An Evaluation of Known Remaining Oil Resources in the State of Oklahoma

Project on Advanced Oil Recovery and the States

Prepared by

Interstate Oil and Gas Compact Commission

November 1993

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An Evaluation of Known Remaining Oil Resources in the State of Oklahoma

Volume VII

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**Project on Advanced Oil Recovery and the States
Interstate Oil and Gas Compact Commission**

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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 a part of this larger effort by the IOGCC, this report focuses on the potential economic benefits of improved oil recovery in the state of Oklahoma. Individual reports for seven other oil producing states and a national report have been separately published by the IOGCC. 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 Oklahoma oil reservoirs.
- The remaining resource, over 27 billion barrels, is the target for future improved oil recovery techniques. However, a significant portion of this remaining oil resource has already been abandoned. An even greater portion is in imminent danger of abandonment if cost-effective and efficient recovery techniques are not applied.
- 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 needed to reacquire the leases, rebuild the infrastructure, and more importantly, drill new wells to regain access to the Oklahoma target resource.
- Oklahoma's future as a premier energy producing state depends very 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, given the steady decline in Oklahoma production and reserves and the increased level of well abandonment over the last decade.
- The effective transfer of existing technology could result in 900 million to 1.2 billion barrels of new reserves from analyzed Oklahoma reservoirs at oil prices ranging from \$20/B to \$28/B, more than replacing Oklahoma 1991 proved reserves.
- Technology advances resulting from a focused RD&D effort could result in *additional* post-conventional reserves of 0.6 to 1.1 billion barrels. The effective transfer of existing technology, coupled with the development and application of new technologies, could double or triple current proved reserves in Oklahoma, over the \$20/B to \$28/B price range.
- Public sector revenues from future improved oil recovery activity would total between \$4.5 and \$7.5 billion given currently available recovery practices and oil prices of \$20/B to \$28/B. Technology advances could increase these totals by \$2.0 to \$4.7 billion over the same price range, with roughly 50% of the total flowing to the state treasury.

- Potential improved oil recovery would replace imports of foreign oil, keeping between \$18 billion and \$31 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 higher due to multiplier effects as this money circulates.

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 117 major Oklahoma reservoirs in a consistent manner and on an individual basis, the results of which have been aggregated to arrive at the statewide total as discussed in this report.

Overall, well abandonments and more stringent environmental regulations could limit economic access to Oklahoma'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 oil producers. Development and application of advanced oil recovery technologies could have even greater benefits to the state and 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, Oklahoma oil production could be maximized. The resulting increase in production rates, operator profits, state and Federal tax revenues, and energy security will benefit both the state of Oklahoma and the nation as a whole.

I. OVERVIEW

A. THE PROBLEM: DECLINING OKLAHOMA OIL PRODUCTION

Nearly two-thirds of the oil discovered in the state of Oklahoma will remain trapped in the reservoir at the conclusion of conventional oil recovery operations. The total known original oil-in-place in Oklahoma has been estimated at 41.5 billion barrels (Figure I-1). More than 13 billion barrels had already been produced at the end of 1991. Roughly 700 million barrels of proved reserves are still producible under existing economic conditions, using currently available technologies. The remaining 27.4 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

Oklahoma Oil Resource

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

- Declining state production and reserves. Oklahoma oil production has declined by 35% from 1984 through 1991 (Figure I-2A). Crude oil reserves decreased by more than 20% over the same time period (Figure I-2B). The average size of new field discoveries has been relatively small and reserves per well has decreased.
- Increased level of well abandonment. The state of Oklahoma currently produces oil from roughly 94,000 wells. Many of these wells are "marginal" wells producing at or near their economic limit. In 1990, over 70% of Oklahoma production came from stripper wells. Once production ceases, these wells must be routinely tested to prove that they are not pollution hazards, and plugged and abandoned if they fail the test. In a period of high production costs and low oil price, many of these wells are being abandoned. A recent analysis by the Department of Energy (DOE) has concluded that from 37% to 45% of the nation's remaining oil resources had been abandoned by the end of 1991.¹ 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 rebuild the infrastructure and drill replacement wells.² Such an economic burden will not likely be justified by the incremental oil revenues from future improved recovery techniques.

The future of Oklahoma oil production and reserves depends very strongly on the development and application of cost-effective and efficient technology. In the past, technology advances have made substantial contributions to Oklahoma oil production. The development of new exploration techniques and secondary recovery technology has acted to reverse past production declines and has allowed Oklahoma to maintain and increase its producible oil and gas resources. Oil producers in the state of Oklahoma have also pioneered the development of enhanced oil recovery technologies, particularly improved waterflooding techniques. The opportunity exists for a program of RD&D, combined with an integrated program of technology transfer to all sectors of the Oklahoma petroleum community, to arrest the decline in production and maximize recovery of the state's oil resource.

B. THE OPPORTUNITY: OIL RECOVERY THROUGH ADVANCED TECHNOLOGY

The remaining oil resource constitutes a huge target for future recovery operations. The 27.4 billion barrels of known unrecovered oil in the state of Oklahoma is of two types: mobile oil and

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¹ "Abandonment Rate of the Known Domestic Oil Resource", U.S. DOE, 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

Oklahoma Production and Reserves

A) Annual Production

B) Reserves

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 oil that 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 Oklahoma is 9.6 billion barrels. This oil is an important target for future improved recovery efforts. Several improved primary and secondary recovery processes (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. Processes such as these are relatively low in cost and could increase production levels quickly. While such techniques have already been used by some operators in selected reservoirs, 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 17.8 billion barrel remaining *immobile* oil resource in Oklahoma is the target of 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 ones, 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

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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.

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 117 Oklahoma reservoirs, accounting for nearly 27 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 were 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 tax situation in Oklahoma. The FY 1991 Federal EOR tax credit, as well as state EOR and ASR tax incentives are included in this analysis.
- The results presented in this report reflect only the benefits and reserve potential associated with the 117 analyzed reservoirs (more than 64% of total known Oklahoma OOIP as shown in Figure I-3). No attempt is made to extrapolate the results to the remaining Oklahoma resource not available in the TORIS database.
- All recovery potential evaluated in this report are for future new projects only, and they do not include incremental reserves from existing EOR projects. However, the expansion to the existing projects, if technically and economically feasible, are evaluated as part of future new projects in this report.

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-4. Implemented technology, if more widely applied, could add between 0.9 and 1.2 billion barrels of incremental reserves across the entire oil price range. Advanced technology applied to the same resource base could stimulate an additional 0.4 to 1.3 billion barrels of incremental resources. In effect, improvements in process performance and application could nearly double the reserves possible under implemented technology conditions. 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 negligible if prices remain at or below \$20/B. Incremental recovery at a price of \$28/B would total only about 160 million barrels. However, over a price range of \$20/B to \$28/B, advances in EOR technology

Figure I-3

Oklahoma Oil Resource

Data Coverage of EOR and ASR Analyses

Source: BPO TORIS, 1992

EIA, 1992

API/AGA, 1980

could stimulate an additional 220 to 810 million barrels of incremental reserves. This means that a total of 220 million to 970 million barrels of potential EOR recovery exists under the two levels of technology at oil prices of \$20/B to \$28/B.

Reserve additions attributed to ASR techniques are substantial but are impacted much less by oil price changes than EOR. About 900 million barrels of ASR reserves could be added in the implemented technology case at an oil price of \$20/B, growing only slightly to 960 million barrels as oil prices increase to \$28/B. Research on process improvements, specifically improved polymer flooding and profile modification combined with geologically targeted infill drilling, could increase ASR potential by more than 40%. With advances in technology, incremental ASR reserves could total about 400 million barrels more than implemented technology over the price range analyzed, for a total of 1.3 billion barrels of potential ASR reserves.

Future advanced oil recovery activities will generate revenues for Oklahoma and the Federal treasury through increased production taxes and oil industry-related sales 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, newly implemented improved oil recovery projects in Oklahoma could directly generate \$1.3 billion in state revenues. At the same oil price, advanced technology could generate an additional \$0.7 billion, for a total of \$2.0 billion in state revenues (Figure I-4B). At an oil price of \$28/B, application of currently available EOR and ASR technology could contribute \$2.4 billion to the Oklahoma state treasury while the application of advanced methods could increase these revenues by an additional \$2.3 billion to a total of \$4.7 billion.

