DOE/BC/14431-1 (Vol. 1)
Distribution Category UC-122

AN EVALUATION OF KNOWN REMAINING
OIL RESOURCES IN THE UNITED STATES

Project on Advanced Oil Recovery and the States

October 1994

Work Performed Under Contract DE-FG22-89BC14431

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ACKNOWLEDGMENTS

An Evaluation of the Known Remaining Oil Resource in the United States is one in a series of reports of the Project on Advanced Oil Recovery and the States, conducted by the Interstate Oil and Gas Compact Commission (IOGCC). The overall project was initiated by "seed money" grants from the States of Oklahoma and New Mexico in 1985. This report was prepared under grant number DE-FG22-89BC14431 from the U.S. Department of Energy, Bartlesville Project Office (BPO) to the IOGCC.

The analysis presented in this report is based on an updated and upgraded version of the databases and models developed by the National Petroleum Council (NPC) in 1984. The NPC models and data, as well as computer time, were made available for this study by BPO. Special acknowledgment to Mr. R. Michael Ray, Deputy Director of BPO, is extended for his valuable technical advice and guidance and to Mr. Thomas Wesson, BPO Director, for his encouragement and assistance.

Special recognition is due to those who directly performed the work of the project. ICF Resources Incorporated of Fairfax, Virginia, served as the IOGCC's principal contractor, responsible for the study design, computer modeling, analysis, interpretation, and report preparation. ICF's Project Director was Dr. Jerry P. Brashear; Mr. Khosrow Biglarbigi was the Project Manager; and the critical project staff included Mr. Hugh D. Guinn, and Mr. Donald J. Remson (engineering and computer modeling); Mr. Karl Lang, Dr. Frank Morra (Consultant), and Mr. Jeff Enright (analysis and report generation); Mr. Marc Greenberg, Ms. Sohinaz Sotoudeh, and Mr. Mike Schildkraut (editing, research, and analytical support); Mr. Alan B. Becker (Final Review); Ms. Barbara Jones (Administrative Assistant), Ms. Cheryl A. Labrecque (Senior Staff Assistant), Ms. Mary Bowers (Staff Assistant) and Ms. Barbara Gillen (word processing support).

Special recognition is also due to the members of the DOE/IOGCC Peer Review Committee; Mr. Lloyd Elkins, Dr. Alan Emanuel, Dr. Lee Gerhard, Dr. Donald Green, Dr. John D. Haun, Mr. Joseph E. King, Dr. Charles Mankin, Dr. David Martin, Dr. Donald Oltz, Dr. Fred H. Poettmann, Mr. William C. Stewart, and Dr. G. Paul Willhite.

This analysis was conceived and commissioned by W. Timothy Dowd, Executive Director of the IOGCC through June 1993. Mr. Dowd's keen interest in promoting the development of the nation's resource base has been the guiding force behind this study. To the degree that the results of this work help to improve the recovery of oil from U.S. reservoirs, Mr. Dowd's goals for the IOGCC will have been furthered. Mr. Bob Cooper, former Associate Director of the IOGCC, and Mr. Jerry Simmons (Associate Director) provided liaison and coordination among the participating organizations.

While acknowledging the assistance of all these contributors, error of fact, analysis, or interpretation are the responsibility of the IOGCC and the principal contractor's project director.

Christine Hansen
Executive Director
November 1993

EXECUTIVE SUMMARY

The Interstate Oil and Gas Compact Commission (IOGCC) has conducted a series of studies to evaluate the known, remaining oil resource in twenty-three (23) states. The primary objective of the IOGCC's effort is to examine the potential impact of an aggressive and focused program of research, development, and demonstration (RD&D) and technology transfer on future oil recovery in the United States. As part of a larger effort by the IOGCC, this report focuses on the potential economic, social, and political benefits of improved oil recovery to the nation as a whole. Individual reports for major oil producing states have been separately published. The individual state reports include California, Illinois, Kansas, Louisiana, New Mexico, Oklahoma, Texas, and Wyoming. Several major technical insights for state and Federal policymakers and regulators can be reached from this analysis.

- At the conclusion of conventional recovery operations, nearly two-thirds of the known original-oil-in-place will remain in the U.S. oil reservoirs.
- The remaining resource, 351 billion barrels, is the target for future improved oil recovery techniques. However, a significant portion of this remaining oil resource (37% to 45%) has already been abandoned. An even greater portion is in imminent danger of abandonment if cost-effective and efficient recovery techniques are not applied to the U.S. reservoirs.
- Resource abandonment will significantly impact the economic producibility of future production and reserves under improved oil recovery techniques. This is because major capital investments will be required to reacquire the leases, rebuild the infrastructure, and more importantly, drill new wells to regain access to the target resource.
- America's energy future depends strongly on the development of efficient and cost-effective oil recovery technologies, technology transfer to domestic producers, and the timely and successful application of such technologies. The urgency for such an integrated RD&D effort has never been greater because of the sharp decline in the domestic production and reserves and the accelerating level of well abandonment over the past decade.
- The effective transfer of existing technology could result in 9 to 14 billion barrels of new reserves from analyzed U.S. reservoirs at oil prices ranging from \$20/B to \$28/B, potentially increasing the country's proved reserves by 50%.
- Technology advances resulting from a focused RD&D effort could result in *additional* post-conventional reserves of 8 to 14 billion barrels, for a total of 17 to 28 billion barrels. The effective transfer of existing technology, coupled with the development and application of new technologies, could double the current proved reserves in the United States.
- Public sector revenues from future, improved oil recovery activity would total between \$32 and \$68 billion with the application of existing technology and oil prices of \$20 to

\$28 per barrel. Technology advances could increase these totals to \$54 – \$115 billion over the same price range, with roughly 60% of the total flowing to the Federal treasury.

- Potential improved oil recovery would replace imports of foreign oil, keeping between \$100 and \$670 billion in the U.S. economy. This figure is only the direct cost of imports avoided due to increased domestic activity. The true value to the country is actually much higher due to multiplier effects as this money circulates in the economy.

The analysis presented in this report is based on the databases and models available in the Tertiary Oil Recovery Information System (TORIS). TORIS is a tested and verified system maintained and operated by the Department of Energy's Bartlesville Project Office. The TORIS system was used to evaluate over 2,300 major reservoirs in a consistent manner and on an individual basis, the results of which have been aggregated to arrive at the national total.

Overall, well abandonments and more stringent environmental regulations could limit economic access to the nation's known, remaining oil resource. The high risk of near-term abandonment and the significant benefits of future application of improved oil recovery technology, clearly point to a need for more aggressive transfer of currently available technologies to domestic oil producers. Development and application of advanced oil recovery technologies could have even greater benefits to the nation. A collaborative, focused RD&D effort, integrating the resources and expertise of industry, state and local governments, and the Federal government, is clearly warranted. With effective RD&D and a program of aggressive technology transfer to widely disseminate its results, domestic oil production could be maximized. The resulting increase and improvement in production rates, employment, operator profits, state and Federal tax revenues, and energy security will benefit the nation as a whole.

I. OVERVIEW

A. THE PROBLEM: DECLINING UNITED STATES OIL PRODUCTION

Nearly two-thirds of the oil already discovered in the United States will remain in the reservoirs at the conclusion of conventional oil recovery operations. The total known original oil-in-place in the United States is estimated at 533 billion barrels (Figure I-1). Over 157 billion barrels had already been produced at the end of 1991. Nearly 25 billion barrels of proved reserves are still producible under existing economic conditions using currently available technologies. The remaining 351 billion barrels is the target for newer, more efficient recovery technologies and advances in geoscientific understanding that must be developed through an integrated public and private research effort.

Figure I-1

Known Domestic Oil Resource

The urgency for technology development and its effective application by the U.S. oil industry has never been greater. The two factors that have combined to make technology development critical are:

- Declining U.S. production and reserves. Domestic oil production has declined by 17% from 1985 through 1991 (Figure I-2A). Crude oil reserves have also decreased by 17% since 1980 (Figure I-2B). The reserve additions in recent years have not been sufficient to replace production volume. Unlike the 1968 Prudhoe Bay discovery in Alaska, the average size of new field discoveries has been relatively small and reserves per well have decreased significantly.
- Increased level of well abandonment. The United States currently produces oil from more than 600,000 wells. Over 75% of these wells are "marginal" wells producing at or near their economic limit. Once production ceases, these wells must be plugged and abandoned. A recent analysis by the Department of Energy (DOE) has concluded that 37% to 45% of the remaining oil resources had been abandoned by the end of 1991.¹ The reasons for these abandonments are threefold: (1) low oil prices, particularly as experienced from the mid-1980s; (2) maturing domestic oil resource; and (3) the absence of cost effective post-conventional recovery techniques. Well abandonments will have a significant impact on economic access to the remaining resource for application of future improved recovery techniques. It is estimated that once a lease is abandoned, it will require an oil price *increase* of \$10/B to \$25/B to reacquire the lease, rebuild the infrastructure, and drill replacement wells to regain access to the oil resource.² Such an economic burden will not likely be justified by the incremental oil revenues from future improved recovery techniques.

The future of U.S. oil production and reserves, and the nation's energy security, depends strongly on the development and application of cost-effective and efficient technology. In the past, technology advances have made substantial contributions to U.S. oil production. The development of new exploration techniques, secondary recovery technology, and offshore drilling technology have acted to reverse past

¹ "Abandonment Rate of the Known Domestic Oil Resource", U.S. Department of Energy, Bartlesville Project Office, Bartlesville, OK (June 1990).

² Brashear, J.P. et al "Effect of Well Abandonments on EOR Potential," JPT, December 1991.

Figure I-2

United States Production and Reserves

A) U.S. Crude Oil Production (1980 - 1991)

B) U.S. Crude Oil Reserves (1960 - 1991)

production declines and allowed the United States to maintain and increase its producible oil and gas resources. The United States has also pioneered much of the development of enhanced oil recovery technology. The opportunity exists for a program of RD&D combined with an integrated program of technology transfer to all sectors of the U.S. petroleum community, to arrest the decline in production and maximize recovery of the nation's resource.

B. THE OPPORTUNITY: OIL RECOVERY THROUGH ADVANCED TECHNOLOGY

The remaining oil resource constitutes a huge target for future recovery operations. The 351 billion barrels of known unrecovered oil in the United States is of two types: unrecovered mobile oil and immobile oil. Even though mobile oil is displaceable by water, it has been uncontacted or bypassed during conventional primary production or water flooding and thus remains unrecovered. Immobile oil is trapped in the reservoir pores by viscous and capillary forces and cannot be displaced by water.

The estimated unrecovered mobile oil (UMO) resource in the U.S. is 113 billion barrels. This oil is an important target for future advanced recovery efforts. Several improved primary and secondary recovery processes (i.e., infill drilling, profile modification, and polymer flooding), collectively referred to as advanced secondary recovery (ASR), could be used in innovative ways to produce a substantial portion of this resource. These processes are relatively low in cost and could increase production levels quickly. These techniques have already been used by some operators in selected reservoirs, but continued research and aggressive technology transfer are critically needed to improve, streamline, and adapt these techniques to site-specific reservoir conditions and broaden their applications.

The 238 billion barrels of *immobile* oil resource in the United States is the target for a number of other recovery techniques. Miscible, chemical, and thermal recovery processes directed at producing immobile oil are referred to as enhanced oil recovery (EOR). While these processes generally require larger investments and higher operating costs than conventional recovery processes, they are capable of producing substantial volumes of incremental oil with substantial economic benefits. Further advances in EOR technology are foreseeable if a focused, research-intensive approach is adopted to make process improvements ready for field application.

Technology Assessment Method

The benefits of RD&D in oil recovery technology assessed in this report are based on the models and databases available through the Tertiary Oil Recovery Information System (TORIS). The TORIS methodology and analytical tools were originally developed by the National Petroleum Council (NPC)³ for its 1984 evaluation of nationwide EOR potential. DOE has since maintained and updated the system through its Bartlesville Project Office (BPO).⁴ DOE has also upgraded the capability of the system to evaluate the nation's unrecovered mobile oil through ASR techniques. In this report, the future potential of EOR and ASR techniques are examined with the following key assumptions and considerations:

- A total of 2,307 reservoirs in 23 states, accounting for 344 billion barrels of original oil-in-place, were individually analyzed for their EOR and ASR potential.
- Two levels of technology are considered: (1) implemented technology -- defined as the application of currently available post-conventional techniques; and (2) advanced technology -- defined as the improvements in process performance and applicability which are likely to occur over the next decade as the result of ongoing RD&D efforts.
- For each technology level, benefits are evaluated at several oil prices ranging from \$16/B to \$36/B (1991 dollars).
- All economic analyses reflect the current Federal tax structure and the specific oil production and income tax situations in each of the 23 analyzed states. The fiscal year (FY) 1991 Federal EOR tax credit, as well as EOR and ASR tax incentives in states where such incentives exist, are included in this analysis.
- The results presented in this report reflect only the benefits and reserve potential associated with the 2,307 analyzed reservoirs (64% of total known U.S. OOIP as shown in Figure I-3). No attempt is made to extrapolate the results to the remaining resource not in the TORIS database.
- All recovery potential evaluated in this report are for future new projects only, and they do not include reserves from existing enhanced oil recovery projects. However, the expansions to the existing projects, if technically and economically feasible, are evaluated as part of future new projects in this report.

This report discusses the aggregated results for the nation as a whole, while the results for each of the 23 analyzed states are summarized in the appendices volume. Separate reports have been prepared

³ National Petroleum Council, *Enhanced Oil Recovery*, Washington, DC, 1984.

⁴ *Producing Unrecovered Mobile Oil: Evaluation of Potential Economically Recoverable Reserves in Texas, Oklahoma, and New Mexico*, DOE, May 1990.

Figure I-3

United States Oil Resource Data Coverage of EOR and ASR Analyses

Source: BPO TORIS, 1992
EIA, 1992
API/AGA, 1980

for those states with significant future reserve potential: California (Volume II), Illinois (Volume III), Kansas (Volume IV), Louisiana (Volume V), New Mexico (Volume VI), Oklahoma (Volume VII), Texas (Volume VIII) and Wyoming (Volume IX).

C. BENEFITS DERIVED FROM IMPROVED OIL RECOVERY

Potential incremental reserve volumes and resulting direct state and local revenues that could be generated through improved oil recovery (EOR and ASR) techniques under both the implemented and advanced technology cases are shown in Figure I-4A. Implemented technology, if more widely applied, could add between 7 and 15 billion barrels of incremental reserves across the oil price range. Advanced technology applied to the same resource base could stimulate an additional 5 to 15 billion barrels of incremental resources for a total of 12 to 30 billion barrels beyond currently proven reserves. In effect, improvements in process performance and application could double the reserves possible under implemented technology conditions and potentially replace current U.S. proved reserves at moderate price levels. This clearly provides a major justification for a focused RD&D and technology transfer program.

The potential for expanded application of EOR techniques using implemented technology is limited if prices remain around \$20 per barrel; incremental EOR recovery at this price would total about 3 billion barrels. However, implemented technology EOR could add almost twice this amount of reserves at a higher oil price of \$28/B. At this oil price, advances in EOR technology could stimulate an additional 10 billion barrels of incremental reserves, thus, generating a total of 16 billion barrels of incremental recovery under the two levels of technology for the analyzed reservoirs. This could increase the nation's current proved reserves by nearly two-thirds.

Reserve additions attributed to ASR techniques are also substantial but are less sensitive to oil price changes than EOR. Over 6 billion barrels of ASR reserves could be added in the implemented technology case at an oil price of \$20/B, growing only slightly to 8 billion as oil prices increase to \$36/B. Research on process improvements, specifically improved polymer flooding and profile modification combined with geologically targeted infill drilling, could increase ASR potential by 50% to 70%. With advances in technology, incremental ASR reserve additions could total 4 to 5 billion barrels more than implemented technology over the price range analyzed, for a total of 10 to 13 billion barrels of potential ASR reserves.

