hydrocarbons, this process is not widely used. However, the process of injecting air into subsurface aquifers in order to recover more of the contaminated groundwater is being frequently used. DOE has conducted several projects to investigate the potential of air injection for oil recovery and although it does not perform well in recovering petroleum this process is quite efficient at recovering contaminated groundwater.

CO_2 Sequestration

Carbon dioxide sequestration is a method to isolate CO_2 generated from fossil fuel combustion and reduce the amount of CO_2 that ends up in the atmosphere. Sequestration techniques involving oil and gas reservoirs draw heavily on the technology and knowledge of the enhanced oil recovery (EOR) method of gas flooding. One sequestration technique involves using industrially-produced CO_2 for enhanced oil recovery in reservoirs currently under production. Natural sources of CO_2 are typically used in oil recovery.

The total amount of CO_2 used for enhanced oil recovery in 1999 was about 40 million metric tons (a rate of about 2 billion cubic feet per day, or about 10 million metric tons of carbon per year). This is roughly 1% of the carbon dioxide released annually in recent years from the burning of fossil fuels in the United States.

A study in Texas (Finley and Holtz) indicated a substantial potential for using utility plant boiler effluent as a CO_2 supply source for flooding mature oil reservoirs. They found that between 12 and 20 years of CO_2 production from lignite- or coal-fired boilers located near producing oil and gas fields can be sequestered from these generation facilities. Another technique involves injecting the CO2 into depleted oil and gas reservoirs. The global sequestration capacity in abandoned reservoirs is estimated to be 130 to 500 gigatons of carbon. This capacity is equivalent to 20-80 years of current global carbon consumption via fossil fuels, since about six gigatons of carbon are emitted into the atmosphere globally each year from fossil fuels. The technology for injecting CO_2 into formations which could store the CO_2 has been developed by the EOR program.

International EOR Projects

This discussion focuses on international EOR projects that can be related to the research and development activities of the U.S. Department of Energy. As oil producing regions around the world become more mature and depleted, the demand for the technology to recover more of the remaining oil reserves will increase. The enhanced oil recovery technologies developed and proven in the United States are already being applied overseas. The export of this technology is important for the U.S. economy in a number of ways. The income provided by these EOR industries directly helps to reduce the trade deficit and maintain a globally competitive petroleum industry. Moreover, the continued oil production from foreign countries, specifically non-OPEC countries, contributes to the world oil resource and helps to moderate the price of oil. The following are examples of EOR technologies that are being applied in foreign countries based upon technologies developed in the U.S. No international benefits are included in the benefits calculations, section FE 6.

The use of carbon dioxide flooding is being used to enhance heavy oil recovery from the Bati Raman heavy oil field in Turkey. The Turkish Petroleum Corporation is producing oil from fields located in southeastern Turkey based upon carbon dioxide flooding technology developed in the SACROC project in the Permian Basin of West Texas. The primary difference in the two regions is the oil fields in Texas produce oil which is much lighter and can be produced by miscible flooding. Immiscible carbon dioxide application to enhance heavy oil recovery has been experienced by the Turkish Petroleum Corporation (TPAO) in Bati Raman, Ikiztepe and Camurlu oil fields. It is estimated that the primary recovery from these three fields will be quite low and in the case of the Camurlu field only about 1% of the original oil in place will be recovered. Because of the high molecular weight of heavy oils, the miscibility pressure is usually higher than the reservoir pressure. Therefore, the success of CO_2 injection in heavy oil fields should rely primarily on the oil-swelling effect of CO_2 after it goes into solution and its viscosity-reduction effect. Based upon current production figures, it is estimated that as much as

7-23% of the remaining oil can be produced by CO_2 injection. As of January 1998, 34 million barrels of incremental oil has been recovered from the project. This project successfully demonstrates that CO_2 is effective under immiscible conditions in recovering a low gravity oil by an interwell flooding process.

Saga Petroleum (now Norsk Hydro) is using a fractional flow simulation model developed by the University of Texas at Austin to analyze the results of their foam field test in the Snorre field located in the North Sea. The fractional flow model fit the field data well and guided the process of a more quantitative history matching using simulation. This field trial was successful and is undergoing a major expansion by Norsk Hydro. The field trial also borrowed the alternating slug foam process developed by the University of Texas under a DOE grant.

A field located in Canada is being considered for an enhanced oil recovery process based upon a risk analysis performed using a simulation program developed in partnership with DOE. The Weyburn field is being considered for a miscible CO_2 flood by PanCanadian Petroleum Limited and the design of the flood is based upon CO_2 flooding in the Permian Basin. In addition, several members of the design team are also key personnel in several DOE projects. At the end of primary and secondary production, 65% of the original oil in place still remains. A risk assessment using a simulation model approach was undertaken to combine the technical with the non-technical issues associated with the project in order to define the full cycle opportunities and risks. The risk assessment process was used to optimize the project configuration, to focus the team on key issues, and to find ways to mitigate the risks inherent in the project. Input data forming the basis of this assessment incorporated information and opinions from internal experts, industry consultants and other analogous CO_2 floods in the Permian Basin. The CO_2 for the project is being supplied from normally vented gas at the Great Plains Synfuels processing plant located in North Dakota. This project is unique in several aspects. It will be Canada's first major CO_2 project and PanCanadian's single largest capital investment. It will also be the world's largest cooperative project for reducing CO_2 emissions into the atmosphere. It also demonstrates the extensive use of horizontal drilling to optimize performance.

The Avile reservoir of the Puesto Hernandez field, located in the Neuquen Basin in West-Central Argentina is being evaluated as a potential CO_2 injection project. This oil field produces associated gas containing approximately 60 percent CO_2, which has previously been vented to the atmosphere. The project assessed the feasibility of extracting and injecting the CO_2 into the field to recover additional oil using an immiscible displacement process. Following an evaluation including core floods, compositional simulation, and facilities evaluation, the process was found both to have technical and economic promise in terms of improved oil recovery, and to result in reduction of both CO_2 and methane emissions, the later being an especially potent greenhouse gas. The success of this type of project would create a unique common ground for those concerned with reducing global warming and those concerned with supplying society's energy needs. The project evaluation relies on the principles and practices proven in CO_2 injection in the Permian Basin. Using a conservative interpretation of the available field data, the project is estimated to recover approximately 4 percent of the original oil in place and reduce greenhouse gas emissions by 714,000 carbon equivalent metric tons.

The Sleipner fields located in the Norwegian sector of the North Sea are owned and operated by a consortium of oil companies including Statoil, Esso, Norsk Hydro, Elf and Total Fina. The reservoir in the Sleipner Vest Field produces primarily natural gas which is rich with gas condensate and approximately 2.5 percent CO_2. Because of environmental concerns regarding global warming, Statoil is developing a process to remove the CO_2 from the produced gas and injecting the CO_2 into an aquifer of the Utsira Formation. The injection of the CO_2 in this manner will prevent the atmospheric release of approximately one million tons per year of carbon equivalent metric tons or a cumulative twenty million metric tons through the life of the field. The CO_2 can also be produced at a later time for increased oil recovery purposes should a candidate oil field become available. The simulation of the Utsira aquifer and the design of the CO2 injection process were accomplished with the knowledge gained from CO_2 projects in the U.S. As more attention is focused on the issue of global warming and the sequestration of CO_2, the practical experience gained from oil recovery projects in the U.S. will become more important.

Large scale polymer flood projects have been conducted in the Daqing Field located in China. It has been reported that polymer flooding had been applied in six areas of the field encompassing an area of around 14,600 acres. There were 465 injection wells and 537 producing wells. Polymer injection is reported to have recovered an additional 12% of the original oil in place over and above what could have been recovered by waterflooding. Several successful alkaline-surfactant-polymer (ASP) projects have also been conducted in the Daqing Field, to recover a greater amount of oil than was possible by polymer injection alone. These projects were judged to be technically and economically successful, recovering about 20% of the original oil in place more than could be achieved by waterflooding alone.

The use of "Microbially Enhanced Oil Recovery" or MEOR technology is now commercially used for the stimulation of producing wells in Venezuela, China, and Indonesia. Most of the treatments have been in the heavier oil reservoirs that are dealing with wax problems. MEOR treatments have been applied in more than 100 producing wells in the LL-05 reservoir in the Lake Maracaibo Field, Venezuela. More than 75% of the treatments have been successful. These treatments are being conducted by Micro-Bac, a U.S. company. Successful producing well treatments have also been reported in the DaGang Field and the Zhuangxi Field in China.

Research conducted by DOE has been directed toward the reduction of costs for the generation of steam, the reduction of wellbore heat losses to maximize steam quality at the reservoir face, and the improvement of sweep efficiency. Steamflooding remains the dominant EOR process in the United States. The process is also very important in Canada and in Venezuela for the recovery of heavy oil. The cold production of heavy oil under primary recovery conditions has been the single most important development in heavy oil recovery in recent years. An estimated 130,000 barrels of oil per day are being produced in Venezuela by this method. A production level of around 650,000 barrels per day is expected within the next few years.

Other Related Developments

The development of polymers intended for enhanced oil recovery processes have been applied to a number of other areas with substantial economic success. As an example, a gel which was developed for water control in oil wells has since been introduced as a fire retardant. The gels ability to bind large volumes of water makes the gel an excellent fire protection material. This capability also creates other uses for the gel material such a liquid absorbent in spill containment such as baby diapers.

Polymers developed for mobility control in oil recovery processes are also being applied in a number of ways not originally envisioned. The U.S. Navy is using EOR polymers for drag reduction on submarines and other submersibles. The polymer's ability to reduce the drag coefficient of the submarine allows the sub to glide through the water more quietly which is very important for the Navy's mission. The navy is also using polymers for on-board water remediation which allows ships to stay out to sea for longer periods of time.

Other industries are discovering uses for the polymers developed for enhanced oil recovery. The same polymers which are used for mobility control in chemical flooding of oil fields are also being used to reduce the friction or drag in shaving cream. The economics of using polymers in this fashion are much more favorable than in oil recovery. Polymers are also being used in the pharmaceutical industry because of their ability to become soluble in water and to respond to certain stimuli.

Several ancillary benefits have developed from the chromium acetate gel technology. First, the gel has been used as a chemical liner (in place of steel casing and cement) for the curve portion of horizontal wells. Especially when the curve portion occurs in a gas cap, conventional technology has not provided an effective wellbore seal in the vicinity of the curve. More than 100 horizontal wells have been drilled and treated with this gel technology at a cost savings of $300,000 per well. Second, chromium acetate gels have been applied to control lost circulation during drilling operations. Third, these gels have been applied in environmental applications to reduce migration of contaminated fluids through soils and to serve as impermeable liners under tanks. Finally, the gels have been used to consolidate loose soils and to prevent mudslides.

Summary

In summary, there have been numerous technologies developed for the petroleum industry with DOE's support. This research has contributed to the recovery of oil for the nation and will continue to do so for the foreseeable future. As more oil fields around the world are depleted, the U.S. oil industry will have a technological lead in enhanced oil recovery which can be transferred overseas. Other industries will continue to discover uses and applications for the technology developed with DOE's assistance in ways which cannot be visualized at this time. Finally, the environmental industry has adopted many of enhanced oil recovery technologies because the basic scientific principles are the same. It would be difficult to quantify the value of this research to the hydrology industry, but it would be fair to say that the protection of our nation's drinking water is as important, if not more so, than the recovery of our petroleum resources.

FE 4. For each year from 1979 to 1999, what was the cost of the DOE R&D support for each of the technologies identified (in constant 1999 dollars)/ What cost-sharing arrangements with industry or other institutions were in place (total project lifetime constant 1999 dollar amounts). Organize by R&D stage of development (for example, basic research, applied R&D, demonstration, commercial deployment).

The tables below show the Enhanced Oil Recovery budgets from 1978 to 2000. The budget tables are broken out by the six major research areas as defined in FE 1 of this report. Research in these areas is both basic and applied research. There has been a general change in emphasis from early basic research to increasing levels of applied research throughout this time period.

Cumulative EOR Budgets by Method from 1978 to 2000

Nominal Budgets (Thousand Dollars)

	DOE	**CS**	**Total**
Thermal Methods	36,826	12,776	49,602
Gas Methods	34,160	8,280	42,440
Chemical Methods	38,013	9,373	47,386
Microbial Methods	15,322	3,008	18,330
Novel Methods	6,193	2,436	8,629
Simulation Work	13,659	4,709	18,368
Totals	**144,173**	**40,582**	**184,755**

1999 $ Budgets (Thousand Dollars)

	DOE	**CS**	**Total**
Thermal Methods	44,121	13,766	57,886
Gas Methods	43,893	9,961	53,854
Chemical Methods	48,067	11,539	59,606
Microbial Methods	17,859	3,501	21,360
Novel Methods	6,739	2,456	9,195
Simulation Work	16,533	5,816	22,349
Totals	**177,212**	**47,038**	**224,250**

DOE FUNDING

Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	250	103	103	664	1,449	1,449	1,564	1,564	1,564	644	644
Gas Methods	474	847	1,109	1,450	1,062	1,224	1,136	1,336	1,307	1,283	1,283
Chemical Methods	723	1,232	1,056	1,246	1,116	1,053	1,053	956	865	865	865
Microbial Methods	0	0	149	224	224	241	241	224	393	329	125
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	10	10	10	200	516	776	776	776
Annual Totals	**1,448**	**2,181**	**2,416**	**3,594**	**3,860**	**3,977**	**4,194**	**4,596**	**4,905**	**3,897**	**3,693**
Cumulative Totals	**1,448**	**3,629**	**6,046**	**9,640**	**13,500**	**17,477**	**21,671**	**26,267**	**31,173**	**35,070**	**38,763**
1999 $ Deflators	0.4602	0.4986	0.5445	0.5953	0.6324	0.6573	0.6819	0.7034	0.7189	0.7405	0.7657

1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	544	206	189	1,116	2,290	2,204	2,293	2,223	2,175	870	841
Gas Methods	1,031	1,699	2,036	2,435	1,679	1,862	1,666	1,900	1,819	1,732	1,675
Chemical Methods	1,570	2,470	1,939	2,094	1,765	1,602	1,545	1,360	1,203	1,168	1,129
Microbial Methods	0	0	274	376	354	367	354	318	547	444	163
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	17	16	16	294	734	1,080	1,049	1,014
Annual Totals	**3,146**	**4,375**	**4,438**	**6,038**	**6,104**	**6,050**	**6,151**	**6,534**	**6,823**	**5,263**	**4,823**
Cumulative Totals	**3,146**	**7,520**	**11,958**	**17,996**	**24,100**	**30,150**	**36,301**	**42,835**	**49,659**	**54,922**	**59,744**

COST SHARE FUNDING

Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	0	0	0	11	11	11	11	11	11	0	0
Gas Methods	2	2	66	487	262	262	198	99	34	132	132
Chemical Methods	0	156	239	279	205	205	205	123	39	39	39
Microbial Methods	0	0	12	13	13	22	22	13	196	184	183
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	0	0	0	295	295	295	295	295
Annual Totals	**2**	**158**	**317**	**790**	**491**	**499**	**730**	**542**	**575**	**650**	**649**
Cumulative Totals	**2**	**160**	**478**	**1,268**	**1,759**	**2,258**	**2,988**	**3,530**	**4,105**	**4,755**	**5,404**
1999 $ Deflators	0.4602	0.4986	0.5445	0.5953	0.6324	0.6573	0.6819	0.7034	0.7189	0.7405	0.7657

1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	0	0	0	19	18	17	16	16	16	0	0
Gas Methods	4	4	121	818	414	398	290	141	47	179	173
Chemical Methods	0	314	440	469	324	311	300	175	54	52	51
Microbial Methods	0	0	22	22	21	33	32	19	273	248	239
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	0	0	0	433	419	410	398	385
Annual Totals	**4**	**318**	**583**	**1,328**	**776**	**760**	**1,071**	**770**	**800**	**877**	**848**
Cumulative Totals	**4**	**322**	**905**	**2,233**	**3,009**	**3,768**	**4,839**	**5,609**	**6,409**	**7,286**	**8,134**

TOTAL FUNDING

Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	250	103	103	675	1,460	1,460	1,575	1,575	1,575	644	644
Gas Methods	476	849	1,175	1,936	1,324	1,485	1,333	1,436	1,341	1,415	1,415
Chemical Methods	723	1,388	1,296	1,526	1,321	1,258	1,258	1,079	904	904	904
Microbial Methods	0	0	161	237	237	263	263	237	590	513	308
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	10	10	10	495	811	1,071	1,071	1,071
Annual Totals	**1,450**	**2,340**	**2,734**	**4,385**	**4,351**	**4,476**	**4,924**	**5,138**	**5,480**	**4,547**	**4,342**
Cumulative Totals	**1,450**	**3,789**	**6,523**	**10,908**	**15,259**	**19,735**	**24,660**	**29,797**	**35,278**	**39,824**	**44,166**
1999 $ Deflators	0.4602	0.4986	0.5445	0.5953	0.6324	0.6573	0.6819	0.7034	0.7189	0.7405	0.7657

1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research

	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Thermal Methods	544	206	189	1,135	2,308	2,221	2,309	2,239	2,190	870	841
Gas Methods	1,035	1,703	2,158	3,253	2,093	2,260	1,956	2,041	1,866	1,911	1,848
Chemical Methods	1,570	2,783	2,379	2,563	2,088	1,914	1,845	1,535	1,257	1,220	1,180
Microbial Methods	0	0	295	398	374	400	385	337	820	693	402
Novel Methods	0	0	0	0	0	0	0	0	0	0	0
Simulation Work	0	0	0	17	16	16	726	1,153	1,490	1,447	1,399
Annual Totals	**3,150**	**4,692**	**5,021**	**7,365**	**6,880**	**6,810**	**7,222**	**7,305**	**7,623**	**6,140**	**5,671**
Cumulative Totals	**3,150**	**7,842**	**12,863**	**20,228**	**27,108**	**33,918**	**41,140**	**48,444**	**56,067**	**62,208**	**67,878**