Increased production from EOR and ASR could offset oil imports, which in turn, would reduce the national trade deficit, and increase national economic activity. The value of the oil produced, the product of reserves and their effective oil price, is a simple measure of Oklahoma's contribution to reducing the trade deficit. As shown in Table I-1, this figure could total between \$18 billion and \$31 billion under the implemented technology scenario, over the \$20/B to \$28/B range. Advanced technology could further decrease imports by an *additional* \$12 billion to \$34 billion. The additional value of domestically produced oil by EOR and ASR techniques generates significant direct economic activities as capital spending, profits, royalties, and taxes are circulated through the U.S. economy rather than paid internationally to buy foreign oil.

Figure I-4

Potential Impact of Advanced Technology

A) Incremental Reserves

B) Direct State and Local Revenues

Table I-1

Summary of Benefits from Technology Advances in EOR and ASR in Oklahoma

Oil Price and Technology Level	Potential Reserves (Billion Barrels)	Incremental State and Local Revenues (\$ Billions)	Incremental Imports Avoided** (\$ Billions)	Increased Federal Revenues (\$ Billions)
<u>At \$16/B</u>				
Implemented Technology	0.9	1.0	13.8	2.3
<u>Advanced Technology*</u>	<u>0.4</u>	<u>0.5</u>	<u>8.0</u>	<u>1.0</u>
Total	1.3	1.5	21.8	3.3
<u>At \$20/B</u>				
Implemented Technology	0.9	1.3	17.8	3.2
<u>Advanced Technology*</u>	<u>0.6</u>	<u>0.7</u>	<u>11.9</u>	<u>1.4</u>
Total	1.5	2.0	29.7	4.6
<u>At \$24/B</u>				
Implemented Technology	1.0	1.8	23.8	4.1
<u>Advanced Technology*</u>	<u>1.0</u>	<u>1.6</u>	<u>24.3</u>	<u>1.8</u>
Total	2.0	3.4	48.1	5.9
<u>At \$28/B</u>				
Implemented Technology	1.2	2.4	31.1	5.1
<u>Advanced Technology*</u>	<u>1.1</u>	<u>2.3</u>	<u>33.5</u>	<u>2.4</u>
Total	2.3	4.7	64.6	7.5
<u>At \$32/B</u>				
Implemented Technology	1.2	2.9	37.4	6.6
<u>Advanced Technology*</u>	<u>1.2</u>	<u>2.5</u>	<u>37.5</u>	<u>4.1</u>
Total	2.4	5.4	74.9	10.7
<u>At \$36/B</u>				
Implemented Technology	1.3	3.4	43.3	8.1
<u>Advanced Technology*</u>	<u>1.2</u>	<u>3.3</u>	<u>49.5</u>	<u>5.7</u>
Total	2.5	6.7	92.8	13.8

*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.

D. CONCLUSIONS

The development, testing, and wide-scale application of currently available improved oil recovery technologies could stimulate incremental reserves of roughly 1 billion barrels from the state of Oklahoma'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 one-half to one billion barrels could be produced over this price range using EOR and ASR techniques. Even with the successful development and application of these technologies, however, more than 10 billion barrels of immobile oil would still remain in the analyzed reservoirs as a long-term target for future advances in EOR, and more than 9 billion barrels of mobile oil would remain as a long-term target for future advances in ASR processes (Figure I-5). While this target is substantial, it unfortunately will not remain a target indefinitely. Well abandonments have already limited economic access to a portion of the resource. The timely development and application of new recovery technology is crucial to maintain 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 Oklahoma and to the Federal government and substantial additional indirect benefits to both 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 state of Oklahoma, 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 both the state and 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-5

Oklahoma Remaining Oil Resource After Advanced Technology Recovery

II. BACKGROUND AND OBJECTIVES

A. TRENDS IN OKLAHOMA OIL PRODUCTION AND RESERVES

Oil production in Oklahoma, the nation's fourth largest oil producing state, accounted for over 5% of the U.S. lower-48 production in 1991, even though statewide production had fallen to a post-World War II low. Technology advances, including waterflooding, caused Oklahoma production to increase throughout much of the 1960s, reaching a decade high level of almost 231 million barrels in 1967 (Figure II-1). Production then began a long decline continuing to this day, which was interrupted only by a brief period of recovery from 1980 to 1984 when oil prices reached their highest levels ever. From 1967 until 1979, the first period of major decline, production dropped to a 1979 low of 144 million barrels annually, an average decline of over 3% per year (Figure II-1). Production stabilized and increased slightly from 1980 to 1984, rebounding to almost 168 million barrels in 1984. The price collapse of 1985-1986 ended this period of improvement, and production has since dropped to an all-time low of 92 million barrels in 1992. This downward trend (over 5% decline per year) seems likely to continue in the future due to poor project economics brought about by low oil prices, limited technologies, and a relatively restricted number of remaining exploration and development opportunities in what has been an actively explored state.

Similar trends can be seen in Oklahoma's crude oil reserves (Figure II-2). Reserves peaked in 1955 at two billion barrels, but since then have declined steadily to less than 35% of that total. Although reserves fluctuated briefly during the exploration boom from 1980 to 1984, lower oil prices brought a resumption of the downward trend in the years that followed. At the peak of exploration, the number of Oklahoma producing wells jumped over 40%, climbing from fewer than 72,000 in 1975 to more than 102,000 in 1985 (Figure II-3). Well levels in the following five years declined to around 95,000 in 1990 but increased to over 101,000 wells in 1991. This increase is partially due to an increase in the number of well recompletions and operation of extra rigs. Most of these additional producing wells represent more intensive field development efforts by Oklahoma operators, as can be witnessed by the consistent declines in reserves per producing well since 1975 (Figure II-3). Oklahoma reserves per producing well now stand at close to 7,000 barrels, less than 40% of the 18,000 barrels reported in 1971.

Compounding the problem of reduced reserves and production is the increased number of economically marginal stripper wells over the past twenty years (Figure II-4). Stripper wells produce

Figure II-1

Oklahoma Crude Oil Production (1950 - 1991)

Figure II-2

Oklahoma Crude Oil Reserves (1950 - 1991)

Figure II-3

Figure II-4

small quantities of oil (and often large volumes of water) and are extremely vulnerable to price changes. Another oil price collapse would result in mass abandonments of stripper wells and immediate loss of access to the reservoirs which are penetrated by them. For all intents and purposes, once reservoirs are abandoned and the wells are plugged, improved recovery techniques are economically infeasible.

Together, these trends indicate the maturity and advanced stage of development of Oklahoma's resource base. These trends have major implications for employment, economic activity, and the tax base in Oklahoma. In 1975, Oklahoma had over 38,000 people employed in the extraction of oil and gas (Figure II-5). This number rose to 102,000 in 1982, when drilling activity reached its peak, but has since declined to just over 40,000 in 1991. Over the same period, the wellhead value of oil produced in Oklahoma increased from \$2.8 billion (in constant 1991 dollars) in 1975 to a peak of \$6.5 billion in 1981, before plunging back to \$2.1 billion in 1991 (Figure II-6). These changes in employment and the production value of oil have adversely affected Oklahoma's tax base. Persistence of the oil production decline will continue to have a detrimental effect on the economic vitality of the state and its treasury, unless the slide can somehow be arrested.

Revenues from production taxes on oil and gas increased from \$211 million (in constant 1991 dollars) in 1973 to a peak of nearly \$871 million in fiscal year 1984, only to decline by 53% to \$412 million in fiscal year 1992 (Figure II-7). This significant loss in state revenues has been caused by the dual effect of lower product prices and declining oil and gas production, trends which expected to continue. The loss of oil and gas revenue has had a significant impact on total state tax revenues. In fiscal year 1983, when oil prices were still high, oil and gas production taxes contributed more than 26% of all state tax revenues in Oklahoma (Figure II-8). This percentage has fallen dramatically, to just over 10% of total tax revenues in fiscal year 1992. Oil production severance taxes represent more than 4% of the total taxes collected in Oklahoma. Despite significant revenue losses caused by the decline in oil and gas production, revitalization of the Oklahoma economy is beginning to occur through diversification of the industrial base in the state. However, oil and gas production will continue to play a vital role in the state's economy and recovery of the remaining resource could be maintained by encouraging the application of enhanced recovery techniques.

Vast quantities of Oklahoma's known oil resource will remain unrecovered in known reservoirs at the conclusion of conventional primary and secondary operations. The total known original oil-in-place (OOIP) in Oklahoma is estimated at 41.5 billion barrels (Figure II-9). Of this resource, 13.4 billion barrels

Figure II-5

Total Oil and Gas Employment in Oklahoma (1970 - 1991)

Figure II-6

Annual Wellhead Value of Oklahoma Oil and Gas Production (1961 - 1991)

Figure II-7

Oklahoma Oil and Gas Severance Taxes (FY1971 - 1992)

Figure II-8

Oklahoma Oil and Gas Severance Taxes as a Percent of Total State Taxes (FY1971 - 1992)

have already been produced, and 700 million barrels were recognized as proved reserves at the end of 1991, for a total estimated ultimate recovery by conventional technology of 14.1 billion barrels. The remaining 27.4 billion barrels, nearly two-thirds of the total known resource, remains as the target for newer, more efficient extraction technologies.