Future advanced oil recovery activities will generate revenues for the various oil producing states and the Federal treasury through increased production taxes and oil industry-related sales and income taxes. The revenue estimates in this study consider only direct revenues from recovery activities in the analyzed reservoirs and exclude any additional indirect benefits from multiplier or "ripple" effects within the state or national economy. Under implemented technology at \$20/B, improved oil recovery projects could directly generate \$32 billion in total public sector tax revenues. At the same oil price, advanced technology could generate an additional \$21 billion, for a total of \$53 billion in public sector revenues (Figure I-4B). At an oil price of \$28/B, application of currently available EOR and ASR technology could contribute \$68 billion to public treasuries while the application of advanced methods could increase these revenues by an additional \$47 billion to a total of \$115 billion.

Increased domestic production from EOR and ASR could offset oil imports, a result which would reduce the trade deficit, and increase economic activity. The value of the oil produced, the product of reserves and their effective oil price, is a simple measure of their value in reducing imports. As shown in Table I-1, this figure could total between \$100 billion and \$320 billion under the implemented technology scenario, over the \$20 to \$28/B range. Advanced technology could further decrease imports by an *additional* \$65 billion to \$350 billion. The additional value of domestically produced EOR and ASR generates significant direct economic activity as capital spending, profits, royalties, and taxes are circulated through the U.S. economy rather than exported to buy foreign oil. To the degree multipliers increase the direct benefit estimated, EOR and ASR production could stimulate over \$1 trillion in future benefits to the U.S. economy.

A Strategic RD&D Approach

Given the substantial benefits of technology development and above all its urgency, it is imperative that a strategic approach be taken to efficiently and effectively utilize available and limited resources. The recent approach by DOE to implement its Oil Program Plan relies on a method of categorizing future EOR and ASR potential in order to prioritize its RD&D effort.

It is important to note that recovery potential is not uniformly distributed over the analyzed reservoirs. In fact, a significant portion of future EOR and ASR may be found in a few key types of reservoirs.

Figure I-4

Potential Impact of RD&D and Technology Transfer

A) Additions to Current Reserves

B) Incremental Direct Public Sector Revenues

Table I-1

Summary of Benefits from Technology Advances in EOR and ASR

Oil Price and Technology Level	Potential Reserves (Billion Barrels)	Total Public Sector Revenues	Incremental State and Local Revenues (\$ Billions)	Incremental Imports Avoided** (\$ Billions)	Increased Federal Revenues (\$ Billions)
At \$16/B					
Implemented Technology	6.9	20.1	6.9	99.3	13.2
Advanced Technology*	<u>5.3</u>	<u>10.7</u>	<u>4.9</u>	<u>65.7</u>	<u>5.8</u>
Total	12.2	30.8	11.8	165.0	19.0
At \$20/B					
Implemented Technology	9.4	32.5	11.6	162.3	20.9
Advanced Technology*	<u>8.0</u>	<u>21.0</u>	<u>10.4</u>	<u>132.0</u>	<u>10.6</u>
Total	17.4	53.5	22.0	295.2	31.5
At \$24/B					
Implemented Technology	12.1	51.2	20.7	241.6	30.5
Advanced Technology*	<u>11.3</u>	<u>31.2</u>	<u>14.7</u>	<u>240.9</u>	<u>16.5</u>
Total	23.4	82.4	35.4	482.5	47.0
At \$28/B					
Implemented Technology	13.6	67.7	26.6	320.7	41.1
Advanced Technology*	<u>14.1</u>	<u>46.8</u>	<u>24.3</u>	<u>350.5</u>	<u>22.5</u>
Total	27.7	114.5	50.9	671.2	63.6
At \$32/B					
Implemented Technology	14.5	89.7	32.4	392.4	57.3
Advanced Technology*	<u>14.3</u>	<u>72.9</u>	<u>30.2</u>	<u>403.8</u>	<u>42.7</u>
Total	28.8	162.6	62.6	796.2	100.0
At \$36/B					
Implemented Technology	15.4	111.1	38.3	466.4	72.8
Advanced Technology*	<u>15.1</u>	<u>95.3</u>	<u>36.9</u>	<u>484.2</u>	<u>58.4</u>
Total	30.5	206.4	75.2	950.6	131.2

*Advanced is incremental over implemented technology.

**Imports Avoided = Reserves times effective wellhead price; to the extent that 1 barrel of domestic oil replaces 1 barrel of imported oil, imports avoided estimates the reduction in foreign trade deficit.

Figure I-5

Incremental Recovery Potential for the Top Ten Geologic Classes* (\$32/B Oil Price, Advanced Technology)

* TORIS Reservoirs only

The results of the DOE prioritization analysis indicate that over 75% of the known remaining oil resource and nearly 82% of post-conventional (post-primary and post-secondary) recovery potential is concentrated in only eight geologic classes (Figure I-5). Because the reservoirs in each class have similar geologic character and thus similar production limitations and barriers, RD&D activities focused on critical uncertainties limiting the producibility in each of these key classes is expected to yield the largest benefit at the lowest possible cost. The DOE has already begun its RD&D effort in two grouping of reservoirs by sponsoring cost-share projects with industry. The two classes are (1) fluvial dominated deltaic reservoirs, and (2) shallow shelf (open and restricted) carbonate reservoirs. The DOE is currently preparing to undertake RD&D work in a third class of reservoirs, slope-basin of basin clastic reservoirs.

D. CONCLUSIONS

The development, testing, and wide-scale application of currently available improved oil recovery technologies could stimulate incremental reserves ranging from 7 billion to 12 billion barrels from the nation's largest, most mature reservoirs at oil prices of \$16/B to \$24/B. With the technology advances resulting from focused RD&D, an additional 15 billion barrels could be produced from analyzed reservoirs using EOR and ASR techniques, more than doubling current U.S. proven reserves. Even with the successful development and application of these technologies, however, 132 billion barrels of immobile oil would still remain in the analyzed reservoirs as a long-term target for future advances in EOR, and 57 billion barrels of mobile oil would remain as a long-term target for future advances in ASR processes (Figure I-6). While this target is substantial, it unfortunately will not remain a target indefinitely. Well abandonments have already limited economic access to a significant portion of the U.S. resource base. The timely development and application of new recovery technology is crucial to maintaining economic access to the remaining domestic oil resource.

The results of this analysis have important policy implications. Domestic oil production generates significant direct revenues to the producing state and to the Federal government and substantial additional indirect benefits to the state and national economies. In addition to stimulating reserves, production, and economic activity, the application of improved oil technology would enhance the nation's energy security. However, integrated efforts and initiatives are needed to achieve these goals. These efforts should include:

- Collaborative RD&D;
- Aggressive technology transfer; and
- Appropriate tax and regulatory policies at state and Federal levels.

A collaborative RD&D effort between the oil industry, universities, state and local governments, and the Federal government focused on improving advanced oil recovery technology and its application in key geologic settings would benefit operators, the producing states, and the entire nation. With sound planning and clear, attainable goals, state policies can be effectively integrated with Federal and private programs to dramatically increase production to the benefit of the nation's treasuries, economies, and citizens. State and Federal tax incentives can be instituted, or where already in place could be modified to improve their effectiveness, in order to help domestic EOR/ASR projects compete with foreign investment opportunities. In addition, regulatory policy makers could design regulations which reflect both

the true risks to health, safety and the environment and the economic risk of resource loss through abandonment.

Figure I-6

II. BACKGROUND AND OBJECTIVES

A. DECLINING PRODUCTION AND RESERVES IN THE UNITED STATES

The oil industry in the United States is in the midst of a prolonged period of declining production and proved reserves (Figure II-1A). Annual crude oil production in the United States peaked at over 3.5 billion barrels in 1970. Over the next six years, low oil prices led to a decline of over 15% to under 3 billion barrels in 1976. As oil price and demand began to increase in the mid-to late 1970s, U.S. production levels rose, reaching nearly 3.2 billion barrels in 1978. The oil industry boom of the early 1980s led to further increases in production; despite falling prices, annual production increased by nearly 146,000 barrels between 1981 and 1985. The price shock of 1986, however, caused a production decline that lasted through 1990. In 1991, U.S. crude oil production recovered slightly to 2.7 billion barrels, an increase of less than 1% over the previous year. The 1990-1991 level of production represents the lowest production performance in the U.S. since 1962.

The 25 billion barrels of proved reserves in 1991 is the lowest level of reserves in the U.S. since the late 1940s. U.S. reserves have been in a general period of decline (with a few exceptions) since the mid-1960s (Figure II-1B). In 1970, however, reserve levels increased by over 30% when estimates from the 1968 Prudhoe Bay discovery in Alaska were included in the booked reserve totals. During the 1970s, reserves declined by nearly 12 billion barrels and reached 27 billion barrels in 1979. In 1980, reserves increased by nearly 3 billion barrels; a large portion of this increase, however, is attributable to a change in accounting methodology as the U.S. Energy Information Administration assumed the reserves reporting duties formerly conducted by the American Petroleum Institute.

Despite these production and reserves trends, a significant portion of the nation's original oil-in-place (OOIP) is still in the ground; nearly two-thirds of the 533 billion barrels of OOIP will remain unrecovered after conventional operations end (Figure II-2). This 351 billion barrel remaining resource can be divided into two segments -- immobile oil (oil not contacted by conventional primary and secondary recovery techniques due to viscous and capillary forces in the reservoir) and mobile oil (oil areally or vertically bypassed by conventional primary and secondary recovery techniques).

The nearly 113 billion barrels of unrecovered mobile oil (UMO) is the target for a number of advanced recovery processes -- polymer flooding, profile modification, and infill drilling -- collectively

Figure II-1

A) U.S. Crude Oil Production (1960 - 1991)

Figure II-1A. Total US Prod v. Price (1960-1991)

USPROD

B) U.S. Crude Oil Reserves (1960 - 1991)

Figure II-1B. Total US Res v. Price (1960-1991)

USRES

Figure II-2

U.S. Oil Resource

referred to as advanced secondary recovery (ASR). Over 238 billion barrels of immobile oil remains as a target for a number of tertiary extraction techniques -- gas miscible, chemical, and thermal processes -- known as enhanced oil recovery (EOR). A brief overview of the EOR and ASR recovery techniques is presented in Volume X, Appendix A. Recovery operations directed at each of these resources could play a critical role in sustaining U.S. oil production levels and reducing the nation's growing dependence on imported oil.

A maturing resource combined with low prices and tough environmental regulations is causing an increase in well abandonments. As marginally economic wells are shut in and abandoned, *economic* access to the portion of the resource contacted by these wells is lost forever. As of 1991, 35% to 45% of the nation's remaining oil-in-place (ROIP) had been abandoned (Figure II-3). If oil prices remain in the \$16/B to \$20/B range, as much as 85% of the ROIP could be abandoned by the year 2020. Improved recovery technologies (EOR and ASR) to contact and produce this resource need to be quickly developed and efficiently transferred to operators in the field before access to this huge remaining resource disappears.

Figure II-3

Cumulative Abandonment of Remaining Oil-in-Place at Various Oil Prices

B. OVERVIEW OF IMPROVED OIL RECOVERY METHODS

The oil remaining after conventional primary and secondary recovery lies in two defined regions within each reservoir: the swept and the unswept zones. In the swept zone of the reservoir, conventional production and waterflooding operations have typically recovered a significant portion of the original concentration of oil. The oil remaining in this water-swept zone is trapped in the reservoir pore spaces or on the surface of the pores by capillary and surface tension forces. Additional flooding with water can produce very little of this immobile oil; the swept zone is at the "waterflood residual" level of oil saturation.

In the unswept zone of the reservoir, conventional recovery processes have not swept the pore space, and the mobile oil saturation can range from low to high depending upon the efficiency of the primary recovery mechanism (e.g., high saturations for pressure depletion or lower saturations for natural

water drive). The objective of many infill drilling programs, improved waterflooding projects (profile modification), and other reservoir management techniques is to contact and produce unswept zones.

1. Enhanced Oil Recovery

Proven enhanced recovery processes designed to displace the immobile oil target are classified into three categories: gas-miscible, chemical, and thermal. EOR activities have played a significant and growing role in U.S. production over the last decade (Figure II-4A). In 1980, 320 million barrels of crude oil production (nearly 4% of total U.S. production) was attributable to EOR projects. Over 76% of that total was produced by thermal EOR processes. Most of the remainder was produced by gas miscible processes. In 1988, nearly 226 million barrels were produced by EOR projects (75% from thermal EOR, 21% from miscible EOR, and 4% from chemical EOR). By 1992, EOR projects accounted for nearly 278 million barrels of production, 10% of total U.S. production. While thermal EOR processes accounted for over 60% of EOR production, miscible processes are becoming increasingly important and wide-spread, accounting for nearly all of the remaining 40% of EOR production.

Even as production attributable to EOR increased during the late 1980s, the number of active domestic EOR projects was decreasing (Figure II-4B). From 1980 to 1986, the number of active domestic EOR projects increased from 226 to 546. Eighty-six additional thermal EOR projects, 70 additional miscible EOR projects, and 164 additional chemical EOR projects were implemented during this time period. The price shock of 1986 and the resulting industry downturn led to a decrease in the number of EOR projects being implemented in U.S. reservoirs. The total number of projects in 1992 was 248, less than half the number of active projects in 1986. Chemical EOR projects decreased by 180 projects, dropping to 26 in 1992. Thermal EOR projects also saw a sharp decrease with 70 fewer active projects (from the 1986 high) in 1992. Relatively speaking, miscible EOR active projects counts suffered only a minor setback, falling from 104 in 1986 to 89 in 1992. While project counts have decreased, the production associated with these projects has increased, reflecting the economics facing the industry and advancements in efficiency and technology, and the time delay in incremental oil production that is inherent in these projects. Only the most productive projects in the most promising producing areas are economic at current oil prices.

Figure II-4

U.S. EOR Project Activity

A) U.S. EOR Production (1980 - 1992)

B) U.S. EOR Projects (1980 - 1992)

2. Advanced Secondary Recovery

Mobile oil remains in the reservoir after conventional recovery for a variety of reasons. Foremost of these is reservoir heterogeneity, the complex variation of rock properties among zones in the producing interval. Reservoirs may consist of a large number of individual compartments, reflecting internal heterogeneity. These compartments are formed by depositional processes that originally formed the reservoir, or by diagenesis or tectonic activity that later altered the rock bodies. Exceedingly complex reservoirs may have compartments formed by all of these processes. At a given well spacing, some compartments containing oil are not in pressure or fluid communication with existing producing wells. At wide well spacings, much of the rock volume in a heterogeneous reservoir will not be contacted by existing wells, leaving large volumes of oil at or near original pressure and saturation. These compartments provide a major target for infill drilling and future recovery operations conducted at closer well spacings.

Mobile oil also remains in reservoir compartments that have been contacted, but inefficiently swept by secondary recovery methods that utilize existing well configurations. At wide well spacings, significant volumes of oil are areally bypassed due to small-scale variations in reservoir continuity, to the higher viscosity of oil than injected water, and to permeability variations within the reservoir. The effectiveness of water injection is further limited by vertical layering in the reservoir. Water preferentially enters the more permeable layers of the reservoir, leaving the less permeable rock layers unswept at relatively high remaining oil saturations.

Several geologic factors influence the volume, distribution, and potential future production of unrecovered mobile oil (UMO). A major factor commonly influencing recovery potential is reservoir genesis, or the type of system that originally deposited the reservoir rock. Internal reservoir architecture is profoundly affected by the depositional system of the initial reservoir sediment, which controls the distribution of different types of rock "packages," and by the pore structure that plays host to later diagenetic rock and fluid alterations. Other important geologic factors include trap style and source rocks. Reservoirs that have common depositional histories may have very similar internal reservoir architecture, but will be modified by post-depositional diagenesis. That modification will vary from basin to basin depending on geohistory.

Recovery of remaining mobile and immobile oil from known fields is a highly cost effective method for increasing oil production and reserves. Over 51% of reserve additions in the United States since 1979 have come from the intensive development of older fields. A large portion of these new reserves have resulted from improved primary and secondary recovery methods, including implementation of waterflooding and pressure maintenance programs, drilling of additional wells to improve reservoir contact, and selective recompletion of existing wells to improve performance. Several distinct methods for producing UMO have emerged: infill drilling to tap uncontacted reservoir compartments, recompletion of production and injection wells to contact and sweep previously bypassed portions of the reservoir, polymer flooding to overcome unfavorable waterflood injection fluid characteristics, and profile modification to reduce the permeability contrast between reservoir layers. These techniques are all tested and proven methods for producing mobile oil remaining in the reservoir.