DOE FUNDING												
Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	1,334	2,573	1,677	2,239	1,963	2,835	2,957	2,426	2,521	2,724	1,198	2,383
Gas Methods	2,875	2,792	2,077	3,305	2,524	2,078	779	760	621	970	1,348	1,523
Chemical Methods	2,385	3,399	3,150	4,998	2,458	1,610	1,738	1,417	1,392	2,315	1,565	556
Microbial Methods	1,528	1,896	1,023	1,285	1,045	1,091	1,107	751	785	850	892	920
Novel Methods	1,740	351	44	0	235	0	0	240	204	624	1,057	1,698
Simulation Work	2,573	1,961	1,579	1,504	425	683	625	396	-12	277	573	0
Annual Totals	**12,434**	**12,971**	**9,549**	**13,330**	**8,650**	**8,297**	**7,206**	**5,990**	**5,511**	**7,760**	**6,633**	**7,080**
Cumulative Totals	**51,196**	**64,168**	**73,717**	**87,047**	**95,697**	**103,994**	**111,199**	**117,189**	**122,700**	**130,460**	**137,093**	**144,173**
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230
1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	1,678	3,116	1,960	2,554	2,187	3,094	3,158	2,542	2,591	2,765	1,198	2,329
Gas Methods	3,617	3,380	2,426	3,769	2,811	2,267	832	796	638	984	1,348	1,489
Chemical Methods	3,000	4,115	3,681	5,701	2,738	1,757	1,856	1,485	1,431	2,350	1,565	543
Microbial Methods	1,923	2,296	1,195	1,466	1,164	1,191	1,182	787	807	863	892	899
Novel Methods	2,189	425	51	0	262	0	0	251	210	633	1,057	1,660
Simulation Work	3,237	2,374	1,845	1,715	473	745	667	415	-12	281	573	0
Annual Totals	**15,644**	**15,706**	**11,159**	**15,205**	**9,636**	**9,054**	**7,696**	**6,276**	**5,663**	**7,876**	**6,633**	**6,921**
Cumulative Totals	**75,388**	**91,094**	**102,253**	**117,458**	**127,093**	**136,147**	**143,843**	**150,119**	**155,782**	**163,658**	**170,291**	**177,212**
COST SHARE FUNDING												
Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	143	0	0	0	0	7,150	3,800	0	389	80	958	189
Gas Methods	678	1,029	1,021	600	307	450	324	330	320	460	664	421
Chemical Methods	1,697	1,319	1,527	665	763	642	0	0	0	227	502	503
Microbial Methods	300	207	93	269	192	193	193	193	193	242	121	153
Novel Methods	60	0	0	0	0	0	0	116	115	415	1,273	457
Simulation Work	615	715	615	391	288	385	0	0	0	75	75	75
Annual Totals	**3,493**	**3,270**	**3,256**	**1,925**	**1,550**	**8,820**	**4,317**	**639**	**1,017**	**1,499**	**3,593**	**1,798**
Cumulative Totals	**8,897**	**12,167**	**15,423**	**17,349**	**18,899**	**27,719**	**32,036**	**32,675**	**33,692**	**35,191**	**38,784**	**40,582**
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230
1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	180	0	0	0	0	7,802	4,058	0	400	81	958	185
Gas Methods	853	1,246	1,193	684	342	491	346	346	329	467	664	412
Chemical Methods	2,135	1,597	1,784	759	850	701	0	0	0	230	502	492
Microbial Methods	378	251	109	307	214	211	206	202	198	246	121	150
Novel Methods	75	0	0	0	0	0	0	122	118	421	1,273	447
Simulation Work	774	866	719	446	321	420	0	0	0	76	75	73
Annual Totals	**4,395**	**3,960**	**3,805**	**2,196**	**1,727**	**9,625**	**4,611**	**669**	**1,045**	**1,521**	**3,593**	**1,758**
Cumulative Totals	**12,529**	**16,489**	**20,294**	**22,490**	**24,216**	**33,841**	**38,452**	**39,121**	**40,166**	**41,688**	**45,281**	**47,038**
TOTAL FUNDING												
Nominal Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	1,477	2,573	1,677	2,239	1,963	9,985	6,757	2,426	2,910	2,804	2,156	2,572
Gas Methods	3,553	3,821	3,098	3,905	2,831	2,528	1,103	1,090	941	1,430	2,012	1,944
Chemical Methods	4,082	4,718	4,677	5,663	3,221	2,252	1,738	1,417	1,392	2,542	2,067	1,059
Microbial Methods	1,828	2,103	1,116	1,554	1,237	1,284	1,300	944	978	1,092	1,013	1,073
Novel Methods	1,800	351	44	0	235	0	0	356	319	1,039	2,330	2,155
Simulation Work	3,188	2,676	2,194	1,895	713	1,068	625	396	-12	352	648	75
Annual Totals	**15,927**	**16,242**	**12,806**	**15,255**	**10,200**	**17,117**	**11,523**	**6,629**	**6,528**	**9,259**	**10,226**	**8,878**
Cumulative Totals	**60,093**	**76,335**	**89,140**	**104,396**	**114,595**	**131,712**	**143,235**	**149,864**	**156,392**	**165,651**	**175,877**	**184,755**
1999 $ Deflators	0.7948	0.8259	0.8558	0.8767	0.8977	0.9164	0.9363	0.9545	0.9731	0.9853	1.0000	1.0230
1999 $ Budgets (Thousand Dollars) - Enhanced Oil Recovery Research												
	1989	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Thermal Methods	1,858	3,116	1,960	2,554	2,187	10,896	7,216	2,542	2,990	2,846	2,156	2,514
Gas Methods	4,470	4,626	3,620	4,454	3,153	2,759	1,178	1,142	967	1,451	2,012	1,900
Chemical Methods	5,135	5,713	5,465	6,460	3,588	2,457	1,856	1,485	1,431	2,580	2,067	1,035
Microbial Methods	2,300	2,547	1,304	1,773	1,378	1,401	1,388	989	1,005	1,108	1,013	1,049
Novel Methods	2,265	425	51	0	262	0	0	373	328	1,054	2,330	2,107
Simulation Work	4,011	3,240	2,563	2,161	794	1,165	667	415	-12	357	648	73
Annual Totals	**20,039**	**19,665**	**14,964**	**17,401**	**11,362**	**18,679**	**12,306**	**6,945**	**6,709**	**9,397**	**10,226**	**8,678**
Cumulative Totals	**87,917**	**107,583**	**122,546**	**139,947**	**151,310**	**169,988**	**182,295**	**189,240**	**195,948**	**205,346**	**215,572**	**224,250**

FE 5. For each of the technologies identified, describe qualitatively (and quantitatively, where possible) what would have happened in this area had there been no DOE role.

Gas Flooding

The U. S. Government has played an important role in accelerating the commercialization of carbon dioxide flooding by providing basic data that allowed industry to focus its activities when it later became interested in the technology. In the 1970's through the early 1980's, DOE-funded projects were investigating the basic fluid properties of carbon dioxide with respect to pressure, temperature, and oil composition. The development of Minimum Miscibility Pressure (MMP) correlations was a major part of the research. Without the DOE-funded research at major universities that developed the basic understanding of the properties of carbon dioxide flooding, the oil industry would not have been able to determine which properties should be given high priority in its applied research.

Currently, <u>DOE is funding the only public research in the United States relating to improving reservoir sweep by modifying the viscosity of the carbon dioxide.</u> Nearly all of the major oil companies have closed their research centers and those, which are not closed, do not have a major emphasis on EOR. If the current DOE research is successful, it could increase oil production by carbon-dioxide injection by four fold.

Thermal Methods (Heavy Oil)

DOE's thermal R&D has accelerated thermal technology implementation by providing a foundation of early basic research and demonstrations, providing public resource assessments, and working on process enhancements that industry has little interest in. The program has also developed and demonstrated technologies specifically for use by small independent operators that do not have access to other research. In addition, the DOE assessments and studies of thermal recovery in the Naval Petroleum Reserves helped the efficient stewardship of these national assets. Without the DOE R&D, thermal recovery technology would have been delayed, would be less efficient and would not be available to many small operators.

Today, most major oil companies have stopped their research on ways to improve heavy oil recovery.   DOE continues to support basic and applied research in this area. Heavy oil recovery projects include improved methods for implementing steam floods and basic research in heavy oil recovery.

Chemical Methods

There were several DOE and industry chemical flooding projects conducted in the late 1970's to mid 1980's. Most of the projects were technical successes, but were not economic successes. Without the DOE field tests, projects and the reasons for failures would not have been reported. DOE publication and analyses have lead the entire industry to focus on reservoir description for all improved recovery technologies.

Since the mid-1980s, every major oil company has either stopped, or essentially stopped work on surfactant flooding processes.   However, DOE helped sponsor a research field pilot test using an Alkaline-Surfactant-Polymer (ASP) method in the late 1990's. The project won the Hart's Award for the best Mid-continent EOR Project in 1998. This pilot test shows that small independent oil companies can apply this type of recovery.

DOE is one of the few remaining resources for reliable and objective information in this area. Most of the technical articles are written by companies that have a product to sell. The projects funded by DOE are especially helpful in establishing some objectivity on the types of applications of polymer gels.

Microbial Enhanced Oil Recovery

The Microbial Enhanced Oil Recovery (MEOR) process involves the use of microbes placed in the reservoir to generate chemicals that aid in the solubility of oil, improve the sweep efficiency, or near wellbore cleanup. MEOR methods have the potential to be applied by smaller producers and have environmental applications for oil clean-up operations.

There is little, if any, research being conducted by major oil companies in this area. Without DOE support, the basic MEOR research as well as field trials would come to a stop. Therefore, a field demonstration of the ability of in-situ indigenous microoganisms in the North Blowhorn Creek Oil Field to reduce the flow of injection water in the more permeable zones of the reservoir would not have occurred. This project is expected to recovery 500,000 barrels of incremental oil and extend the life of the field at least 12 years.

Novel Methods

Novel methods are those that do not fit within conventional EOR methods. A current novel method uses seismic vibrations to help shake the oil loose. Other such methods may involve electric heating or microwave heating which will reduce the viscosity of heavy oil. There is little industrial support for such advanced recovery methods that do not currently show near term economic benefit. However, it is difficult to predict which of these Novel Methods will be applied in the future.   DOE funding provides the only high-risk R&D that could lead to a major breakthrough.

Reservoir Simulation

In the 1978 to 1986 time frame, large companies spent millions of dollars on consulting and in-house simulation projects. Without DOE the smaller-scale simulators used by smaller independent oil and gas operators would not have been developed and used as they are today.

Statements Supporting DOE's Role in EOR Research

Kenneth R. Pittaway, Sr. Staff Engineer, Conoco, Letter to the National Petroleum Technology Office, dated February 21, 2000)

> "The U. S. Department of Energy has long provided support to research that will increase the use and availability of the country's petroleum resource. I approve of that support and of the continued efforts to increase recovery of our remaining reserves, including those that remain in place after conventional means are exhausted."

Letter to Mr. Daniel H. Lopez, President, New Mexico Tech, from Honorable Jeff Bingaman, United States Senator, New Mexico, dated May 31, 2000.

> "I am a strong supporter of the oil and gas research programs through the Department of Energy (DOE) and understand the need for a continue competitive process for procurement."

Letter from Scott C. Wehner, Project Engineer, Texaco, dated February 16, 2000.

> "We believe the CO2 program at the PRRC (Petroleum Research Recovery Center, New Mexico Institute of Mining and Technology) and is a valuable resource for continuation of research that will delay the abandonment of marginal domestic reservoirs and maximize the potential of our CO2 flooding capability. We encourage the National Petroleum Technology Organization and the Department of Energy to continue support of CO2 research at the New Mexico Tech."

Letter from Jairam Kamath, Team Leader, Chevron, to NPTO, dated February 28, 2000.

> "Chevron will soon be conducting a CO2 pilot in low permeability diatomite rocks in the Lost Hills field, California. These diatomite reservoirs contain several billion barrels of oil and are an important source of domestic oil. We believe the CO2 program at PRRC adds value to our efforts to maximize our domestic energy resource, and we encourage the National Petroleum Technology Organization to continue support of the CO2 program."

Letter from John Godwin, President, Driver Production, Inc. to Jerry Casteel, NPTO, Dated September 29, 1998.

> "We worked with the National Petroleum Technology Office (NPTO) on a Flue Gas Repressurization Project where we increased reservoir pressure on an 80 acre tract containing six oil wells. The economics of this project showed a three-fold increase in oil and gas production due to the formation repressurization over the twelve month life of the project.

Letter from J. F. Griggs, Manager, Reservoir Engineering and D. D. Bruning, Production Technology, Phillips Petroleum Company to Thomas C. Wesson, Director, Bartlesville Project Office dated August 15, 1994.

> "This letter is to express support for some of the basic research being funded by the U.S. Department of Energy. In particular, we feel the work being conducted by Dr. Randy Seright at the New Mexico Petroleum Recovery Research Center in the area of placement and utilization of polymer gels is valuable to the industry and will enable the industry to utilize polymer gels more effectively."

Letter from E. Thomas Strom, Senior Staff Chemist, Mobil to Thomas C. Wesson, Director, Bartlesville Project Office dated January 5, 1994.

> "Mobil has had a very high opinion of the work carried out at the Polymer Science Department at Southern Mississippi. …. I urge DOE to continue to fund Southern Mississippi group's work on new EOR chemicals."

FE-6. For each of the technologies identified, fill in the matrix from the benefits framework. List separately any assumptions used in estimating the benefits of the R&D.

Table 6-1. ENHANCED OIL RECOVERY MATRIX SUMMARY

	Realized	**Options**	**Knowledge**
Economic Benefits/Cost	1978 to 2005 cumulative Total Program Benefit of $15,356 million, Public Sector Return of $4,473 and cost of $209 million 1999 constant dollars (see annual graph below) ----includes: • Incremental oil and natural gas production • Improved efficiency of finding and producing • Increased production on Federal Lands • Reduced well abandonment	Qualitative • Reduced well abandonment • Future monitoring potential for CO2 sequestration (see detailed background material)	Qualitative • Knowledge base of basic reservoir properties necessary to implement Enhanced Oil Recovery with directions for future applications and future research • Enhanced Recovery screening models for use by the industry • Software programs that are used by industry and researchers (see detailed background material)
Environmental Benefits/Cost	Qualitative • Chemical EOR technology is successfully applied to water control problems, reducing water disposal. • MEOR technology used for clean-up and remediation	Qualitative • Reduced water pollution • Reduced environmental due to elimination of recovery methods that introduce undesirable materials.	Qualitative • Gas research will be basis of CO2 sequestration in geologic repositories • Recovery methods can be tailored for minimal environmental impact
Security Benefits/Cost	Qualitative • Maintain domestic oil industry infrastructure and ability to increase	Qualitative • Project results provide a strong national knowledge base – Captures technical expertise of	Qualitative • Data for evaluation of the industry capabilities is collected throughout the life

	production in time of crisis • Transfer technology to independent producers (increasingly important part of domestic production)	domestic industry to improve efficiency and makes it available to all of industry (CNES 1998 Goal IV, Objective 1, page 23)	of the projects. Can be used to predict domestic industry productivity and potential.

FE Research Development and Demonstration Metrics

There are many products developed in our RD&D programs that can be included into any discussion on benefits/metrics. But, the major concept of benefits suggests that we measure what we produce. In that vein, this task would be easy. Fossil Energy produces RD&D. We develop our RD&D programs to solve specific, known problems associated with oil and gas exploration, development, and processing, and then prepare and manage procurements that end up as awards to companies to do specific things to solve the identified problems. Our metrics would be how well we performed in planning and implementing these RD&D programs. Fossil Energy has performed in an excellent manner to plan and develop its RD&D programs. We have used portfolio analyses, roadmapping exercises, partnerships, feedback workshops, modeling systems to analyze programmatic options, industry meetings, peer reviews, and a myriad of other techniques to plan and organize our efforts – always focusing upon our customers and the resource base we are trying to address. Fossil Energy is very successful in implementing its assigned RD&D program areas.

When review panels and others are tasked to review our benefits to the public, the first question is usually how much energy, be it oil, gas, or electricity, do you produce. The fact is that our control on how the RD&D performed in our programs is used is very limited. These limitations are centered upon our ability to contact our customers and influence them to use the new tools, techniques, technologies, or other products to increase energy recovery and availability.

In developing our planning tools, FE has developed modeling systems which allow us to estimate how much of the resource base may be affected by new technology development, upgrading of existing technologies, or simple efficiency gains in operations. Fossil Energy has also developed other supporting systems to be able to supply metrics to answer most of the questions being asked about benefits. There are, of course, many ways to estimate metrics and many programmatic parameters that could be considered. First and foremost, Fossil Energy is a government agency and not a producing company. Whenever a new product is developed, it is not applied only to a few properties that an individual company owns or operates. The new product is applied to all of the resource base that the new product may affect. While an individual company may expect rates of return of 10-20 percent for a new development, the government would expect many times this return as the product will be used by multiple companies on multiple properties. Therefore, the return on investment will be much higher than for an individual company. Other parameters that could be used to develop metrics is public sector revenues versus public sector investments, jobs created or maintained, environmental emissions reduced, efficiency gains in all aspects of petroleum exploration, production, and refining, and reduced costs attributable to the new products.

For this series of reports looking at the benefits of the Fossil Energy oil and gas programs, DOE will report both the economic activity (monetized production plus cost savings) and the Public Sector Return (Federal and state taxes, Federal royalties on Federal lands, and state production taxes). While both of these benefit measures are based upon the production of oil and gas, they are not similar. One is the value of production, while the other is the value of the production to the government.

Quantitative Benefit Estimation

We utilized several data sources, model results, and analyses, in a multi-step process to define quantitative benefits for the Enhanced Oil Recovery Technology Programs. Two estimates are presented in the graphs below. The first is Total Program Benefit. This is a measure of the value of all oil and gas production in the U.S. due to the DOE program and all cost savings. This estimate does not contain any tax or royalty revenue. The second estimate is the Public Sector Return. This is a relatively conservative estimate because the benefits of incremental oil and gas domestic production due to the DOE programs are measured as revenue that is returned to the federal, state or local treasuries and not the total value of the production. The major steps in these estimates are:

STEP ONE – Modeled or used actual project results for the benefit of new technologies.

STEP TWO – Identified the portion of the benefits attributable to DOE funded research and to Industry research. The benefits of all new technology are modeled using the Total Oil Recovery Information System (TORIS) and the Gas Supply Analysis Model (GSAM). Three unique scenarios are modeled:

- No new technology,
- Industry technology only, and
- DOE and Industry technology from R&D

The incremental benefit of the DOE programs are calculated by subtraction of the Industry only benefits from the DOE+Industry benefits.

STEP THREE – Calculated gross benefits due to DOE research in categories of:

- Oil production
- Natural gas production
- Dollars Saved due to increased efficiency

STEP FOUR – Calculate the Total Program Benefits and Public Sector Return. A complete discussion of the modeling assumptions and procedures are contained in Appendix B.

Total Program Benefits:
Total Program Benefits are based on oil and gas production times oil and gas price tracks (uses Energy Information Administration (EIA) historical data and future year price tracks). In addition, Total Program Benefits include cost savings from improved efficiencies for exploration, production and refining operations.