The 27.4 billion barrels of remaining unrecovered oil falls into two categories: mobile and immobile oil. Unrecovered mobile oil, which has been bypassed by conventional primary and secondary recovery efforts, accounts for 9.6 billion barrels of the unrecovered resource. This oil is the target for polymer flooding, profile modification, and infill drilling, known collectively as advanced secondary recovery (ASR). The remaining 17.8 billion barrels represent immobile oil that must be recovered by a variety of tertiary recovery technologies that are collectively known as enhanced oil recovery (EOR).

Figure II-9

Oklahoma Oil Resource

Should ASR and EOR projects be actively initiated in Oklahoma, much of the state's production and oil activity could be sustained well into the next century. A brief discussion of the analyzed EOR and ASR processes is contained in Volume X, Appendix A.

B. IMPROVED RECOVERY ACTIVITIES TARGETING THE REMAINING RESOURCE

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 operations have recovered a significant portion of the original concentration of oil. The oil remaining in this 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 oil; the swept zone is at the "waterflood residual" level of oil saturation. The volume previously occupied by displaced oil now contains injected water (or, in some cases, natural gas). In their current stage of development, EOR processes are generally expected to reach only those portions of reservoirs previously swept by conventional techniques.

In the unswept zone of the reservoir, conventional recovery processes have not swept the pore space, and the oil saturation can range from low to high depending upon the primary recovery mechanism (e.g., pressure depletion or water drive). The objective of many infill drilling programs, improved waterflooding projects (profile modification), and other reservoir management techniques is to contact the oil in the unswept zones. Only after these zones have been swept by water are EOR operations generally considered feasible.

1. Enhanced Oil Recovery

Proven enhanced recovery processes are classified into three EOR categories: gas-miscible, chemical, and thermal. Miscible flooding projects have been ongoing for several years in Oklahoma. At least two of this state's projects used nitrogen as an injectant. Phillips has performed nitrogen flooding in the Binger field of Caddo County since 1977. The results have been very successful with production of 1,800 barrels of oil per day. Another type of injectant used in Oklahoma is hydrocarbon; Oxy USA has been using this in the Northeast Purdy field in Garvin County to produce more than 2,000 barrels of oil per day. Despite limited availability of carbon dioxide, operators commonly utilize it for flooding. Several pilot projects and at least one commercial project have been conducted using this injectant.

ARCO's Garber field in Garfield County showed successful recovery results utilizing carbon dioxide flooding. The carbon dioxide-miscible projects in Oklahoma received this gas from an industrial source. Cities Service and Atlantic Richfield built a 140-mile pipeline to take carbon dioxide from Farmland Industries fertilizer plant near Enid, and deliver it to the Garvin and Stephens counties' fields. This pipeline, which can transport 33 million cubic feet of carbon dioxide per day, started its delivery in September 1982.

Chemical flooding EOR (surfactant and alkaline flooding) has shown some promise in Oklahoma. Nevertheless, the high cost of chemicals combined with limited field applications have made these projects economically risky, especially in periods of fluctuating oil prices. The development of low cost, widely applicable chemicals is necessary for this technique to achieve its full potential. In particular, alkaline flooding has limited applications and potential, due to the characteristics of the reservoirs in Oklahoma.

Thermal EOR processes include steam drive, steam soak, and in-situ combustion. The hydrocarbon displacement properties and the economics of steam soak and steam drive processes have been extensively demonstrated in several locations, especially California. Steam EOR projects account for about three-fourths of all EOR production in the U.S. and are recognized as commercially proven technologies in heavy oil (less than 20° API gravity) reservoirs at depths less than 3,000 feet. At least one steam project is underway in Sho-Vel-Tum field of Carter County in Oklahoma, with promising results. Despite some promising projects, its further application to Oklahoma's reservoirs may be limited due to unfavorable reservoir characteristics and relatively higher process costs. Thermal recovery, however, remains the prevalent EOR technique in the U.S., and therefore, could ultimately have wider applications in Oklahoma.

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 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 spacing.

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.

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 Oklahoma reservoirs. In the Mississippi Limestone in southwestern Garfield County, Oklahoma, infill drilling began as early as 1970. Union Texas Division of Allied Chemical Corporation drilled new wells to test the adequacy of drainage by the original well. The results justified additional developments, and a significant number of new wells

have since been drilled.¹ Throughout the years, operators have been able to decrease the average drilling times and well costs by approximately 45% through the optimization of both air and mud drilling practices, streamlining of casing programs, and an increased ability to avoid downhole problems.² The results have indicated recovery improvements that are attractive under the current economic conditions. Further advancement in technologies used in this process will optimize the recovery level, and thus increase this technique's profitability.

Clearly, some portion of the oil bypassed at current spacing can be recovered by well-designed, advanced waterflooding techniques, and significant portions of this oil could be recovered with the combined application of both polymer injection and infill drilling. Polymer flooding seems to be the current process of choice in Oklahoma. Over 20 polymer projects have been conducted since 1980 by Mobil, Phillips, and other operators. These projects have been generally proven to be economically profitable. Although high chemical costs constrain its utilization at low oil prices, polymer flooding holds significant potential for future recoveries. Profile modification also could significantly increase production in Oklahoma.

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.

There are several other processes and recovery techniques which were not included in this analysis which may have potential in Oklahoma. Application of these techniques would further increase potential recovery and add to the estimates contained in this analysis. Immiscible gas and nitrogen gas EOR projects could enhance Oklahoma oil recovery. In addition, improvements in reservoir management and

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¹ Maddox, G.D., "Infill Drilling in the Mississippi Limestone — Garfield County, Oklahoma," SPE Paper No. 6462, 1977.

² Flournoy, C.M., "The Optimization of the Red Oak Infill Drilling Program in the Arkoma Basin," SPE Paper No. 18054, 1988.

improvements in waterflood patterns, waterflood rates of injection, and the timing of inception of water floods show significant potential as recovery techniques. To the extent that these techniques and others currently being transferred (i.e., injection water compatibility) improve potential oil recovery, the results presented in this report will be understated.

C. OBJECTIVES OF THE PRESENT STUDY

The present study analyzes the incremental reserves, public sector revenues, and statewide 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 widespread application of currently available technology, and *advanced technology*, which assesses the impact of the effective 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 RD&D. 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.

One hundred and seventeen reservoirs, accounting for 26.6 billion barrels of original oil-in-place (over 64% of the total known resource in Oklahoma), were included in this analysis. These reservoirs contain 18.2 billion barrels of remaining oil resource (Figure II-10). The 6.6 billion barrels of UMO is the target for application of ASR processes and 11.6 billion barrels 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 RD&D program to improve recovery methods (advanced technology) and subsequently transfer those methods to a broad public-private audience. The results and conclusion 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-10

Oklahoma Remaining Oil Resource After Conventional Operations

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

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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 focused 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

• <u>Original Volumetrics</u> -- Original Oil-in-Place -- Reservoir area -- Net thickness -- Porosity -- Initial water saturation -- Initial oil saturation -- Initial formation volume factor • <u>Current Volumetrics</u> -- Current oil saturation (swept zone) -- Current formation volume factor • <u>Fluid Data</u> -- Oil gravity and viscosity -- Connate water viscosity -- Connate water salinity -- Initial GOR -- Current GOR -- Injection water salinity -- Crude oil fractions & properties (being added)	• <u>Geologic Variables</u> -- 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) • <u>Development & Performance Data</u> -- 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

Screening Criteria for EOR Candidates-Implemented Technology Case

Table III-2

		Miscible Flooding		Chemical Flooding	Alkaline	(Carbon Dioxide)	Steam	In-Situ Combustion
Screening Parameters*		Units		Surfactant	Alkaline		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	---		>40	---		≥0.20***	≥0.20***
Permeability Average (k)	md	>40		>20	---		250	35
Transmissibility (kh/μ)	md-ft/cp	---		---	---		≥5	≥5
Reservoir Pressure (PR)	psi	---		---	---		≤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.

