Energy Research at DOE WAS IT WORTH IT?

Energy Efficiency and Fossil Energy Research 1978 to 2000

Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy

Board on Energy and Environmental Systems

Division on Engineering and Physical Sciences

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Importantly, the committee recognizes the contribution of Roger Bezdek, whose analytic support and keen advice were essential to the completion of its work.

Finally, the chair is acutely aware of the extraordinary efforts of the members of the committee and of the staff of the Board on Energy and Environmental Systems of the (NRC). Every member of the committee contributed to the analysis of the case studies that form the foundation of this report and to the deliberations on the report itself. The staff, led by Richard Campbell, managed a very complicated and voluminous process in accordance with the highest standards of the NRC. What the committee was able to accomplish of the ambitious agenda set by Congress is entirely due to the efforts of these persons.

The report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remains confidential to protect the integrity of the deliberative process.

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While these individuals provided constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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ENHANCED OIL RECOVERY

Program Description and History

Conventional methods of oil recovery, including primary and secondary recovery, achieve, on the average, about 35 percent recovery of the original oil in place, less if the oil is heavy or viscous. The volume of oil remaining in already-discovered reservoirs in the United States is on the order of 340 billion barrels. Conventional wisdom in the 1970s held that additional recovery would involve a physical or chemical change in the reservoir or its contained fluids to move oil that was immobile.

Common enhanced recovery methods include chemical methods (use of surfactants, alkaline-enhanced chemicals, and polymers and gels); gas flooding methods, generally using CO_2 and enriched natural gas (to develop miscibility) and flue gas and nitrogen (generally to maintain reservoir pressure); microbial enhanced oil recovery, where the action of microbes ferments hydrocarbons and produces a by-product that is useful in oil recovery; and thermal methods to reduce the viscosity of heavy oils, most commonly by injecting steam (steam flooding) or by the introduction of heat in the reservoir by burning part of the oil in a reservoir (in situ combustion).

Initial work by DOE in enhanced oil recovery was a part of field demonstration projects started by the U. S. Bureau of Mines in 1974 and taken over by DOE in 1978. Twelve of the field projects involved chemical floods, five involved carbon dioxide injection, and six were thermal/heavy oil projects. These projects were initiated after the Arab oil embargo and were conducted at a time when imports were increasing and stated national policy was to increase domestic production. Applying advanced technology to the large base of unrecovered oil in existing domestic reservoirs was an obvious strategy to enlarge domestic production. The strategy was embraced by both industry and government, as the program was cost shared.

With the exception of steam flooding, the early demonstration of enhanced oil recovery (EOR) techniques was largely uneconomic, with some, but not significant, incremental oil recovery. The most significant information coming from these early experiments with EOR was the knowledge that the geological and engineering parameters of individual fields were insufficiently known. Most reservoirs were much more geologically complex than then judged.

The DOE Enhanced Oil Recovery program was significantly redirected in FY 1979. The programs that had been basically oriented to commercialization were to be phased out and funding for the EOR demonstrations went to zero in FY 1989. Since then, the program has focused on research, although some small-scale pilot projects have been conducted and some assistance is provided to independent operators. The program is designed to involve academia, government research organizations, and industry with programs in chemical methods, gas flooding, microbial methods, heavy oil recovery, novel methods, and reservoir simulation.

Funding and Participation

The EOR demonstration programs managed by DOE from FY 1978 through FY 1989 expended of approximately $110 million, with industry cost sharing amounting to about $200 million. These are carried by DOE under its field demonstration program.

Under the multitiered pricing of oil in the late 1970s and early 1980s, oil recovered with EOR techniques qualified for an incentive price. This proved difficult to administer and led to significant legal disputes between industry and government. It is judged not to have been a major factor in calculations of DOE costs and benefits.

From 1978 through 2000, DOE funded approximately 230 projects (exclusive of the early EOR field demonstrations) in thermal, gas, chemical, and microbial EOR and sponsored the development of reservoir simulators, screening models, and databases. A total of $177.2 million (1999 dollars) has been expended, with an additional $47 million in cost sharing, for a DOE share of 79 percent (see Table F-29). Approximately equal amounts, about 25 percent each, were expended in support of programs in thermal, gas, and chemical methods; about 10 percent of the total was expended each for microbial methods and simulation work; and about 4 percent supported so-called novel methods (downhole electric heating, microwave heating, seismic wave stimulation, and wettability reversal) (OFE, 2000p).