The effectiveness of infill drilling has been demonstrated in many U.S. reservoirs. Several publications have also discussed the large potential of infill drilling in specific reservoir settings.¹ In some cases, infill drilling to close spacing can double the reservoir volume effectively contacted at conventional spacing, if economics will support the cost of the relatively large number of wells required. The potential benefits of geologically targeted infill drilling have been assessed by several studies.^{2,3,4} The process has been evaluated in detail by the Bureau of Economic Geology (BEG) at the University of Texas at Austin. The evaluation in Dune Field⁵ in Texas indicates the substantial recovery potential and economic enhancement possible through targeted drilling.

¹ Gould, et al., "Infill Drilling for Incremental Recovery," *Journal of Petroleum Technology*, March 1989.

² ICF Resources Incorporated and the Bureau of Economic Geology, University of Texas at Austin, *Producing Unrecovered Mobile Oil: Evaluation of Potential Economically Recoverable Reserves in Texas, Oklahoma, and New Mexico*, prepared for: U.S. Dept. of Energy/Office of Planning and Environment/Office of Fossil Energy and Bartlesville Project Office, 1989.

³ Fisher, W.L., "Can the U.S. Oil and Gas Resource Base Support Sustained Production?" *Science*, Volume 236, No. 4809, 26 June 1987, 1631-1636.

⁴ Tyler, et al., *Oil Accumulations, Production Characteristics, and Target for Additional Recovery in Major Oil Reservoirs in Texas*, the Bureau of Economic Geology, The University of Texas at Austin, Geological Circular 84-2, 1984.

⁵ Bebout, et al., *Characterization of the Grayburg Reservoir, University Lands Dune Field, Crane County, Texas*, the University of Texas at Austin, Bureau of Economic Geology, Report of Investigations, No. 168, 1987.

Taken alone, infill drilling, polymer flooding, and profile modification are effective processes for producing mobile oil; they are often even more effective when applied in combination, which allows the processes to complement one another. For example, polymer injection and profile modification can be used to increase the waterflood sweep efficiency not only in previously contacted compartments, but also in compartments newly contacted by infill drilling. These synergies maximize the cost-effectiveness of mobile oil recovery and encourage the coordinated, multiple application of techniques in selected reservoir settings.

It is also important to note that many large EOR projects involve a certain degree of infill drilling, recompletions and redesign of injection/production patterns. This means that at least a portion of the incremental oil production response attributed to an EOR project is likely to be due to mobile oil recovery. While this synergy was not explicitly modeled in this analysis, it is evident that in actual practice a degree of ASR is present in most EOR applications.

C. OBJECTIVES OF THE PRESENT STUDY

The present study analyzes the incremental reserves, public sector revenues, and nationwide economic activity that could result from the implementation of the improved EOR and ASR techniques described above. The potentials for EOR and ASR production are evaluated separately, and each is considered for two technology levels: *implemented technology*, which assesses recovery potential given the nationwide application of currently available technology, and *advanced technology*, which assesses the impact of the nationwide application of potential technological advances. Comparison of the results of these two evaluations provides the basis for assessing the benefits of improved technology provided by R&D. To achieve the nationwide application, and therefore receive the maximum benefits of both levels of technology assessed in this report, it is critical that the United States work to: (1) effectively transfer to operators currently available technology (implemented technology), and (2) develop an R&D program to improve recovery methods (advanced technology) and subsequently transfer those methods to a broad audience. All of the analyses are conducted over a range of crude oil prices from \$16 to \$36 per barrel (in constant 1991 dollars). This price range encompasses the long-term prices likely to prevail over approximately the next 30 years.

Over 2,300 reservoirs accounting for 344 billion barrels of original oil-in-place (64.5% of total known original oil-in-place in the U.S.) were included in this analysis. These reservoirs contain 220

billion barrels of remaining oil resource (Figure II-5). The 70 billion barrels of UMO is the target for application of ASR processes and 150 billion barrels of remaining immobile oil is the target for application of EOR processes. To achieve the required level of application, and therefore receive the maximum benefits of both levels of technology assessed in this report, it is critical that state and local governments, the Federal government, and the oil industry work collaboratively to: (1) effectively transfer to operators currently available technology (implemented technology), and (2) develop a focused R&D program to improve recovery methods (advanced technology) and subsequently transfer those methods to a broad public-private sector audience. The results of this study will provide valuable insights for state and Federal policymakers in their efforts to maximize domestic production and improve the nation's energy security.

Figure II-5

III. APPROACH TO THE ANALYSIS

A. INTRODUCTION

This analysis was performed using the Department of Energy's Tertiary Oil Recovery Information System (TORIS) developed for the 1984 National Petroleum Council (NPC) analysis of the nation's enhanced oil recovery (EOR) potential.¹ Although TORIS was originally designed to evaluate EOR potential only, the system's capabilities have since been expanded to incorporate evaluations of the unrecovered mobile oil (UMO) resource, the target for advanced secondary recovery (ASR). The upgraded TORIS system assessed the recovery potential of immobile oil and UMO in the United States. The following sections in this chapter will briefly discuss the:

- Development of TORIS;
- Enhancement of TORIS to evaluate the UMO resource;
- Scope of the current analysis;
- Adaptations to TORIS for this analysis;
- Estimation of benefits, costs, and economic impacts; and
- Limitations of the analytical approach.

B. GENERAL METHODOLOGY: THE NPC BASIS

In March 1982, the U.S. Secretary of Energy requested that the NPC prepare a report on the nationwide potential and the economics of incremental EOR. The NPC is the official petroleum industry advisory committee to the Secretary. Members of NPC, who are appointed by the Secretary, represent all segments of petroleum interest, such as production, refining, marketing, and environmental, and include many chief executive officers. The NPC is supported entirely by the voluntary contributions of its members.

In response to the Secretary's request, the NPC mounted a two-year effort that consumed more than 50 professional man-years and nearly \$7 million of in-kind services. EOR experts from industry (majors, independents, service companies and consulting firms), universities, government, and private, non-profit organizations participated. The NPC EOR study committee utilized and built upon data bases

¹ National Petroleum Council, *Enhanced Oil Recovery*, Washington, DC, 1984.

of individual reservoir characteristics and computer models that were under development by the U.S. Department of Energy's (DOE), Office of Fossil Energy. After augmentation, adaptation, and validation, the data bases and models were remanded to the DOE's Bartlesville Project Office (BPO) for maintenance, updating, and subsequent application. These data bases and models are components of a larger system, the Tertiary Oil Recovery Information System (TORIS).

By the agreement of the Assistant Secretary for Fossil Energy, the present study enjoys access to TORIS and the assistance of BPO, although its participation is limited strictly to providing the data base, models, and assistance for the technical analysis. The BPO and DOE neither contribute to nor endorse the study design or the interpretations presented in this report. The approach used by the NPC and in the present study to evaluate the EOR resource consists of the major phases listed below.

1. Reservoir Data Compilation. Detailed data describing the properties of the individual, significant oil reservoirs are compiled. Numerous public and private sources of information are consulted to complete and validate the reservoir data base. The principal elements of the TORIS data base are displayed in Table III-1. Representatives of the operating companies review the data elements of each reservoir at least three times for consistency and accuracy; automated validity checks are performed on the entire data base.
2. Resource Screening Models. Each reservoir is subjected to a screening process designed to identify the technical applicability of the respective EOR processes under what the NPC defined as "implemented", or currently available, technology. The specific criteria applied to screen each EOR process are shown in Table III-2. In addition, the reservoirs are screened under what the NPC defined as "advanced" technology, available through concerted research and development. Table III-3 displays the technical criteria for "advanced" EOR technology.
3. Process Performance Models. Each reservoir that satisfies the technical criteria is then analyzed by a detailed process performance model at each level of technical applicability. The models for each process have been previously reviewed in detail and calibrated to actual field results. NPC study committees review and test this calibration. The models are reservoir-specific and, therefore, estimate incremental oil production from EOR as a function of reservoir properties and process design for each reservoir independently. Incremental production is that which is recovered in excess of production by conventional primary and secondary techniques at current field conditions.
4. Economic Evaluation. Each reservoir is then evaluated for its economic feasibility by estimating the income attributable to the incremental EOR production and the investment, operating costs, and taxes required to support the implementation of the process as designed and installed in the field. Detailed costing algorithms reflect EOR design (both "implemented" and "advanced"), reservoir depth, region, and other factors. The energy component of each cost element is adjusted to reflect the oil price being analyzed. A

Table III-1

Key Elements in the Current TORIS* Reservoir Data Base

- Original Volumetrics
 - Original Oil-in-Place
 - Reservoir area
 - Net thickness
 - Porosity
 - Initial water saturation
 - Initial oil saturation
 - Initial formation volume factor
- Current Volumetrics
 - Current oil saturation (swept zone)
 - Current formation volume factor
- Fluid Data
 - Oil gravity and viscosity
 - Connate water viscosity
 - Connate water salinity
 - Initial GOR
 - Current GOR
 - Injection water salinity
 - Crude oil fractions & properties (being added)
- Geologic Variables
 - Lithology
 - Depth
 - Temperature
 - Original and current pressure
 - Permeability
 - Permeability variation index
 - Clay content
 - Gross thickness
 - Dip angle
 - Geologic age code
 - Presence of gas cap, faults, shale breaks
 - Geologic play, depositional system, trap type
 - Areal and vertical heterogeneity descriptors
 - Pay continuity (estimated)
- Development & Performance Data
 - Recovery efficiency
 - Cumulative production
 - Annual production
 - Current injection rate
 - Cumulative volume of injectant by type
 - Well spacing
 - Number of producing & injecting wells
 - Water cut

*Tertiary Oil Recovery Information System, maintained and operated by the Bartlesville Project Office of the U.S. Department of Energy

Table III-2

Screening Criteria for EOR Candidates-Implemented Technology Case

Screening Parameters*	Units	Chemical Flooding		Miscible Flooding	Thermal Recovery	
		Surfactant	Alkaline	(Carbon Dioxide)	Steam	In-Situ Combustion
Oil Gravity	°API	---	<30	≥25	10 to 34	10 to 35
In-situ Oil Viscosity (μ)	cp	<40	<90	---	≤15,000	≤5,000
Depth	Feet	---	---	---	≤3,000	≤11,500
Pay Zone Thickness (h)	Feet	---	---	---	≥20	≥20
Reservoir Temperature (TR)	°F	<200	<200	---	---	---
Porosity (ϕ)	Fraction	---	---	---	≥0.20***	≥0.20***
Permeability Average (k)	md	>40	>20	---	250	35
Transmissibility (kh/ μ)	md-ft/cp	---	---	---	≥5	≥5
Reservoir Pressure (PR)	psi	---	---	≥MMP**	≤1,500	≤2,000
Minimum Oil Content at Start of Process ($S_o X \phi$)	Fraction	---	---	---	≥0.10	≥0.08
Salinity of Formation Brine (TDS)	ppm	<100,000	<100,000	---	---	---
Rock Type	---	Sandstone	Sandstone	Sandstone or Carbonate	Sandstone or Carbonate	Sandstone or Carbonate

* Other criteria of a geological and depositional nature were also considered. Generally, reservoirs with extensive faulting, lateral discontinuities, or overlying gas caps are not prime candidates for field-wide EOR application. These factors were considered during the manual screening step when they could be identified.

** MMP denotes minimum miscibility pressure, which depends on temperature and crude oil composition.

*** Ignored if oil saturation (S_o) X porosity (ϕ) criteria are satisfied.

Source: NPC, 1984.

Screening Criteria for EOR Candidates-Advanced Technology Case

Table III-3

		Screening Parameters*		Units	Chemical Flooding		Miscible Flooding	Thermal Recovery	
Oil Gravity		°API		---	<30		>25	---	
In-situ Oil Viscosity (μ)		cp		---	<100		---	---	
Depth		Feet		---	---		---	<5,000	
Pay Zone Thickness (h)		Feet		---	---		---	≥ 15	
Reservoir Temperature (TR)		°F		---	<250		---	---	
Porosity (ϕ)		Fraction		---	---		---	$\geq 0.15^{***}$	
Permeability Average (k)		md		---	>10		---	≥ 10	
Transmissibility (kh/ μ)		md-ft/cp		---	---		---	---	
Reservoir Pressure (PR)		psi		---	---		$\geq \text{MMP}^{**}$	$\leq 2,000$	
Minimum Oil Content at Start of Process ($S_o X \phi$)		Fraction		---	---		---	≥ 0.08	
Salinity of Formation Brine (TDS)		ppm		---	$<200,000$		---	---	
Rock Type		---		---	Sandstone or Carbonate		Sandstone or Carbonate	Sandstone or Carbonate	

* Other criteria of a geological and depositional nature were also considered. Generally, reservoirs with extensive faulting, lateral discontinuities, or overlying gas caps are not prime candidates for field-wide EOR application. These factors were considered during the manual screening step when they could be identified.

** MMP denotes minimum miscibility pressure, which depends on temperature and crude oil composition.

*** Ignored if oil saturation (S_o) X porosity (ϕ) criteria are satisfied.

Source: NPC, 1984.

discounted cashflow analysis is performed for each reservoir at a number of oil prices and minimum rates of return.

5. Technology Development. For each reservoir that is determined to be economic at a given price, the performances of the applicable EOR processes are compared. Each reservoir is then assigned the process producing the greatest quantity of incremental oil. In the NPC assessment, the reservoirs are then scheduled for development on the basis of their relative economic attractiveness and time-phased against a series of supply and environmental constraints. This procedure is modified somewhat in the present study, as described below.

The NPC reported its findings on a national basis for four oil prices, ranging from \$20 to \$50 per barrel, three minimum rates of return (zero, ten, and twenty percent), and two levels of technology performance -- "implemented," meaning available at present, and "advanced," meaning available in the future due to successful completion of currently ongoing R&D. The present study uses the NPC reservoir data base, models, and methodology just as the NPC developed them, except as described in sections C and E. The NPC methodology is described at length in its final report.²

C. BUILDING ON TORIS: THE EVALUATION OF UNRECOVERED MOBILE OIL RESOURCES

TORIS evaluations have historically focused on the recovery of immobile or waterflood residual oil. In 1988, TORIS' capabilities were expanded to include an evaluation of the unrecovered mobile oil (UMO) resources in Texas, Oklahoma, and New Mexico.³ This expansion was accomplished by enlarging the system to consider the recovery potential of extended primary and secondary recovery operations in unswept portions of the reservoir, in a manner consistent with the current capabilities to analyze the tertiary recovery target (residual oil in previously swept zones). The system development and initial limited applications that were completed under the DOE UMO study are reported in detail in a topical report by the DOE.³

² *Ibid.*

³ ICF Resources Incorporated and the Bureau of Economic Geology, University of Texas at Austin, *Producing Unrecovered Mobile Oil: Evaluation of Potential Economically Recoverable Reserves in Texas, Oklahoma, and New Mexico*, prepared for: U.S. Department of Energy/Office of Planning and Environment/Office of Fossil Energy and Bartlesville Project Office, 1989.

Since 1989, the TORIS ASR models have been upgraded to more accurately describe and evaluate the UMO resources. The enhancements included the following:

- Development of an infill drilling model which processes five-spot waterflood to five-spot infill as well as five-spot waterflood to nine-spot infill;
- Development of a methodology to determine key reservoir heterogeneity elements needed for modeling infill drilling potential. The heterogeneity elements are "reservoir continuity" and "Vertical Permeability Stratification Index" (Dykstra-Parson coefficient). The methodology relies on the history match of production data to determine the heterogeneity elements;
- Validation of the infill drilling model and history match methodology on nine actual field results as well as results of a black oil simulator;
- Integration of a newly developed infill model with other models in TORIS to process infill drilling in combination with polymer flooding or profile modification; and
- Validation of criteria for implemented as well as advanced technology infill drilling.

A preliminary draft report of all developmental work is available through the U.S. Department of Energy, Bartlesville Project Office. The draft report is currently being finalized, and it will be available to the general public in a very near future.

UMO, the target for advanced primary and secondary recovery operations, consists of oil that is uncontacted or bypassed during conventional production that can be displaced from the reservoir by waterflooding. "Uncontacted oil" refers to oil trapped in isolated compartments in reservoirs uncontacted by wells at current spacing, while "bypassed" oil has been contacted by existing wells but unswept by secondary recovery processes. The volume, location, and properties of the UMO depend on the geologic history of the reservoir, the fluid characteristics of the oil, and the drilling and development history of the reservoir.