Table III-3

Screening Criteria for EOR Candidates-Advanced Technology Case

Screening Parameters*	Units	Chemical Flooding		Miscible Flooding	Thermal Recovery	
		Surfactant	Alkaline	(Carbon Dioxide)	Steam	In-Situ Combustion
Oil Gravity	°API	---	<30	≥25	---	---
In-situ Oil Viscosity (μ)	cp	<100	<100	---	---	≤5,000
Depth	Feet	---	---	---	≤5,000	---
Pay Zone Thickness (h)	Feet	---	---	---	≥15	≥10
Reservoir Temperature (TR)	°F	<250	<200	---	---	---
Porosity (ϕ)	Fraction	---	---	---	≥0.15***	≥0.15***
Permeability Average (k)	md	>10	>10	---	≥10	≥10
Transmissibility (kh/ μ)	md-ft/cp	---	---	---	---	---
Reservoir Pressure (PR)	psi	---	---	≥MMP**	≤2,000	≤4,000
Minimum Oil Content at Start of Process ($S_o X \phi$)	Fraction	---	---	---	≥0.08	≥0.08
Salinity of Formation Brine (TDS)	ppm	<200,000	<200,000	---	---	---
Rock Type	---	Sandstone or Carbonate	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.

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 research, development, and demonstration (RD&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

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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 the 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 Recovery 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	- 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	- 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 or ASR process and the

level of technology. The risk premium is modeled as an increase in the hurdle rate as shown by Table III-6. 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 -Miscible	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 state and national economies. 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 117 of the largest Oklahoma reservoirs, accounting for over 64% of estimated original oil-in-place (OOIP) in Oklahoma. The reservoirs represented in the data base include oil zones in every region of the state. 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 Oklahoma. 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 structure in Oklahoma, including tax incentives for EOR and ASR projects. This incentive provides forgiveness for production taxes for the first three project years or until project payback (whichever comes first) for all qualified EOR and ASR projects. In this analysis, it is assumed that all EOR and ASR projects qualify for the incentive.

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.

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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

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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 generally small relative to the total benefit, but important to the overall aggregate analysis.

1. Benefits to State and Local Treasuries

The benefits to Oklahoma 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 the state's treasury is only one segment of the benefits of advanced oil recovery processes. The citizens of Oklahoma 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 the state 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 the state of Oklahoma 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 citizens of Oklahoma. 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 Oklahoma, 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 Oklahoma (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 Oklahoma 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 Oklahoma and its citizens.

The additional jobs, wages, and benefits created by improved 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 Oklahoma oil resource. Direct Federal 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 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 excludes 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

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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 in Oklahoma 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 the 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 date 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 OKLAHOMA 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 Oklahoma reservoirs. 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 refer 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 117 reservoirs for their EOR and ASR potential. The results of this analysis were not extrapolated to the rest of the reservoirs making up the Oklahoma resource.

B. RECOVERY OF THE REMAINING IMMOBILE OIL RESOURCE

1. Production and Reserves

With currently implemented technology, potential recovery using EOR technologies in Oklahoma is severely limited over the price range analyzed. EOR processes (carbon dioxide (CO₂)-miscible) would

not be economic until oil prices reach \$24/B, and then could yield 90 million barrels of incremental reserves. The outside potential of implemented technology at \$36/B is 160 million barrels, representing a 23% increase in the state's current proved reserves (700 million barrels in 1991) (Table IV-1A and Figure IV-1A).

The analysis model (as discussed in Chapter III) projects the timing of incremental reserves and production from projects which (a) have completed primary production; (b) are economically viable; and (c) may be started under a series of national-level constraints on financial factors (such as investment capital) and resources (such as carbon dioxide). Since the potential for implemented technology in Oklahoma is limited to one CO₂-miscible project at \$24/B and two such projects at prices over \$28/B, the precise timing of reserve additions has considerable uncertainty. The expected time-series of production at \$24/B and \$32/B is shown in Figure IV-1B.

At \$24/B, the single EOR project would not be available for tertiary operations until the year 2000. Conventional waterflooding will not reach its economic limit until the year 2000, at which time the CO₂-miscible EOR project would be started, using current implemented technology. In this case, production could gradually increase as patterns are added, reaching a peak of 8.4 million barrels per year, in 2012. At \$32/B, two projects could be economic and production could peak at 10 million barrels in 2013. Although those quantities are small, they would represent 9% and 11%, respectively, of Oklahoma's 1991 oil production of 92 million barrels.

2. Increases in State and Local Revenues

Production from Oklahoma EOR projects could also increase state and local revenues through production taxes, sales taxes on purchased materials used in the projects, and corporate and personal income taxes. Oklahoma does have an EOR tax incentive which provides production tax forgiveness for three years or until project payback, whichever comes first. The potential production tax revenue presented here represents tax receipts after expiration of the incentive. The estimated revenues would be generated directly from oil production or operations in the analyzed reservoirs. Once a project is economically viable, the state and local revenues generated over the life of the EOR project is largely a function of oil prices. A significant portion of these revenues could result from production taxes. At prices below \$24/B, no projects would be economically viable using current technology, and therefore, no additional revenue would be generated for the state (Figure IV-2). However, at \$24/B, about \$192

Table IV-1A

**Incremental Reserves from EOR by Process
Implemented Technology
(Million Barrels)**

Oil Price (\$/B)	CO ₂ -Miscible	Chemical	Thermal	Total
\$16	0	0	0	0
\$20	0	0	0	0
\$24	90	0	0	90
\$28	159	0	0	159
\$32	160	0	0	160
\$36	160	0	0	160

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	0	0	0	0
\$20	0	0	0	0
\$24	1	0	0	1
\$28	2	0	0	2
\$32	2	0	0	2
\$36	2	0	0	2

Figure IV-1

Reserves and Production Response from CO₂-Miscible EOR Techniques

Implemented Technology

A) Incremental EOR Reserves from CO₂-Miscible Projects

- * There was no economic thermal or chemical reserves potential in analyzed reservoirs.
- ** No EOR projects were economic in analyzed reservoirs for oil prices below \$24/B.

B) Annual Production from CO₂-Miscible EOR Reserves

Figure IV-2

Direct State and Local Revenues from EOR Production Implemented Technology

* No EOR projects were economic in analyzed reservoirs for oil prices below \$24/B.

million in incremental revenues could be generated, with production taxes contributing over 75% of the total and corporate income and sales tax revenues accounting for most of the remainder. At a \$28/B oil price, one additional project could be economic. Production tax revenues of \$308 million plus \$35 million in sales tax receipts and income taxes of \$58 million, for a total of \$401 million could be received by the state. At the outside potential, \$512 million in state revenue could be generated by implemented technology at an oil price of \$36/B.

3. Effects on the State Economy

In addition to increasing direct state and local tax revenues, implemented technology EOR would benefit Oklahoma by increasing economic activity and by creating new jobs. The effects of EOR on the state economy are estimated conservatively: (1) only direct effects are included (i.e., no economic multiplier due to secondary effects); and (2) the direct effects are limited to benefits believed to accrue predominantly to the state of Oklahoma and its citizens. Only intangible drilling costs, royalties, state and

local taxes (as defined in the previous section), and operating costs, exclusive of purchased injectants, are included in the calculation of state economic activity. Tubular steel products, injection and production equipment, purchased EOR injectants, corporate return on capital, and Federal taxes are all excluded from this definition of state economic activities. Royalties may be overstated to the extent that they are paid to the Federal government (i.e., for production on Federal lands). While the excluded elements undoubtedly aid Oklahoma's citizens to some degree, a substantial portion of the benefits will be enjoyed by citizens of other states. The calculated economic effects are understated, however, to the extent that local manufacture or retail sales of these cost items provide economic benefits within Oklahoma, injectants produced or manufactured in Oklahoma are employed, or economic "multipliers" occur.

At oil prices below \$24/B, current EOR technology would not increase in-state economic activities. At high oil prices, operating costs could account for at least 62% of these economic effects; state taxes could represent around 15%; intangible investment could be about 2%; and royalties could constitute about 21% of the total (Figure IV-3). At \$24/B, incremental benefits to the state economy could exceed \$1.3 billion. At the highest oil price considered, an estimated \$3.4 billion of statewide direct economic activity could be stimulated by EOR projects. The small number of implemented technology EOR projects could generate from \$36 million at \$24/B to \$49 million at \$32/B in additional wages during peak years and create or maintain from 800 to 1,100 additional jobs (Figure IV-4).