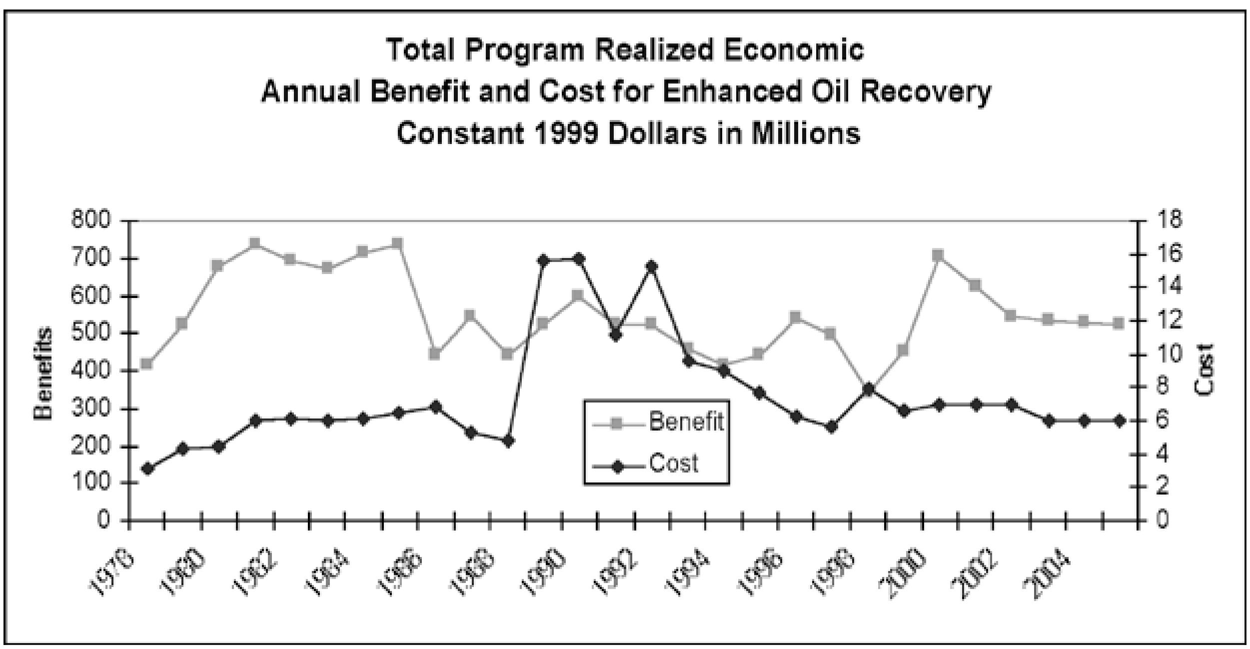
Public Sector Return Benefits:
The tax rates below are average rates based on TORIS modeling studies/results conducted in Tulsa, Oklahoma, by the National Petroleum Technology Office. These studies encompass more that 65% of U.S. oil production, and the average effective tax rates listed below are representative for domestic production. These are:

- Federal Tax 12.85% of total production value
- State Tax 1.90% of total production value
- Production and Severance Taxes 4.55% of total production value

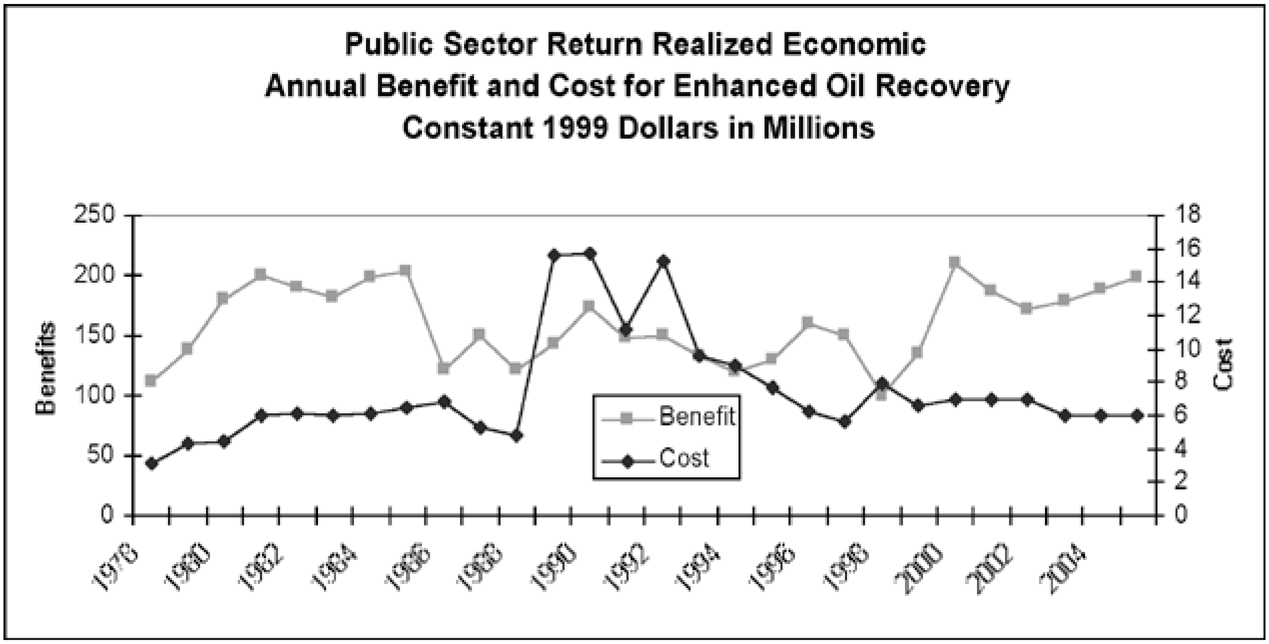
The above tax factors are applied to the economic value of the incremental production due to the DOE program. The product is then added to the Royalties from production on Federal Lands to determine the Public Sector Return. {Royalty rates for production from Federal Lands range from 13 to 16% based on Bureau of Land Management (BLM) and Minerals Management Service (MMS) historical data.}

Public Sector Return is then added to dollars saved from improved efficiencies for exploration, production and refining operations.

STEP FIVE – Convert the annual nominal dollar benefits to constant year 1999-dollar benefits.



Graph 6-1. Total Program Benefit and Cost for the EOR Program (1978-2005).



Graph 6-2. Public Sector Return and Cost for the EOR Program (1978-2005).

Table 6-1. Nominal Data for Realized Economic Benefits for EOR Programs.

The backup data in nominal dollars. Oil in million barrels, gas in BCF, dollars in millions.

Natl. Oil Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	3	3	3	3	3	4	4	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
Cumulative	3	7	9	12	16	20	24	29	34	39	45	51	57	62	69	75	81	87	93	99	105	112	118	124	131	137	143	149
Natl. Gas Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	5	4	4	4	4	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	9	9	8	8	8	8	8	8
Cumulative	5	9	13	17	21	26	32	39	46	53	61	69	76	84	93	101	109	117	125	134	142	151	159	168	176	185	193	202
$ Saved	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	28	48	70
Cumulative	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14	43	91	161
Econ. Activity $	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	54	73	103	123	123	123	136	145	89	112	95	116	138	125	128	115	107	116	143	135	94	127	202	183	159	156	152	148
Cumulative	54	126	229	352	475	598	734	880	969	1,081	1,176	1,292	1,431	1,556	1,684	1,799	1,906	2,022	2,165	2,300	2,394	2,521	2,723	2,906	3,066	3,221	3,373	3,521
Federal Oil Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
Cumulative	1	1	2	2	3	3	4	5	6	7	8	9	10	11	13	14	15	17	18	20	21	23	25	26	28	30	32	33
Fed. Gas Prod.	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	1	1	1	1	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Cumulative	1	3	4	5	7	8	10	12	14	17	19	22	25	27	30	33	36	39	42	46	49	52	55	59	62	65	69	72
Fed. Royalties $	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Annual	1	2	2	3	3	3	4	4	3	3	3	3	4	4	4	4	4	4	5	6	4	5	8	8	7	6	6	6
Cumulative	1	3	6	9	12	15	19	24	26	29	32	35	39	43	47	51	54	58	64	69	73	78	87	94	101	107	113	119

Explanation of Table Elements

This is the basis of the data used to estimate the quantitative benefit. Data are presented in unadjusted terms.

National Oil Production

The annual and cumulative oil and natural gas liquids production due to the DOE research program. Units are millions of barrels. This is estimated either by direct evidence in completed projects or by modeling assessments. This is net oil production and includes production from exploration reserves and development activities. In other words, this represents the oil and natural gas liquids that are produced in the U.S. due to the DOE oil research program.

National Gas Production

The annual and cumulative natural gas production due to the DOE research program. Units are billions of cubic feet. This is estimated either by direct evidence in completed projects or by modeling assessments. This is net gas production and includes production from exploration reserves and development activities. In other words, this represents the natural gas that is produced in the U.S. due to the DOE oil research program.

Cost Savings $

The annual and cumulative dollar savings from improved efficiencies for exploration, production and refining operations. These dollar savings could be from incrementally more effective use of existing technology (e.g. better seismic technology resulting in fewer dry holes), new technology utilization (less costly drilling), avoided cost (less water production), or general business efficiency (quicker less costly permitting). These savings are estimated either by direct evidence in completed projects or by modeling assessments. These net dollar savings derive from improved efficiencies for exploration, production and refining operations. These cost savings are above and beyond the cost to apply a new technology.

Economic Activity $

The annual and cumulative value in million dollars of the incremental production due to the DOE program. This is directly calculated based on incremental oil, natural gas liquids, and natural gas production in the first two rows times the appropriate product price tracks (historical prior to and inclusive of 1999; AEO forecast for 2000 and beyond).

Public Sector Return $

The Public Sector Return is an estimate of the taxes, royalties and other payments to the pubic entities and the dollars saved. It is calculated from the first three rows of this table. Average tax rates for public sector revenues are based on TORIS studies and include effective rates for Federal Tax, State Tax, and Production and Severance Taxes. These factors are applied to the economic value of the incremental production due to the DOE program. Royalties from Federal Lands are based on historical data from the BLM and the MMS. Taxes and Royalties are added to the dollars saved, resulting in the Public Sector Return. Annual quantitative values are graphed in constant 1999 dollars at the beginning of this section.

Federal Oil Production

The annual and cumulative amounts of the total U.S. oil and natural gas liquids production on Federal Lands due to the DOE program in millions of barrels. This is a subset of the production in row one.

Federal Gas Production

The annual and cumulative amounts of the total U.S. natural gas production on Federal Lands due to the DOE program in billions of cubic feet. This is a subset of the production in row two.

Federal Royalties $

The annual and cumulative royalty payments from production on Federal Lands. Calculated based on the production in rows one and two times the historical effective royalty rates from the BLM and the MMS.

General Considerations in EOR Benefits of DOE Program

An estimate has been made of the benefits that have resulted from DOE's EOR research program over the years. The contributions made by DOE are known by the industry to be highly significant, but it is difficult to quantify the contribution on a monetary basis. In spite of the uncertainties, estimates have been made covering a range of variables that are considered reasonable. The following discussion summarizes the key thought process that was used in arriving at the estimated benefits of the DOE research program.

Initially, a comparison was made between the costs for finding and developing new oil through exploration and for the recovery of additional oil from existing reservoirs. This comparison is worthwhile to make since the budgets within a company often compete between exploration and for the enhancement of its existing production. This competition of funds indicates that the costs for acquiring additional reserves by the two methods are often within the same range. The finding costs are well documented within the literature. By comparing these published numbers with the EOR data being used in this analysis, it will be possible to develop an increased confidence in the credibility of the EOR-related data being used. The following data summarizes the costs for the finding and development of oil, the costs for acquiring new reserves, and the production costs (*Energy Exploration and Exploitation*, 1999):

Table 6-2. Cost Parameters for Exploration and Development

Cost Parameter	**1993 $/bbl**	**1994 $/bbl**	**1995 $/bbl**	**1996 $/bbl**	**1997 $/bbl**	**5-Year $/bbl**
Finding and Development						
Worldwide	4.25	4.35	4.06	4.03	4.33	4.20
United States	5.15	4.53	4.34	5.90	6.90	5.42
Proved Reserves and Acquisition						
Worldwide	2.12	3.88	3.37	3.16	3.42	3.15
United States	3.75	4.31	3.76	3.70	4.47	4.03
Production Costs						
Worldwide	4.36	4.05	4.19	4.24	4.23	4.21
United States	4.40	4.07	4.04	4.15	3.99	4.12

As shown, the finding and development costs have been above $5 over a 5-year period. Technology enhancements have been keeping the finding and development costs from escalating in recent years. The application of 3-dimensional seismic technology has been a big factor in the recent decline of finding and development costs (Quinland, 1999).

The table below shows documented data on the average costs for EOR production. The investment costs for EOR are the combination of the expenditures for the injectant (solvent/chemical/steam) and for equipment (capital). The investment costs for the various processes therefore are $4.15 for CO_2, $2.98 for ASP, $1.69 for polymer, and $4 for steamflooding. An average investment cost of around $4 is considered appropriate since most of the EOR production in the United States comes from steamflooding and from CO_2 flooding.

A comparison of the two tables indicates that the investment costs for the finding and development of new reserves ($5.42) are actually higher than for the implementation of enhanced oil recovery processes ($4.00). Additionally, there is less risk in the EOR processes since the oil is known to exist and the reservoir characteristics have already been largely defined during the process of producing the field.

Table 6-3. Cost Components on a Dollars Per Barrel Basis

Cost Component	**CO_2***	**ASP****	**Polymer*****	**Steam Flood******
Royalty, taxes	3.60	3.60	3.60	3.60
Operating costs	2.70	2.70	2.40	3.00
Solvent/Chemical/Steam	3.25	2.18	1.69	3.00
Capital	0.80	0.80	-	1.00
Total, $/barrel	**10.35**	**8.65**	**7.69**	**10.60**

* Kinder-Morgan, www.shellco2.com
** Surtek, ASP floods in Minnelusa, www.surtek.com
*** Green (1998)
**** Dauben International Energy Consultants (estimate)

The following general procedure was used in the assessment of the benefits of the DOE research program:

1. Use the semi-annual surveys in the *Oil and Gas Journal* to determine the value of the total EOR production in the United States. The data were interpolated for the years between the surveys. The revenues received from the sale of the incremental crude oil production were based upon the average price of oil during the year, adjusted for a 1999 price level.

2. Determine the expected profit received from the sale of the crude oil. This was determined by computation of the gross proceeds from the sale of the crude oil less the expected costs for royalties, taxes, operating expenses, injectants, and capital.

3. Determine the net benefit attributed to the DOE research program by assigning a certain percent of the net proceeds from the sale of the incremental oil. Two cases were used to cover the expected range of benefits. This step is the most critical, and the rationale for the selected numbers is discussed below.

The profit is the gross price of the crude oil less the cost component shown in the above table. An average cost was estimated to be $10.50 per barrel, reflecting the components of CO_2 flooding and steam injection. For an assumed 1999 price of $17.25 per barrel, the net profit is $6.25 per barrel. The percent profit is then computed to be 36% of the selling price of oil.

The benefits of the DOE research programs were computed by using a range of percentages of the total revenues received by the sale of the produced oil from EOR operations. The two cases covering this range are 1%, and 5% of the total oil production. The corresponding ranges based upon the net oil prices are approximately 2.8, and 13.9%. The base case is considered to be the 1% of gross production, corresponding to about 2.8% of the net production.

The key issue in this analysis is the percent of the net proceeds made by the operator that can be contributed to the DOE. There is no quantitative way to handle this issue. Qualitatively, it can be expected that the DOE program would have a benefit of at least that achieved by exploration and by the actual implementation of EOR projects. A good case can also be made for a higher benefit ratio because of the known effectiveness of the DOE program. The following are some of the factors that have increased the impact of the DOE role.

- DOE research has been focused on overcoming the technical and economic constraints in EOR operations and in extending the range of applicability.

- DOE has been extremely active in the transfer of technology through its extensive partnerships with industry, the publishing of numerous reports, workshops, special conferences, and the maintenance of a good web site. The numerous requests for information and for software from the web site are an indication of the industry use of the technology.

- DOE has led the industry in certain critical high impact areas. These include the: (1) the development of modified polymer gel systems that have had a high pay out for the modification of injection profiles and for the shut off of excessive water in producing wells; (2) the development of the lower cost ASP process that is now being used throughout the world; (3) large contributions to the MEOR process, which is now being used to stimulate production from the heavier oil reservoirs; (4) the co-funding of a steamflood project in the Cat Canyon Field, that led to the expansion of the technology to other fields; (5) the development of software, that has been extensively used by industry to improve the performance of their fields; and (6) the development of concepts for the use of horizontal wells to improve the performance of waterfloods and EOR projects.

- DOE has increased the value of its expenditures by requiring the co-funding of individual projects. Cost sharing has increased the value of DOE's contributions by an average of 26% over the years.

The above examples reinforce the large impact of the DOE programs. In the final analysis, however, the percent of the total value of the nation's total EOR that can be contributed to DOE must be estimated based upon judgment factors. Because of the uncertainty in selecting a single value, several values have been selected to show the expected range of benefit ratios.

Table 1 shows the numbers used in making the assessment. All values are reported in 1999 dollars. The initial line shows the average price for oil on a per barrel basis for each year. The next few lines show the annual and cumulative budgets for both the DOE and cost-shared contributions. The DOE contribution is then computed on an annual basis to be 1% of the value of the oil received by industry. Graph 6-3 shows the cumulative benefits of the total EOR production in the United States for the 1%, and 5% values. Graph 6-4 shows the comparative yearly benefits of the DOE expenditures and the value of the 1% of the total EOR production.

The table below summarizes a range of the calculated benefit ratios.

Table 6-4. Range of the Calculated Benefit Ratios

Parameter In $1999 (000,000s)	1% (2.8% of net)	5% (13.9% of net)
Projected DOE expenditure	209	209
Value of oil attributed to DOE	1536	5119
Benefit Ratio	7.3	25.0

The 1% level indicates a benefit ratio of 7.3. This is considered to be the base case. This case assumes that DOE has been effective in the transfer of its technology to the industry and has successfully leveraged its research dollars in an effective way. The 5% case is considered to be at the high end of the potential benefit range. This case assumes that DOE has been highly effective in the transfer and promotion of technology.