Potential incremental oil recovery and related economic benefits are estimated for the three processes currently used to improve mobile oil displacement. These processes are referred to as advanced secondary recovery (ASR) and include: infill drilling, profile modification treatments (permeability contrast reduction), and polymer-augmented waterflooding. A modified polymer-waterflood predictive model is used to evaluate each process. Selected combinations of these processes are also evaluated in this study.

Consistent with TORIS EOR evaluations, the analysis of UMO considers both current technology and advanced technology. The advanced technology analysis estimates the potential improvement in recovery possible after successful RD&D. For polymer flooding and profile modification treatments, advances in technology are projected to increase both the reservoir temperature and the formation salinity thresholds that currently limit the application of these processes. Table III-4 shows the process technical screens that are used in evaluating reservoirs for polymer flooding and profile modification treatments under current and advanced technology scenarios.

Table III-4
Screening Criteria for
Advanced Secondary Processes

	<u>Polymer*</u>		<u>Profile Modification</u>	
	<u>Current</u>	<u>Advanced</u>	<u>Current</u>	<u>Advanced</u>
Reservoir Temperature (°F)	<200	<250	<180	<250
Formation Brine Salinity (ppm)	<100,000	<200,000	<100,000	<200,000
Permeability (md)	>20	>10	>20	>10
Oil Viscosity (cp)	<100	<150	<100	<150
* Source: NPC, 1984				

Infill drilling potential is also evaluated under implemented and advanced technology scenarios. Current knowledge of reservoir heterogeneity limits drilling to highly favorable reservoirs where blanket-pattern drilling at uniform spacing can yield a profit. Increased continuity in the implemented technology case is estimated by the reservoir-wide average improvement in continuity possible with a reduction in spacing to one-half the current level. The advanced technology scenario assumes that improved geologic description would target infill wells to more promising segments of each reservoir. The TORIS models represent this assumption by dividing the reservoir into two parts, a more continuous (homogeneous) region and a less continuous (heterogeneous) region. Each region is then separately analyzed to determine

its economic potential for infill drilling at subsequent one-half reductions in well spacing down to five acre spacing, or one-eighth of current spacing, the maximum reduction evaluated in this study. The specific criteria for both the implemented technology and the advanced technology infill drilling is shown in Table III-5. The entire methodology (data, models, highgrading, and analytical systems) was developed and implemented in a manner fully compatible with the existing TORIS structure.

Table III-5

Screening and Approach for Advanced Technology Infill Drilling

Technology Level	Criteria
Implemented	<ul style="list-style-type: none"> - 5-spot waterflood to 5-spot infill - 15% minimum real rate of return - Minimum well spacing of 10 acres before infill drilling - One drill down
Advanced	<ul style="list-style-type: none"> - 5-spot waterflood to 5-spot infill - 10% minimum real rate of return - Highgrade into homogenous and heterogeneous portions - One drill down in homogeneous portion - Up to three drill downs in heterogeneous portion - Well spacing after infill greater than 5 acres

D. SCOPE OF THE ANALYSIS

The cases selected for this analysis include six oil price assumptions and two levels of technology application. The cases are run, first incorporating either EOR or ASR processes individually, and then in combination. TORIS selects from five EOR recovery methods and five ASR methods for each reservoir in the database. A reservoir could be assigned only one EOR process and/or one ASR method for each case considered.

The nominal crude oil prices (West Texas intermediate adjusted for transportation costs and gravities less than 40° API) range from \$16/B to \$36/B in \$4 increments, all stated in constant 1991 dollars. The prices are selected to bracket the likely prices over the next 30 years. A minimum real (after inflation) rate of return of 10% is used to estimate discounted cash flows and project profitability for all analyses. In addition, a risk premium is also considered depending on the EOR/ASR process and the level

of technology. The risk premium is modeled as an increase in the hurdle rate as shown by the following table. The risk premium was recommended by the TORIS peer review committee.

Table III-6

Risk Premium For Implemented and Advanced EOR and ASR Processes

	Cost of Capital	Risk Factors		Hurdle Rates	
		Implemented Technology (%)	Advanced Technology (%)	Implemented Technology (%)	Advanced Technology (%)
Alkaline	10	15	0	27	10
Surfactant	10	15	0	27	10
In-Situ	10	15	5	27	16
Polymer	10	5	0	16	10
Profile Modification	10	5	0	16	10
CO ₂	10	5	0	16	10
Steam	10	5	0	16	10
Infill Drilling	10	5	0	16	10

At each oil price, two technology cases are analyzed; the "implemented" and the "advanced" case. Implemented technology reflects the applicability and level of performance of the respective processes (EOR or ASR) which are currently available. Advanced technology considers the likely improvements in process performance and applicability that can be achieved within the next decade if a focused, effective R&D program is successfully completed.

All cases are analyzed in detail to examine their impact on estimated oil reserves, oil production, state and Federal revenues, and the economy. The results of these analyses, addressing the benefits from incremental production, are reported in Chapters IV and V which discuss the effects of EOR and ASR processes for implemented technology and advanced technology, respectively.

E. ADAPTATIONS FOR THE PRESENT STUDY

Several adaptations to the NPC approach were necessary to conduct the present analysis. None is a significant departure from the NPC methodology.

1. Data Editing and Additions

Based on a lengthy data search using state and library sources, the NPC reservoir data have been reviewed and updated for 2,307 of the largest U.S. reservoirs, accounting for 65% of estimated original oil-in-place (OOIP) in the U.S. The reservoirs represented in the data base include oil zones in every region of the nation. The largest reservoirs are more completely represented in the data, but reservoirs as small as 5 million barrels are also analyzed in the study. The data base is, therefore, believed to be representative of the diverse oil producing formations across the United States. Data from the Energy Information Administration on the production of oil, gas, and water from 1970 to 1992 has been added for all reservoirs, thereby permitting decline curve analyses (used in the timing algorithm, discussed below) and validation of the estimated ultimate conventional recovery.

2. State and Federal Taxes

The present study uses current tax structure along with the actual tax rates in the TORIS economic models. The Federal taxes are estimated based on the new corporate tax rules established by Congress in the Tax Reform Act of 1986 and signed into law in October 1986. This law provides for a 34% marginal rate on corporate income taxes and changes the depreciation schedules and expense rules. In addition, the present study includes the new Federal EOR tax credit as passed by Congress in FY91. The new Federal EOR tax credit provides a credit equal to 15% of all qualified enhanced oil recovery costs on projects that began or were significantly expanded after December 31, 1990. The "qualified enhanced oil recovery costs" are defined as tangible property investments, intangible drilling and development costs, and purchase costs of tertiary injectants. The tax credit is contingent upon professional certification, in advance, that the EOR project is capable of producing more than an insignificant increase in ultimate recovery. Because the goal of the incentive is to make the application of EOR techniques economic at lower oil prices, where project economics are most impacted, the incentive is gradually phased out at oil prices above \$28/B. For every \$1/B that the average benchmark price for the preceding year exceeds

\$28/B, the incentive is reduced by 2.5 percentage points for the subsequent year, so that a complete phasing out of the incentive would occur at an oil price of \$34/B.

The study also accounts for the current state tax incentives effective since 1983. These incentives in the states of Alabama, Kansas, Louisiana, Mississippi, New Mexico, North Dakota, Oklahoma, and Texas, typically suspend or reduce the severance tax on incremental production until payout, or for some specified time period. This incentive is only applicable to qualified projects, as determined by each state's regulations.

3. Cost and Price Data

An informal survey of industry representatives has determined that the NPC costing algorithms for investments are still valid for the present study, provided that prices analyzed are consistent with the year of the cost data. The only exception to the use of the NPC's cost algorithms is the cost of enhanced recovery injectants delivered to the field. The NPC assumed a CO₂ purchase price in the Permian Basin of West Texas and Eastern New Mexico of \$1.25 per thousand standard cubic feet (Mcf) at an oil price of \$30/B. The NPC adjusted for changes in oil price using the equation:

$$\text{CO}_2 \text{ Price (\$/Mcf)} = \$0.50 + \$0.025 \times \text{Oil Price (\$/B)}.^4$$

However, the base price and adjustment equation were established at higher oil prices and before the completion of major CO₂ pipelines or significant CO₂ deliveries to the region. An informal poll of pipeline and field operators suggests that the CO₂ prices at present and into the near future will be lower (relative to oil prices) than the NPC had assumed. The CO₂ purchase price in West Texas has been adjusted for changes in oil price using the equation:

$$\text{CO}_2 \text{ Price (\$/Mcf)} = \$0.50 + \$0.02 \times \text{Oil Price (\$/B)}.$$

This equation results in a CO₂ price of \$0.90/Mcf at the \$20/B oil price. CO₂ prices in other regions of the state are assumed to be double the West Texas price, based on previous NPC surveys.

⁴ National Petroleum Council, *Enhanced Oil Recovery*, Washington, DC, 1984.

Chemical injectant costs have also been adjusted based on a survey of operators and suppliers. Polymer costs, assumed to be \$1.60 per active pound by the NPC, have been reduced to \$1.33 per active pound based on the current cost of low temperature, low salinity polymers. The cost is increased where oil and reservoir properties dictate the use of high molecular weight polymers. Surfactant costs used by the NPC were based on a primary surfactant cost of \$0.32 per active pound and a secondary surfactant cost of \$0.44 per active pound. The surfactant slug cost based on these components was \$7.00/B. Prices paid by operators in recent field tests show this cost to be too low. Survey information shows that primary surfactant costs are higher (\$0.63/active pound), resulting in a \$10.17/B surfactant slug cost at a \$30/B oil price.⁵ Chemical costs have been adjusted for oil price changes as had been done in the NPC analysis, based on the energy component of the chemicals for different oil prices.

4. Benefits Estimation

The NPC did not calculate all of the individual items used in the present study's estimation of benefits. Special algorithms have been developed to estimate the number of jobs created, wages paid, and personal income taxes collected based on other elements already contained in the economic model. These algorithms are discussed further in Section F of this chapter.

5. Project Timing

The NPC's national perspective permitted a timing algorithm based principally on the assumption that the most economically attractive reservoirs would be developed first, given some broad constraints. A more detailed timing approach for both EOR and ASR was used in the present study. Timing for the application of EOR recovery techniques is estimated in two steps. First, project starting dates for EOR that are documented in the literature are used to time recently started operations. Second, when project start up dates are not available, the year that average well abandonment will occur for each reservoir under conventional recovery is estimated. This abandonment date is based on the projected rate of decline and economic limit of conventional recovery for each reservoir. EOR recovery is then phased in to occur reservoir-wide, at the latest, by three years following the estimated abandonment date. Projects that are not timed in by this data are assumed abandoned and are excluded from the analysis. The timing of ASR

⁵ Ray, et al., *Potential Crude Oil Production from Enhanced Oil Recovery*, U.S. Department of Energy, Bartlesville Project Office, 1986.

reserves development and production was accomplished using the Crude Oil Policy Model (COPM) because the TORIS timing model was not suited for ASR for technical reasons. COPM simulates the development of an aggregate resource as a function of project economics, while simultaneously accounting for abandonment of the undeveloped portion of the resource and technology transfer constraints. Inputs to COPM include the total resource potential, development and production costs, technology availability dates, technology penetration rates, abandonments rates, and reserves development rates. Outputs from the model include annual production, reserve additions, abandonments, development costs, operating costs, wages, and taxes. Reserves estimates were supplied by TORIS.

Total reserves were disaggregated into two categories, reserves available with implemented technology and incremental reserves available through the application of advanced technology. Appropriate model parameters were selected for each of these resource categories. The technology availability dates were set to 1993 for implemented technology and 2000 for advanced technology. Technology penetration rates were set at 75% in 12 years for implemented technology and 75% in 8 years for advanced technology, with the advanced technology case representing an aggressive technology transfer effort. Abandonment rates for both implemented and advanced technology were set to 3% of the undeveloped resource per year prior to technology availability and 1.5% per year after technology becomes available. Reserves development rates corresponded to typical field development profiles.

F. ESTIMATION OF BENEFITS, COSTS, AND ECONOMIC IMPACTS

The NPC study analyzed each reservoir from the perspective of the operator deciding whether to implement advanced oil recovery processes. The present study does the same in evaluating the economic viability of each reservoir. Thus, the benefits and costs to the operators are explicitly captured in the net cash flow calculations of individual projects. Under each of the various cases analyzed, projects yielding a net present value greater than the hurdle rate are assumed to be developed. This assumption is the basis for the projection of potential incremental production and reserves.

The incremental benefits and costs of EOR and ASR are estimated and reported on an annual as well as a cumulative basis. As previously discussed, reservoir timing is based on the estimated abandonment of the resource due to production decline, except for major reservoirs in which activity suggests earlier project start dates. Projects are phased in over a 5- to 10-year period to achieve full project development before this abandonment would occur. Annual estimates of benefits are based on the

total economic resource produced in a given year. These annual values are reported for a twenty-seven year period, 1993 to 2020. Cumulative benefits include the sum of the annual benefits plus any additional benefits that would accrue after 2020. The total length of time for the life of all projects varies considerably depending on the process, oil price, and tax treatment. The vast majority of cumulative production and benefits occur in the twenty-seven year period of focus in this study. The additional benefits that occur after 2020 are small relative to the total benefit, but important to the overall aggregate analysis.

1. Benefits to State and Local Treasuries

The benefits to state and local treasuries from advanced oil recovery processes are the additional tax revenues attributable to implementation of the projects. These taxes include gross production taxes on oil, sales tax on equipment and material purchases, and corporate and personal income taxes on wages paid and operator profits. Evaluating these benefits under the current tax structure involves estimating the sum of these revenues as they apply to the development of the projects and the activities associated with the incremental production from advanced recovery projects.

2. Direct State Economic Effects

The effect on a state's treasury is only one segment of the benefits of advanced oil recovery processes. The state's citizens also gain from the increased economic activity. Only the direct effects of the incremental activity are included, not the economic "multiplier" or indirect "ripple effect" activities (e.g., pipeline construction, retail sales, etc.). The direct impact on each state's economy is defined as the sum of net revenues to the state and local treasuries (as presented above); royalties to individuals, corporations, and the state; expendable (intangible) drilling materials and services; and operating costs excluding injectant purchases. It is assumed that these funds flow predominantly to each state and its citizens.

Excluded from this state economic activity definition are cashflows that generally benefit citizens of other states in larger proportion than they benefit the producing state's citizens. These include costs for tubular steel products installed in wells, injection and production equipment, purchased tertiary injectants, and other oil field materials typically manufactured out-of-state. To the extent that these goods are marketed by distributors in the producing state, the direct benefits of these "retail pass-through" to the

state are omitted from the estimates of direct state economic activity. Similarly, while it is recognized that a portion of tertiary injectants, especially chemicals, may originate in the producing state (generating royalties, employment, taxes, and/or other economic activity), estimating these quantities is outside the scope of the present study. Other excluded items include federal taxes, corporate debt service, and return on capital. While the citizens of each producing state obviously benefit from these excluded elements as U.S. citizens, or as employees and stockholders of companies providing services, they share them with a much larger population. Thus, the definition used for direct economic effects understates the actual benefits to each producing state and its citizens.

The additional jobs, wages, and benefits created by advanced oil recovery are also estimated. Labor costs (wages and fringe benefits) are calculated by isolating the labor component of all major cost elements. Table III-7 summarizes the major cost elements and their respective labor and material components. Labor costs are converted into estimated numbers of jobs by dividing total wages by the average oil field wages (including benefits) reported by the U.S. Department of Labor.⁶ Sales tax revenues are calculated based on the materials component of these costs, assuming purchasers would pay the appropriate state tax on these goods.

3. National Effects

The Federal government benefits substantially, both directly and indirectly, from increased recovery of the domestic oil resource. Direct taxes total 5% to 20% of the value of each barrel of oil recovered. Each additional barrel of domestic production can replace a barrel of imports. Therefore, each dollar used to purchase the incremental barrels of domestic oil that would otherwise pay for imports is, potentially, a dollar reduction in the trade deficit.⁷ To estimate the direct effects on import replacement (i.e., excluding multiplier effects), the gross revenue from the additional production is used. This measure of gross revenues incorporates direct in-state economic activity and excluded elements discussed in the section above. In this sense, the estimated increase in import replacement represents a more complete measurement of direct economic impacts, excluding multiplier effects. In addition, corporate and

⁶ U.S. Department of Labor, Bureau of Labor Statistics, 1985.