4. Effects on the National Economy

Increased oil recovery from EOR in Oklahoma would also benefit the nation as a whole. National benefits would accrue in several ways: increased Federal corporate and personal income tax revenues, replacement of oil imports, and a reduction in the foreign trade deficit. An additional barrel of domestic oil production could replace a barrel of imported oil; thus, any increase in production could enhance the nation's energy security. The addition of as much as 90 million to 160 million barrels of reserves in Oklahoma would expand the nation's proved reserve base.

EOR activity in Oklahoma contributes to the Federal treasury through personal and corporate income taxes on operator profits and wages (Figure IV-5A). At \$24/B, EOR activity could increase direct Federal revenue by \$13 million. At \$36/B, \$578 million could be stimulated by EOR. At or above \$32/B, corporate income taxes could account for between 77% and 84% of this total, depending on the oil price, and personal income taxes makes up the remainder.

Figure IV-3

Direct State Economic Activity* from EOR Production

- * To the extent that royalties go to the Federal government (i.e. fields on Federal lands), royalties as a portion of state economic activity may be overstated.
- ** No EOR projects were economic in analyzed reservoirs for oil prices below \$24/B.

Figure IV-4

Jobs and Wages from EOR Production

As imports are replaced by domestic production, funds that would otherwise flow to oil exporting countries to pay for imported oil could be spent domestically. Thus, EOR in Oklahoma could help reduce the trade deficit, enabling this money to instead circulate through the U.S. economy, creating additional benefits. Imports avoided through the implementation of current EOR technology in Oklahoma would be valued at \$2.2 billion added over the life of the projects at an oil price of \$24/B (Figure IV-5B). The outside potential of imports avoided could reach \$5.8 billion at \$36/B. The benefit of the avoided imports reflects the value of increased domestic production (effective wellhead price multiplied by reserves).

C. RECOVERY OF THE REMAINING MOBILE OIL RESOURCE

This section will discuss the application of currently available advanced secondary recovery (ASR) processes, which target mobile oil, on the same set of reservoirs. These recovery technologies are distinct, and, since they focus on mutually exclusive resource targets, the amounts of oil recoverable from each are additive. Both technologies could be implemented in individual Oklahoma reservoirs and, if done, the benefits (resource, revenues, economic activity, etc.) would be additive. There are some potential synergies due to economic efficiencies associated with simultaneous employment of the EOR and ASR technologies; thus, there is the possibility that economic benefits could be even greater than the sum of the benefits from this separate analysis of EOR and ASR techniques.

1. Production and Reserves

The resource potential from applying ASR techniques to Oklahoma reservoirs is not particularly sensitive to oil price. At oil prices ranging from \$16/B to \$36/B, ASR could stimulate between 870 million and 1.1 billion barrels of incremental reserves in Oklahoma. At \$20/B, incremental ASR reserves could amount to nearly 900 million barrels, which is 83% of the nearly 1.1 billion barrels of oil economically accessible at \$36/B.

This analysis evaluates three categories of ASR processes -- profile modification and polymer flooding, infill drilling, and infill drilling in combination with profile modification or polymer flooding (combination processes). As shown in Figure IV-6A and Table IV-2A, infill drilling, both by itself and in combination with other processes, could play a predominant role in ASR recovery, accounting for most of the incremental reserves at all analyzed oil prices. At oil prices of \$20/B and lower, the combination processes could contribute from 454 to 458 million barrels of reserves, while infill drilling alone could

Figure IV-5

National Impact of EOR Production

Implemented Technology

A) Direct Federal Revenues

* No EOR projects were economic in analyzed reservoirs for oil prices below \$24/B.

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.

** No EOR projects were economic in analyzed reservoirs for oil prices below \$24/B.

contribute 329 million to 354 million barrels of reserves. At or below \$32/B, the percentage of total ASR reserves stemming from infill drilling, either alone or in combination with other processes, would account for at least 90% of the total potential.

As oil prices increase, infill drilling by itself could become more economic. At \$28/B, infill drilling alone would contribute nearly 40% of the 957 million barrels of total incremental reserves, close to the 51% contribution by the combination processes. At an oil price of \$32/B, infill drilling by itself could stimulate 431 million barrels (about 43%) of the 1.0 billion barrels of incremental reserves while the combination processes account for 49% (over 490 million barrels). At \$36/B infill accounts for 41% of the 1.1 billion barrel potential, while combination processes yield 47%.

Table IV-2B shows that between 51 and 57 ASR projects could be economic in Oklahoma over the analyzed oil price range. Most of these projects use infill drilling, either alone or in combination with other processes. Across all considered oil prices, infill drilling projects account for 83% to 86% of all projects, roughly split between infill drilling applied alone and the combination processes.

Applied without infill drilling, polymer flooding and profile modification projects could contribute between 87 to 126 million barrels to Oklahoma reserves across all oil prices considered in this analysis, about 10% of the total potential. This apparent lack of sensitivity to oil price does not mean that these techniques are of marginal importance. Rather, as the oil price rises, the more expensive, but more prolific, infill drilling and combination projects become economic. Thus, reservoirs that would utilize polymer flooding and profile modification projects at lower oil prices would switch to the more prolific techniques at higher oil prices. In fact, the bulk of incremental reserves could be attributed to combining polymer flooding and profile modification with infill drilling at all considered oil prices.

Figure IV-6B displays the expected annual production from all ASR processes at oil prices of \$16/B and \$32/B. As shown above, the dominant ASR technique could be infill drilling, either alone or in combination with polymer flooding or profile modification. The incremental reserves from ASR therefore require a considerable amount of drilling. At \$16/B, the incremental ASR reserves could replace Oklahoma's existing reserves. However, ASR must compete for drilling capital and infrastructure capacity (rigs, crews, investment dollars) with other oil industry activities such as domestic exploration, gas drilling, and international ventures. This could slow the pace of ASR development in some reservoirs. A substantial portion of the potential ASR reserves is thus at risk of abandonment prior to the availability

Table IV-2A

**Incremental Reserves from ASR by Process
Implemented Technology
(Million Barrels)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification	Infill Drilling	Infill Drilling with Profile Modification or Polymer Flooding	Total
\$16	87	329	454	870
\$20	87	354	458	899
\$24	89	356	460	905
\$28	90	381	486	957
\$32	90	431	492	1013
\$36	126	432	492	1050

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 with Profile Modification or Polymer Flooding	Total
\$16	9	21	21	51
\$20	9	23	21	53
\$24	9	23	21	53
\$28	8	25	22	55
\$32	8	27	22	57
\$36	8	27	22	57

Figure IV-6

Reserves and Production Response from ASR Techniques

Implemented Technology

A) Incremental Reserves by ASR Process

B) Annual Production from ASR Reserves

of drilling resources for its development. Over 36% of the potential reserves could be abandoned over the life of the projects.

Annual ASR production at an oil price of \$16/B could average about 9.9 million barrels per year over the 1993 to 2020 period. At an oil price of \$32/B, annual production could average over 11.6 million barrels per year over the same period. To put the potential contribution of ASR into perspective, 9.9 million barrels per year would add about 11% to Oklahoma's 1991 oil production rates and 11.6 million barrels per year would add 13%.

2. Increases in State and Local Tax Revenues

Figure IV-7 shows the expected growth in state revenues from ASR production and the proportional contributions of production taxes, sales taxes, and corporate and personal income taxes to the total. Production tax receipts account for the largest portion of total state revenues from ASR over all prices considered. Production taxes alone would generate \$613 million of the \$992 million in direct state tax revenues at \$16/B. At \$24/B, about \$1.6 billion could be generated for the state through ASR activities, with 61% of that amount from production taxes. At \$36/B, nearly \$2.9 billion in direct state and local revenues could be generated from implemented technology ASR activities. State corporate income tax receipts could contribute \$310 to \$900 million (around 32%) of the total direct state revenues across the analyzed oil price range.

3. Effects on the State Economy

Figure IV-8 displays the total state economic activity in Oklahoma associated with potential ASR production. Total state economic activity from the processes could range from \$6.5 billion at \$16/B to \$15.8 billion at \$36/B. At intermediate oil prices, state economic activity could be increased by \$7.9 billion at \$20/B and \$11.4 billion at \$28/B due to ASR activities. Due to the predominance of infill drilling projects, the intangible portion of drilling and developing investment could be a significant contributor to state economic activity. At \$16/B, 42 of 51 economic projects could involve infill drilling and intangible investment could account for \$1.9 billion (29%) of the \$6.5 billion of direct in-state economic benefits. At the \$16/B price, operating costs (excluding injectants) could provide 29% of the benefits, while royalties could provide 26%. At \$36/B, 49 of 57 viable projects could involve infill drilling. At this very high price, royalty payments of \$4.7 billion could contribute nearly 30% of the

Figure IV-7

Direct State and Local Revenues from ASR Production Implemented Technology

\$15.8 billion in state economic activity. Intangibles could drop to 27% of the total, while operating cost could account for over 25%.