Table 6-5. Benefits of DOE Funding ($000's)

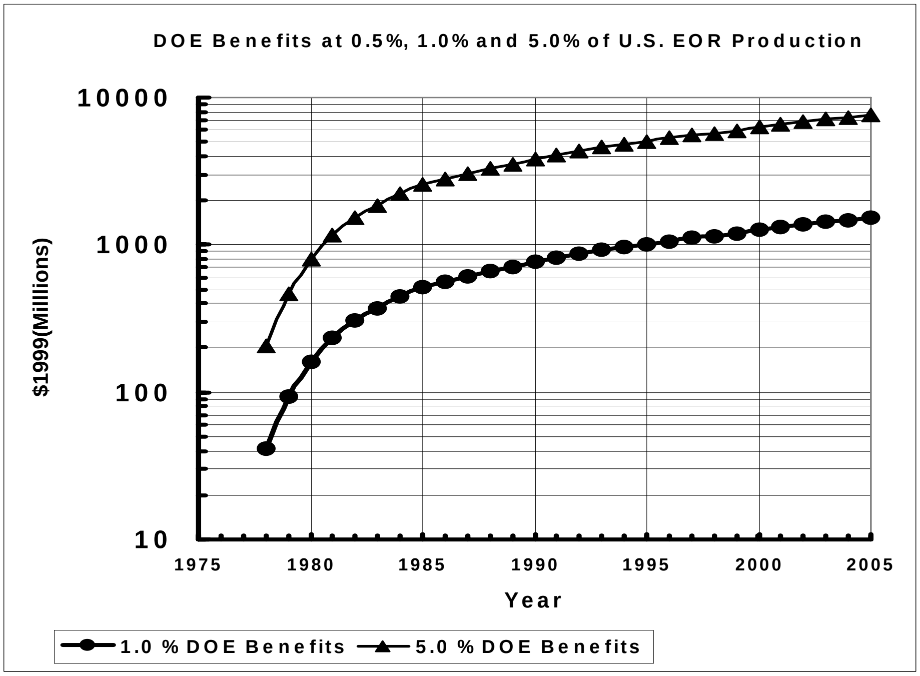
Parameter	1978	1979	1980	1981	1982	1983	1984	1985
1999 Adjusted Oil Price, $/bbl	31.66	43.46	62.24	62.24	53.05	44.57	42.35	38.37
DOE $1999	3,146	4,375	4,438	6,038	6,104	6,050	6,151	6,534
Cost Share $1999	4	318	583	1,328	776	760	1,071	770
Total $1999	3,150	4,692	5,021	7,365	6,880	6,810	7,222	7,305
Cumulative DOE $1999	3,146	7,520	11,958	17,996	24,100	30,150	36,301	42,835
Cumulative Cost Share $1999	4	322	905	2,233	3,009	3,768	4,839	5,609
Cumulative Total $1999	3,150	7,842	12,863	20,228	27,108	33,918	41,140	48,444
DOE at 1% $1999	41,599	52,088	67,572	73,668	69,203	66,965	71,305	73,840
Cumulative at 1% $1999	41,599	93,688	161,260	234,929	304,132	371,097	442,402	516,243

Parameter	1986	1987	1988	1989	1990	1991	1992	1993
1999 Adjusted Oil Price, $/bbl	19.47	24.48	19.02	22.75	26.35	21.85	20.76	17.98
DOE $1999	6,823	5,263	4,823	15,644	15,706	11,159	15,205	9,636
Cost Share $1999	800	877	848	4,395	3,960	3,805	2,196	1,727
Total $1999	7,623	6,140	5,671	20,039	19,655	14,964	17,401	11,362
Cumulative DOE $1999	49,659	54,922	59,744	75,388	91,094	102,253	117,458	127,093
Cumulative Cost Share $1999	6,409	7,286	8,134	12,529	16,489	20,294	22,490	24,216
Total $1999	56,067	62,208	67,878	87,917	107,583	122,546	139,947	151,310
DOE at 1% $1999	44,443	54,205	44,348	52,1093	59,793	52,205	52,048	45,741
Cumulative at 1% $1999	560,686	614,892	659,240	711,349	771,143	823,348	975,397	921,138

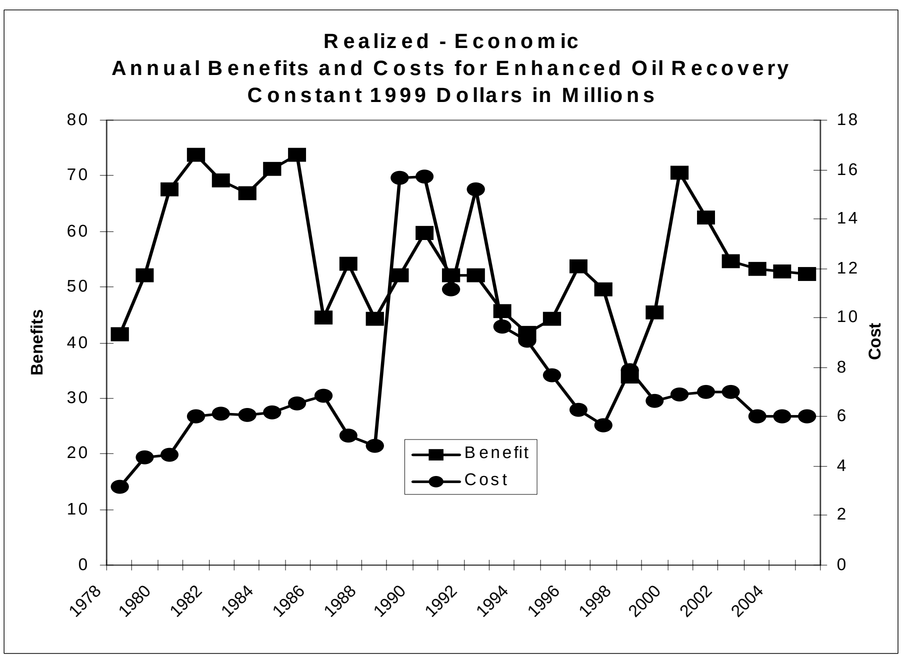
Table 6-5. Benefits of DOE Funding ($000's) - continued

Parameter	1994	1995	1996	1997	1998	1999
1999 Adjusted Oil Price, $/bbl	16.93	18.31	21.62	19.04	12.22	17.25
DOE $1999	9,054	7,696	6,276	5,663	7,876	6,633
Cost Share $1999	9,625	4,611	669	1,045	1,521	3,593
Total $1999	18,679	12,306	6,945	6,709	9,397	10,226
Cumulative DOE $1999	136,147	143,843	150,119	155,782	163,658	170,291
Cumulative Cost Share $1999	33,841	38,452	39,121	40,166	41,688	45,281
Total $1999	169,988	182,295	189,240	195,948	205,346	215,572
DOE at 1% $1999	41,775	44,171	53,689	49,628	33,988	45,337
Cumulative at 1% $1999	962,913	1,007,084	1,060,774	1,110,402	1,144,390	1,189,728

Parameter	2000	2001	2002	2003	2004	2005
1999 Adjusted Oil Price, $/bbl	27.07	23.44	20.07	19.32	18.58	17.87
DOE $1999	6,921	7,000	7,000	8,000	8,000	8,000
Cost Share $1999	1,758	-	-	-	-	-
Total $1999	8,679	7,000	7,000	8,000	8,000	8,000
Cumulative DOE $1999	177,212	184,000	191,000	197,000	203,000	209,000
Cumulative Cost Share $1999	47,038	-	-	-	-	-
Total $1999	224,250	-	-	-	-	-
DOE at 1% $1999	70,559	62,509	54,526	53,370	52,704	52,237
Cumulative at 1% $1999	1,260,287	1,322,797	1,377,323	1,430,693	1,483,398	1,535,635



Graph 6-3. Cumulative DOE Benefits at 1.0%, and 5.0% of the U. S. EOR Production



Graph 6-4. Yearly DOE Benefits at 1.0% of the U. S. EOR Production

The Total Program Realized Economic Benefits Of Completed EOR Technology Is Estimated To Be $15.4 Billion.

The Public Sector Return Realized Economic Benefits Of Completed EOR Technology Is Estimated To Be $4.5 Billion.

Descriptions of qualitative benefits are organized by the six technology areas within EOR (1. Gas, 2. Thermal, 3. Chemical, 4. MEOR, 5. Novel, and 6. Simulation)

Gas Flooding Methods

The injection of gas in order to recover oil from reservoirs which have already undergone primary and secondary recovery is already finding applicability in the United States. It has taken over thirty years for carbon dioxide flooding (CO_2 Flooding) to become a major contributor to the U.S. oil production. The road to the current success of carbon dioxide flooding has involved the cooperation of government (Energy Research & Development Administration, the predecessor of the Department of Energy) universities and industry. Many of the initial problems associated with this process have been solved. New challenges have emerged, which if solved, can greatly increase the oil recovery from current and future carbon dioxide floods.

Between 1977 and 2000 DOE has funded forty-eight projects in gas flooding methods for enhanced oil recovery. The majority of the contracts were awarded to universities including New Mexico Institute of Mining & Technology, the University of Kansas, Stanford University, and the University of Pittsburgh among others. Of the total contracts thirty seven were awarded to universities, two to the State of Texas, two to NIPER, three to independent researchers, two to BDM, and two to Morgantown Energy Technology Center. The research from these projects has led to some of the most significant advancements in enhanced oil recovery. Realized benefits include pioneering research that demonstrated that gas flooding methods, specifically carbon dioxide injection, would recover additional oil without detrimental effects to the reservoir. Optional benefits were those which provided insight into the oil recovery mechanism of gas flooding and methodologies to optimize the performance of enhanced oil recovery. Additional environmental benefits include the knowledge gained of carbon dioxide sequestration for the prevention of global warming.

Realized Economic Benefits

New Mexico Petroleum Recovery Research Center (PRRC): 1978-2000 A total of six contracts with the New Mexico Institute of Mining & Technology and the New Mexico Petroleum Recovery Research Center have been awarded by DOE from 1979 through 1994.

Carbon dioxide flooding. Three percent of all domestic crude oil (about 180,000 barrels per day) is produced by injecting carbon dioxide into aging reservoirs to force out oil that conventional production techniques cannot recover. The gas mixes with some of the remaining oil in the reservoir, and creates a miscible bank of fluid that pushes additional oil to production wells. In large part, industry gained confidence in carbon dioxide flooding technology through a series of eight field tests conducted in the 1970s and co-financed by oil companies and the Department of Energy and its predecessors.

Because of the success of carbon dioxide-enhanced oil recovery, carbon dioxide pipelines have been built throughout west Texas and eastern New Mexico, the principal regions of successful carbon dioxide miscible flooding. With the completion of the LaBarge pipeline, carbon dioxide-enhanced recovery has also been extended to oil fields in Wyoming and could reach others in North Dakota. Today, roughly 68,000 Americans are employed directly and indirectly because of this oil recovery technology. Moreover, data developed through the Department's laboratory research has saved the domestic oil producers at least $10 million by allowing them to accelerate development of other recovery processes.

The research program has led to a number of accomplishments as listed below:

CO_2 Mobility Control:

- Selective Mobility Reduction (SMR), mobility reduction that is greater in the higher permeability regions than in the lower permeability regions, has shown to be a wide spread phenomena. The degree of this phenomena dependents on surfactant type, surfactant concentration, rock type (some surfactants performed better in sandstone than dolomite and vice versa), and flow velocity.
- Lignosulfonate, a weak foaming agent, was initially tested as a sacrificial agent (an agent added to reduce the adsorption loss of the expensive good forming agents. Not only did Lignosulfonate reduce adsorption, the required concentration of the good foaming agent for the desired mobility control was reduced by as much as 80%.

Flow Mechanisms:

- It was observed that residual oil is mobilized more effectively in CO_2-foam displacements than either water alternating with gas or pure CO_2 displacements.
- In CO_2 foam the surfactant solution can inhibit oil/CO_2 contact and oil recovery because the CO_2 preferentially flowed through the surfactant solution phase.
- Foam is generated in high pressure CO_2 system by upstream snap-off as well as downstream snap-off and bubble subdivision, which are equally important foam generation mechanisms.

Phase Behavior:

- Measured the viscosity, density, and composition of each phases described that occurs during displacement of crude oil by CO_2 in reservoirs, thus the pressure, temperature, and composition conditions are defined for the phase behavior of many mixtures of dense CO_2 and crude oils.
- Research results discovered that in a single-phase high-pressure crude oil system, as CO_2 is added, the viscosity general decreases and the density increase. The viscosity of the mixture is between that of the crude and CO_2 and the density is usually higher than either the crude or CO_2 at the pressure and temperature of interest.
- In a two-phase system the presence of extracted hydrocarbons in the dense CO_2-rich phase can result in increased viscosity relative to pure CO_2 even at CO_2 concentrations greater than 90-mole %.
- The presence of small amounts of nitrogen mixed with the CO_2 stream results in a drastic reduction of the CO_2-rich phase viscosity compared to the values obtained using pure CO_2 solvent. The adverse impact of N_2 on phase behavior and fluid properties could have dramatic effects on a nitrogen-contaminated CO_2 flood, resulting in poor recovery.

Interfacial Tension (IFT):

- Based on the exponent 3.88 derived from the physics literature, new parachors of pure substances commonly encountered in petroleum fluids are obtained from carefully selected density and surface tension data. The parachor is the molecular weight of a liquid times the fourth root of its surface tension, divided by the difference between the density of the liquid and the density of the vapor in equilibrium with it.
- A new method for experimentally determining low IFT at high pressure was developed based on a static force balance on the lower half of the pendant drop. Comparisons between the shape factor method and the new method were consistent at high IFT (> 10mN/m) and tests at low IFT (<1mN/m) indicate it to be more accurate than the shape factor method.

Gravity Drainage:

- Tests of CO_2 gravity drainage in naturally fracture reservoir indicate that oil drains faster in high permeability cores and decreases with increasing water saturation.
- Based on Darcy/s law and film flow theory, a new mathematical model has been developed to describe free-fall gravity drainage with equilibrium fluids. Comparisons of wetting phase recoveries given by the new model with 20 sets of experimental data obtained under thermodynamic equilibrium show better accuracy over the existing models.
- The diffusion equation has been solved numerically to estimate gas concentration in the porous media. A procedure has been developed to couple equilibrium gravity drainage with

diffusion in order to describe non-equilibrium gravity drainage with diffusion in order to describe non-equilibrium gravity drainage. Using this procedure and measured fluid properties, experimental data obtained from four CO_2 gravity-drainage experiments under thermodynamic non-equilibrium conditions have been matched.

Injectivity:

- During 1999 a literature review of injectivity limitations associated with alternating the injection of water with CO_2 (WAG) was completed. This brought forth a number of possible causes of lower than expected injectivity during WAG cycles, but with no clear solutions. A forum on injectivity in June 1999 also confirmed that injectivity was a problem and that the cause and solutions were evasive.
- The CO_2-foam field trial performed at East Vacuum Grayburg San Andres Unit proved that strong foam could be formed in-situ and that the apparent in-situ mobility of CO_2 after foam generation was approximately one-third of that observed during the baseline CO_2 injection. In-situ mobility calculated using Hall plots were comparable to falloff test results.
- Fuzzy controllers in conjunction with neural networks have been successfully used to establish beginning point and parameter adjustment for production history-matching problems in reservoir simulations.

New Mexico State University, Las Cruces, New Mexico CO_2 Formation Damage Study, Final Report, July, 1983, occasional reports from industry suggested that the use of carbon dioxide to enhance the recovery of tertiary oil might be causing formation damage. This project was undertaken to define the mechanisms responsible for such occurrences.

- Although several possible damage mechanisms were identified, the results of the research program showed that none were severe enough to destroy the profitability of the recovery process.

- Laboratory experiments suggest that a given reservoir is a commercial candidate for CO_2 flooding, a decision can be made to proceed with the process while staying alert to the possible need to remedy some future reservoir damage.

University of Utah The precipitation of asphaltene during carbon dioxide flooding can severely impact the producibility of a well.

- Laboratory studies directed toward the Rangely Field are focused on determining the chemical mechanisms for asphaltene precipitation and the effect on the permeability of the reservoir. These studies have help develop methods for managing the asphaltene precipitation the effectiveness of carbon dioxide flooding for this field.

SumX Corporation, Austin, TX, Corrosion Due to Use of Carbon Dioxide for Enhanced Oil Recovery This work was a literature and information search to document the specific effects of CO_2 corrosion and to identify promising methods for controlling corrosion in fields using CO_2 injection. One of the goals of the study was to assemble and evaluate data on corrosion in CO_2 environments and the effect of other chemical species.

- Engineering metals are not attacked by CO_2 under oil field environments unless liquid water is also present. Mixtures of CO_2 and liquid water attack plain and low alloy steel. Attack on these bare metals may become serious at a CO_2 partial pressure as low as 4 psi and it increases with CO_2 partial pressure although not in direct proportion.
- Fluid flow rate is an important factor in CO_2/water corrosion. Practically all stainless steels and similar resistant alloys are not particularly subject to corrosion by CO_2/water mixtures alone, even at high CO_2 pressures.
- Elevated levels of CO_2 can aggravate the corrosive effects of other species such as hydrogen sulfide, oxygen, and chloride.
- Mixtures of CO_2, carbon monoxide, and water can cause stress corrosion cracking of plain steels.

Stanford University, Stanford, California The objectives of this work is to develop methods to predict accurately the performance of the gas injection process in a given reservoir so that improved process designs are possible. The approach was to combine theory and experiment to delineate underlying physical mechanisms, and then build that understanding into simulation tools.

The following key results are documented:

- When gravity segregation and viscous fingering are both important, two-dimensional calculations of displacement performance do not reflect accurately what happens in three-dimensional flows. Gravity segregation is more important in three-dimensional flow than it is in two-dimensional flow.
- Streamtube/streamline simulation techniques are demonstrated for a variety of injection processes in two and three dimensions. The resulting calculations are orders of magnitude faster than conventional finite difference simulation, and they are free of adverse effects of numerical dispersion.
- Development of miscibility multicomponent systems. A theory is outlined that results form a significant effort to describe how multicontact miscible displacement really works. The theory explains condensing/vaporizing behavior, which is now understood to be a very common displacement mechanism in CO_2 floods and enriched gas injection projects.
- The method developed to calculate Minimum Miscibility Pressures demonstrated for four-component systems points the way to a thermodynamically rigorous way to calculate displacement pressures and gas compositions required for very efficient displacement.

Thermal Methods

Between 1978 and 2000 seventy-one thermal/heavy oil research projects were funded by DOE through the National Petroleum Technology Office (formerly the Bartlesville Project Office). Of these twenty were through universities, seven were by industry, six were conducted at National laboratories and 38 were done at the DOE in-house laboratory at NIPER. Many of the individual projects reflect continuing development of successful methods for thermally enhanced oil recovery developed in the original contract to a particular organization. The goals of funding of the thermal projects were to take industry practice and improve efficiency, test new parameters of thermal recovery, access the risks of new thermal methodology, and further the development of new heavy oil recovery technologies in areas untried by industry. Advances in thermal technology by all companies have increased heavy oil production to 10% of total U.S. daily oil production, and represent 70% of California production. Numerous presentations and publications were made by these projects. Highlights of the most successful projects follow:

Realized Economic Benefits

Stanford University Petroleum Research Institute (7 contracts)

Heavy oil research program (multiple U.S. DOE cost-shared with industry contracts originating from 1976 to present) covers thermal oil production: steam and in-situ combustion, laboratory and field testing of foam for steam diversion, education of students and technology transfer. 165 students have participated in the program, 120 technical reports have been written, and 220 papers authored. International technology transfer was also undertaken through SUPRI's support of U.S. DOE agreements with Canadian and Venezuelan research organizations and the International Energy Agency (IEA).

The Petroleum Research Institute was established in 1976 with the primary purpose of pursuing enhanced oil recovery research in heavy oil reservoirs. Principal financial support was from the U. S. Department of Energy, Stanford University and grants from the oil industry. Industrial support was formalized in 1980 with the formation of the SUPRI Industrial Advisory Committee. Through the years, all the major oil companies have participated ; Amoco, ARCO, Chevron, Exxon, El Aquitaine, Mobil, OXY, PDVSA, Shell International and Texaco.

SUPRI program contribution to the development of technology in heavy oil production has been acknowledged by several awards including a Homer H. Lowry Award in 1990 by U.S. DOE and award of "Thermal Pioneer" a by the Society of Petroleum Engineers in 1998 to Professor Bill Brigham. Professor Frank Ramey received similar "Thermal Pioneer" recognition from industry and U.S. DOE. Students educated through research under SUPRI have gone on to become some of the world's leading technical petroleum engineering researchers at other universities and energy companies, or have become managers and presidents of domestic, international and nationalized oil companies throughout the world, and energy ministers of a number of countries.

An abbreviated list of major accomplishments with their year of publication and technical report number:

- Delineation of the effect of temperature on the absolute and relative permeability of sands and sandstones (1981:TR27, 1982:TR35, 1983:TR47 1999: TR111).
- Well testing technology for thermal recovery projects (1982:TR33, 1986:TR54, 1989-TR68).
- Technology for application of foam to enhance recovery in steam injection projects
  - ♦ Screening protocol for surfactants (1984:TR38)
  - ♦ Pore-level mechanics of foam generation and mobility control (1984:TR37, 1986:TR54, 1996:TR100, 1997:TR110).
  - ♦ Imaging of in-situ displacement in homogeneous and heterogeneous porous media (1992:TR82, 1992: TR84, 1998:TR112)
  - ♦ Mechanistic modeling of foam displacement (1997:TR109).
  - ♦ Field pilot project (1983).
- Correlations for prediction of field wide in-situ combustion performance (1981:TR11, 1979:TR13b)
- Methodology for laboratory testing of in-situ combustion dynamics of displacement and kinetics of oxidation reactions (1982:TR22, 1982:TR26, 1982:TR32, 1985:TR46, 1993:TR91)
- First public domain applications of X-ray CT for high resolution, nondestructive imaging of multiphase flow in porous media. (1989:TR66).