Results

A principal accomplishment of the program in the early stages was the recognition of the critical importance of reservoir characterization in the deployment of EOR strategies. Notable R&D accomplishments include advancements in the understanding and control of CO_2 based EOR, especially development of chemicals and foams for mobility control; fundamental research on the miscibility of multicomponent systems; new technologies for thermal-based EOR; and introduction of microbial EOR.

Benefits and Costs

DOE estimates its EOR program and technologies have stimulated production of some 167 million barrels of oil equivalent move than would have been produced with industry acting alone. It credits its program with 2.8 percent of annual domestic EOR production. A net revenue value of 17.5 percent of sales revenues, equal to $3.50/bbl when domestic price is $20/bbl, was used to convert incremental production to benefits.

From 1978 through 2000 the DOE EOR program spent $177 million (1999 dollars) and attracted $47 million of cost share. In return for this investment, the program has provided $625 million (1999 dollars) in cost savings to oil producers, with a benefit/cost ratio of 3.5 to 1 (or 2.8 to 1 including the cost shared portion of the expenditure). Including incremental federal estate revenues gives a total of about $700 million Table F-29). Benefits will likely accrue in future years from the application of DOE-sponsored EOR research. Environmental benefits may accrue from the adaptation of CO_2 based EOR technology to CO_2 sequestration in geologic formations.

TABLE F-29 Benefits Matrix for the Improved Enhanced Oil Recovery[a] Program

	Realized Benefits/Costs	Options Benefits/Costs	Knowledge Benefits/Costs
Economic benefits/costs	DOE R&D costs: $177 million Industry costs: $47 million Benefits: $700 million[b] Reserve growth from existing fields and recovery of larger amounts of movable oil	Improved waterflooding and wettability	Research on understanding and control of CO_2 based enhanced oil recovery[c] Fundamental research on miscibility of multi-component systems New technologies for thermal based enhanced oil recovery Development of microbial enhanced oil recovery Research on chemical methods, gas flooding, microbial methods, heavy oil recovery, novel methods, and reservoir stimulation Knowledge of geological and engineering parameters[d] Recognition of the importance of reservoir characterization in the deployment of EOR strategies Changed view of reservoirs and fluid behavior[e]
Environmental benefits/costs	Application of chemical EOR technology to water control problems, reducing water disposal and water pollution Microbial technology used for cleanup and remediation	None	Research on CO_2 sequestration in geologic reservoirs
Security benefits/costs	Reduced oil imports	None	None

[a] Unless otherwise noted, all dollar estimates are given in constant 1999 dollars through 2000.
[b] FE contends that its program is responsible for maintaining a critical mass of technology innovation in EOR and transferring this technology, particularly to independents. A net revenue value of 17.5 percent of sales revenues, equal to $3.50/bbl when the domestic price is $20/bbl, was used to convert incremental production to benefits. Net revenues were set at 17.5 percent of sales revenues and were linked to changes in domestic crude oil prices. FE R&D was allocated 2.8 percent of annual EOR production, which equals about 20,000 BPD of additional oil production in 2000 and 167 million barrels cumulative additional oil production from 1978 to 2005. According to FE, this resulted in $625 million in industry savings and $87 million in incremental federal and state revenues for total of about $700 million. The estimates were developed using the Total Oil Recovery Information System (TORIS) and the Gas Supply Analysis Model (GSAM).
[c] Especially development of chemicals and foams for mobility control.
[d] The most significant information resulting from these early experiments with EOR was the knowledge that the geological and engineering parameters of individual fields were insufficiently known.
[e] The virtual failure of the early EOR field demonstrations in terms of direct benefits was extremely important to a changed view of reservoirs and fluid behavior. In addition, this early experience allowed redirection of the EOR program from field demonstrations to a more research focused effort so that as complex reservoirs are understood well enough for effective deployment of EOR methods, better techniques will be at hand.