The implementation of ASR techniques could significantly contribute to employment in the state of Oklahoma. Figure IV-9 displays the annual number of jobs that would be created or maintained by ASR projects. The annual trends in jobs created or maintained closely match the production trends for ASR. At an oil price of \$16/B, jobs could peak at 486. At \$32/B, the number of jobs created or maintained could peak at about 875. At this price, as much as \$39 million in wages could be paid in the peak employment year.

4. Effects on the National Economy and Budget

Figure IV-10 shows the national benefits of implementing current technology ASR in Oklahoma. Federal revenues from ASR production could range from about \$2.3 billion to more than \$7.5 billion over the oil price range analyzed. Figure IV-10A shows that nearly all of these revenues could stem from corporate income taxes. At moderate oil prices (\$20/B to \$28/B), implemented technology ASR activities could increase direct Federal revenues by \$3.2 billion to nearly \$5.0 billion.

Figure IV-8

Direct State Economic Activity* from ASR Production

* To the extent that royalties go to the Federal government (i.e. fields on Federal lands), royalties as a portion of state economic activity may be overstated.

Figure IV-9

Jobs and Wages from ASR Production

The addition of 870 million to 1.1 billion barrels of domestic oil could significantly replace imported oil. To the extent that one barrel of domestic oil replaces one barrel of imported oil, the trade deficit would be reduced and the value of the domestic oil would be spent in the U.S. economy rather than abroad. Imports avoided by ASR production in Oklahoma could be valued between \$13.8 billion and \$37.5 billion over the oil price range analyzed (Figure IV-10B). As the increased Oklahoma production replaces oil imports, the U.S. trade deficit would be reduced and national security would be enhanced as the nation's vulnerability to future supply disruptions is diminished. This additional domestic spending from avoided imports could greatly impact the economy, as other activity is indirectly stimulated by economic multipliers.

D. CONCLUSIONS

At implemented technology levels, EOR and ASR processes could make a significant contribution to the reserve base and the Oklahoma and national economies, as well as to domestic energy security. At a \$24/B oil price, EOR processes could add 90 million barrels to Oklahoma reserves while ASR techniques could add nearly 900 million barrels of incremental reserves. The application of current EOR and ASR technologies in concert could potentially add nearly 1.0 billion barrels of incremental reserves at this price, more than replacing Oklahoma's current proved reserves. As discussed in the next chapter, improved geoscientific understanding of reservoirs and enhanced process performance could increase these benefits if the required research can be cost effectively completed and transferred to the producers.

The state of Oklahoma and its citizens stand to gain significantly from the increased production resulting from incremental reserves. Production increases could generate \$1.3 billion to \$2.8 billion in additional state and local revenues over the next 25-plus years assuming oil prices range between \$20/B to \$32/B. Total state economic activity could be boosted by \$7.9 billion to over \$17 billion. Furthermore, several hundred jobs could be created or maintained with the successful implementation of EOR and ASR. 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 in Oklahoma 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 to the attainment of these estimated benefits.

Figure IV-10

National Impact of ASR Production

Implemented Technology

A) Direct Federal 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.

As shown in Figure IV-11, the oil that will remain in the analyzed reservoirs after production by both current operations and by wide-scale application of currently available EOR and ASR processes, constitutes an important resource target for improved recovery technologies. Of the 11.7 billion barrels of immobile oil resource analyzed in this study, implemented technology EOR practices could produce an estimated 160 million barrels at an oil price of \$36/B, leaving over 11.5 billion barrels of remaining immobile oil in the analyzed Oklahoma reservoirs. Of the 6.6 billion barrels of unrecovered mobile oil in the reservoirs analyzed, implemented technology practices could produce an estimated 1.1 billion barrels at \$36/B, leaving 5.5 billion barrels in these reservoirs. The large size of the remaining resource clearly warrants a focused RD&D program that will test and speed the implementation of advanced technology to capture additional oil reserves.

Figure IV-11

Oklahoma Remaining Oil Resource After Implemented Technology Recovery

V. BENEFITS OF INCREASED RECOVERY FROM THE KNOWN REMAINING OIL RESOURCE IN OKLAHOMA WITH TECHNOLOGY ADVANCES

A. INTRODUCTION

While currently available EOR and ASR extraction techniques could contribute substantially to Oklahoma's reserve base, technological advances in these processes resulting from a concerted RD&D effort would have far more dramatic effects on the state's production and reserves. Development and wide-scale application of newly developed methods could result in the recovery of a much greater portion of the remaining mobile and immobile oil resources in the state.

The present analysis evaluates both the benefits and the associated economic impacts of advanced technology oil recovery. Evaluations of advanced technology EOR and ASR in the state of Oklahoma are presented separately; moreover, because they target different portions of the resource, EOR and ASR potentials are independent and additive. Given that the modeled advances in technology are conservatively defined, improvements in recovery processes resulting from RD&D not envisioned in this analysis could add substantially to the estimated reserve potentials. Well abandonments, however, could limit access to the resource and increase project costs if EOR and ASR are not applied before conventional production ceases. Immediate action is therefore necessary to realize the benefits of these advanced technology processes.

B. RECOVERY OF THE REMAINING IMMOBILE OIL RESOURCE

1. "Advanced" Technology Defined

EOR processes, as currently "implemented," have severe limitations. Some current EOR techniques can only be applied to a limited number of reservoirs that exhibit a narrow range of suitable property values (e.g., temperature, salinity, oil viscosity). The resulting sweep efficiency of EOR processes is also often relatively poor, contacting only a small portion of the residual oil remaining in the previously waterflooded zone. Injectants are expensive, often approaching the value of the oil they are designed to recover. The National Petroleum Council (NPC) predicted gradual improvements in EOR performance and project economics as current processes are improved and further tested both in the lab

and in the field. These advanced processes will 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 are tested and proven commercially. 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 Oklahoma enhanced oil recovery will be advances in chemical flooding, and to a lesser extent, in miscible and steam flooding. 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 to a larger number of reservoirs. This study also assumes that advances in chemical flood technology will result in improvements in injection rate, interfacial tension reduction, reduced chemical retention, and lower costs, thereby improving the recovery and economics of chemical projects. In addition, 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 in Oklahoma could stimulate a substantial amount of incremental reserves over the oil price range analyzed (\$16/B to \$36/B). Table V-1A and Figure V-1 show the comparison between the EOR reserves potentially generated through the application of advanced technology EOR processes. The greatest increase in incremental reserves due to advanced technology could occur near the upper end of the analyzed price range, at oil prices of \$36/B, where advances in EOR technology could stimulate an additional 980 million barrels of oil over implemented technology potential for a total of over 1.1 billion barrels in incremental reserves. At oil prices of \$20/B and below, there is no potential for incremental EOR reserves under implemented technology. Therefore, all incremental reserves (130 million to over 220 million barrels) could be attributed to advances in EOR technology.

The potential incremental reserves that could be contributed by each of the advanced technology EOR processes considered in this analysis are also shown in Table V-1A. At \$16/B, advanced chemical flooding could be the only source of incremental reserves, adding over 130 million barrels of oil. At

Figure V-1

Incremental Reserves by EOR Process Implemented Technology vs. Advanced Technology

\$20/B, advances in chemical EOR techniques could contribute over 220 million barrels. CO₂-miscible flooding would not be economic in Oklahoma until oil prices reach \$24/B under both advanced and implemented technology. At \$28/B, technology advances to CO₂-miscible flooding could generate only marginal additions to implemented technology potential. Advanced technology CO₂-miscible flooding could generate a total potential of over 160 million barrels of incremental reserves at oil prices ranging from \$28/B to \$36/B.

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 CO₂-miscible projects could remain the same, as a limited number of geological settings in Oklahoma are amenable to this process. The estimated increase in reserves could be largely due to the improving performance of chemical processes in the advanced case; 22 of 25 advanced case projects use chemical EOR processes. Only one small thermal project would be economic and only at relatively high oil prices. If RD&D efforts are effective, the improvement of surfactant flooding techniques (both in terms of reduced injectant cost and increased salinity resistance) could result in this technology becoming the dominant EOR process in Oklahoma.