- Methodology and results for optimizing steamflood performance (1996:108, 1997:TR109).
- Feasibility and mechanisms of thermal recovery from low permeability fractured porous media (1995:TR101, 1998:TR113, 1998:TR114).

University of Southern California (7 contracts)
The contracts with University of Southern California have been designed to carry out fundamental studies in several areas of thermal recovery including:

- Chemical additives to improve steamfloods.
  - ♦ Developed methodology to measure relative permeabilities as a function of oil-water interfacial tension.
  - ♦ Determined surfactant adsorption as a function of temperature.
  - ♦ Developed chemical-steam simulator.
  - ♦ Analysis of foams and additives for mobility control.
- Displacement and flow properties of fluid in phase change in porous media determined.
  - ♦ Identified condensation-evaporation phase change and heat transfer affects.
  - ♦ Determined the onset of gas flow in solution gas drive in porous media.
- Identified the effect of reservoir heterogeneity at various scales.
- Modeled flow properties of non-Newtonian fluids.
  - ♦ Fluids involving stress
  - ♦ Foams and Gingham plastics
- Developed optimization methods to maximize various measures of thermal recovery processes.
- Improved methodology for oil recovery from fractured reservoirs producing from vertical or horizontal wells.
- Supported research of nine PhD students and 2 post-doctoral students.
- Partial publication list cites 33 significant publications in refereed journals.

NIPER/ IITRI/BDM-Oklahoma/ TRW-Petroleum Technology (38 contracts)
The contracts conducted at the NIPER facility represent work done by the DOE Bartlesville Project Office and National Petroleum Technology Office in-house laboratory from 1978 to 2000. A wide variety of thermal/ heavy oil investigations were funded ranging from thermal processes for light and heavy oil in the 1980s to heavy oil feasibility studies in the mid-1990s, and ongoing pilot demonstrations in Alaska. Thermal process research objectives: (1) Improve the understanding of the basic mechanisms responsible for thermal light and heavy oil production using thermal methods including steam. (2) Accelerate development and expansion of the U.S. resource base recoverable using steamflooding as the production technology. (3) Accelerate improved thermal technology development.

- Published a steam injection processes handbook for independent producers.
  - ♦ The handbook is still a standard reference at major Petroleum Engineering colleges and universities.
  - ♦ Over 3,000 copies of the handbook in English have been distributed.
  - ♦ The handbook has been translated into Chinese and Spanish and over 2,000 copies are in use in these languages.
- Conducted U.S. heavy oil resource assessment and database: heavy oil resource is 105 billion barrels.

- ♦ Regional studies were conducted on major basins in U.S. as part of feasibility study:
  - ▪ Appalachian Basin
  - ▪ Illinois and Michigan basins
  - ▪ Rocky Mountain region
  - ▪ Mid-Continent region
  - ▪ California basins
- Supported research to improve thermal recovery at two DOE Naval Petroleum Reserve fields; the shallow oil steamflood at Elk Hills, California (NPR-1), and Teapot Dome field, Wyoming (NPR-3).
  - ♦ Provided concurrent laboratory support of NPR-1 steamflood to show reasons for low oil production and fines migration observed in field.
  - ♦ Analyzed 10 years of production and research on the highly fractured Shannon sandstone, and worked with DOE field personnel to improve oil production.
  - ♦ Lessons learned from this steamflood have been transferred to other pressure-depleted, consolidated, tight, fractured heterogeneous light oil reservoirs across U. S.
- Conduct international transfer of technology in thermal oil production between DOE and Venezuela.
- Design and construct a high-temperature, high-pressure laboratory and develop procedures and apparatus to conduct laboratory steamfloods at field conditions.
- Analysis of performance and economics of paraffinic crude oil production.
- Participated in technical exchange with industry.
  - ♦ Amoco in-situ combustion research consortium.
  - ♦ Sponsored United Nations Institute for Training and Research (UNITAR) Centre for Heavy Crudes and Tar Sands.
- Schrader Bluff field, Alaska CRADA with British Petroleum.
  - ♦ Initial screening studies of polymer flooding, gas injection, and in situ combustion to evaluate best methods for increased production.
  - ♦ Evaluate in situ combustion to develop technological innovations to maximize utilization of Alaskan heavy oil reservoirs. Following laboratory experiments a field pilot was recommended.
  - ♦ Study of potential oil recovery using gas injection processes.
    - ▪ Carbon dioxide/natural gas liquid mixtures can reduce Schrader Bluff crude oil viscosity by up to 70%.
    - ▪ Simulation studies predict incremental recovery of 2% OOIP for Schrader Bluff lean gas, 11% for Prudhoe Bay miscible injectant, and 20% for a mixture of carbon dioxide/natural gas liquids.

<u>Kawasaki Thermal Systems, Inc. (1 contract)</u>

The wellbore heat loss program objective was to establish a body of valid heat loss data from an active steam injection well. This field data was used to validate a comprehensive wellbore heat loss software program. The field data was also used by industry to calibrate their thermal numerical models.

- A test well on a Texaco lease in the Kern River field, California yielded a large body of data.
- Six steam injection test cases were run in the well.
  - ♦ The insulated string exhibited thermal conductivity to measure heat loss at couplings and conductors.

    - Data from heat flux sensors can be utilized to provide accurate calculations of energy loss.
    - No appreciable difference in heat flux to earth from insulated string to conductor.
- Developed a wellbore heat loss model verified and calibrated with temperature data.
- Deliverable was the user-friendly SIMSTEAM software and SIMSTSTEAM User's Guide.

<u>Lawrence Livermore National Laboratory (continuing contracts 1984 to 2001)</u>
A major segment of the Lawrence Livermore contracts was the development and application of surface and borehole electromagnetic (EM) methods for oil-field characterization and monitoring of in situ changes in electrical conductivity during EOR operations.

Stimulation is often required in heavy oil fields particularly in California and Venezuela. Current single-use wells limit stimulation options; through temporary loss of production, the difficulty of monitoring stimulation progress in situ, and the necessity of drilling new supplemental monitoring wells. The objective of the study was to provide a solution using multiple-use wells, which are capable of producing fluids, stimulation and monitoring well progress. Lawrence Livermore worked in conjunction with AERA Energy, Chevron and Steam Tech Environmental Services to develop and test "In-Well Imaging and Heating: Multiple-Use Well Design". A separate contract was a feasibility study of steam drive options under specific reservoir conditions.

- Developed and used Electromagnetic (EM) methods to characterize heavy oil reservoirs during enhanced oil recovery operations.
    - Conduct 3-D finite-difference forward modeling on crosswell EM induction time-lapse imaging of natural gas reservoirs.
    - Develop instrumentation and software leading to the testing of single borehole EM induction system.
    - Conduct multiple deployment long-term crosswell EM survey in conjunction with through-steel-casing monitoring.
    - Conduct field tests on recording electromagnetic signatures produced during hydrofracturing.
- Developed multiple-use wells for imaging heavy oil well processes using EM technology:
    - Provides for improved reservoir characterization
    - Facilitates evaluation of remaining oil-in-place.
    - Allows for economic production monitoring and stimulation from a single well.
- Developed electrical resistance tomography (ERT) as an extension of EM technology.
    - EM/ERT can map subsurface resistivity distribution
    - EM/ERT used to map shallow active processes in test well in 1997.
    - 4D-ERT used to map reservoir temperature over time.
    - Use of 4D-ERT for interwell, casing-to-casing, field simulations.
- Developed innovative and economic heating processes:
    - Ohmic heating, a hybrid thermal stimulation which uses electric heat to preheat reservoir.
    - Hybrid heating simulations results in more uniform heating of the reservoir.
    - Developed horizontal electrodes to heat the pay zone more effectively.
    - Hybrid thermal stimulation tested for heavy oil production on California leases.

- ♦ Simulations indicate 6 months of preheating will substantially accelerate production at the beginning and result in higher cumulative oil recovery.
- Conducted a feasibility study on steam drive in diatomite reservoirs.

Chemical Methods

Chemical enhanced oil recovery processes have the greatest potential to recover immobile oil (oil trapped in the reservoir by capillary forces) – an estimated 250 billion barrels resource in the domestic U.S. This oil cannot be recovered by drilling more wells, by horizontal wells, or any method that does not reduce the interfacial tension between the oil and the water. Chemical recovery methods such as surfactant-polymer, micellar-polymer or alkaline-surfactant-polymer can recover both mobile and immobile oil. They are the only processes that have been successfully demonstrated in the field to recover oil from low pressure, depleted oil reservoirs. Major barriers to widespread use of chemical processes are the high cost of the chemicals and loss by both adsorption on the reservoir rock and mixing with reservoir brine and oil.

The Department of Energy has funded 73 research projects addressing chemical enhanced oil recovery processes since 1975. Thirty-eight (52%) of the projects were conducted by universities, twenty-three (32%) by research organizations, four (6%) by service companies, three (4%) by national laboratories, three (4%) by government agencies, one (1%) by a consultant and one (1%) by and independent operator.

Realized Economic Benefits

Water Production Control using Polymer Gels:

Reduction of the amount of water produced during oil production is a major issue in the oil industry for both environmental and economic reasons. When polymer gel systems are properly applied, oil is recovered with less production of water, extending the lives of the well/field. In some applications there are increases in oil recovery. Operating costs are reduced with less water production and the potential for environmental damage in disposing the produced water is reduced.

In the United States, more than 8 barrels of salt water are produced for every barrel of oil totaling an annual production of more than 25 billion barrels of salt water. The annual cost of treating and disposing this water is between 5 and 10 billion dollars. For each one-percent reduction in water production, the cost saving to the oil industry could be as much as $100 million per year. The gel polymers and other chemical blocking agents studied in DOE-funded projects have been shown to be effective in reducing water production.

In a project by New Mexico Petroleum Recovery Research Center (DE-AC26-98BC15110) work was performed to improve polymer gel technology for plugging fractures to reduce water production. The primary benefit of the technology from this project has been to increase the understanding and reliability of water shutoff applications that use gels. Success rates above 80% are now commonly quoted. During the 1990’s, more than 2,000 gel treatments were applied using the main gel researched in this project. These treatments were documented to reduce water production by over 500,000 barrels of water per day and increase oil production by over 8,000 barrels of oil per day. For 43 treatments in Wyoming, 5 million barrels of incremental oil were recovered at a cost of $0.41 per barrel.

An example of the magnitude of cost savings that can be realized is ARCO's application of the polymer gel technology in their Prudhoe Bay, AK field. Gel treatments resulted in an oil production increase of 8,030,000 barrels oil per year yielding $40,150,000 per year (at a cost of $5 per incremental barrel). In addition to increased oil recovery, water production was decreased by 6,935,000 barrels of water per year. At average water disposal costs of $0.50 per barrel, a $3,467,500 per year savings was realized. Total economic benefit to ARCO from 1995-2000 was $218,087,500.

Chevron also applied gel treatments in Rangely Field, CO resulting in the production of 685,000 incremental barrels of oil. The 4.2 million dollar cost of the treatments was recovered in 8 months

In the Phillips Petroleum Co. Nitschke A No. 2 well, in the Texas Panhandle, a conformance control gel treatment saved $32,800 in water disposal costs in 1995. Incremental oil production during the year was 6.25 barrels of oil per day. At the average 1995 price of $16.76/bbl, the well generated additional annual revenues of $38,233. Additional savings in lifting costs and reduced maintenance were also realized. One year later (Dec 1996) the well was still producing at 38 barrels of oil per day.[3]

The University of Kansas project (DE-AC26-99BC15209) provided fundamental knowledge and understanding of how polymer gel systems can improve volumetric sweep of waterfloods and reduce water production. Results from the research provided a mechanistic understanding of how gelled polymer treatments work, particularly the chemistry, the placement process and the performance of the treatments.

This work has increased the use of gelled polymers by: (1) creating a wider acceptance of the technology by increasing the confidence and reducing the mystery of the technology; (2) applying the technology in a more direct and efficient manner; (3) eliminating misapplications of the technology; and (4) developing and exploiting the mechanisms that are identified in the research to improve oil recovery and reduce water production.

Examples of results from this work are as follows:

- Developed formulations for gelled polymer systems that were used for sweep improvement in southeastern Kansas oil fields.
- Obtained rheological data for these systems.
- Demonstrated that gelled polymer systems could be formulated that are thermodynamically stable over long periods of time after formulation.
- Field-tested chrome-redox polyacrylamide polymer systems for sweep improvement in southeastern Kansas oil fields, resulting in both reduction of water channeling and increased oil production.
- Transferred this technology to Russell Engineering for use in the Savonburg Field and to Mr. Fred Gee who ran a small well treating business in southeastern Kansas.
- Discovered the mechanisms that control in-depth treatment of porous rock using chrome-

polymer systems and developed a mathematical model that simulated this behavior for the chrome redox–polyacrylamide system.

- Discovered reasons that chromium-xanthan gel systems failed when used for in-depth treatment of carbonate rocks in both laboratory and field applications.
- Developed and tested two gel systems that effectively reduce the permeability of sandstone cores to carbon dioxide at supercritical conditions.
- Discovered that gels dehydrate after placement when subjected to pressure gradients. This provides an explanation of what happens to a gel after placement in a porous matrix or fracture.
- Several companies that provide polymer services in the United States and worldwide provided the following comments in support of this research:
  - Instrumental in providing lower-cost gel systems that exhibit desirable properties.
  - Instrumental in developing techniques to pump gels full bore/bullhead without damaging oil productivity.
  - Research on fundamental concepts has resulted in better understanding of gel systems, how they function in reservoirs, develops a wider acceptance of the technology and gives oil producers more confidence in the application of gel treatments.
  - Research on complex chemistry and placement techniques is necessary for conformance treatments to continue to improve on both a technical and an economic basis.

Alkaline Surfactant Polymer:

A low-cost improved oil recovery technology using mixtures that contain alkaline and synthetic surfactants was optimized and demonstrated in a project conducted by consultant Troy French (75-99SW45030). Although Alkaline Surfactant Polymer (ASP) flooding technology has been demonstrated to recover 30% of the original oil in place in some fields, the process had never been conducted in shallow fluvial reservoirs such as those at the Sho-Vel-Tum field, OK, the ninth largest oil field in the U.S.

Preliminary laboratory studies were conducted to design the ASP pilot project. Coreflood tests determined that oil recovery was highest when alkaline surfactant was followed by polymer and when an alkaline preflush was used in cores that were saturated with brine containing divalent ions.

The ASP flooding technology was successfully demonstrated in the Sho-Vel-Tum field test. Before this project, the four production wells in the demonstration area were producing about four barrels of oil per day, typical for older producing wells that have been waterflooded for many years. Through February 1999 approximately 12,6000 barrels of oil (20% of the original oil in place) were produced. After the ASP flood, daily production leveled out at about 22 barrels of oil per day representing a fivefold increase over preflood rates.

The resource base for technologies and methods developed in the project is 6-10 million barrels of oil, of which 2 million barrels of reserves could potentially be made economic by application of the ASP technology.[5]

MEOR Methods

Between 1978 and 2000 DOE has funded thirty-nine projects in microbial enhanced oil recovery (MEOR) technology. Fifteen organizations were sponsored with the majority of contracts representing continuing work at the University of Oklahoma and NIPER, the DOE Bartlesville Project Office in-house laboratory. Of the total contracts, 18 went to universities, 4 to national laboratories, 4 to independents, 1 to a state, and 12 to NIPER. Significant improvements and innovations resulted from certain projects. Realized benefits were those that showed specific enhanced oil recovery. Optional benefits were those that showed increased knowledge of some stage of MEOR technology development, but were not field tested to demonstrate positive enhanced oil recovery. Additional benefits from two of the projects apply in environmental remediation.

Realized Economic Benefits
<u>Mississippi State University</u> - Microbial selective plugging technology (2 contracts)
The project developed information on the microflora indigenous to subterranean oil reservoirs, with special emphasis on their potential role in microbial enhanced oil recovery. In regard to the microbial residents of subterranean oil reservoirs, the following was learned:

- The driving force of this MEOR technology was the economic and technical successful field demonstration at North Blowhorn field, Alabama, which has increased ultimate recovery 595,000 bbl over natural decline and extended reservoir life five additional years. This was preformed under the Class I field demonstration project by Hughes Eastern Corp as documented in the 2000 NRC report Field Demos.
- Significant numbers of microorganisms were present in all 5 reservoirs examined (ranging in depth from 805 ft to 14,492 ft). 100-fold increase in microorganisms in effluents was observed in core tests.
- Each reservoir had a somewhat distinctive microflora.
- Of the 37 pure culture isolates examined, all grew anaerobically and produce one or more products of potential value to MEOR - gas, acid, emulsifiers, polymers, solvents.
- Microbial isolates would colonize stratal materials (limestone, sandstone, clay shale) and their growth in sandpacks caused alterations in the flow of water through the sandpack.
- None of the reservoirs contained sulfate-reducing microorganisms.
  - ♦ Ultramicrobacteria were present in one reservoir.
  - ♦ The results of this investigation support the concept that microorganisms indigenous to subterranean oil reservoirs are valuable to enhancing oil recovery.

<u>University of Oklahoma, Norman, OK</u> - Microbially Enhanced Oil Recovery Research (9 contracts
The Microbially Enhanced Oil Recovery Research Laboratory has had a number of contracts from the DOE from 1981 to 1993 and 1998 to 2000. The continuing research program has been a multidisciplinary effort to study microbial plugging to improve sweep efficiency, biosurfactant production, molecular engineering of the surfactant structure, and engineering studies to determine the effectiveness of the biosurfactants in oil recovery. Major accomplishments are as follows:

- Development of a microbial selective plugging process to improve sweep efficiency.

- Successful field demonstration of the microbial selective plugging process.
- Development of a microbial process to control souring by addition of nitrate and/or specialized nitrate Busing bacteria.
- Demonstration that nitrate addition can control souring in high temperature reservoirs.
- Isolation and characterization of the most effective biosurfactant-producing bacterium known.
- One of the first to realize that oil reservoirs are not sterile environments and development of beneficial uses of indigenous micro-organisms.
- Provided evidence for the existence of a diverse microbial community in a hypersaline environment.
- Development of the first mathematical model to simulate microbial activity in porous media and to predict permeability reduction.
- Discovery of the fundamental processes by which micro-organisms grow through porous media.
- Development of experimental protocols for MEOR research which are now standard practice worldwide.
- Development of a microbial process to recover oil from carbonate reservoirs.
- Isolation and characterization of novel halophilic micro-organisms from oil reservoirs.
- Experimental demonstration that oil recovery is proportional to biosurfactant production.
- Development of an improved growth medium to support vigorous anaerobic growth of our biosurfactant-producing bacterium.
- Cloning and partial sequencing of the genes involved in biosurfactant production in *Bacillus licheniformis* strain.

<u>Idaho National Engineering and Environmental Laboratory (INEEL) FEW 5AC312</u>
Research at INEEL has focused on the application of biotechnology for exploration and production as well as for the mitigation of detrimental field conditions. Early work focused on the elucidation of microbial mechanisms responsible for oil production with emphasis on heavy oils. The work documented the applicability of microbial surfactants that were either generated in situ or applied after ex situ generation, and that surfactants produced by *Bacillus licheniformis* were not inactivated by reservoir conditions or oil composition. Instrumentation to evaluate interfacial tensions by video image analysis of inverted pendant drops was also developed to measure the changes mediated by microbial surfactants.