⁷ Although constraints caused by limited financial or personnel resources may result in delayed national benefits due to short-term deferral of projects in other states, the aggregate benefits to the nation should be achieved as all economic projects will ultimately be developed.

Table III-7

Labor and Materials as Percentage of Total Cost in EOR Projects

<u>Investments</u>	<u>% Labor</u>	<u>% Materials</u>	<u>% Other</u>
Drilling Wells	18	55	27
Work-overs	15	63	22
Equipping Wells	10	50	40
Pipe Installation	10	50	40
Plant Installation	16	46	38
<u>Expenses</u>			
Field Operations	33	58	9
Plant Operations	38	57	5
Production Treating	0	100	0
Overhead	100	0	0

Sources:

Investments

- Drilling and Work-overs
 - NPC, 1984
 - EIA, 1984
 - Professor Neil J. Dikeman, University of Oklahoma, 1986
- Equipping Wells
 - Industry estimate
- Pipe Installation
 - Industry estimate
- Plant Installation
 - Modern Cost Engineering Technologies, Herbert Popper, page 82-83

Expenses

- Field Operations
 - EIA, 1984
- Plant Operations
 - NPC, 1984
 - EIA, 1984 (power and chemicals)
- Production Treating
 - By definition
- Overhead
 - NPC, 1984

individual Federal income taxes are estimated to assess the direct effects of incremental oil recovery on the Federal treasury.

G. LIMITATIONS TO THE ANALYTICAL APPROACH

The approach followed by this study has limitations that should be considered in utilizing its results. Some of these follow from the adoption of the NPC methodology; others result from the need to limit the scope of the present effort. It is also important to note that the results of this analysis are not forecasts of future oil recovery; they are estimates of the recovery potential of selected EOR and ASR processes.

The NPC approach, while the most credible and flexible methodology available, has certain distinct limitations. One problem is the reliance on averaged reservoir and fluid properties. Oil reservoirs are actually highly heterogeneous, with erratic properties throughout the field. The use of averaged properties belies the fact that portions of an individual reservoir could be highly attractive as an advanced technology oil recovery prospect even if the whole reservoir, on average, is not economic. Given the present methodology, reservoirs must be economically accepted or rejected as whole units, unless advanced geoscientific knowledge allows the reservoir to be evaluated in segments. The methodologies of both the present study and the NPC assume that the least favorable 20% of any reservoir would not be developed under EOR or ASR operations.

A second limitation is the use of regional costing algorithms. Although developed from the best available data and explicitly adjusted for variations in energy costs and specific reservoir characteristics, they do not reflect site-specific cost variations applicable to specific operators. Thus, this study does not necessarily use the actual costs of individual projects. To the extent that the average costs used understate or overstate the true project costs, the actual results will be higher or lower than the analysis estimates.

A third limitation is the use of simplified process performance models. While the models used in this project are extensively calibrated, they are designed to analyze large numbers of individual reservoirs quickly and simultaneously. Therefore, while they incorporate all the relevant reservoir engineering concepts, they are relatively simplified and generalized. In this simplified state, the models cannot be as accurate as highly detailed reservoir simulators in which very specific reservoir features and process designs may be evaluated (such as assessments used in the actual design of specific projects). The

present study assumes these models are appropriate for aggregate analyses but not necessarily for individual reservoirs. Further, these models are explicitly designed to estimate only incremental recovery resulting from advanced oil recovery processes after completion of conventional production operations. Laboratory and limited field data suggest that application of some of these techniques before the economic limit of conventional recovery could yield more than the sum of conventional and advanced oil recovery, but this is not reflected in the models.

An additional limitation arises from the methodological convention of "constant price" analysis. The use of this convention is consistent with the NPC's original nationwide study, conducted during a period of relatively stable, rising oil prices, and differentiates the effect of oil price from other effects. It can, however, cause a distortion, especially in times of declining or radically changing oil prices. The "hidden" assumption of this convention is that each of the respective oil prices analyzed must be attained by the time (and be expected to continue at that level after) the decision to commit specific reservoirs to enhanced recovery or advanced mobile oil recovery operations is made. This decision is generally made several years before the reservoir's final, actual economic limit is reached under conventional technology. To the extent this condition is not met, existing wells reaching their economic limits at lower prices will be shut-in and abandoned, making them unavailable for use in advanced oil recovery projects, as assumed. The economic model assumes that all existing wells will be utilized in future operations, although older wells may require workovers. Should "premature" abandonments occur, these wells would need to be redrilled, resulting in additional incremental investment not included in this analysis (although necessary workovers are included in the assumed cost). Redrilling would result in substantially increased costs and would thus increase the minimum oil price at which advanced oil recovery processes are profitable for certain reservoirs. The net effect of this analytic convention could overstate the economic reserves and production and the corresponding economic benefits. Under these conditions, the "constant price" convention introduces an optimistic bias to the present analysis.

Finally, the analysis follows the NPC approach, which assumed that project operation would be conducted by an integrated major oil company. This approach, in most cases, presents the least favorable corporate tax treatment for investments and revenues from advanced oil recovery projects and assumes a relatively high overhead on operations. Independent producers operate with a different corporate structure, tax situation, and overhead rate. Because most costs used in this analysis are not affected by total project size and some non-integrated operators would enjoy more favorable tax treatment, smaller

independent producers should receive the same benefit as a major oil company from application of advanced oil recovery processes, possibly even at lower oil prices than projected in this evaluation.

None of the above limitations invalidate the results of this analysis. Given the uncertainty of the size and combinations of the optimistic and pessimistic biases introduced by these limitations, it is assumed that the approach is valid and the resulting projections are reasonable. To avoid misinterpretation of particular reservoirs, and to respect the confidence in which some project and reservoir data were obtained, no reservoir specific data is provided in the reports generated from this analysis. However, in cases where the results seemed unusual, the modeling specifications for specific reservoirs were examined in-depth to ensure the validity of the results.

IV. INCREASED RECOVERY FROM THE KNOWN REMAINING OIL RESOURCE IN THE UNITED STATES UNDER IMPLEMENTED TECHNOLOGY

A. INTRODUCTION

This chapter discusses the post-conventional reserve additions and potential economic impacts attributable to the application of currently available (implemented technology) oil recovery methods in analyzed reservoirs throughout the U.S. Chapter V discusses the incremental reserves and benefits under advanced technology methods attainable through RD&D. The TORIS reservoirs analyzed in this study are individually modeled to evaluate their potential for incremental production and reserves by tertiary and advanced secondary recovery techniques under a variety of oil prices and economic conditions. Some key technical assumptions and considerations regarding the analysis in this report are:

- The incremental production and reserves refers to future recovery estimated for the analyzed EOR and ASR techniques. Such production and reserves are above and beyond the recovery attainable by primary and secondary recovery techniques.
- Both light oil (API > 20 degree) and heavy oil (API ≤ 20 degree) resources are considered in this analysis.
- All EOR and ASR recovery potential evaluated in this report reflect future new projects only, and they do not include incremental reserves from existing (ongoing) EOR and ASR projects. However, the expansion to the ongoing projects, if technically and economically feasible, are evaluated as part of future new projects in this report.

All reservoirs are screened for technical criteria and are analyzed in detail using the process performance and economic models described in Chapter III. The results are based on the evaluation of 2,307 reservoirs for their EOR and ASR potential. No effort is made to extrapolate the results of this analysis to the rest of the reservoirs making up the nation's resource.

B. RECOVERY OF THE REMAINING IMMOBILE OIL RESOURCE

1. Production and Reserves

Over the price range analyzed, EOR processes (carbon dioxide-miscible, chemical, and thermal) could stimulate from 1.2 billion to 7.2 billion barrels of incremental reserves using implemented

technology (Figure IV-1A and Table IV-1A). This potential represents an increase of up to 30% of the 1991 proved reserves (24.6 billion barrels) in the United States. As the oil price rises above \$20/B, EOR processes become increasingly prolific, and substantial incremental reserves could become economically recoverable. The 3.2 billion barrels of potential EOR reserves at \$20/B could increase by an estimated 1.4 billion barrels, almost 45%, with a \$4/B increase in the oil price. At an oil price of \$32/B, EOR techniques could generate total reserve additions of 6.6 billion barrels.

Among the EOR processes considered in this analysis, carbon dioxide (CO₂) miscible flooding and thermal processes are the most dominant processes under current technology and economic conditions. As shown in Table IV-1A, the reserve additions due to CO₂-miscible flooding ranges from 250 million barrels at the low oil price of \$16/B to 1.7 billion barrels at \$24/B. As the oil prices rise to \$32/B, the incremental reserves stimulation by CO₂-miscible flooding increases to 2.8 billion barrels. These reserves estimates are for future, new projects and expansions to ongoing projects. They do not include the ongoing CO₂ projects in the West Texas and Eastern New Mexico region. The reserves for the ongoing CO₂-miscible EOR projects are reported at 1.2 billion barrels.¹ The incremental reserve additions by thermal processes range from 1.0 billion to nearly 2.8 billion barrels at an oil price range of \$16 to \$24/B. The incremental reserves by thermal methods could reach 3.3 billion barrels at a relatively high oil price of \$32/B. These reserves estimates are also for future new thermal projects and expansions to ongoing projects. They do not include the ongoing steamflood projects in California and elsewhere. The reserves for the ongoing thermal projects are reported at 2.2 billion barrels.² The incremental reserves by chemical flooding are somewhat smaller, ranging from zero to 500 million barrels across the analyzed oil prices. The apparent reason for this is the high chemical cost (about \$10 per barrel of slug) as well as the high risk associated with a relatively unproven process technology.

Table IV-1B shows the number of EOR projects that would be initiated at different oil prices. Of the reservoirs evaluated in this analysis, less than 10% are economic to develop with current EOR technology at oil prices of \$36/B or below. CO₂-miscible floods and thermal processes account for about 90% of the EOR projects considered economic in the \$24/B to \$36/B price range and chemical processes about 10%. At oil prices of \$20/B or below, nearly all of the EOR projects are CO₂-miscible flooding and thermal projects.

¹ ICF Resources, Inc. "An Assessment of the Status of CO₂ Injection in the Cortez Pipeline Service Area." February 1992.

² California Department of Conservation, Division of Oil and Gas. "77th Annual Report." 1991.

Table IV-1A

**Incremental Reserve Additions from EOR by Process
Implemented Technology
(Billion Barrels)**

Oil Price (\$/B)	CO ₂ -Miscible	Chemical	Thermal	Total
\$16	0.25	0.00	0.99	1.24
\$20	0.99	0.02	2.17	3.18
\$24	1.74	0.15	2.76	4.65
\$28	2.55	0.21	3.21	5.97
\$32	2.79	0.46	3.30	6.55
\$36	2.99	0.46	3.77	7.22

Table IV-1B

**Estimated Number of Economic EOR Projects by Process
Implemented Technology
(Project Counts)**

Oil Price (\$/B)	CO ₂ -Miscible	Chemical	Thermal	Total
\$16	10	0	12	22
\$20	18	3	18	39
\$24	51	10	27	88
\$28	86	13	35	134
\$32	93	15	39	147
\$36	103	15	45	163

In most cases, the economic projects are in the large reservoirs, but size alone is not a major determinant of EOR economics. The reservoirs that have been found to be uneconomic for EOR tend to be characterized by heterogeneities that cause sweep, by both conventional and tertiary injectants, to be less than optimal. As a result, these reservoirs show poor recovery and require larger volumes of the injectant to contact and recover the tertiary oil. Technological advances that effectively address these problems could substantially increase the potential production from EOR methods in the U.S. Such improvements in EOR technology are clearly a target for concentrated RD&D; their potential impact on EOR is discussed in Chapter V.

The timing of EOR project initiation in each reservoir that is economic at a specific price is scheduled according to that reservoir's projected decline rate under conventional recovery techniques. The annual incremental production resulting from enhanced oil recovery is determined by phasing-in economic projects based on the demonstrated economic limit of conventional production (as well as other constraints) as discussed in Chapter IV. Figure IV-1B shows the expected annual production from all EOR processes for oil prices of \$16 and \$32 per barrel. At \$16/B, EOR production gradually increases to 56 million barrels per year by the turn of the century. The EOR production then remains in the 45 to 55 million per year range between the years 2000 and 2010. Figure IV-1B also shows the production for the higher oil price of \$32/B as an upper limit.

2. Increases in State and Local Revenues

EOR production would also directly increase state and local revenues through production taxes, corporate and personal income taxes on operator profits and wages paid, and sales taxes on purchased materials used in the projects. The revenues projected in this study are generated directly from oil production or improved recovery operations in the analyzed reservoirs. The results are not extrapolated to determine the potential revenues that would be generated from EOR projects in the remaining U.S. reservoirs, nor do they include royalties from production on state owned or Federal lands. State and local revenues generated over the life of the EOR projects vary considerably with oil prices (Figure IV-2A). At \$16/B, \$1.0 billion in incremental state revenues could be generated, with production taxes contributing 55% of the total. A \$24/B oil price could yield production tax revenues of \$3.3 billion plus \$2.5 billion in other tax receipts. At \$28/B, the state revenues total \$8.8 billion, while at the highest price case of \$36/B, \$13.8 billion of additional state and local revenues are generated directly by EOR.

Figure IV-1

Reserves and Production Response from EOR Techniques

Implemented Technology

A) EOR Reserves by Recovery Process

B) Annual Production from EOR Reserves

3. Effects on the National Economy

Increased oil recovery from EOR projects would be a substantial benefit for the nation as a whole. National benefits would accrue in five ways: replacement of oil imports, increased Federal corporate and personal income tax revenues, increased public sector revenues, improved foreign trade deficit, and jobs created or maintained. The addition of as many as 7.2 billion barrels of reserves by EOR would expand the nation's proved reserves base. As each additional barrel of domestic oil production replaces a barrel of imported oil, the nation's energy security would be enhanced.

EOR activity in the United States contributes to the Federal treasury through personal and corporate income taxes. As shown in Figure IV-2B, increases in Federal revenues attributable to EOR would range from \$600 million at \$16/B oil price to \$5.5 billion at the higher oil price of \$24/B. Federal corporate income taxes would account for between 70% to 80% of this total depending on the oil price, and personal income taxes would make up the remainder. Negative annual Federal revenues could result from taxable losses generated during the initial implementation phases of many EOR projects, as well as from the EOR tax credit as enacted by Congress in FY91. These offset the Federal income tax liability from other profitable activities associated with the EOR projects, therefore causing a negative Federal revenues for the first few years of project life.

The public sector revenues from EOR, defined as the sum of direct Federal plus direct state revenues, are shown in Figure IV-3A for the analyzed oil prices. The public sector revenues range from \$1.6 billion to \$11.3 billion at a \$16/B to \$24/B oil price range. For oil prices below \$28/B, the Federal portion of the total public sector's revenue is about 50%. However, as oil prices rise above \$28/B, the Federal portion increases to 60%-65% because of the Federal EOR tax credit phase-out for oil prices greater than \$28/B.

In addition to directly replacing imported oil, increased domestic production would reduce the foreign trade deficit. To the extent that one barrel of domestic production replaces one barrel of imports, the money spent purchasing the incremental domestic oil lowers the foreign trade deficit. At \$16/B, this added element of import replacement could total \$13.4 billion over the life of domestic EOR projects (Figure IV-3B). At the maximum analyzed oil price of \$36/B, over \$175 billion dollars in import replacement is possible through currently defined EOR technologies.

Figure IV-2

Tax Revenue Impact of EOR Production

Implemented Technology

A) Direct State and Local Revenues

B) Direct Federal Revenues

Figure IV-3

National Impact of EOR Production

Implemented Technology

A) Public Sector Revenues

B) Imports Avoided*

* To the extent that 1 barrel of domestic oil replaces 1 barrel of imported oil, imports avoided measures the reduction in the foreign trade deficit.