Lessons Learned

The principal lesson learned from DOE's activities in EOR programs stemmed from the marginal results obtained by the early EOR field demonstration programs. The conclusion drawn was simply that reservoirs were much more geologically complex than had previously been believed. Enhanced oil recovery techniques that worked well in the laboratory were difficult to deploy effectively in complex reservoirs. This led to programs in field demonstration that would substantially enlarge the ability to characterize complex reservoirs and the important finding that as much as half of the unrecovered oil in complex reservoirs could be recovered without expensive EOR techniques, if the reservoir and its fluid behavior could be properly understood. Consequently, reserve growth from exisiting fields with the recovery of larger amounts of movable oil has become a major element in U.S. production and in the projected resource base. For example, the Department of the Interior now estimates a resource base for oil and gas such that future reserve growth exceeds future new field discovery by 3 to 1 in the case of oil. The virtual failure of the early EOR field demonstrations in terms of direct benefits was critical to a changed view of reservoirs and fluid behavior. In addition, this early experience allowed redirection of the EOR program from field demonstrations to a more research-focused effort so that as complex reservoirs are understood well enough for effective deployment of EOR methods, better techniques will be at hand.

FIELD DEMONSTRATION PROGRAM

Program Description and History

The Field Demonstration program, as the name implies, seeks to test different technologies and concepts at the field level. Such tests will result in incremental production and be classed as successful or they will fail. Field tests can also be technical successes but commercial failures.

The Field Demonstration program has had a long and varied history, reflecting changed views about how reservoirs and the fluids within them behave, the evolution of different deployable technologies, and, of course, varying oil prices.

The original Field Demonstration program was begun by the Bureau of Mines in 1974 and transferred to DOE in 1978. It was designed to test the efficacy of different EOR technologies. The conventional wisdom of the time, shared by government and industry, was that oil remaining in reservoirs after conventional primary and secondary recovery was residual or immobile oil, that is, the reservoir or the fluids within the reservoir must be either physically or chemically modified to render the oil mobile and recoverable. This was acknowledged to be an expensive process due to the cost of EOR techniques, but oil prices were historically high at the time and widely expected to be much higher.

Twelve of the original field projects tested chemical floods, five involved CO_2 injection, and six were thermal/heavy oil projects. The projects directly involved industry with substantial cost sharing. While some incremental oil was produced from some of the projects, most were uneconomic, especially those with chemical floods and to a lesser extent, those involving steam and gas injection. These early EOR field tests were to show dramatically that the geological and engineering parameters of individual fields were poorly understood. Most reservoirs, especially those containing large volumes of unrecovered oil, were much more complex geologically than had been expected. This recognition, plus the policies of the incoming administration in the early 1980s, led to a substantial reduction and redirection of the program.

In the early 1980s analyses by the Texas Bureau of Economic Geology of the 450 largest reservoirs in Texas were to show that about half of the oil remaining in existing reservoirs and classed as unrecoverable was, in fact, mobile oil and that the volume of remaining unrecovered mobile oil was directly related to complexity or heterogeneity of reservoirs (Galloway et al., 1983). That complexity was shown to be primarily related to the architecture of the reservoir, which in turn resulted from its depositional origin. Improved understanding of the geological and engineering parameters of reservoirs could lead to increased recovery of mobile oil by advanced secondary recovery techniques as well as improved recovery by enhanced recovery techniques, that without adequate understanding of the heterogeneity of a reservoir, deployment of advanced recovery technologies was likely to be ineffective. The Texas study also showed that a large universe of reservoirs could be grouped into plays based on common depositional origin and common fluid behavior. Thus, the knowledge of a fully characterized reservoir could be directly extrapolated to other reservoirs in the play.

DOE adopted the play concept, applied it nationwide, and instituted in the mid-1980s the Reservoir Life Extension Field Demonstration program, which would be called the Reservoir Class Program in the early 1990s. This was also a time of low to very low oil prices, when a large number of reservoirs in danger of premature abandonment. In the 1990s it was also clear that the domestic oil industry was being operated by a larger percentage of independent producers.