- Evaluation of microbiologically produced surfactants and polymers for application in production facilities.
- Production of surfactants from agricultural residuals (high starch streams from potato processing).
- Application of microbial polymers for flow conformance and water shut-off.
- Production of surfactants from agricultural residuals results in reduction of waste stream.
- Design and operation of a bioreactor for surfactant production and separation in a single step.
- Evaluation of wettability led to documentation of brine composition as a key element in oil recovery.
- Program has provided technical growth in following areas:
  - ♦ Microbial oxidation of sulfides.
  - ♦ Enzymatic transformation of sulfur heterocycles at supercritical fluid conditions.

- ♦ Evaluation of wettability and imbibition on oil recovery.
  - ♦ Subsurface fluid transport and microbial partitioning.
  - ♦ Effect of wettability and rate dependent imbibition on subsurface contaminant distribution.
- Research at INEEL has generated one patent on MEOR processes.

BDM Oklahoma/ NIPER - Biotechnology and Biological systems for in situ recovery (12 projects)
Projects were operated through the Bartlesville Project Office at the NIPER facility by Illinois Institute of Technology Research Institute (IITRI) and BDM Oklahoma. The objective of the projects was to develop an engineering methodology for designing and applying microbial systems to improve oil recovery. Microbial research has improved the understanding of mechanisms in oil mobilization by microbial formulations and transport of microbes and their metabolites in porous media, and the implementation of two microbial-improved waterflood field pilots. The concepts and data have formed the basis of applied research needed to develop an engineering methodology for designing and optimizing microbial formulations for specific field applications. Specific achievements are as following.

- Single well MEOR treatment to demonstrate a cost-effective biotreatment technology to prevent and remove well-damaging agents such as paraffin, hydrogen sulfide and iron sulfide, and scale.
  - ♦ 165 wells in 15 reservoirs in Oklahoma, Kansas, Texas, New Mexico and Wyoming were treated.
  - ♦ All wells demonstrated decreases in hydrogen sulfide levels.
  - ♦ Additional field data showed increased production and reduced operating costs.
  - ♦ Technology offers producer an economic, practical and effective treatment for field operations.
- In situ recovery and/or upgrading of heavy hydrocarbons and method for predicting how these processes will be effective in field applications.
  - ♦ Results indicate improved oil recovery by combining the process of microbial enhanced hydrocarbon oxidation with ASP flooding techniques.
  - ♦ Other microbial systems have shown increased oil production in corefloods, and decreases in interfacial tension.

Microbial enhanced oil recovery process field tests conducted by NIPER demonstrated 13% and 20% improvements in oil recovery rates. It is estimated that 5-6 million bbls of oil could be recovered by the application of MEOR technology. The microbial waterflooding technology developed and patented from the DOE project was licensed to BioEngineering International, Inc. and was used successfully for field treatments. The laboratory work has also led to the development of a permeability modification technology and a patent application in that area.

Simulation

Energy production is central to the mission of DOE. Increased domestic oil production using advanced technologies of improved oil recovery processes involves numerical modeling of such processes to minimize the risk involved in development decisions. The oil industry is requiring much more detailed analyses with a greater demand for reservoir simulations with geological, physical, and chemical models of much more.

There are two general types of reservoir simulations that are addressed in the DOE program. First, there are those that use existing simulations either in new ways or applies them to new situations. And, second, there are those that push the state-of-the-art to develop new processes or significantly improve existing processes. The first is an application of existing technology while the second is the development of new scientific methods and approaches. The DOE program uses both of these types of simulations, but tends to emphasize the new scientific approach as the development of new science becomes the application that produces more oil.

From 1978 to 2000, there were 22 projects in simulation. They were with 4 different universities (9), 3 national laboratories (3), 2 small businesses (2), Government laboratories (4) and the M&O contractor (4).

State-Of-The-Art:

Simulation generally functions by dividing an area of interest into small grid blocks that are each analyzed separately. The blocks define the area of interest and critical values for each of the blocks are determined and monitored in relation to each of the other blocks in the grid. The grid in an oil reservoir is generally three-dimensional and hundreds or thousands of blocks are used to describe the complete grid. As the values in each block change, corresponding values are determined for each of the other blocks in the grid. This type of analysis requires extensive mathematical modeling and use of powerful computers.

Databases are crucial to proper simulation modeling as the values that are assigned to each of the blocks need to be based on factual information for a realistic assessment of the simulation's performance.

Reservoir simulation has made good advancement over the last 10 years. However, the simulators are not so advanced that oil recovery can be modeled completely and the reservoir performance predicted. Additional research is needed to develop new state-of-the-art simulators that can better predict the field performance. Current projects are to develop new or to make major extensions to "mainframe or supercomputer" simulators by using new methods, parallel computational methods, or other viable techniques. Also, scaled down simulators are being developed which are adequate for "desktop" or "workstation" systems that would be beneficial to the smaller oil producer. Simulators which would modify or improve the application of the above oil recovery processes to horizontal wells are also being developed.

A more detailed analysis is required to reduce the risk of investment decisions. This requires reservoir simulation studies that use geological and physical models of much greater detail than in the past. Millions of reservoir cells are now common in many geological reservoir descriptions. Moreover, greater accuracy in physical models is required to minimize the risk involved in development decisions. These requirements impose tremendous mathematical and computational challenges, but several key technologies are now available. Among these are the use of massive parallelism, more accurate physical models, accurate and flexible gridding of the reservoir, fast and robust solvers, and integration with other applications.

Although computer processor speed is increasing rapidly, the challenge of simulating large, complex reservoirs will only be met by harnessing the power of the new generation of parallel computers and clusters of PCs. Furthermore, sheer computational power alone is not sufficient to simulate multiple complex physical processes. New algorithms are required to ensure that the numerical implementation of these models is meaningful.

DOE Sponsored Work:

Contracts have been awarded by the DOE for research in simulation development over the past several years. A summary of the number of contracts awarded in each of the years and funding (1999 dollars) is presented in the table below. Note that the funding for each project is shown at the beginning of an effort. If the work continued over move than one year, those funds would be applied to the period of time of the project.

Of these contract efforts, three areas stand out as examples of benefits of the DOE simulation work. They include the UTCHEM model development at the University of Texas, the MASTER (Miscible Applied Simulation Techniques for Energy Recovery) development of statistical analysis and modeling of reservoirs, and the development of the predictive and screening models. While some of these projects have been superceded by more recent work, their use at the time they were developed led to an increase in recoverable oil and more economical operation.

In addition to allowing the more efficient recovery of oil, one of the principal benefits of simulation is that it provides options for environmental effects. The use of simulation allows an examination of the recovery of oil and the examination of the related environmental impact before the recovery begins. A trade-off can be made to allow the optimum oil recovery with the minimum environmental impact on a case-by-case basis.

Discussion of Principal Projects:

UTCHEM

DOE-sponsored research has resulted in the development of a chemical flooding simulator named UTCHEM that was developed by the University of Texas at Austin includes options for projecting the behavior of tracers, polymers, polymer gels, surfactants and alkaline agents injected into oil reservoirs. The simulator can also be used for profile control, tracer tests, formation damage, soil remediation, microbial enhanced oil recovery, surfactant/foam, and wettability alteration. The simulator is being used by more 60 organizations including more than 20 oil companies. Better management of reservoirs has saved these companies more than $23 million, $8 million of which will flow back to the U.S. Treasury.

MASTER

The reservoir simulator Miscible Applied Simulation Techniques for Energy Recovery (MASTER) was completed in 1991 by the Morgantown Energy Technology Center to predict the performance of miscible gas injection projects. MASTER is a 3-dimensional, multicomponent simulator that can simultaneously track stock tank oil, natural gas, water, up to four solvent species, and a surfactant. MASTER uses mixing parameters to account for the density and viscosity changes that occur with the development of a miscible gas displacement. The model is intended to approximate the results that can be obtained with a fully compositional simulator.

The model was developed using the code from the BOAST model that had earlier been developed for DOE.

The major advantage of MASTER is its capability to predict a wide range of reservoir applications, including primary recovery, waterflooding, and miscible gas flooding. The model has a switch that allows the miscible gas portion to be turned on or off as required. Thus, it is possible to use the model for history-matching the performance of a primary recovery operation or a waterflood, and then turn on the appropriate switch to predict the performance of a miscible gas project. This capability allows the model to honor the appropriate reservoir description and the fluid saturations that exist at the time the miscible gas project is initiated.

Studies indicate that use of the processes in MASTER generated a 3-billion barrel increase in potential reserves.

Predictive and Screening Models

EOR predictive models developed in the program are easy-to-use predictive models that can estimate the oil production rate over time for various enhanced oil recovery processes and the associated economics of the recovery. The programs allow an operator to inexpensively estimate whether the payback period for enhanced recovery technologies warrants the expenditures to full evaluate and develop a producing property. The models for steamflooding, in-situ combustion, polymer flooding, surfactant flooding and CO2 miscible floods were developed in conjunction with the National Petroleum Council and Scientific Software Intercomp, More than 1000 computer copies of the models have been distributed to oil field operators, drilling and service companies, consultants, and researchers.

EOR screening models were developed for the purpose of estimating the amount of oil that can be recovered for a prospective reservoir. These models were made available to the industry and they were also used in the National Petroleum Council study on enhanced oil recovery in 1984. These models were developed by Scientific Software under the terms of a joint agreement between DOE and the Ministry of Energy and Mines of the Republic of Venezuela. Predictive models were developed for chemical flooding, CO_2 flooding, in-situ combustion, polymer flooding, and steamflooding. The screening models were revised during the NPC study, and final versions made available to the industry. The revised models predict performance based upon a correlation with actual field data. The accuracy of such models lies between simple screening guidelines and the results of a reservoir simulator.

Use of the model allows a quick determination of the amount of oil that can be recovered from a proposed EOR application. This capability allows the operator to make a quick assessment of project feasibility and helps him to avoid unnecessary costs in pursuing a project with low potential. At the same time, the operator can proceed with higher confidence in undertaking a more detailed study if the screening model indicates a favorable result.

The basic advantage of the predictive models is the ability to screen a large number of prospective reservoirs for EOR potential. This capability exists because of the minimal data requirements and the simplicity of the model to use. The operator can then concentrate on those specific reservoirs that have the highest potential.

The software is currently available on the NPTO website. The use of these models has saved the industry $400 million by screening out uneconomical projects.

Summary of Simulation Qualitative Benefits:

UTCHEM:
- Used by more than 60 organizations including 20 oil companies.
- Saved $23 million.
- Has put $8 million back into the US treasury through taxes.

MASTER:
- Allows determination of CO_2 flooding.
- Permits a 3 billion-barrel increase in potential reserves.

Predictive/Screening
- Early estimators of oil that could be recovered from prospective reservoirs.
- They are estimated to have saved the industry $400 million by screening out uneconomical projects.

Background Materials for Economic Options Benefits

Novel Methods

DOE periodically funds projects that have high potential for the improved recovery of oil but which are still in the early development phase. There is a higher-than-normal associated risk in the outcome of the results. This category of research is considered to be important in the identification of promising new technologies, although the budget has been relatively low over the years.

Three projects are discussed below to illustrate the types of projects that are being evaluated in the novel methods budget. These summaries describe the process, the potential benefits, and assess the remaining development challenges.

Seismic Stimulation

Seismic wave stimulation is a novel process that is receiving increased attention within the industry. The premise is that high-energy seismic waves can re-distribute the oil droplets in a high water saturation environment to create a mobile oil phase. The seismic waves may be transmitted to the reservoir by large sized surface vibro-seismic devices or by downhole devices that generate the energy close to the reservoir. The Russians have been developing this process for nearly 40 years and have conducted numerous field tests (Beresnev, 1994). This process is considered to have particular potential for waterfloods that are in a mature stage of development. Interest in the process has increased in the United States over the past few years and field tests are now being conducted in several locations.

DOE funding has been provided to Los Alamos National Laboratory for conducting a cooperative laboratory and field test program designed to evaluate the seismic stimulation process. Cooperating companies include AERA Energy, Chevron, Conoco, Halliburton, Marathon, Phillips, and Texaco. Companies that provide a service for seismic stimulation include Etrema Products, Inc., (Ames, Iowa) and Applied Seismic Research (Plano, Texas). A web site maintained at http://www.ees4.lanl.gov describes the activities of the cooperative program. DOE is also supporting a field test with Oil and Gas Consultants International, Inc.

A review of the various studies and field tests indicate that the process has technical merit. The seismic waves appear to create a mobile oil phase at water saturations that are near to the normal residual oil saturation. The process appears to improve oil recovery by several mechanisms, including a reduction of capillary pressure, the coalescence of oil films, the movement of dispersed oil droplets, degassing of oil, and viscosity reduction. Dr. Beresnev, who has studied the process for many years, considers capillary pressure reduction to be the dominant mechanism.

The total data from the various field tests demonstrate clearly that the process does increase oil recovery. However, results are variable and inconsistent, and there is a notable lack of data to arrive at a strong conclusion. Experience has shown that it has been difficult to relate laboratory data with the field experiences. The biggest need at this stage is well-designed field tests that will permit a quantitative evaluation of performance. Chevron is currently conducting a seismic stimulation project in the Lost Hills diatomite reservoir in central California, with increased oil cuts in more than 60 wells. A large seismic stimulation project conducted for Caltex in Sumatra, Indonesia, is reported to have been successful (World Oil, 2000).

The seismic stimulation process has large benefits if the technology and economics are confirmed. Because of the ability to mobilize oil at high water saturations, it will be possible to extend the life of the mature waterfloods in the country. Competing processes that can displace residual oil saturation require the injection of expensive chemicals or gases that develop miscibility with the crude oil.

The biggest challenge will the development of a sufficiently powerful seismic stimulation source that will permit the effective movement of energy through out the interwell area. The tendency is for seismic waves to be attenuated as they move out into the reservoir, especially by gas saturation.

Oil Wettability

A project entitled "Evaluation of Reservoir Wettability and Its Effects on Oil Recovery" is now underway at New Mexico Institute of Mining and Technology, Socorro, New Mexico (Buckley 1999). The objectives of this 5-year project are: (1) to achieve improved understanding of the surface and interfacial properties of crude oils and their interactions with mineral surfaces, (2) to apply the results of surface studies to improve predictions of oil production from laboratory measurements, and (3) to use the results of this research to recommend ways to improve oil recovery by waterflooding. The project is now in its third year of funding.

In the first part of the study, the goal has been to test improved methods of oil characterization for prediction of the wettability-altering potential. Four medium gravity crude oils were characterized based upon the API gravity, the acid number and the base number. The oils in this group had varying amounts of asphaltenes. It was determined that the crude oils having the highest ratio of base to acid number gave the greatest alternation of wetting on mica surfaces. It was further determined that the asphaltene content of the crude oil could be correlated by refractive index measurements. In the second part of the study, the goal has been to improve the tools for assessing the wetting alteration that occurs between crude oils, brine, and rock surfaces.

An improved understanding of the mechanisms of wettability has been developed by the studies to-date. These studies have further determined the crude oils that are most susceptible for wettability alteration. Ultimately, it is hoped that the improved understanding of mechanisms will lead to a method whereby the wettability can be altered to achieve improved oil recovery. Past studies have indicated that a water-wet condition is preferred to an oil-wet condition because of the higher oil recovery that can be achieved. Injection of pH-altering fluids has been evaluated in past studies for wettability reversal.

The major expected benefits of the research program are (1) development of a procedure that will permit the identification of reservoirs where the wettability is susceptible to alteration, and (2) development of improved methods for achieving the wettability reversal. These capabilities will permit the improved recovery of oil.

The biggest challenge will be the identification of a fluid that is sufficiently low in cost and which is also capable of moving through the reservoir to contact the in-place crude oil. Because of reservoir heterogeneities, it is likely that a wettability alteration procedure will only affect that portion of the reservoir that can be readily contacted by another fluid.

Improved Waterflooding and Wettability

A research program is now underway to evaluate the effects of brine composition on the efficiency of a waterflood. This project is being conducted by the Idaho National Engineering and Environmental Laboratory (INEL) in conjunction with the University of Wyoming and BP Amoco. Information about the project is available at the web site located at www.inel.gov/engineering/fossil/environ.

The basic premise of the project is that the adjustment of the brine chemistry can influence the recovery efficiency that is achieved in waterflooding. The usual practice is to select a water source that is readily available and which does not introduce any problems related to corrosion, formation damage, or the souring of the produced water. Selection of a water source based upon these criteria is useful in the avoidance of problems, but does not necessarily lead to the maximum recovery that can achieved. A growing amount of laboratory data is indicating that the recovery can be enhanced through the adjustment of the constituents of the injected brine.

The research conducted to-date has identified three key conditions that are required for the process to be effective. These include (1) the presence of polar components in the crude oil that can adsorb on the rock surfaces, (2) the presence of clay in the rock, and (3) the presence of connate water. The current work is focusing on the effects of the crude oil, rock properties (especially clays), and the composition and amount of connate water in the rock. It is hoped that this program will lead to development of screening criteria that can be used for the selection of suitable field test candidates. BP Amoco is currently evaluating prospective reservoirs for a field test of the process. Several candidate locations are being considered.

The major potential benefit of the process is the improvement of oil recovery at a low cost. The improved recovery is achieved by the shifting of the wettability from an oil-wet to a water-wet condition. The incremental costs over a conventional waterflood are expected to be minimal. The research now underway will be instrumental in the selection of reservoirs that will be the most suitable.

The major challenges will be in the practical implementation of the process. Usually, the sources of water for a waterflood are limited. A relatively fresh water will be required, which may be available from nearby shallow zone aquifers. Surface waters are not normally recommended due to the inherent problems in dealing with bacteria and varying solids content. Precautions also have to be taken to avoid clay dispersion and plugging that can occur when injecting fresh water into a sandstone reservoir containing reactive clays.

SEISMIC STIMULATION

- Many of the key variables affecting performance have been identified.

WETTABILITY

- Concepts have been developed for reversing wettability to improve oil recovery.

Gas EOR

<u>New Mexico Institute of Mining and Technology, Socorro, New Mexico</u> A field test of using CO_2 foam to improve the sweep and effectiveness of a CO_2 flood was conducted in the East Vacuum Grayburg/San Andres Unit operated by Phillips Petroleum Company.

The CO_2 foam field trial performed proved that a strong foam could be formed in situ and that the foam reduced the mobility of CO_2 by one-third that observed during the baseline CO_2 injection. Incremental oil was produced in three of the 8 producers in the pattern, and gas cycling was dramatically reduced in the "offending" well as a direct result of surfactant injection.

<u>University of Pittsburgh</u> Development of Novel Mobility Control Methods to Improve Oil Recovery by CO_2. Promising ways of thickening CO_2 are being investigated using polymers dissolved in the dense CO_2 to increase its viscosity by the needed extent. This research has led to the development of several polymer compounds that act as thickeners for injected CO_2. The results of this research will greatly increase the effectiveness of CO_2 flooding and will also significantly reduce the cost of conducting enhanced oil recovery.

Thermal EOR

<u>University of Texas at Austin DE-AC22-90BC14661</u>
Oil recovery by steam injection is a proven, successful technology for non-fractured reservoirs, but has received only limited study for fractured reservoirs. The domestic potential from

naturally fractured reservoirs is tens of billions of barrels of oil. Oil remaining in bypassed matrix blocks has resulted in low recovery efficiency from fractured reservoirs. The objectives of the study were to quantify the amount of oil producible by stream recovery methods and develop a numerical model for predicting oil recovery in naturally fractured reservoirs during steam injection.