Successful application of EOR projects could create or maintain a substantial number of jobs in the U.S. (Figure IV-4). The number of jobs created or maintained by new EOR projects during the peak years could reach 1,440 per year, by the year 2000 at \$16/B. At \$32/B, the peak is over 14,000 per year in the year 2000. While the annual jobs created or maintained does decline steadily after the peak, a substantial number is still possible by the year 2020 at each oil price. Total incremental annual wages paid could reach over \$600 million.

C. RECOVERY OF THE REMAINING MOBILE OIL RESOURCE

This section will discuss the application of currently available advanced secondary recovery (ASR) technology in the analyzed reservoirs. These two distinct recovery technologies, enhanced oil recovery and advanced secondary recovery, have been addressed separately to illustrate the potential benefits of each. However, since the resource target of these two technologies is mutually exclusive, both could be implemented in U.S. reservoirs, and the results are independent and additive. Given the potential synergies in the simultaneous application of EOR and ASR technologies, reserve additions and economic benefits could be even greater than the sum of the two.

Figure IV-4

1. Production and Reserves

Depending on the oil price, advanced secondary recovery techniques applied in the reservoirs analyzed could stimulate 5.7 to 8.2 billion barrels of oil to current proved reserves in the United States (Figure IV-5A and Table IV-2A). Advanced secondary recovery techniques are less costly to implement than EOR recovery processes, and therefore ASR incremental reserves are less sensitive to changes in the oil price. A larger percentage of the ASR target could be recovered at low oil prices than is possible with EOR. At \$20/B, incremental ASR recovery could amount to 6.3 billion barrels, which is nearly 77% of the oil economically recoverable at \$36/B.

This analysis evaluates five ASR processes: polymer flooding, profile modification, infill drilling, and combinations of infill drilling with polymer flooding or profile modification. Polymer flooding and profile modification projects are grouped together in the following discussion, as is infill drilling combined with polymer flooding and profile modification. Infill drilling, both by itself or in combination with the other processes, plays a predominant role in ASR, accounting for 80% to 90% of the incremental reserves at analyzed oil prices. At \$16/B, the combination processes could contribute 3.2 billion barrels of reserves, while infill drilling accounts for 1.4 billion barrels of the total. As oil prices increase, infill drilling by itself becomes slightly more economical because revenues increase along with oil prices. At \$28/B, infill drilling by itself would contribute 35% of the 7.7 billion barrels of total reserves, compared to over 50% contribution by the combination processes. Polymer flooding and profile modification techniques, applied alone, would contribute about 1.0 billion barrels to total reserves across all oil prices considered in this analysis. Table IV-2B shows the number of projects expected to be economic at each price for individual recovery methods. At oil prices of \$16/B to \$24/B, the total number of ASR projects ranges from 570 to 683.

Figure IV-5B displays the expected annual production from all ASR processes for oil prices of \$16/B and \$32/B. Timing of the ASR potential has been carried out according to the methodology discussed in Chapter IV. Annual ASR production at both prices is highest in 2015. The peak at \$16/B is about 175 million barrels and the peak at \$32/B is about 250 million barrels, nearly 10% of current domestic production. ASR projects are undertaken as reservoirs reach their economic limit. In this study, ASR projects are assigned initiation dates considering rig availability and technology transfer; projects are therefore phased in over time and some fields are abandoned and excluded from the analysis. This abandonment, which is reflected in the annual production of Figure IV-5B, is on the order of 30% over the life of the ASR projects. Accelerated technology transfer can reduce this loss.

Table IV-2A

**Incremental Reserve Additions from ASR by Process
Implemented Technology
(Billion Barrels)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification	Infill Drilling	Infill Drilling and Polymer Flooding or Profile Modification	Total
\$16	1.09	1.41	3.16	5.66
\$20	0.96	1.67	3.63	6.26
\$24	1.01	2.60	3.81	7.42
\$28	1.02	2.74	3.90	7.66
\$32	1.02	2.98	3.91	7.91
\$36	1.06	3.11	3.98	8.15

Table IV-2B

**Estimated Number of Economic ASR Projects by Process
Implemented Technology
(Project Counts)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification	Infill Drilling	Infill Drilling and Polymer Flooding or Profile Modification	Total
\$16	131	142	297	570
\$20	128	166	346	640
\$24	127	189	367	683
\$28	127	214	380	721
\$32	145	234	379	758
\$36	134	259	386	779

Figure IV-5B displays the expected annual production from all ASR processes for oil prices of \$16/B and \$32/B. Timing of the ASR potential has been carried out according to the methodology discussed in Chapter IV. Annual ASR production at both prices is highest in 2015. The peak at \$16/B is about 175 million barrels and the peak at \$32/B is about 250 million barrels, nearly 10% of current domestic production. ASR projects are undertaken as reservoirs reach their economic limit. In this study, ASR projects are assigned initiation dates considering rig availability and technology transfer; projects are therefore phased in over time and some fields are abandoned and excluded from the analysis. This abandonment, which is reflected in the annual production of Figure IV-5B, is on the order of 30% over the life of the ASR projects. Accelerated technology transfer can reduce this loss.

2. Increases in State and Local Revenues

Figure IV-6A shows the expected growth in state revenues from ASR production and the proportional contributions of production taxes, corporate and personal income taxes, and sales taxes to the total. Production tax receipts account for the largest portion of total state revenues from ASR over all prices considered. Corporate income taxes and sales taxes comprise the bulk of the remainder. The direct state revenues range from \$5.9 billion to about \$14.9 billion at the oil price range of \$16/B to \$24/B. If oil prices were to increase of \$32/B, potential direct state revenues could total over \$20 billion.

3. Effects on the National Economy and Budget

Substantial direct Federal revenues could be generated from activities associated with ASR production (Figure IV-6B). Most of the additional revenues (93% to 96%) are from corporate income taxes. At the lower analyzed oil prices, \$16/B and \$20/B, between \$12 billion and \$18 billion in direct Federal revenues are possible. As the oil price approaches \$36/B, nearly \$50 billion in direct Federal revenues could be generated by ASR activities.

The implementation of the ASR projects could significantly increase total public sector revenues (Figure IV-7A). The public sector revenues ranges from \$19 billion at \$16/B oil price to \$40 billion at \$24/B. As an outer limit, the public sector revenues attributed to the ASR projects could reach as high as \$75 billion at a \$36/B oil price. Domestic ASR production could reduce the country's payments for imported oil by between \$86 billion and \$272 billion over the price range analyzed (Figure IV-7B). As the increased U.S. production replaces oil imports, the U.S. trade deficit would be reduced and national

Figure IV-5

Reserves and Production Response from ASR Techniques

Implemented Technology

A) ASR Reserves by Recovery Process

B) Annual Production from ASR Reserves

Figure IV-6

Tax Revenue Impact of ASR Production

Implemented Technology

A) Direct State and Local Revenues

B) Direct Federal Revenues

Figure IV-7

National Impact of ASR Production

Implemented Technology

A) Public Sector Revenues

B) Imports Avoided*

* To the extent that 1 barrel of domestic oil replaces 1 barrel of imported oil, imports avoided measures the reduction in the foreign trade deficit.

energy security would be enhanced as the nation's vulnerability to future supply disruptions is diminished. Additional impacts will be indirectly stimulated in the economy as the wages, taxes and profits stimulated by ASR are recirculated.

The implementation of ASR techniques could significantly contribute to employment in the nation (Figure IV-8). The annual trend in jobs created or maintained closely tracks the production trend for ASR. At an oil price of \$16/B, job additions would peak in the year 2016 at over 4,600. At the higher oil price of \$32/B (as an outside limit), the number of jobs created or maintained would peak at nearly 9,300 in the same year. At this oil price, over \$400 million in wages would be paid in the peak employment year.

Figure IV-8

Jobs and Wages from ASR Production

D. CONCLUSIONS

The existing level of EOR and ASR technologies could make substantial contributions to the U.S. economy, as well as to domestic energy security. At a \$24/B oil price, EOR processes could add 4.6 billion barrels to the nation's reserves while ASR techniques could add 7.4 billion barrels of additional oil recovery. The application of current EOR and ASR technologies, in concert, could potentially add more than 12 billion barrels of reserves at this price, almost half the U.S. current proven reserves.

The U.S. and its citizens stand to gain significantly from the increased production resulting from incremental reserve additions. Production increases from EOR and ASR projects could generate up to \$40 billion dollars in additional Federal revenues over the next 25-plus years, while stimulating \$13.5 billion in direct revenues for individual states. Jobs would be created or maintained, and state economic activity would increase. The national economy would benefit through decreased oil imports, reductions in the trade deficit, and increased Federal corporate and personal income tax revenues. Maximizing recovery of the known oil resource should therefore be an important goal for state and Federal policy makers. While these benefits would be available using currently available technology, the true potential would not be realized without an aggressive program of technology transfer. The estimated potential assumes wide application of these technologies. A collaborative technology transfer effort between the public and private sectors is critical in order to attain these estimated benefits.

Even with the substantial oil recovery possible using implemented technology, the known remaining oil resource is vast. Over 140 billion barrels of immobile oil and nearly 62 billion barrels of mobile oil will remain in analyzed reservoirs at the completion of implemented technology EOR and ASR projects, even at improbably high price levels (Figure IV-9). This remaining oil is the target for collaborative public and private RD&D efforts focused on improving recovery technologies and the understanding of reservoir architecture. Chapter IV discusses the potential benefits of the improved technologies which are foreseeable assuming a focused, effective RD&D effort.

Figure IV-9

Remaining Oil Resource After Implemented Technology Recovery

V. BENEFITS OF INCREASED RECOVERY FROM THE KNOWN REMAINING OIL RESOURCE IN THE UNITED STATES THROUGH TECHNOLOGY ADVANCES

A. INTRODUCTION

While wider use of currently available enhanced oil recovery (EOR) and advanced secondary recovery (ASR) processes could contribute substantially to the United States' reserves base, development and wide-scale application of technological advances in these processes resulting from a collaborative, focused RD&D effort between the public and private sectors would have far more dramatic effects on the country's oil production. Over 200 billion barrels of oil will remain in analyzed reservoirs after economic implemented technology EOR and ASR projects are complete. This chapter discusses the impact of advanced technology EOR and ASR on oil recovery and the associated economic benefits. Evaluations of advanced technology EOR and ASR potential in the United States are presented separately; however, because they target different portions of the resource, EOR and ASR potential are independent and additive. Given that the advances in technology modeled in this analysis are conservatively defined, improvements in recovery processes resulting from research and development not envisioned in this report could add substantially to the estimated reserve potentials. However, well abandonments could limit access to the resource and increase project costs if EOR and ASR are not applied before conventional production ceases. Immediate actions are therefore necessary to realize the benefits of these advanced technology processes.

B. RECOVERY OF THE REMAINING IMMOBILE RESOURCE

1. "Advanced" Technology Defined

Enhanced oil recovery processes, as currently applied, have severe limitations. Some current EOR techniques can only be applied in a limited number of reservoirs with properties which fall within a narrow range of suitable values (temperature, salinity, oil viscosity, etc.). The sweep efficiency of EOR processes is often relatively poor; only a small portion of the residual oil remaining in the previously waterflooded zone is contacted. Injectants are expensive, often approaching the value of the oil they are designed to recover, which places a burden on project economics. The National Petroleum Council (NPC) predicted gradual improvements in EOR performance and project economics as current processes are

improved and tested in the lab and field. These advanced processes are predicted to gain operator acceptance as the research and development efforts of oil companies, universities, state geologic surveys, and the Federal government proceed and as field applications prove commercial viability. In this report, the IOGCC delayed the advanced technology availability date from the NPC's assumption of 1995 to the year 2000 to reflect the slower pace of RD&D activities in recent years caused by relatively low oil prices.

The major improvements in technology that are likely to impact U.S. enhanced oil recovery will be advances in chemical and thermal EOR applications. Roughly 60% of the predicted increase in EOR potential attributed to technology advances is chemical flooding potential, while 35% is thermal. For advanced technology chemical flooding, the NPC modeled the effects of increasing the salinity and temperature tolerance of injectants, thus enabling them to be applied in a larger number of reservoirs. This study also assumes that advances in chemical flood technology would result in improvements in injection rate, interfacial tension reduction, reduced chemical retention, and lower costs, thereby improving the recovery and economics of chemical projects. Additionally, the study assumes substantial reductions in the associated risk of EOR processes modeled as a reduction in the minimum rate of return or hurdle rate required for project implementation. For advanced technology thermal recovery, the NPC modeled the effects of an improvement in the ability to inject steam at greater depths and into thinner, lower permeability reservoirs.

2. Production and Reserves

With technology advances, EOR could stimulate a substantial amount of incremental reserves over the analyzed oil prices (\$16/B to \$36/B). Figure V-1 and Table V-1A show the comparison between the EOR reserves potentially generated through the application of advanced technology EOR processes and implemented technology EOR processes as discussed in Chapter III. At \$20/B, reserve additions due to technology advances would be more than equal those generated in the implemented technology case. At \$28/B, advanced technology could add 9.8 billion barrels of reserves over implemented technology for a total of 15.8 billion barrels. The recoverable reserves at \$28/B are nearly 64% of the nation's 1991 proved reserves (24.7 billion barrels).

The potential reserve additions contributed by each of the advanced EOR processes considered in this analysis are also shown in Figure V-1. Over the \$16/B to \$36/B range, advanced chemical flooding and advanced thermal recovery processes can contribute approximately equal amounts to the total

Figure V-1

Incremental Reserves by EOR Process Implemented Technology vs. Advanced Technology

potential. Advanced technology CO₂-miscible flooding potential would be about half that of either thermal or chemical in the analyzed U.S. reservoirs.

Technology advances have the largest impact on chemical and thermal EOR potential (Table V-1A). Under implemented technology, chemical EOR had very limited potential (up to 460 million barrels at the highest analyzed oil prices). Technology advances, however, could stimulate an additional 1.1 billion to 6.3 billion barrels of reserves over the analyzed price range. Economically producible thermal EOR reserves due to technology advances increase between 1.1 billion barrels and 3.7 billion barrels at analyzed oil prices above \$16/B for a total potential of 3.2 billion to 7.4 billion barrels of reserves.

The number of EOR projects for each process type is shown in Table V-1B. The comparison of the project count by process indicates the reasons for the increase in reserves under advanced technology. The number of economic miscible projects essentially does not change (in fact, a small decrease is noted as more productive chemical floods are implemented in certain reservoirs instead of miscible projects) in going from implemented technology to advanced. However, a 20% increase in resource potential indicates that advanced technology miscible flooding is more efficient than the implemented technology process in

Table V-1A
Incremental Reserve Additions from EOR by Process
Implemented Technology vs. Advanced Technology
(Billion Barrels)

Oil Price (\$/B)	CO ₂ Miscible		Chemical		Thermal		Total	
	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*
\$16	0.25	0.25	0	1.11	0.99	1.11	1.23	2.47
\$20	0.97	1.15	0.02	2.24	2.17	3.25	3.16	6.63
\$24	1.74	2.04	0.15	4.74	2.76	5.27	4.65	12.04
\$28	2.55	3.05	0.21	6.51	3.21	6.23	5.97	15.78
\$32	2.79	3.33	0.46	6.33	3.30	6.79	6.56	16.45
\$36	2.99	3.68	0.46	6.79	3.77	7.43	7.22	17.90

* This is the total reserves with advanced technology -- implemented technology plus the increment due to technology advances.

Table V-1B
Estimated Number of Economic EOR Projects by Process
Implemented Technology vs. Advanced Technology
(Project Counts)

Oil Price (\$/B)	CO ₂ Miscible		Chemical		Thermal		Total	
	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced
\$16	10	10	0	37	12	17	22	64
\$20	18	18	3	88	18	37	39	143
\$24	51	49	10	175	27	59	88	283
\$28	86	81	13	245	35	79	134	405
\$32	93	90	15	235	39	99	147	424
\$36	103	99	15	251	45	115	163	465

the reservoirs analyzed. The number of thermal projects in the advanced technology case is about two times the number in the implemented technology case at oil prices of \$20/B and higher. This increase is roughly proportional to the increase in reserve additions for thermal processes, indicating that the bulk of the reserves due to advances in this case results from improved project economics; the additional reserves due to advanced technology are coming from reservoirs that were not economic to develop under implemented technology. The large increase in recovery per chemical flood EOR project indicates substantial additional improvements in recovery using advanced technology, particularly at prices in the \$20/B to \$28/B range.