Funding and Participation

The cost of the Field Demonstration Programs, from 1978 to 1999, was $259 million (1999 dollars) plus the industry cost share of $368 million (see Table F-30). Approximately one half of the budget was spent on the initial 23 EOR field demonstrations and the other half on some 39 projects of the Reservoir Class Program (OFE, 2000q).

Results

Using its TORIS (Total Oil Recovery Information System), DOE calculates that the Field Demonstration program will result in 1291 million barrels of incremental oil production and 1736 Bcf of incremental gas production from 1996 to 2005. It also assumes that net revenues will amount to 17.5 percent of sales revenue, that 4 to 6 percent of production come from federal lands; and that state severance taxes will average 4.55 percent. These conditions applied to the calculated volume of increased incremental production give net revenues to industry of $4462 million (1999 dollars). The DOE expenditure for the program from 1978 to 2000 amounts to $259 million (1999 dollars) with an industry cost share of $368 million (1999 dollars). This yields a benefit to cost ratio of 17.2 to 1 or 7.1 to 1 if the industry cost share is included. DOE calculates $758 million (1999 dollars) from federal royalties and additional state severance taxes due to displacement of imports. In addition, improved screening models and a number of software programs have been developed and are now being used by industry and researchers.

Benefits and Costs

Based on the above, the committee assigned a benefit to DOE of $2.2 billion (see table F-30).

Lessons Learned

The basic lesson learned early on was that oil and gas reservoirs, with very few exceptions, were much more complicated that previously believed. With that recognition came the important lesson that effective deployment of any reservoir technology depends on thorough geologic characterization of the reservoir. The best recovery technology deployed into a poorly understood reservoir is ineffective, or if by chance it is effective, the operator will not know why and will not be able to repeat the success. In terms of direct economic benefits, the Reservoir Class program predicated on reservoir characterization and play or class definition was very much more successful than the original field demonstration where the tested reservoirs were not well characterized, and it is generally regarded in industry and the research community as one of DOE's most successful programs.

TABLE F-30 Benefits Matrix for the Field Demonstration Program[a]

	Realized Benefits/Costs	Options Benefits/Costs	Knowledge Benefits/Costs
Economic benefits/costs	DOE R&D cost: $259 million[b] Industry costs: $368 million Estimated benefits of $2.2 billion[c]	None	Postmortems of enhanced oil recovery and thermal recovery processes suggest directions for future applications and future research Enhanced recovery screening models and software programs for use by industry Reservoir characterization and class definition[d] Determined that the geological and engineering parameters of individual fields were poorly understood[e] Data used to predict domestic industry productivity and potential[f] Mobilized the technical expertise of domestic industry to improve efficiency and made it widely available
Environmental benefits/costs	Reduced air emissions, surface footprints, and waste volumes Reduced water production[g]	Demonstration of technologies with minimal impact in harsh and sensitive environments	Subsurface imaging and chemical treatments that could be applied to near surface or surface environmental problems
Security benefits/costs	Increased U.S. oil production	Maintenance of U.S. oil industry infrastructure and ability to increase production if required	None

[a] Unless otherwise noted, all dollar estimates are given in constant 1999 dollars through 2000.
[b] Approximately one half of the budget was spent on the initial 23 EOR field demonstrations and the other half on 39 projects of the Reservoir Class program.
[c] FE estimates using TORIS (Total Oil Recovery Information System) that the Field Demonstration program will result in 1291 million barrels of incremental oil production and 1736 Bcf of incremental gas production over the period from 1996 to 2005. It assumes that net revenues amount to 17.5 percent of sales revenue, that four to six percent of production comes from federal lands, and that state severance taxes average 4.55 percent. These conditions applied to the estimated volume of increased incremental production yield estimated net revenues to industry of $4,462 million. FE also estimates that the program will generate $758 million from federal royalties and additional state severance taxes due to displacement of imports. Based on the above, the committee assigned a benefit to DOE of $2.2 billion.
[d] In terms of direct economic benefits, the Reservoir Class program predicated on reservoir characterization and play or class definition was dramatically more successful than the original field demonstration, where the tested reservoirs were not well characterized, and it is generally regarded in industry and the research community as one of DOE's most successful programs.
[e] The program demonstrated that about half of the oil remaining in existing reservoirs classified as unrecoverable was, in fact, mobile oil and that the volume of remaining unrecovered mobile oil was directly related to the complexity or heterogeneity of reservoirs. It showed that oil and gas reservoirs, with very few exceptions, were much more complicated than previously believed. It also proved that most reservoirs, especially those containing large volumes of unrecovered oil, were much more complex geologically than expected, and that effective deployment of any reservoir technology depends on thorough geologic characterization of the reservoir.
[f] Data for evaluation of the industry capabilities are collected throughout the life of the projects, and these data can be used to predict domestic industry productivity and potential.
[g] This results from better reservoir management and better well placement attributable to improved technology.