- Conducted experimental study to construct and operate apparatuses to isolate mechanisms affecting recovery.
- Determined how to measure and model thermal expansion and capillary imbibition rates at relatively low temperatures in various lithologies and matrix block shapes.
- Design apparatuses to measure thermal expansion and capillary imbibition rates at high temperature.
- Designed apparatus to measure the maximum gas saturations within a matrix block.
- Designed apparatus to measure thermal conductivity and diffusion of a porous media.
- Developed a dual porosity thermal reservoir simulator to model temperature affects.
- Tested the thermal reservoir simulator prediction functions in a series of experimental fractured reservoir simulations.

Chemical EOR

Mixed Surfactant Systems

Research conducted by BDM-Oklahoma (98-A03 Task 02) demonstrated that surfactant chemical systems can be adjusted to have optimal properties over a wide range of reservoir conditions. The mixed surfactant studies conducted in this project showed that surfactant loss can be reduced by two orders of magnitude, salinity tolerance can be increased up to 20% NaCl, and temperature tolerance can be increased up to 90°C by combining effective oil-mobilizing surfactant systems with surfactants or other chemicals that alter optimal recovery conditions. This allows advanced oil recovery applications to a much broader range of reservoir conditions. These systems are still relatively expensive, however, which limits the application opportunities while oil prices remain low. The potential for this technology will improve with higher oil prices. Economics of chemical improved oil recovery processes was improved by using low-concentration surfactants with alkaline additives.[5]

"Smart" Water-Soluble Polymer Systems

The focus of the coordinated research program conducted by Mississippi State University (DE-AC26-98BC15111)[6] is the development of environmentally responsive copolymers that increase production of oil left in the ground after primary production. This project has successfully constructed advanced, environmentally safe polymer systems with rheological (flow) behavior that can be changed in situ in response to reservoir conditions of pH, electrolyte (salt) concentration, and temperature. These "smart" water-soluble polymer systems rely on "triggers" strategically placed along the water-soluble polymer backbone that when activated by lowering salinity or increasing pH can increase polymer viscosity in situ. Increased polymer viscosity allows increased oil recovery by improving mobility control and sweep efficiency. They polymer was licensed for development by Oryx, a major independent oil company.

Other significant contributions from this project are the development and construction of a packed-bed and screen extensional rheometer that aids in the investigation and development of effective advanced polymer systems at various flow conditions.

Microbial EOR

<u>Fairleigh Dickinson University DE-AC22-90BC14666</u>
This novel MEOR project was designed as a low-cost method for small independent oil companies to define reservoir characteristics to improve oil production with a biological tracer. The following successes were attained:

- The bioluminescent tracer could make a significant contribution to reservoir characterization and to environmental monitoring.
- Determined the critical growth parameters of the bacterial cultures collected from a variety of connate and marine environments.
- Three cultures selected which had natural luminescence, and were tolerant to variation in nutrient additions, salts and temperature.
- Intensity of luminescence of selected bacteria is easily distinguished by the human eye and requires no sophisticated technical knowledge or instrumentation.
- Tests were preformed to adapt the selected cultures to formation waters, and to facilitate transport through representative reservoir cores.
- Bacteria introduced to formation waters exhibited a slight lag in growth rate, but luminescence was not affected. Adaptation to oil reservoirs was successful because the bacteria thrive in brine conditions.
- Bacteria were anaerobic and able to pass easily through sandstone and carbonate cores.

<u>University of Michigan</u> *MEOR research in fluid conductivity and core plugging*
In situ core plugging experiments and transport experiments using the bacteria, *Leuconostoc*, demonstrated that cellular polysaccharide production increased cell distribution in porous media.

- Cellular polysaccharide production also causes a decrease in media permeability.
- Core plugging experiments showed the feasibility of this system to divert injection fluid from high permeability zones into low permeability zones for profile modification.
- Controlled placement of cells and rates of polymer production are needed.
- *In situ* growth caused the following three injection pressure regimes .
  - ♦ Initially no measurable change in injection pressure.
  - ♦ Dramatic increase in injection pressure.
  - ♦ Injection pressure oscillations.
- These coincide with the development of an internal biofilm that initially does not restrict flow until thickness becomes significant. At a critical point the biofilm undergoes sloughing which produces cell and dextran aggregates and pressure oscillations.
- Overall effects of nutrient injection rate and nutrient concentration results in a faster rate of porous media plugging.

<u>Injectech, Inc.   DE-AC22-90BC14663</u>
Injectech tested oil reservoirs to identify the organic and inorganic components, which form the nutritional resource for naturally occurring microorganisms.

- Materials present in connate or flood water include the following:
  - ♦ Sulfates
  - ♦ Carbonates

- ♦ Volatile fatty acids
- ♦ Nitrogen-containing corrosion inhibitors.
- ♦ Phosphorous-containing scale inhibitors
- ♦ Trace elements

- Species of sulfate reducing bacteria and denitrifying bacteria were isolated from reservoir water and were found to utilize volatile fatty acids and dissolved carbonates.
- Volatile fatty acids (VFA) were identified, as the key factor in determining which fields will suffer with sulfide and microbial problems.
- Introduction of inorganic nitrate to the waterflood can produce favorable reservoir profile modification by increasing the denitrifying microbial population.
- Denitrifying bacteria, *Thiobacilli,* has the capability of attacking carbonates in effecting rock dissolution and gas generation increasing oil release and recovery.

Oklahoma State University, Stillwater, OK   DE-AS19-80BC10302
The project was designed to test the growth of two strains of the bacteria. *Clostridium* was considered to have the highest potential for microbial enhanced oil recovery processes. These organisms are anaerobic, and capable of producing large amounts of gas from carbohydrates. The research should be beneficial in providing guidelines for designing *in situ* experiments and processes.

- Strains tested grow well on simple media. However, growth is much faster on a rich complex media.
- Sodium chloride was found to inhibit growth and gas production.
- Sodium chloride toxicity was more pronounced in some strains than others.
- Supplementation of manganese ions to the medium may somewhat reduce salt toxicity.
- The low pH of sandstone cores limits the successful production of gas.
- Beet molasses was found to be very satisfactory as a source of nutrients for the bacteria.

Simulation

UTCHEM:
Allows profile control to better use reservoirs and study formation damage.

MASTER:
Predicts a wide range of reservoir applications (primary recovery, waterflooding, and miscible gas flooding).

Predictive/Screening:
Allowed a quick determination of pursing economical projects.

All:
Recovery method can be selected to optimize oil production.

Chemical Methods

Surfactant-Enhanced Alkaline Flooding for Light Oil Recovery

The research conducted by the Illinois Institute of Technology (DE-AC22-92BC14883) is a combination of experimental and theoretical studies to advance current understanding of surfactant-enhanced alkaline flooding for tertiary oil recovery. The objective of the research was to develop an effective, cost-efficient surfactant-enhanced alkaline flood. The research program addressed the technical constraints that occur in each step of the combined surfactant-alkaline flooding process for light oil recovery. These include better understanding of the mechanisms by which the oil is displaced, investigation of crude oil-alkali-surfactant interactions; mobility control through in-situ formed emulsions, and better predictive models and simulators for improving process performance and predictability.

Several previous investigations had found that the ultralow interfacial tension between crude oil and alkali occurs at very low concentrations of alkali. Most investigations employ a single alkaline chemical which buffers at a specific pH however experiments conducted at the Illinois Institute of Technology clearly showed that this pH may not be the optimal pH to obtain ultralow interfacial tension. To get the optimal pH, the alkaline solution must be formulated at low concentrations and in doing so, the concentration of the alkali is too low to survive the transport through the reservoir due to the influence of external factors such as divalent ions, acids, rock and dispersion. The experiments conducted showed that one way to lessen the influence of these external factors is to mix the alkalis in the appropriate ratio to obtain the optimal pH for low interfacial tension at high concentrations of alkali. At these high alkali concentrations, the alkali can survive the transport through the reservoir and maintain low interfacial tension throughout the flood.

On the basis of prior laboratory and field test data, the application of alkaline flooding alone will not achieve the theoretical recovery potential. However, the addition of surfactants and the use of mobility control polymer will allow the potential of the process to be realized with many of the low cost advantages of pure alkaline systems.

Novel Mixtures of Surfactants

The aim of the research conducted by Columbia University (DE-AC26-98BC15112) was to develop improved extraction processes to mobilize and produce the oil remaining after conventional production techniques. The high cost of chemical processes and significant losses of chemicals by adsorption on reservoir minerals and precipitation has limited the utility of chemical flooding operations. This research developed and evaluated novel mixtures of surfactants for improved oil recovery, with emphasis on designing cost-effective processes compatible with existing conditions and operations and ensuring minimal chemical loss. The advantage of using surfactant mixtures instead of individual surfactants is that interfacial behavior of the mixtures can be synergistic and can be manipulated by adjusting surfactant type and properties, such as mixing ratio and the order of addition. Unfortunately, past fundamental research in these systems has been mostly using single surfactants while commercial systems invariably are mixtures.

The objective of the research was to develop a full understanding of the adsorption/desorption of mixed surfactants at solid-liquid interfaces. The research approach was multi-pronged and involved using both conventional techniques for measuring adsorption/desorption isotherms, surface tension, zeta potential, wettability and heat of adsorption; and advanced spectroscopic (fluorescence, electron spin resonance and nuclear magnetic resonance) techniques for probing the nanocharacteristics of the adsorbed layer.

Major accomplishments of this work were:

1. Microstructural properties (surfactant aggregation orientation) of the adsorbed surfactant layer that control rock wettability were determined in-situ for the first time
2. All commercial processes use mixed surfactants. By developing a novel method for measuring monomer concentrations of each species in mixed micellar systems, regular solution theory was found to fail and a new model was developed for mixed micellization, taking into account synergy and competition between different species in adsorption and desorption.
3. A new hypothesis of co-existence of different type of mixed micelles was prepared based on results for mixed cationic - anionic surfactant system.

Novel Methods

Seismic Stimulation

- Field tests have demonstrated that the process works.
- Additional lab and field tests are needed to better understand the variables affecting performance and to define the range of applicability.

Wettability

- Plans are being made for the conducting of a field test.

Simulation

UTCHEM:

- Allows an improved use of recovery methods.
- Provides modeling information, techniques, and methods that led to use of robust simulators on desktop computers.

MASTER:

Results from existing fields were used to predict the recovery from new fields.

Predictive/Screening:

The simple screening models provided information that led to the development of reservoir simulators

Chemical EOR

Water Production Control using Polymer Gels

The reduction of water production and subsequent disposal through use of polymer gels provides a significant reduction in environmental impact. In one project alone, ARCO decreased the amount of produced water over a 3-year period by 20 million barrels in a Prudhoe Bay field. With an U.S. annual production of more than 20 billion barrels of salt water, the potential to reduce saltwater disposal environmental liability and costs is large. In another gel treatment application in Rangely Field, CO a reduction in produced water of 98 barrels per day was realized.

Alkaline Surfactant Polymer Project

Alkaline surfactant polymer (ASP) technology not only increases oil production but also reduces water production. ASP floods are also attractive in that the chemicals used are non-toxic which reduces disposal liability.

EOR Technologies

EOR technologies can significantly increase production in some maturing fields resulting in drilling fewer new wells. This minimizes the environmental impact by reducing the number of pumping jacks and associated surface support equipment, production pipe flow lines, and electrical power lines traditionally required by oil field development practice. The volume of drilling fluids that require disposal is also decreased as well as the possibility of cross-flow continuation of known targeted formations.

Increased productivity resulting from the application of EOR processes reduces abandonment of marginal wells and offshore platforms. Abandonment of wells can translate to noncompliance with environmental standards. Improved economics in the field allow the operator to meet or exceed requirements for clean operations.

Microbial EOR

BDM Oklahoma/NIPER Biotechnology and Biological systems for in situ recovery (12 contracts)

The program has provided one of the few reports about environmental research relating to microbial enhanced oil recovery (MEOR). Results show that a key component in the oil mobilization mechanism is the capability of microorganisms to produce localized high concentrations of products at an oil-water interface. The concepts and data have formed the basis of applied research needed to develop an engineering methodology for designing and optimizing microbial formulations for specific field applications.

- Microbial gel formation is soil. Developed a polymer producer, which will retain its ability to form polymer in the presence of soil to be used in bioremediation.
- Corefloods were run to evaluate the performance of microbially gelled biopolymer for oil recovery.
- An aquifer contaminant remediation model was developed. A test run showed enhanced remediation because of microbial treatment.
- Experiments were run to investigate the effect of soil on polymer production by a polymer.
- Long-term core studies were initiated to determine the stability of a biopolymer.

- A nutrient study was done to optimize polymer production by two biopolymers.
- Soil packs were designed to conduct experiments using native cores to evaluate the stability of polymer systems for soil remediation.

Idaho National Engineering and Environmental Laboratory FEW 5AC312
Research at INEEL has focused on the application of biotechnology for exploration and production as well as for the mitigation of detrimental field conditions.

- Application of novel sulfide oxidizing, nitrate-reducing bacteria to treat produced water or sweeten gas.
- Demonstration of technology in a 19-well field pilot deemed an economic and technical success.

Simulation

- Improved ability to meet regulations.
- Reduced waste volumes.

Background Materials for Environmental Option Benefits

Novel Methods

Processes will demonstrate minimal environment impact in harsh or sensitive areas.

Simulation

- Reduced water production due to examination of alternatives before the recovery begins.
- Reduced environmental exposure by selecting a method for oil recovery that should be the most efficient.
- Reduced environmental exposure by eliminating recovery methods that could introduce undesirable material.

Background Materials for Environmental Knowledge Benefits

Gas Methods

With more and more attention focused on global warming and the long term effects on the earth's climate, there is a growing interest in carbon dioxide sequestration. Carbon Dioxide is considered by many prominent research scientists to be a major greenhouse gas emission which is generated by fossil fuel combustion.   An effort is now underway by industrialized nations to reduce the amount of CO_2 which ends up in the atmosphere by storing or sequestration of CO_2. The sequestration techniques involving oil and gas reservoirs draw heavily on the technology and knowledge of the enhanced oil recovery (EOR) method of gas flooding.

A sufficient amount of CO_2 to conduct a field project at Schrader Bluff field located on the

North Slope of Alaska can be obtained from ongoing oil production operations at Prudhoe Bay. Futhermore, reinjection of this CO_2 has a positive environmental impact to the ecosystems of Alaska by reducing overall emissions of greenhouse gases. The greatest benefit may be to demonstrate the feasibility of this technology to other oilfield operations. Application of the technology would significantly reduce emissions from production facilities in Alaska and elsewhere.

Novel Methods

Plans for using a dilute brine will not create any environmental risks in the field.

Simulation

- Examination of different potential recovery methods allows comparison of the recovered oil to its environmental impact.
- Producing additional oil from existing wells reduces new environmental impact.

Background Materials for Security Realized Benefits

More than 10 percent of domestic production is obtained from enhanced oil recovery projects, helping to maintain the domestic oil industry.

Simulation

- Allows additional oil to be extracted from U.S. fields.
- Transfer technology to smaller operators who have some of the fields that can benefit from the use of simulation.

Background Materials for Security Option Benefits

- Results provide a strong national knowledge base.
- Allows the examination of alternative methods of oil recovery.

Background Materials for Security Knowledge Benefits

- Information and results can be used to build better models that lead to even greater oil recovery.
- Can be used by the domestic industry to predict the amount of recoverable oil from U.S. fields.

FE 7. Provide a list of terminated DOE R&D programs in the period for 1978 to 2000 and the reason(s) for their termination. What happened to each technology area afterward (e.g., was it continued by industry or abandoned)? How much total DOE funding was provided for each?

There have been no terminated programs, however, there has been a considerable shift in emphasis from 1978 to 2000. This shift in emphasis is described below for each of the above areas. Each EOR area is described below with a graph showing DOE funding and the total oil revenue by year for that process. The oil total revenue in constant 1999 dollars is taken from the Oil and Gas Journal. This journal publishes EOR data even years. The plot of the revenue, rather than production, reflects the impact on the oil industry. The DOE funding is also plotted to show how funding is modified to adjust to the current situation without eliminating the long-term nature of the research program.

Gas Flooding.

Initially, gas flooding was the injection of natural gas (methane) enriched with ethane, propane or butane to increase the solubility properties of the oil. The enriching agents help the injected gas become miscible with the oil and hence the name miscible flooding. However, natural gas became such a valuable product that miscible flooding is rarely used when natural gas is the injected gas. In the early 1970's, it was found that carbon dioxide could be used to recover oil and it could develop miscibility with the oil under proper conditions. Thus, much of the early work was in funding developing an understanding of the process. As the process became more understood, the funding shifted to research that would help implement carbon dioxide flooding in the field. Current research is directed at improving sweep and lowering the minimum miscibility pressure to make the process applicable to more reservoirs.

From 1978 until about 1988 most of the funding was directed a basic research. As the revenue from carbon dioxide flooding began to increase the DOE funding was focused on method to improve field performance (1988 - 1996). The revenue from oil production began to drop in 1997 and there was another shift in research to develop better way to sweep the reservoir (1998-2000).

Thermal (Heavy Oil) Recovery.

The recovery of heavy oil is usually accomplished by the introduction of heat into the reservoir. The major EOR processes that have been traditionally used include steam injection and in-situ combustion.

From 1978 to 1987, the funding for heavy oil was related to methods to improved field performance, mainly in steam flooding, steam injection and in-situ combustion. The funding for thermal methods decrease from 1988 to 1990 as research concerning in situ combustion lost favor.

Although the steam flooding field projects had been implemented for several years, industry recognized there was not much research on the mechanism of heavy oil recovery. DOE began to fund research in this area from 1991 to 1998 mainly through a consortium of oil companies and

Stanford University. However, to the low oil price in the late 1990s, it became apparent that methods need to be developed which can help produce heavy oil at low oil prices. This type of research has been funded from 1999–2000.

Chemical Methods.

Chemical methods include the use of surfactants, alkaline-enhanced chemicals, and polymers and gels. The micellar-polymer flood is a process designed to recover oil by reducing the interfacial tension that exists between the in-place crude oil and the injected water. DOE funded a significant amount of research from 1978 to 1988. During that time, oil production was from various field projects. However, by the later 1980, most companies had abandoned research in this area even though much of the oil in the United States is recoverable by this method. The DOE funding increase from 1988 to 1992 try to reverse the trend. A small pilot was funded using the Alkaline-Surfactant-Polymer (ASP) process in the late 1998s. Currently there is only one project relating to surfactant flooding being funded.

The advent of low oil prices shifted much of the DOE funding to more near term projects, such as, water shut-off methods. Since 1996, a major part of the chemical methods funding have been directed toward this type of research. It is important to understand, although these methods are important and may be economical, they will not recover the immobile oil which is oil trapped in the reservoir by capillary forces – an estimated 250 billion barrels resource in the domestic U.S.

Microbial Enhanced Oil Recovery (MEOR)

The MEOR process operates by the action of microbes to ferment a hydrocarbon and produce a byproduct that is useful in the recovery of oil. Ideally, microbes could function on the use of crude oil alone. The first DOE funded MEOR projects started in the early 1980s. This process was typically funded as Novel process during this time period. There was virtually no oil production from MEOR until the early 1990s. At time, the funding for MEOR was removed from being classed as a Novel process to a classification of its own. The was a very low funding level until about 1988 the DOE funding level increase. However, the overall funding for MEOR is still very low. There are several new project that show promise and may produce significant oil revenues in the next 5-10 years.