Figure V-2 shows the expected annual EOR production for oil prices of \$16/B and \$32/B for both the implemented and advanced technology cases. At \$32/B, advances in technology could add an additional 135 million barrels per year over implemented technology potential to U.S. oil production within 15 years as a direct result of advanced EOR. The peak production rate of over 380 million barrels per year is 14% of the nation's 1991 production. At \$16/B, advanced technology EOR could generate 40 million barrels per year more than the production estimated under implemented technology before the year 2005, for a total potential production of nearly 100 million barrels per year.

3. Effects on State Revenues

At all oil prices considered in this analysis, the direct revenues to the various oil producing states attributable to EOR could significantly increase with advanced technology (Figure V-3A). Similar to the implemented technology case, production taxes comprise most of the states' total direct revenues with corporate income and sales tax receipts making about the same contribution. Personal income tax receipts contribute the remainder. At the lowest oil price evaluated, state revenues due to advances in EOR technology could amount to just under \$1 billion, nearly equaling implemented technology potential. At \$24/B, advanced technology could generate incremental revenues over implemented technology EOR of nearly \$10 billion; at this oil price, over \$15 billion in direct state and local revenues could be generated by EOR activity. At the higher oil prices of \$28/B to \$36/B, direct state revenues from EOR in the advanced technology case would be equal to or double those generated with implemented technology recovery methods.

Figure V-2

Annual Production from EOR

Implemented Technology vs. Advanced Technology

A) At \$16/B

B) At \$32/B

4. Effects on the National Economy

As discussed in Chapter III, increased oil recovery in the United States through EOR methods would benefit the nation through enhanced energy security, a reduced foreign trade deficit through replacement of imports, expanded direct tax revenues to the Federal treasury, and increased employment. The potential benefits are significantly more pronounced with the development of advanced technology. Up to 11 billion barrels of crude oil could be added to proved reserves due to advanced EOR technology. The 18 billion barrels of potential reserves would represent a significant reduction in imported oil.

Revenues to the Federal treasury, in the form of corporate and personal income taxes, would grow along with reserves as a result of advanced technology (Figure V-3B). At oil prices of \$20/B to \$28/B, technology advances could add between \$1.5 billion and \$7.2 billion to implemented technology potential. At oil prices greater than \$28/B, the incremental increase due to advances in technology could be much more substantial as the Federal EOR tax credit phases out; direct Federal revenues could increase by as much as \$32.6 billion over implemented technology potential for a total of \$55.6 billion. With large increases in direct state, local and Federal revenues, total U.S. public sector revenues increase substantially, particularly at the high end of the analyzed price range (Figure V-4A). Again, the potential is largely driven by the phase out of the Federal EOR tax credit at oil prices above \$28/B.

To the extent that one additional barrel of domestic oil replaces one barrel of imports, advanced technology EOR production also could significantly improve the foreign trade deficit (Figure V-4B). At oil prices between \$20/B and \$28/B, technology advances could increase the amount spent on domestic oil rather than imported oil by \$63.1 billion to \$247.5 billion over implemented technology potential. The total \$107 billion to \$373 billion spent on domestic oil over this price range would be a noticeable reduction in the foreign trade deficit.

Advanced technology also has a positive impact on the nation's employment (Figure V-5). At a relatively high oil price of \$32/B, the development of advanced technology could create or maintain 6,000 to 11,000 jobs per year as an increment over implemented technology between the years 2000 to 2005. Even at the lower oil price of \$16/B, over 2,000 jobs per year could result from development of advanced technology processes in the same time period. Total peak wages (including implemented technology) at \$16/B and \$32/B with advanced technology EOR are estimated at \$180 million and \$1.1 billion, respectively, and would occur before the year 2010.

Figure V-3

Tax Revenue Impact of EOR Technology

Implemented Technology vs. Advanced Technology

A) Direct State and Local Revenues

B) Direct Federal Revenues

Figure V-4

National Impact of EOR Production

Implemented Technology vs. Advanced Technology

A) Total U.S. Public Sector Revenues

B) Imports Avoided*

* To the extent that 1 barrel of domestic oil replaces 1 barrel of imported oil, imports avoided measures the reduction in the foreign trade deficit.

Figure V-5

**Annual Jobs and Wages from EOR Production
Implemented Technology vs. Advanced Technology**

A) At \$16/B

B) At \$32/B

C. RECOVERY OF THE REMAINING MOBILE OIL RESOURCE

1. "Advanced" Technology Defined

The unrecovered mobile oil (advanced secondary recovery) advanced technology case analysis, designed to reflect the potential technological improvements possible from a focused research program in geological reservoir characterization, is conducted in a manner consistent with the implemented technology case analysis. A major assumption is that, by the year 2000, RD&D will improve geologic reservoir characterization techniques to be widely applied, resulting in infill drilling that is targeted only into those portions of the reservoir where project economics will allow drilling to much closer well and injection pattern spacings. This will increase oil recovery and production per well drilled and, therefore, improve the project economics of advanced secondary recovery (ASR), resulting in more activity and much greater recovery under the advanced case than would be possible under the reservoir-wide, blanket drilling program assumed in the implemented technology case. Heterogeneous portions of reservoirs contain a proportionally larger amount of unrecovered mobile oil that is trapped in isolated compartments or bypassed by the injection fluids in conventional recovery operations. By contrast, the more homogenous portions of reservoirs exhibit more efficient conventional recovery and require less intensive drilling. In this study, infill drilling potential is evaluated by dividing each reservoir into two parts, a more continuous (homogeneous) segment and a less continuous (heterogeneous) segment. The economic recovery potential is evaluated independently in each segment, and the closest economic well spacing for each segment is independently selected.

The improved recovery methods discussed in this analysis could have a substantial impact on ASR reserve additions. Additional recovery could be stimulated as the chemical composition of polymer injectants is improved to withstand higher reservoir temperatures (up to 250° F) and/or formation salinities (up to 200,000 parts per million). These improvements would increase the marginal impact of the advanced secondary methods (profile modification and polymer flooding) projected under the implemented technology case whether they are applied alone or in combination with infill drilling. Additional benefits were estimated from the reduction of the associated risk of ASR processes as currently implemented. This was modeled as a reduction in the hurdle rates with technology advances as discussed in Chapter III.

2. Production and Reserves

The development of advanced technology ASR methods through RD&D could significantly increase the nation's oil reserves. Advanced technology ASR could add between 4 and 5 billion barrels to the implemented technology reserves additions across the oil prices considered (Figure V-6). The total ASR reserves potential of 10.8 billion barrels at \$20/B is over 43% of the nation's 1991 proved reserves. ASR is less sensitive than EOR to increases in oil price, but the percentage increase due to advanced technology does decrease with increasing oil price.

Table V-2A shows the distribution of ASR reserve additions by process. Infill drilling in combination with profile modification or polymer flooding would be the most prolific advanced technology ASR process, contributing about 73% of the total additions. Infill drilling by itself decreases from about 38% of the total in the implemented technology case, to only about 12% to 15% in the advanced technology case. This occurs as more of the infill drilling projects are converted to combination projects.

Figure V-6

Incremental Reserves by ASR Process

Implemented Technology vs. Advanced Technology

Table V-2B shows the estimated number of economic ASR projects for both the implemented and advanced technology cases. At all oil prices analyzed, the number of infill drilling projects drops by one-half while the infill drilling reserves drop by 25% to 50% in going from the implemented to the advanced technology case. This corresponds with a 55% increase in the number of combination projects (infill and polymer flooding or profile modification) and a 125% increase in combination project reserves. This behavior can be explained by a shift to combination projects from infill drilling alone by those infill projects which were less effective, along with an increase in the efficiency of combination process projects. The number of economic polymer flooding and profile modification projects under the advanced technology case would increase by about 50% from the implemented case; this increase is proportional to the rise in reserve additions at all oil prices considered. The number of economic projects increases as a result of assumed improvements in the chemical composition of polymer solutions that allow these solutions to withstand more severe reservoir conditions (e.g., higher temperature and higher salinity). Such technological advances would make more reservoirs technically amenable to the economic application of chemical treatment processes.

Figure V-7 displays the projected annual production that could result from ASR technology advances for oil prices of \$16 and \$32/B from the reservoirs analyzed in this study. In both cases, a significant incremental amount of oil could be added to the nation's production over the next 25 years. Production peaks about 2016 in both cases, with a substantial volume of the incremental production occurring in the years beyond 2010.

3. Effects on State Revenues

Under advanced technology, the various oil producing states could receive more than \$14 billion in additional tax revenues over implemented technology for a total of almost \$39 billion from production taxes, corporate and personal income taxes, and oil industry-related sales taxes from activities associated with ASR if oil prices reach \$36/B. This is a 36% increase due to advances in technology (Figure V-8A). At more moderate oil prices (\$20/B to \$28/B), advances in technology could add between \$4.8 billion and \$8.0 billion as an increment to implemented technology potential. The total increase in direct state and local revenues could range from \$15.1 billion to \$25.8 billion over this price range. As in the implemented technology case, the revenue is mostly generated from production taxes and state corporate income taxes. These taxes account for over 90% of the direct state tax revenues added at each of the price levels considered in this analysis. In addition to the increases in state and local revenues, oil producing

Table V-2A

**Incremental Reserve Additions from ASR by Process
Implemented Technology vs. Advanced Technology
(Billion Barrels)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification		Infill Drilling		Infill Drilling and Polymer Flooding or Profile Modification		Total	
	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*
\$16	1.10	1.65	1.41	1.00	3.16	7.05	5.66	9.69
\$20	0.96	1.66	1.67	1.29	3.63	7.84	6.27	10.79
\$24	1.01	1.56	2.60	1.41	3.81	8.41	7.41	11.37
\$28	1.02	1.58	2.74	1.48	3.90	8.87	7.67	11.92
\$32	1.02	1.59	2.98	1.60	3.91	9.14	7.92	12.33
\$36	1.06	1.59	3.12	1.74	3.98	9.26	8.16	12.59

* This is the total reserves with advanced technology -- implemented technology plus the increment due to technology advances.

Table V-2B

**Estimated Number of Economic ASR Projects by Process
Implemented Technology vs. Advanced Technology
(Project Counts)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification		Infill Drilling		Infill Drilling and Polymer Flooding or Profile Modification		Total	
	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced
\$16	131	202	142	67	297	462	570	731
\$20	128	205	166	86	346	522	640	813
\$24	127	204	189	98	367	565	683	867
\$28	127	200	214	104	380	594	721	898
\$32	145	236	234	116	379	592	758	944
\$36	134	211	259	126	386	601	779	938

Figure V-7

Annual Production from ASR

Implemented Technology vs. Advanced Technology

A) At \$16/B

B) At \$32/B

states would benefit from the stimulation of economic activity and creation of new jobs. Operating costs, royalties, intangible investment and sales taxes from ASR projects all make important contributions to each state's economic activity.

4. Effects on the National Economy

As with EOR technology advances, the development of advanced technology for the production of the known unrecovered mobile oil could also benefit the nation. Figure V-8B shows the increase in the incremental revenues to the Federal treasury from personal and corporate income taxes due to advanced ASR technology. Technology advances could add from \$5.6 billion at \$16/B to \$25.8 billion as an increment to potential direct revenues possible using implemented technology ASR. Total direct Federal revenues from advanced technology ASR recovery could range from \$18 billion at the \$16/B oil price to over \$75 billion at \$36/B. Despite the insensitivity of ASR reserves to changes in oil price, potential revenues increase significantly at prices greater than \$28/B due to the phase out of the EOR tax credit which also applies to the use of polymer foams and gels. Almost all of these revenues would stem from increased corporate income taxes. Increases in total public sector revenues (Federal plus state and local revenues) would also increase due to technology advances (Figure V-9A). Over the \$16/B to \$28/B, incremental public sector revenues due to advanced technology could range between \$9 billion and \$23 billion for a total potential public sector revenues of \$28 billion to \$83 billion.

Technology advances would also significantly reduce the amount of money spent on imports (Figure V-9B). Advanced technology ASR could produce an additional 4 to 5 billion barrels over implemented technology further replacing oil imports. This increased production from advanced technology ASR is valued at \$48 billion to \$138 billion. This additional money is directly spent domestically rather than paid to other countries for oil imports to meet the U.S. need for petroleum products. The total value of import replacement of \$134 billion to \$410 billion over the life of these projects would be a significant reduction in the foreign trade deficit.

Figure V-10 presents estimates for the number of jobs and the incremental wages that could result from the application of advanced ASR technology. At a price as low as \$16/B, advanced technology increases and accelerates the annual number of jobs created or maintained. Advanced ASR technology could result in an increase of about 2,000 jobs annually after 2010 at \$16/B. A larger number of incremental jobs are created or maintained by advanced technology applications at the higher price of \$32/B, about 3,000 incremental annual jobs beyond 2010.

Figure V-8

Tax Revenue Impact of ASR Technology

Implemented Technology vs. Advanced Technology

A) Direct State and Local Revenues

B) Direct Federal Revenues

Figure V-9

National Impact of ASR Production

Implemented Technology vs. Advanced Technology

A) Total U.S. Public Sector Revenues

B) Imports Avoided*

* To the extent that 1 barrel of domestic oil replaces 1 barrel of imported oil, imports avoided measures the reduction in the foreign trade deficit.

Figure V-10

**Annual Jobs and Wages from ASR Production
Implemented Technology vs. Advanced Technology**

A) At \$16/B

B) At \$32/B

D. CONCLUSIONS

As discussed in Chapter III, currently available EOR and ASR technologies have the potential to significantly increase reserves and provide substantial economic benefits to operators, the states, and the nation. An aggressive and efficient technology transfer program in both the public and private sectors would bring these available technologies to operators and expedite their field applications. At an oil price of \$20/B, implemented technology EOR and ASR process could contribute over 9.4 billion barrels to the nation's reserves base. At \$28/B, potential reserve additions could reach as high as 13.6 billion barrels.

Advances in technology could significantly increase the potential reserves and associated economic benefits which are possible using implemented technology EOR and ASR. Technology advances could nearly double implemented technology potential reserve additions, adding almost 8 billion barrels, at an oil price of \$20/B. The total potential reserves at this price, over 17 billion barrels, is greater than 70% of the nation's 1991 proved reserves. At an oil price of \$28/B, technology advances could add 14 billion barrels of reserves additions for a total EOR and ASR reserve potential of nearly 28 billion barrels. If this potential were to be realized, advanced technology EOR and ASR would more than replace the nation's 1991 proved reserves.

The activities associated with advanced technology EOR and ASR would generate substantial direct public sector (state and Federal government) tax revenues. At \$20/B, \$21 billion of the \$33 billion of potential direct public sector revenues are attributable to technology advances. At an oil price of \$28/B, over 40% (\$47 million) of the \$114 million in total potential public sector revenues are due to advances in technology. At oil prices above \$28/B, the public sector revenue benefits become more pronounced as the Federal EOR tax credit begins to be phased out. At \$36/B, 46% of the \$206 billion in potential revenues are attributable to advanced technology.

The potential benefits estimated in this analysis will not be possible, however, without effective technology transfer and RD&D programs. Aggressive technology transfer needs to be undertaken by all oil-related entities (operators, producer associations, research universities, state geologic surveys, and state and Federal government agencies) in order to ensure that currently available technologies are disseminated in the oil patch and widely applied in the field. The significant additional benefits derived from technology advances clearly warrant a focused RD&D program to improve advanced oil recovery technologies.

A collaborative effort between the public and private sectors is essential to pool resources and expertise while leveraging risk. Operators, oil companies, research universities, and state geologic surveys need to join with state and local governments and the Federal government to identify the highest priority problems in reservoirs with the largest remaining resources and the greatest threat of abandonment. A focused RD&D effort targeting the identified problems then needs to be undertaken. Chapter V of this volume provides an overview of the approach to this important program and activities already underway to bring it to fruition. An RD&D effort alone is not enough, however, the newly developed technologies need to be transferred to the field for wide-scale demonstration and application. The Department of Energy's Program Opportunity Notice (PON) process is currently applying some of these concepts. The PON process targets those classes of reservoirs with the largest potential resource and greatest threat of abandonments. Near- and mid-term RD&D efforts, jointly funded by the Federal government and private industry, are directed towards the producing problems of these reservoirs. The results, once successfully developed and demonstrated, are to be transferred to other operators facing similar producing conditions. While they are a start, efforts like the PON process are not enough. A more aggressive and focused collaborative RD&D effort will greatly increase domestic production, enhance national energy security, reduce imports, and increase economic benefits associated with oil recovery.