Table V-1A

**Incremental Reserves from EOR by Process
Implemented Technology vs. Advanced Technology
(Million Barrels)**

Oil Price (\$/B)	CO ₂ -Miscible		Chemical		Thermal		Total	
	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*
\$16	0	0	0	132	0	0	0	132
\$20	0	0	0	224	0	0	0	224
\$24	90	90	0	622	0	0	90	712
\$28	159	162	0	809	0	0	159	971
\$32	160	162	0	809	0	11	160	982
\$36	160	162	0	969	0	11	160	1,142

* This potential reflects the total reserves with advanced technology - implemented technology reserves 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	0	0	0	2	0	0	0	2
\$20	0	0	0	4	0	0	0	4
\$24	1	1	0	14	0	0	1	15
\$28	2	2	0	19	0	0	2	21
\$32	2	2	0	19	0	1	2	22
\$36	2	2	0	22	0	1	2	25

Figure V-2 displays the expected annual production from incremental EOR reserves for oil prices of \$24/B and \$32/B for both the implemented and advanced technology cases. At \$24/B, annual EOR production using advanced technology could peak at 14.9 million barrels per year in the year 2008 (Figure V-2A). This could occur four years earlier and yield about 7 million barrels per year more than the implemented technology peak potential. At \$32/B, production could peak in 2007 at 36 million barrels per year and could occur six years earlier and yield about 27 million barrels per year more than the implemented technology peak potential (Figure V-2B). The increases over the implemented technology potential could be attributed to advances in EOR technology.

3. Effects on State Revenues and Economic Activity

At all oil prices considered, the direct tax revenues to the state of Oklahoma attributable to EOR could increase significantly with advanced technology. Of the state's direct revenues, the share of production taxes could be 66% to 76%, corporate income taxes could comprise 18% to 19%, sales tax receipts could contribute around 10%, and personal income taxes could make up the remainder (Figure V-3A). At the two lowest oil prices evaluated (\$16/B and \$20/B), state revenues from advanced technology EOR could range between \$170 million and \$374 million, all of which would be attributable to technology advances at these prices. At \$24/B, advances in EOR technology could generate incremental revenues over implemented technology of nearly \$1.2 billion, for a total of \$1.4 billion. At higher oil prices between \$28/B and \$36/B, total direct state revenues from EOR in the advanced case could be between \$2.2 billion and \$3.2 billion, 81% to 84% of which would be attributable to technology advances.

Direct state economic activity generated by Oklahoma EOR would also grow due to advanced technology (Figure V-3B). The gain in economic benefits would be proportional to the gain in reserves. The advanced case distribution of total economic benefits among the contributing components would be similar to the trend shown for the implemented technology case. At \$16/B, the incremental state economic gain due to advanced EOR technology is estimated to be about \$1.4 billion, all of which is due to the application of technology advances. At \$20/B, advances in technology could stimulate almost \$2.8 billion of additional state economic activity. At oil prices of \$24/B and \$28/B, direct state economic activity could increase by \$9.5 billion to nearly \$15 billion due to technology advances, for a total potential increase of \$11 billion to nearly \$18 billion. At \$36/B, over \$26 billion in economic activity could be generated, 87% of which would be attributable to application of technology advances. Clearly, the state of Oklahoma could accrue substantial benefits from the development and application of advanced EOR technology at any of the oil prices considered in this analysis.

Figure V-2

Annual Production from EOR Reserves

Implemented Technology vs. Advanced Technology

A) At \$24/B

B) At \$32/B

Figure V-3

State Impact of EOR Production

Implemented Technology vs. Advanced Technology

A) Direct State and Local Revenues

B) Direct State Economic Activity*

* To the extent that royalties go to the Federal government (i.e. fields on Federal lands), royalties as a portion of state economic activity may be overstated.

Advanced technology EOR activities could also have a substantial effect on future employment in Oklahoma. At \$24/B, advanced technology EOR could sustain over 960 jobs in the peak production year 2006 (not illustrated). This is about 170 more jobs than the peak employment rate under implemented technology recovery. At \$32/B, advanced technology could create or maintain more than 4,100 jobs in the peak year 2005. Peak wages could increase by \$8 million to \$136 million over implemented technology due to technology advances, for total peaks of \$44 million to \$185 million.

4. Effects on the National Economy and Budget

As discussed in Chapter III, increased oil recovery in the state of Oklahoma through EOR methods would significantly benefit the nation in the areas of enhanced energy security, avoided imports, a reduced foreign trade deficit, and expanded direct revenues to the Federal treasury. The potential benefits could be even more pronounced with the development of advanced technology. Up to 1.1 billion barrels of crude oil could be added to proved reserves using advanced EOR technology, 900 million barrels of which would be attributable to advances in technology. The additional reserves would decrease the nation's reliance on imported oil and consequently enhance energy security.

Revenues to the Federal treasury, in the form of corporate and personal income taxes, could grow along with the increase in reserves as a result of advanced technology (Figure V-4A). At oil prices below \$24/B, all of the increase in direct Federal revenues could be due to the application of EOR technology advances; between \$30 million and \$110 million could be added to the Federal treasury. At oil prices of \$24/B and \$28/B, direct Federal revenues due to technology advances could surpass the implemented technology potential by \$230 million to \$340 million, for a total advanced technology potential of over \$240 million to over \$460 million. At oil prices of \$28/B and below, Federal corporate income tax revenues could be negative for several analyzed projects. This is caused by the Federal EOR tax credit which can be used to offset the tax obligations of other profitable activities, leading to negative corporate income taxes. At \$36/B, after the complete phaseout of the EOR tax credit, applications of technology advances could generate over \$2.8 billion in additional direct Federal revenues, 83% of \$3.4 billion in total potential direct Federal revenues.

To the extent that the increase in EOR production replaces imported oil on a barrel-by-barrel basis, the foreign trade deficit would be reduced by advances in technology. Money spent on domestic oil production rather than on imports would be recirculated within the U.S. economy. The value of the

imports avoided (reserves multiplied by the effective wellhead price of oil) would approximate the improvement in the trade deficit (Figure V-4B). At oil prices of \$16/B and \$20/B, the entire value of imports avoided (from nearly \$2.0 billion to over \$4.3 billion) could result from advances in EOR technology. At oil prices of \$24/B to \$28/B, application of EOR technology advances could generate from about \$15 billion to over \$23 billion of imports avoided over implemented technology for a total potential of almost \$17 billion to more than \$27 billion. At \$36/B, \$35 billion (86%) of the \$41 billion in imports avoided could be attributed to advances in technology.

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 RD&D will allow 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 at closer spacings. This will 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 could have a substantial impact on ASR reserve additions in Oklahoma. Additional recovery would 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 profile modification and polymer flooding projected under the implemented technology case, whether applied

Figure V-4

National Impact of EOR Production

Implemented Technology vs. Advanced Technology

A) Direct Federal 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.

independently or in combination with infill drilling. Additional benefits are 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 Oklahoma's oil reserves. The incremental reserves from advanced technology ASR could range between 1.2 and 1.4 billion barrels for the analyzed Oklahoma reservoirs across the oil prices considered. Over the price range analyzed, the advanced technology potential exhibits about a 30% increase in reserves over the implemented technology potential. This increment could be attributed solely to advances in technology (Figure V-5).

Advances in ASR technology could shift the price-supply relationship to make significant amounts of oil economic to develop at lower prices. Between oil prices of \$16/B and \$20/B, technology advances could increase implemented technology reserves potential by over 370 million barrels to a total of about 1.3 billion barrels of incremental reserves. As oil prices increase above \$20/B, reserve growth through advanced technology ASR would be relatively insensitive to further increases in oil price. Technology advances could generate around 400 million barrels of the 1.3 billion to 1.4 billion barrels of total incremental reserves from ASR.

Table V-2A shows the distribution of the incremental reserves by ASR process. Infill drilling in combination with profile modification or polymer flooding could be the most frequently applied advanced technology recovery method and could generate the largest incremental reserves, contributing about 87% of the total reserve additions. The full potential of the advanced technology case depends both on targeted infill drilling and improved polymer flooding and profile modification techniques; infill drilling by itself could generate 11% to 20% of total advanced case reserve growth, while polymer and profile modification techniques could account for only 14% of the total recovery in the advanced technology case.