Novel Methods

Novel methods are those that do not fit within the conventional EOR processes. These methods are usually determined to have potential as a viable EOR but which are largely unproven. The various processes that fit into this category include injection brine optimization, downhole electric heating, microwave heating, seismic wave stimulation, and pressure pulse enhancement technology. DOE will sometimes support some of the projects within this category based upon the merits of the process.

There is no significant oil benefits from novel processes. However, processes such as Steamflooding, Gas Flooding, Chemical Methods, and MEOR were all considered novel in the past. Injection brine optimization has the potential to add over 500,000 barrel of oil a day to the U.S. production with a very low incremental cost.

Simulation

Reservoir simulators have proven to be useful in the design and prediction of performance from EOR projects. Good progress has been made in the development of EOR models over the past 10 years. In-spite of the progress, additional research is needed to develop the state-of-the-art models that are needed to better design and to predict field performance.

Several DOE-supported projects are now in progress to improve the hardware and software capabilities of reservoir simulators. These projects include both the sophisticated models as well as the scaled-down versions that may be suitable for independent operators. An improved capability to handle horizontal wells is also being developed.

The oil revenue shown for this plot includes Gas Flooding, Thermal Methods, Chemical Methods, MEOR, and Novel Methods. From 1978 to 1983, most of the simulation research was on modeling laboratory results from the various methods. From 1983 until 2000, the modeling funding began to shift to the Chemical Methods with the development of the UTCHEM simulator by the University of Texas at Austin. In the early 1990, some funding was directed to develop field flood simulators for gas flooding and especially carbon dioxide flooding (MASTER). Current work is directly toward improving fluid flow simulators and developing simulators that will help predict mobility control methods for both chemical methods and gas methods.

FE 8. Were there instances where a program was continued after a first commercial sale, and what was the justification for such continuation?

In addressing this issue, it is important to develop an understanding of how EOR processes are commercialized within the oil industry. This process is quite different from many other industries.

Prospective new EOR processes are most often evaluated initially in the laboratory to develop an understanding of the basic mechanisms and to collect data that will be useful in the design of a potential field project. If the laboratory data are promising, a field pilot may be designed using the laboratory data directly or in conjunction with a reservoir simulator. A new EOR technology will always be applied initially for the reservoir conditions that are the most favorable for the process. As the experience grows through laboratory and field-testing, future projects may be implemented in a more difficult environment. The key point is that commercialization does not occur rapidly. Rather, it usually occurs over a period of time and after numerous enhancements have been made to improve the process. In contrast to most other technologies, EOR processes are applied in an environment where it is physically impossible to understand or to control all of the variables that affect performance.

The DOE research programs have focused on overcoming the technical constraints that are limiting the application of the process. By overcoming the technical constraints, the process may become more effective in the recovery of oil or can be applied outside of the previously established range of applicability. The ultimate goal is to increase the applicability of the process and thereby increase the amount of oil that can be recovered within the United States.

Most of the DOE research programs have been conducted on EOR processes where some commercialization of the process has already occurred. However, the research has been focused in critical areas where the removal of technical constraints can greatly improve the applicability of the process. Several examples of this process follow:

Steam injection was initially commercialized in the moderately heavy oil fields located in central California. Because of the favorable reservoir conditions, it was possible in inject large quantities of high-quality steam into the reservoirs with minimum heat loss through the wellbore tubulars. The DOE research programs focused on several areas to improve the efficiency, economics, and range of applicability of steamflooding. DOE-supported research evaluated ways to minimize wellbore heat losses, thereby permitting higher quality steam to enter the reservoir. These methods included the development of insulated tubing, the evaluation of downhole steam generation, and the stimulation of reservoirs to permit higher injection rates. DOE also supported projects to evaluate the cogeneration of steam and electricity as a means of reducing the costs of the project. DOE also supported research to develop foaming and gelling agents that have the potential of minimizing the channeling and gravity override that occurs in steam injection projects.

Carbon dioxide flooding began in the 1970s in the Permian Basin reservoirs of West Texas and New Mexico. Laboratory and field results indicated that a principal constraint of the process is low sweep efficiency, due to the effects of reservoir heterogeneities and to the large differences in viscosity of the crude oil and the displacing gas phase. DOE research has focused on ways that the sweep efficiency can be improved. These include the evaluation of foaming and gelling agents and the use of agents that can directly dissolve in the carbon dioxide and increase its viscosity. DOE also conducted research that extended the applicability of carbon dioxide to the heavier oil reservoirs where significant benefits were received by the action of the carbon dioxide to reduce viscosity and to swell the oil.

DOE conducted a considerable amount of research in the 1970s and 1980s on the development of micellar-polymer flooding, together with other chemical processes. This research focus was selected since micellar-polymer flooding was in the early stages of development and commercial activity had not begun. The research conducted by DOE and by industry was responsible for the enormous progress made in the development of the technology. A highly successful field test was conducted by Exxon using the latest generation of surfactants that could tolerate high levels of salinity and hardness. Unfortunately, the technology did not progress much since that test due to the extremely low oil prices that have prevailed since the mid 1980s. DOE's research programs continued during this time frame with a shift toward systems that were lower in cost and which could perhaps be economic at the lower prevailing oil prices. The alkaline-surfactant-polymer (ASP) process emerged from these early studies and is in use today throughout the world.

Polymer flooding was introduced as a new EOR process in the 1960s and later developed into a commercial process. The DOE research programs conducted during this time frame were focused on ways to improve the stability of polymer, extend the range of conditions where the polymers could be used, and develop new ways that the polymer could be used. DOE had a major role in the development of polymer gel systems that are used commercially today for improving the profiles in injection wells. In a similar way, DOE has contributed greatly to the development of polymer gel systems that are used for the shut off of water in producing wells. Water shut off alone has saved the industry many millions of dollars.

FE 9. What was the total cumulative DOE R&D budget for each sector of the Fossil Energy program (in constant 1999 dollars) for each fiscal year from 1978 to 2000? Organize by Program Sector (i.e., Oil & Gas, Coal & Power Systems).

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS
($ in thousands)

	FY 1978		FY 1979	
ACTIVITY	Constant 1999 $$	Enacted PL 95-74	Constant 1999 $$	Enacted PL 95-465
Oil Shale	62,792	28,900	90,701	45,225
Coal Liquefaction	233,353	107,400	395,948	197,426
Surface Coal Gasification	421,296	193,900	330,110	164,598
Advanced Power Systems	55,840	25,700	53,949	26,900
Direct Combustion	131,234	60,400	103,689	51,701
Adv Res & Tech Dev	108,240	49,900	129,460	64,551
Demo Plants	97,556	44,900		
Magnetohydrodynamics	153,179	70,500	160,444	80,000
In Situ Gasification	27,377	12,600	0	
Enhanced Oil Recovery	100,816	46,400	107,698	53,700
Enhanced Gas Recovery	59,099	27,200	75,960	37,875
Drilling & Offshore Tech	3,476	1,600	5,214	2,600
Advanced Process Tech	3,042	1,400	2,407	1,200
Mining R&D			152,093	75,836
Adv Env Control Tech			14,039	7,000
Program Direction			18,062	9,006
Improved Conversion Efficiency	127,714	58,780	162,490	81,020
Clean Boiler Fuel (Liquef.)				-78,021
Reductions		-50,393		-63,000
Total	1,475,703	679,187	1,519,440	757,617

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS
($ in thousands)

	FY 1980		FY 1981		FY 1982		FY 1983		FY 1984	
ACTIVITY	1999 $$	PL96-126	1999 $$	PL-96-514	1999 $$	PL97-100	1999 $$	PL97-394	1999 $$	PL98-146
Coal Tech & Coal Prep	70,245	38,250	62,993	37,500	34,761	21,984	42,443	27,900	38,130	26,000
Adv Research & Tech Dev	103,117	56,150	97,868	58,261	88,952	56,256	54,690	35,950	67,153	45,790
Coal Liquefaction	459,677	250,306	875,855	521,400	156,197	98,784	57,200	37,600	42,383	28,900
Combustion Systems	93,384	50,850	94,909	56,500	48,296	30,544	36,815	24,200	26,691	18,200
Fuel Cells	48,666	26,500	53,754	32,000	54,494	34,464	45,714	30,050	62,475	42,600
Heat Engines	92,741	50,500	61,145	36,400	24,363	15,408	7,606	5,000	9,533	6,500
Underground Coal Gasif.	18,365	10,000	16,798	10,000	13,054	8,256	9,128	6,000	8,799	6,000
Magnetohydrodynamics	137,734	75,000	112,548	67,000	34,533	21,840	44,117	29,000	43,996	30.000
Mining R&D	126,440	68,850	83,151	49,500	22,390	14,160	0	0	0	0
Surface Coal Gasif.	212,754	115,850	277,001	164,900	83,942	53,088	59,330	39,000	52,488	35,790
Unconventional Gas Rec.	64,845	35,310	51,315	30,548	13,775	8,712	21,146	13,900	22,731	15,500
Advanced Process Tech.	11,109	6,000	6,719	4,000	6,375	4,032	7,606	5,000	7,333	5,000
Drilling & Offshore Tech.	5,509	3,000	3,981	2,370	0	0	0	0	0	0
Enhanced Oil Recovery	42,422	23,100	31,245	18,600	25,577	16,176	9,888	6,500	13,419	9,150
Oil Shale	51,788	28,200	55,514	33,048	30,283	19,152	18,636	12,250	23,685	16,150
Program Direction	22,058	12,011	21,347	12,708	22,162	14,016	0	0	0	0
Hqs Program Direction							13,691	9,000	13,199	9,000

ETC Program Direction							45,638	30,000	49,863	34,000
Prior Year Offsets							(30,632)	-20,136	(40,075)	-27,326
Appropriations Transfers							(112,118)	-73,700	(23,523)	-16,040
FE-Construction Transfer									(38,130)	-26,000
Total	1,560,764	849,877	1,906,144	1,134,735	659,156	416,872	330,898	217,514	380,149	259,214

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS
($ in thousands)

	FY 1985		FY 1986		FY 1987		FY 1988		FY 1989	
ACTIVITY	1999 $$	PL98-473	1999 $$	PL-99-190	1999 $$	PL99-500	1999 $$	PL100-202	1999 $$	PL100-446
Coal Tech & Coal Prep	49,880	35,083	46,259	33,256	51,083	37,826	54,302	41,578	61,560	48,927
Adv Research & Tech Dev	56,886	40,011	49,009	35,233	43,738	32,387	41,632	31,877	32,165	25,564
Coal Liquefaction	36,703	25,815	45,781	32,912	32,556	24,107	35,431	27,129	40,752	32,389
Combustion Systems	42,963	30,218	42,150	30,302	20,449	15,142	28,492	21,816	33,589	26,696
Fuel Cells	58,024	40,811	49,310	35,449	37,927	28,084	42,646	32,653	33,385	26,534
Heat Engines	16,987	11,948	17,828	12,817	16,403	12,146	23,437	17,945	28,727	22,832
Underground Coal Gasif.	8,179	5,753	5,895	4,238	3,201	2,370	3,627	2,777	1,725	1,371
Magnetohydrodynamics	44,042	30,977	40,130	28,850	35,788	26,500	45,711	35,000	46,553	37,000
Surface Coal Gasif.	45,512	32,011	59,828	43,011	33,296	24,655	30,030	22,993	27,123	21,557
Unconventional Gas Rec.	14,540	10,227	12,310	8,850	10,816	8,009	13,758	10,534	14,323	11,384
Advanced Process Tech.	7,690	5,409	7,995	5,748	5,112	3,785	4,473	3,425	5,286	4,201
Enhanced Oil Recovery	16,778	11,801	16,585	11,923	15,140	11,211	21,595	16,535	29,672	23,583
Oil Shale	20.972	14,751	17,571	12,632	14,811	10,967	12,413	9,504	13,249	10,530
Policy & Management	78,938	55,521	85,936	61,780	0	0	0	0	0	0
Program Direction					82,995	61,456	81,076	62,078	84,648	67,277
Plant & Capital Equip					4,389	3,250	23,809	18,230	27,366	21,750
Prior Year Offsets	(14,066)	-9,893	(25,059)	-18,015	(4,196)	-3,107	(8,104)	-6,205	(1,258)	-1,000
FE Construction	(55,728)	-39,196	(11,448)	-8,230	(2,801)	-2,074	0	0	0	0

Transfer										
Appropriations Transfer	(16,066)	-11,300	(6,656)	-4,785	(1,145)	-848	(27,288)	-20,894		
FY85/86 Appr. made in FY84		-15,000	(20,865)	-15,000						
Total	390,911	274,947	432,560	310,971	399,560	205,866	427,040	326,975	478,863	380,595
Clean Coal Technology Annual Apportionment				99,400		149,100		199,100		190,000

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS
($ in thousands)

	FY 1990		FY 1991		FY 1992		FY 1993		FY 1994	
ACTIVITY	1999 $$	PL101-121	1999 $$	PL101-512	1999 $$	PL102-154	1999 $$	PL102-381	1999 $$	PL103-138
Coal Tech & Coal Prep	70,681	58,376	65,115	55,724	58,246	51,063	47,427	42,574	50,285	46,081
Adv Research & Tech Dev	32,374	26,738	36,664	31,376	34,479	30,227	29,543	26,520	31,669	29,021
Coal Liquefaction	42,356	34,982	49,869	42,677	45,014	39,463	41,615	37,357	27,504	25,204
Combustion Systems	40,701	33,615	43,129	36,909	42,980	37,680	40,856	36,676	50,671	46,434
Fuel Cells	46,617	38,501	50,118	42,890	58,522	51,305	56,956	51,128	56,502	51,778
Heat Engines	25,692	21,219	27,595	23,615	20,742	18,184	4,824	4,330	0	0
Underground Coal Gasif.	1,000	826	923	790	0	0	0	0	0	0
Magnetohydrodynamics	49,521	40,900	46,787	40,039	45,953	40,286	33,782	30,325	5,262	4,822
Surface Coal Gasif.	28,741	23,373	17,582	15,046	12,672	11,109	12,110	10,871	17,132	15,700
Unconventional Gas Rec.	17,702	14,620	18,568	15,890	14,339	12,571	32,764	29,412	48,341	44,299
Adv Extrac Process Tech.	4,359	3,600	11,775	10,077	16,472	14,441	12,113	10,874	11,529	10,565
Enhanced Oil Recovery	33,547	27,707	37,085	31,737	42,109	36,916	51,244	46,001	70,616	64,712
Oil Shale	11,058	9,133	20,121	17,219	6,729	5,899	5,997	5,383	0	0
Program Direction	83,713	69,139	79,594	68,115	78,089	68,459	78,717	70,663	80,445	73,719
Plant & Capital Equip	14,767	12,196	18,430	15,772	11,826	10,368	5,031	4,516	4,095	3,753
FE Env Restoration	1,263	1,043	827	708	13,048	11,439	13,767	12,358	14,206	13,018
Co-Op R&D	5,681	4,692	13,890	11,887	12,389	10,861	11,013	9,886	10,445	9,572
Fuels Programs	3,230	2,668	3,451	2,953	3,492	3,061	3,413	3,064	3,262	2,989
Recissions	0	0	0	0	(9,125)	(8,000)	0	0	0	0
Prior Year Offsets	(1,974)	(1,630)		(4,674)	(1,141)	(1,000)	(15,133)	(13,585)	(11,996)	(10,993)
Total	511,030	422,062	536,061	458,750	506,834	444,332	466,038	418,353	469,969	430,674
Clean Coal Technology Annual Apportionment		554,000		390,995		415,000		0		225,000

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS
($ in thousands)

	FY 1995		FY 1996		FY 1997		FY 1998		FY 1999	
ACTIVITY	1999 $$	PL103-332	1999 $$	PL104-134	1999 $$	PL 104-208	1999 $$	PL 105-83	1999 $$	PL105-277
Adv Clean FuelsResearch	41,339	38,707	20,564	19,628	16,601	16,154	16,080	15,844	15,528	15,528
Adv Clean/Eff Power Sys	97,131	90,947	84,114	80,284	71,173	69,257	75,094	73,990	87,676	87,767
Adv Res & Tech Dev	27,212	25,480	22,372	21,353	18,105	17,618	17,841	17,579	19,939	19,939
Natural Gas Research	71,571	67,015	62,571	59,722	72,030	70,091	72,059	71,000	71,007	71,007
Fuel Cells	53,206	49819	54,967	52,464	51,503	50,117	40,810	40,210	44,200	44,200
Oil Technology	87,684	82,102	58,372	55,714	47,208	45,937	49,294	48,569	48,616	48,616
Program Direction	77,430	72,501	69,615	66,446	70,102	68,215	67,762	66,766	69,481	69,481
Plant & Capital Equip	5,375	5,033	4,196	4,005	2,055	2,000	2,570	2,532	2,600	2,600
FE Env Restoration	17,634	16,511	15,631	14,919	13,387	13,027	13,128	12,935	11,000	11,000
Coop R&D	9,745	9.125	6,595	6,295	5,241	5,100	5,927	5,840	6,836	6,836
Fuels Programs	3,227	3,022	2,815	2,687	2,249	2,188	2,205	2,173	2,173	2,173
Mining R&D	0	0	41,908	40,000	5,138	5,000	5,039	4,965	5,000	5,000
General Reduction	(902)	(845)	0	0	0	0	0	0	0	0
Prior Year Offsets	(17,513)	(16,398)	(6,809)	(6,499)	0	0	0	0	0	0
Contract Reform Reduction		(1250)								
Total	471,806	441,769	436,910	417,018	374,792	364,704	367,809	362,403	384,056	384,056
Clean Coal Technology (Annual Apportionment)		37,121		150,000		13,879	(286,000)	(100,000)	(40,000)	(40,000)

FOSSIL ENERGY ENACTED APPROPRIATIONS AND CONSTANT YEAR 1999 DOLLARS

($ in thousands)

	FY 2000	
ACTIVITY	1999 $$	PL106-113
Adv Clean Fuels Research	19,819	20,275
Adv Clean/Eff Power Sys	78,482	80,287
Adv Res & Tech Dev	22,674	23,195
Natural Gas Research	74,081	75,785
Fuel Cells	43,499	44,499
Oil Technology	55,964	57,251
Program Direction	73,782	75,479
Plant & Capital Equip	2,542	2,600
FE Env Restoration	9.775	10,000
Coop R&D	7,223	7,389
Fuels Programs	2,124	2,173
Black Liquor Gasification	13,196	13,500
Adv Metallurgical Process	4,888	5,000
Prior Year Offsets	0	0
Transfer from Biomass	(23,460)	(24,000)
Total	384,587	393,433
Clean Coal Technology (Annual Apportionment)	(142,755)	(146,038)

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Appendix

There were over 260 projects funded in the Recovery Efficiency Processes area from 1978 to 2000.

Gas Flooding	48
Thermal Methods	71
Chemical Methods	73
MEOR	39
Novel	11
Simulation	22
Total	264

A listing of these projects is available from NPTO.

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There are approximately 15 publications for project since each project typically last for 3 years and there are 4 quarterlies and an annual. Therefore, the total number of DOE publications is approximately 3,960 for the Recovery Efficiency Processes or Enhanced Oil Recovery area. Copies of the publications can be obtained by contacting NPTO's Technology Transfer Section.

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