Even after application of advanced technology EOR and ASR, a significant portion of the oil resource will remain unrecovered in the analyzed reservoirs (Figure V-11). At the improbably high oil price of \$36/B, total ASR reserves potential would be 12.6 billion barrels while EOR reserves potential would total 17.9 billion barrels. If this reserves potential were realized, over 57 billion barrels of mobile oil (82% of the mobile oil target) and 132 billion barrels of immobile oil (88% of the immobile oil target) would remain in analyzed reservoirs. In addition, over 131 billion barrels of remaining oil not included in this analysis and any newly discovered oil would still be unrecovered after application of advanced technology EOR and ASR. The known remaining oil-in-place of over 320 billion barrels is the target for further advanced in EOR and ASR technologies. Chapter V discusses an approach to focus research to begin to address key issues limiting oil recovery. By utilizing important findings from this analysis, DOE is identifying reservoir/process combinations likely to maximize future oil recovery.

Figure V-11

U.S. Remaining Oil Resource After Advanced Technology

VI. DEFINING RESEARCH OPPORTUNITIES BASED ON GEOLOGIC RESERVOIR CLASSIFICATION

A. INTRODUCTION: AN INNOVATIVE APPROACH TO PRIORITIZING RD&D

The Department of Energy (DOE), as a major component of its oil program, has a mission to maximize domestic oil recovery. In order to accomplish this goal, DOE's Bartlesville Project Office (BPO) maintains information systems, including TORIS, to provide insights and direction for its oil research program. In addition, BPO seeks to leverage its efforts with state agencies, universities, commercial labs, and operators. As a segment of the National Energy Strategy, the oil program plan is designed to balance competing resources and priorities, and present a cohesive, sensible approach to energy policy.

The current approach to achieving this critical mission begins with an effort to identify the most important research needs facing producers of the most significant domestic reservoirs, (i.e., those with the largest resource and greatest immediate recovery potential). This detailed accounting allows BPO to focus RD&D efforts on eliminating key technical and economic obstacles and reducing major uncertainties limiting domestic oil production. By identifying near-, mid-, and long-term objectives, RD&D can be prioritized based on a quantitative assessment of the potential benefits various resource components could derive.

The success of this approach requires a methodology for combining individual reservoirs into larger groupings (classes) that have similar characteristics and therefore similar research needs to overcome similar production problems. As a part of this study, DOE tasked the IOGCC to work with member states to develop and implement a geologically based classification system that could be applied nationwide. To accomplish this, IOGCC coordinated a multi-year effort and enlisted the assistance of member states' geologic agencies to assign the reservoirs in DOE's TORIS data base to appropriate plays and ultimately to geologic groupings, or classes based primarily upon depositional environment. The results of this study are the first to rely completely on a comprehensive, national assessment using the enhanced and updated database including the newly developed reservoir classification system.

The detailed description of the full classification system has already been published by the DOE¹ and the IOGCC², but this chapter provides an overview of the classification system and its utility to assist DOE in its efforts to focus national oil RD&D. The results indicate that reservoirs in only a few geologic classes account for a vast majority of the recovery potential estimated to be technically and economically viable. Further, the most significant classes identified to meet the near-term objectives are also the most important targets for mid-term and long-term RD&D objectives as well. Therefore, by focusing limited resources on a few significant classes of domestic reservoirs, DOE can assure maximum benefits from its efforts. Further coordination with states and operators with production from these key reservoirs can multiply the benefits which accrue to the nation.

B. CLASSIFICATION OF THE REMAINING OIL RESOURCE

The TORIS reservoirs are classified by depositional environment and, where important, structural or diagenetic features that are critical to understanding, describing, and eventually quantifying reservoir heterogeneity. Due to their unique properties, clastic formations (primarily sandstones) and carbonate formations (primarily limestones and dolomites) are assigned separate classification schemes. Once this fundamental lithology is identified, individual reservoirs are further categorized into classes based upon their unique depositional setting. These settings are defined based on the depositional environment (e.g. fluvial versus marine) and the forces that deposited or altered the reservoir architecture. Where necessary, reservoir classes with extreme diagenetic features were further subdivided. In total, twenty-two (22) unique groupings, or classes, (discussed below) were developed for TORIS reservoirs:

- **Clastic Reservoirs.** Sixteen clastic classes (Figure VI-1) were derived from 28 clastic depositional systems described in the classifier. These classes contain siliciclastic rocks deposited in the paleoenvironmental settings indicated by their names. While some are fairly uniform environments, such as those of the eolian class, others are complex, as in the various deltaic classes. For most reservoirs, a relatively refined description of the depositional processes was possible (e.g., Fluvial-Dominated Deltas), but for others, the

¹ Ray, Michael R., Brashear, Jerry P., and Biglartbigi, Khosrow, "Classification System Targets Unrecovered U.S. Oil Reserves," Oil and Gas Journal (September 30, 1991): 89.

² Geoscience Institute for Oil and Gas Recovery Research, *Reservoir Heterogeneity Classification System for Characterization and Analysis of Oil Resource Base in Known Reservoirs*, prepared for U.S. Department of Energy/Office of fossil Energy, Bartlesville Project Office, 1990.

Figure VI-1

Classification of Clastic Reservoirs

Clastic Reservoirs	Delta	Delta/Fluvial-Dominated
		Delta/Wave-Dominated
		Delta/Tide-Dominated
		Delta/Undifferentiated
	Fluvial	Fluvial/Braided Stream
		Fluvial/Meandering Stream
		Fluvial/Undifferentiated
	Strandplain	Strandplain/Barrier Cores and Shorefaces
		Strandplain/Back Barriers
		Strandplain/Undifferentiated
	Slope-Basin	
	Basin	
	Eolian	
	Lacustrine	
	Alluvial Fan	
	Shelf	

unavailability of data or the complexity of the depositional processes necessitated the use of broader, undifferentiated classes (e.g., Fluvial, Strandplain, Delta).

Carbonate Reservoirs. Six carbonate classes (Figure I-2) were derived from twenty individually described carbonate depositional systems defined in the classifier. The carbonate reservoirs classified were deposited in marine or near marine settings. The class names are descriptive of the location or conditions under which deposition occurred. However, the Shallow Shelf/Restricted carbonate class contains reservoir rock deposited in the nearshore subtidal as well as the shallow shelf environment.

The hypothesis of this approach is that all reservoirs in a defined class will exhibit some similarity in heterogeneity and recovery potential. Because the reservoirs were formed and altered by similar geologic activity, reservoir properties, recovery potentials, and recovery practices will be similar for reservoirs in a class. Hence, findings and demonstration activities in one reservoir will have broader, direct application to many other similar reservoirs. Also, most generic research on understanding basic rock properties and fluid flow will have almost universal application within a class.

Proving this hypothesis will provide major benefits to DOE and to oil producers by focusing research activities and maximizing the benefits of technology transfer programs. Such a system can be used to quickly publicize key class-specific RD&D findings to operators of reservoirs in a particular class. DOE can use such a system to allocate resources to achieve defined research goals with the greatest potential benefit. Also, research can be better coordinated to eliminate redundancies. Researchers and operators of reservoirs in one region can benefit from insights gained by their counterparts in geologically similar reservoirs in other areas, provided technology transfer programs are adequately developed.

When this classification methodology is followed for the TORIS reservoirs, the results indicate that a small number of important classes contain most of the known domestic oil resource (Figure VI-3). The three largest groups, slope-basin clastics, fluvial dominated deltas, and shallow shelf carbonates, collectively account for 141 billion barrels of OOIP. Fifteen percent of the classes account for over forty percent of the resource. These largest classes, combined in some cases with geologically similar smaller reservoir groupings, are the focus of DOE's current efforts in prioritized research.

A distribution of the remaining oil resource, (i.e., oil left in the reservoir at the conclusion of conventional recovery operations), for the most significant geologic groupings is very similar to the

Figure VI-2

Classification of Carbonate Reservoirs

Carbonate Reservoirs	Pertidal	Dolomitization
		Massive Dissolution
		Other
	Shallow Shelf/Open	Dolomitization
		Massive Dissolution
		Other
	Shallow Shelf/Restricted	Dolomitization
		Massive Dissolution
		Other
	Shelf Margin	Dolomitization
		Massive Dissolution
		Other
	Reefs	Dolomitization
		Massive Dissolution
		Other
	Slope-Basin	Other

Figure VI-3

Original Oil-in-Place for 22 Geologic Groupings (Light and Heavy Oil)

As of October 8, 1993

distribution based on original oil-in-place (Figure VI-4). All of the largest groups remain at the top of the priority list, although some reordering is evident. Because this remaining resource is the target for EOR and ASR operations, remaining oil-in-place is an important focal point of RD&D efforts.

While the size of the resource target in each geologic class is an important element in determining its class priority as an RD&D target, the potential recovery of the resource under given economic and technology conditions is also critical. The next section describes the results of the analysis based on estimated EOR and ASR recovery potential over the next ten years. This evaluation provides further focus to the RD&D priorities and activities needed to maximize domestic oil production.

Figure VI-4

Remaining Oil-in-Place for 22 Geologic Groupings (Light and Heavy Oil)

As of October 8, 1993

C. FUTURE RECOVERY POTENTIAL

First order sorting of the results discussed in Chapters IV and V within the defined reservoir classification system provides insights into which reservoir classes stand to realize the greatest benefit from Federal, state, and private efforts to maximize domestic oil recovery.

The overall potential of EOR and ASR under near-term conditions for the top ten geologic classes in the country is significant (Figure VI-5). The current definition of the near-term research objective is to improve the understanding and application of recovery technologies that have already been tested and are currently available for field-wide, commercial application by operators at current oil prices (\$20/B and implemented technology conditions). At current oil prices (\$20/B) and current (implemented) technology, TORIS reservoirs in the top three classes could produce nearly 5.3 billion barrels of oil by defined EOR and ASR methods. This total is over 55% of the total potential for all reservoirs analyzed. If DOE were

to extend RD&D efforts to all top 10 classes, over 9 billion barrels of EOR and ASR would account for 97% of the total national potential.

By focusing demonstration projects and technology transfer programs only in the major geologic classes, DOE has the best chance of maximizing benefits. These efforts can be further focused by concentrating efforts on recovery methods with the greatest potential within each class. For example, advanced secondary recovery (ASR) demonstrations in fluvial dominated deltas (group B) has over ten times the near-term potential payoff of enhanced oil recovery (EOR) projects. Conversely, EOR demonstrations could yield significant benefits in slope-basin reservoirs (group A) where expanded thermal recovery operations are most likely to be profitable in the near-term.

Figure VI-5

**Incremental Near-Term Recovery Potential
Top Ten Geologic Classes*
(\$20/B Oil Price, Current Level of Technology)**

* TORIS Reservoirs only

As of October 8, 1993

However, the current DOE program efforts are not limited to meeting near-term objectives. Advances in technology could alter research priorities if a longer range view is considered. Therefore, the class-based analysis was extended to consider the objective of maximizing recovery over the next ten years and into the next century. This is a key time-frame given the significant number of reservoirs that face abandonment during this period if new recovery technologies are not applied.

The current definition of the mid-term research objective is to directly improve the technical or economic applications of various recovery technologies that could be made commercially available and viable within seven to ten years given an aggressive RD&D effort that addresses key limitations and elevated oil prices (\$32/B, and advanced technology conditions). Details of the assumptions used for the analysis of EOR and ASR under advanced technology are described in Chapter V.

The overall potential for EOR and ASR under mid-term conditions for the top ten geologic classes in the country is even greater than that for the near-term (Figure VI-6). While reordered slightly, the same significant reservoir classes identified in the resource assessment and in the near-term analysis are prominent in meeting mid-term goals. Still, the same three significant classes already identified by DOE as priorities in RD&D are the largest in terms of mid-term recovery potential. By focusing research programs combined with effective demonstration and technology transfer activities in only these classes, over 14 billion barrels of oil could be produced, about one-half of the total mid-term EOR and ASR potential in all reservoirs analyzed. Since the top three classes identified for mid-term RD&D are the same ones identified for the near-term effort, mid-term RD&D to improve oil recovery will benefit substantially from the findings of near-term demonstrations and operator feed-back.

Synergies between improved ASR and EOR could provide additional benefits. Oil recovery potential could be even larger than estimated here because combined applications of the two improved recovery methods usually results in larger recoveries than the summation of independent EOR and ASR projects, as was done in this study.

Expansion to the top ten classes, as originally envisioned by DOE, would account for over 25 billion barrels of EOR and ASR, 88% of the total mid-term potential in all analyzed reservoirs. Again, a small number of reservoir classes contain a vast majority of the future recovery potential. Even if reservoirs in a class prove to be more dissimilar than expected, RD&D focused on improving recovery from the larger reservoirs holds the greatest prospect for success.

Figure VI-6

**Incremental Mid-Term Recovery Potential
Top Ten Geologic Classes*
(\$32/B Oil Price, Advanced Technology)**

* TORIS Reservoirs only

As discussed previously, even with the successful implementation of an aggressive RD&D program and wide-scale application of advanced technologies by a broad range of operators, the remaining known oil resource is massive. The biggest geologic classes will still contain significant quantities of oil that will require even further advances in recovery technology to produce. An additional benefit of the near- and mid-term RD&D efforts will be a much improved understanding and description of the remaining oil resource, hopefully leading to more efficient methods of producing a larger portion of this massive target.

D. DOE APPROACH TO FOCUSING RD&D

DOE has already begun to use the results of this analysis to focus its program. In an effort to leverage disparate, and sometimes overlapping, state, Federal, and private efforts of RD&D, DOE/FE developed a comprehensive Oil Program Implementation Plan to guide its work in this critical area. This plan recommends a program of field-based research on prioritized reservoir classes in order to rapidly develop and demonstrate cost-effective advances in oil recovery technology. The plan also established a framework and organization most likely to realize the enormous production potential of the known domestic oil resource.

Reorganization of the BPO is underway to fully implement the Oil Plan, a comprehensive, multi-disciplinary effort to maximize the Program's benefit to operators and the nation. Three key geologic classes have been identified and work has begun to define the RD&D needs. To date, a total of 25 cost-shared field projects have been awarded in various Fluvial-Dominated Deltaic (Class I) reservoirs and Shallow Shelf Carbonates (Class II). Additional work is currently underway to identify, plan, and fund projects in slope-basin and basin clastic reservoirs (Class III).

A quantitatively based method of focusing RD&D on reservoirs in those geologic classes with the largest resource is the approach most likely to maximize long-range program benefits. However, additional prioritization must consider the near-term (within five years) and mid-term (within ten years) likelihood of recovering this resource. In addition, investigations to resolve critical limitations in currently defined recovery practices will likely lead to the identification of more advanced processes to recover additional oil remaining in the reservoir.

E. CONCLUSIONS

The ongoing efforts by DOE to classify reservoirs in order to improve understanding is beginning to yield important benefits. Most of the known oil resource and much of the advanced process recovery potential estimated in this study lies in a small number of large, potentially prolific reservoir classes. Research and project demonstrations in these key classes holds significant promise for maximizing future oil production.

The work underway in the most important geologic classes holds the greatest potential for cost-effective recovery of the largest volume of domestic oil possible. The top three geologic classes have been identified and screened. Reservoirs in these zones represent forty to fifty-five percent of the resource and recovery potential of all reservoirs analyzed in this study. Future expansion to consider the largest ten classes would provide findings on reservoirs holding nearly all of the potential recovery considered economically viable under realistic economic conditions.

One benefit of this analysis is an improved description and understanding of the resource and a more focused approach to RD&D in important geologic classes. DOE is already using the results of this analysis in its efforts to identify, plan, and implement meaningful EOR and ASR field tests in reservoirs of selected geologic classes. Given the massive identified potential recovery and the significant synergies, these efforts will directly benefit operators, states, and the nation as domestic oil production is increased and U.S. energy and economic security is enhanced.