Another important lesson learned in the program was the need to reflect changed perceptions of the nature of unrecovered oil and to adjust to wide swings in oil and gas prices.

OIL SHALE

Program Description and History

Long before DOE's creation in 1977, the tremendous potential of the Rocky Mountain oil shale deposits led to industry and government interest in researching their possible use. Every time a crude oil shortage threatened in the 20th Century, interest in oil shale would be renewed only to ebb as the threat diminished. The energy crises of the 1970s were the most recent instance of looking to oil shale to expand our energy supply base.

The strong industry interest over the years is evidenced by private sector expenditure of over $3 billion on oil shale R&D. In contrast, total federal spending is estimated at about $400 million. Since its creation in 1977, DOE has spent about $273 million ($447 million in constant 1999 dollars) on oil shale R&D. Only minor amounts have been spent since 1993, when it became clear that crude oil shale production was not close to being economic.

Several technologies are involved in using oil shale, including mining and comminution, direct use for power generation, retorting for the recovery of oil or gas from shale, the upgrading/refining of recovered oil, and processing for specialty by-products. Environmental R&D has been another significant component because recovering shale oil would create many environmental challenges. DOE has supported efforts in each of these areas, with some being emphasized more than others.

- *Mining and comminution.* Issues here related to how to mine and crush the mined shale. DOE has supported water-jet-assisted mining projects, blasting patterns for mining, and ways to control crushing of shale.
- *Power generation.* Other countries, like Estonia and Israel, have used or tried to use shale oil to generate power. From 1978 to 1982, DOE had a memorandum of understanding with Israel to develop technologies for the utilization of Israeli shale oil.
- Retorting. Shale oil can be retorted on the surface or in-situ. Surface retorting requires mining the shale and bringing it to a retort facility on the surface. In situ retorting involves various approaches to creating a retort situation within the site or below surface. DOE supported both types of retort efforts. Efforts supported included the Paraho project, which tested, with some DOD funding, the suitability of using shale oil for military fuels and the Occidental oil shale vertical modified, in situ process. DOE also supported testing of true in situ technology where no mining preparation was done, and the use of in situ techniques on Eastern oil shale, both of which were unsuccessful. The government also supported the Unocal project through a Treasury Department price guarantee for each barrel of oil produced. Before project termination in 1991, 4.7 million barrels of oil (total) were produced. The high cost of a project modification for an external carbon combustor led to termination of the Unocal project.
- *Upgrading/refining.* A critical refining issue for Western shale is the removal of nitrogen. Given the shale recovery issues, DOE has not done much in this area, although some bench-scale tests have been done on nitrogen removal.
- *Specialty by-products.* From 1978 through 1982, DOE did some research on adding high-nitrogen-content Green River shale oil to paving asphalt binder to achieve a longer-life asphalt pavement. Small contracts have been used to examine ways to extract high-value nitrogen compounds from Green River oil shale. Tests have also been done on using spent shale as a support layer for asphalt pavement, as a way of reducing spent shale disposal costs.
- *Environmental.* Almost one-third of DOE R&D funding for oil shale involved environmental studies because of the potential impacts on air quality, water quality, and soil revegetation.

Funding and Participation

DOE's funding history for oil shale is shown in Table F-31. As Table F-31 shows, more DOE funds were spent in the late 1970s and early 1980s, close on the heels of the energy crises. When the crises abated, funding was reduced until it was essentially terminated after 1993, when Congress passed a bill amendment eliminating support for