In the advanced technology case, incremental reserves from combination projects are more than double those from the implemented case (with technology advances accounting for the difference). The incremental reserves from geologically targeted infill drilling are only half those generated using blanket infill drilling. Advanced polymer and profile modification techniques could add 65 million to 70 million

Figure V-5

Incremental Reserves by ASR Process Implemented Technology vs. Advanced Technology

barrels of incremental reserves, for a total of between 150 million and nearly 200 million barrels. Improvements in polymer flooding and profile modification could justify the increased costs involved in implementing these processes, leading to a shift from infill drilling alone to the combination processes. Thus, attainment of the total potential would be critically dependent on linking targeted infill with better secondary chemical processes, since heterogeneity allows wells to be economically justified at much closer spacing than is currently possible, and waterflooding in either old or new wells would contact additional portions of the mobile oil resource bypassed at current spacing using conventional waterfloods. Targeting infill wells would also reduce the front-end investment for each project undertaken by reducing the number of dry holes, thereby making some otherwise uneconomic projects cost-effective at lower oil prices. The number of new ASR projects in Oklahoma ranges from 51 to 57 in the implemented technology case, increasing to only between 58 and 63 with advances in ASR technology. Thus, efficiencies associated with the advanced technology would assist operators in producing an additional 300 to 400 million barrels from roughly the same reservoirs.

Table V-2B shows the estimated number of economic ASR projects by process for both the implemented and advanced technology cases. At oil prices above \$20/B, the number of infill drilling projects (applied alone or in combination with other processes) could be only marginally higher under

Table V-2A

**Incremental Reserves from ASR by Process
Implemented Technology vs. Advanced Technology
(Million Barrels)**

Oil Price (\$/B)	Polymer Flooding and Profile Modification		Infill Drilling		Infill Drilling with Polymer Flooding and Profile Modification		Total	
	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*
\$16	87	152	329	145	454	944	870	1,241
\$20	87	158	354	146	458	974	899	1,278
\$24	89	160	356	154	460	987	905	1,301
\$28	90	196	381	183	486	970	957	1,349
\$32	90	196	431	202	492	971	1,013	1,369
\$36	126	196	432	281	492	972	1,050	1,449

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

Table V-2B

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

Oil Price (\$/B)	Polymer Flooding and Profile Modification		Infill Drilling		Infill Drilling with Polymer Flooding and Profile Modification		Total	
	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced
\$16	9	9	21	7	21	42	51	58
\$20	9	9	23	7	21	43	53	59
\$24	9	8	23	9	21	44	53	61
\$28	8	9	25	10	22	44	55	63
\$32	8	10	27	9	22	44	57	63
\$36	8	10	27	9	22	44	57	63

advanced technology, although the incremental reserves associated with these projects could increase markedly. This increase in recovery from projects that were already economic under implemented technology emphasizes the effectiveness of improvements in polymer flooding and profile modification and targeting infill wells to the more prolific portions of the reservoir. The economics of most projects at these prices are greatly improved by advanced technology because a well-designed, strategic infill drilling program reduces the overall investment and associated operating costs required in a given reservoir.

Figure V-6 displays the projected annual production that could result from ASR technology advances for oil prices ranging of \$16/B and \$32/B from the Oklahoma reservoirs analyzed in this study. In all cases, a significant amount of oil could be added to the state's production over the next 30 years. ASR techniques require considerable amounts of drilling and must compete with other activities (e.g., exploration) and products (e.g., gas) for drilling rigs. A substantial portion of the target resource could be subject to abandonment before drilling capacity is available; 38% of the potential reserves could be abandoned over the life of the projects. Rapid development, transfer, and application of new ASR techniques is necessary to maximize potential.

At \$16/B, advanced case ASR production could reach nearly 30 million barrels per year by the year 2020, 27% of which is attributable to technology advances. At \$32/B oil prices, advances in ASR technology could increase the peak annual production of ASR under the implemented case by nearly 8 million barrels per year, for a total of nearly 33 million barrels per year. At \$16/B the average production over the period of 1993 to 2020 is 12.4 million barrels per year, while at \$32/B, the average is about 13.8 million barrels per year.

3. Effects on State Revenues and Economic Activity

Advanced technology ASR production activities could contribute significantly to state and local tax revenues in Oklahoma (Figure V-7A). At moderate oil prices (\$20/B to \$28/B), technology advances could account for \$330 million to \$510 million (20%) of the \$1.6 billion and \$2.5 billion in total potential state and local revenues. At \$36/B, nearly \$600 million could be added to implemented technology potential by advances in technology, for a total of almost \$3.5 billion in additional state and local revenues. Production taxes (55% to 58%) and state corporate income taxes (36% to 38%) comprise the largest portions of direct state revenues.

Figure V-6

Annual Production from ASR Reserves

Implemented Technology vs. Advanced Technology

A) At \$16/B

B) At \$32/B

In addition to the increases in state and local revenues, Oklahoma would benefit from the stimulation of economic activity and creation of new jobs. State economic activity at oil prices \$20/B to \$24/B could increase by over \$11 billion to nearly \$16 billion using advanced technology ASR. Of this increase, \$3.3 billion to \$4.5 billion could be attributed to technology advances. At \$36/B, the increase due to technology advances could be more substantial; nearly 38% (\$6.2 billion) of the \$22 billion in additional state economic activity is due to advances in ASR technology (Figure V-7B).

A significant number of jobs could be created or maintained by the widespread application of advanced ASR technology in Oklahoma. As the price of oil rises, the total number of jobs created or maintained could grow substantially, with the incremental jobs stimulated directly by advanced technology accounting for much of the increase. In the peak year, advanced ASR technology could result in over 630 jobs annually at \$16/B and 1,060 jobs annually at the \$32/B, about 30% more than those generated under the implemented case (not illustrated). Even at lower prices, the number of jobs created or maintained by advanced technology ASR processes would be highly beneficial to the Oklahoma economy.

4. Effects on the National Economy and Budget

The development of advanced secondary recovery technology could also benefit the nation. Figure V-8A shows a large increase in the incremental revenues to the Federal treasury from personal and corporate income taxes due to advanced technology. At moderate oil prices (\$20/B to \$28/B), total Federal revenues from advanced ASR could range from \$4.5 billion to nearly \$7.0 billion. Of this increase in direct Federal revenues, \$1.2 billion to \$2.0 billion could be attributed to applications of ASR technology advances. At \$36/B, nearly \$2.9 billion (28%) of the more than \$10 billion in potential direct Federal revenues could be generated by technology advances.

The increase in domestic production due to advanced technology ASR could also replace imports and enhance the nation's energy security and independence. The direct value of the increased domestic production could, therefore, represent a decrease in the foreign trade deficit as money spent on domestic oil circulates throughout the U.S. economy rather than abroad. At oil prices ranging from \$20/B to \$28/B, the value of imports avoided could be between \$25 billion and \$38 billion, 30% of which would be attributable to technology advances (Figure V-8B). At \$36/B, 28% (over \$14 billion) of the \$52 billion in avoided imports could be due to the application of advanced technology. Increased production due to advanced technology ASR could therefore increase national security while decreasing the foreign trade deficit.

Figure V-7

State Impact of ASR Production

Implemented Technology vs. Advanced Technology

A) Direct State and Local Revenues

B) Direct State Economic Activity*

* To the extent that royalties go to the Federal government (i.e. fields on Federal lands), royalties as a portion of state economic activity may be overstated.

Figure V-8

National Impact of ASR Production

Implemented Technology vs. Advanced Technology

A) Direct Federal 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.

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 nearly 900 million barrels to Oklahoma's reserves base. At \$28/B, potential incremental reserves could reach over 1.1 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 increase implemented technology potential by over 40%, adding 600 million barrels of incremental reserves, at an oil price of \$20/B. The total potential reserves at this price, over 1.5 billion barrels, is more than double Oklahoma's 1991 proved reserves. At an oil price of \$28/B, technology advances could stimulate over 1.2 billion barrels of incremental reserves for a total EOR and ASR reserves potential of over 2.5 billion barrels, three times more than Oklahoma 1991 proved reserves.

The activities associated with advanced technology EOR and ASR would generate substantial direct state tax revenues. At \$20/B, 700 million of the \$2.0 billion of potential direct state revenues would be attributable to technology advances. At an oil price of \$28/B, over 50% (\$2.4 billion) of the \$4.7 billion in total potential state revenues could be due to advances in 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. 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 specific classes of reservoirs that with exhibit both the largest potential resources and the greatest threats of abandonment. 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 Oklahoma reservoirs (Figure V-9). At the improbably high oil price of \$36/B, total ASR reserves potential would be 1.4 billion barrels while EOR reserves potential would total 1.1 billion barrels. If this reserves potential were realized, over 5.1 billion barrels of mobile oil (78% of the mobile oil target) and 10.5 billion barrels of immobile oil (91% of the immobile oil target) would remain in analyzed reservoirs. In addition, over 9.2 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 nearly 25 billion barrels is the target for further advances in EOR and ASR technologies.

Figure V-9

Oklahoma Remaining Oil Resource After Advanced Technology Recovery