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

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 California

Volume II

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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
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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 California. 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, two-thirds of the known original oil-in-place will remain in California oil reservoirs.
- The remaining resource, 54 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. Major capital investments will be needed to reacquire the leases, rebuild the infrastructure, and more importantly, drill new wells to regain access to the California target resource.
- California's future as a premier energy producing state depends strongly on the development of efficient and cost-effective oil recovery technologies, technology transfer to producers, and the timely and successful application of such technologies, given the decline in California production and reserves and the accelerating level of well abandonment over the past decade.
- The effective transfer of existing technology could result in 2.8 to 3.8 billion barrels of new reserves from analyzed California reservoirs at oil prices ranging from \$20/B to \$28/B, potentially increasing the state's current proved reserves by 80% to 90%.
- Technology advances resulting from a focused RD&D effort could result in *additional* post-conventional reserves of 1.3 to 3.3 billion barrels. The effective transfer of existing technology, coupled with the development and application of new technologies, could more than replace current proved reserves in California.
- Public sector revenues from future improved oil recovery activity would total between \$6.5 and \$13 billion given currently available recovery practices and oil prices of \$20/B to \$28/B. Technology advances could increase these totals by \$2.5 to \$8.8 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 \$34 billion and \$62 billion in the U.S. economy at oil prices in the \$20/B to \$28/B range. This figure is only the direct cost of imports avoided due to increased domestic activity. The true value to the country is actually much higher due to multiplier effects as this money circulates in the economy.
- With the application of existing technology, a state tax incentive for EOR projects, in the form of production and corporate income tax relief until project payout, could increase reserves potential by an additional 200 to 740 million barrels at oil prices of \$24/B and higher. The tax incentive could also increase direct state tax revenues by \$50 million to nearly \$700 million at these prices, while stimulating \$2.5 to \$9.8 billion in state economic activity.
- Technology advances coupled with a state tax incentive could stimulate an additional 510 million to 4.6 billion barrels of incremental reserves over the implemented technology and the current California tax structure case. The combination of the tax incentive and technology advances could stimulate from \$4.7 billion to nearly \$79 billion of increased state economic activity over the potential under implemented technology and the current tax structure.

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 96% of the original oil-in-place (OOIP) in major California reservoirs in a consistent manner and on an individual basis, the results of which have been aggregated to arrive at the statewide total.

Overall, well abandonments and more stringent environmental regulations could limit economic access to California'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, California oil production could be maximized. The resulting increase in production rates, employment, operator profits, state and Federal tax revenues, and energy security will benefit both the state of California and the nation as a whole.

I. OVERVIEW

A. THE PROBLEM: DECLINING CALIFORNIA OIL PRODUCTION

Over two-thirds of the oil discovered in the state of California will remain trapped in the reservoir at the conclusion of conventional oil recovery operations. The total known original oil-in-place in California has been estimated at over 80 billion barrels (Figure I-1). Almost 23 billion barrels had already been produced at the end of 1991. Four billion barrels of proved reserves are still producible under existing economic conditions, using currently available technologies. A little more than 2.2 billion barrels of these reserves are attributable to ongoing steamflood enhanced oil recovery (EOR) projects.¹ The

Figure I-1

Known California Oil Resource

¹ California Department of Conservation (CaDOC), Division of Oil and Gas - 1991; Conservation Committee of California Oil producers (CCCOP), 1991; ICF Resources, 1993.

remaining 54 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.

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

- Declining state production and reserves. California oil production has declined by 17% from 1985 through 1991 (Figure I-2A). Crude oil reserves decreased by roughly the same percentage (Figure I-2B). Although the production decline has leveled off in the last two years, reserve additions have not been sufficient to replace production volume. The average size of new field discoveries has been relatively small and reserves per well have decreased.
- Increased level of well abandonment. The state of California currently produces oil from roughly 41,000 wells. Many of these wells are "marginal" wells producing at or near their economic limit. 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 1991.² 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.³ Such an economic burden will not likely be justified by the incremental oil revenues from future improved recovery techniques.

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

² "Abandonment Rate of the Known Domestic Oil Resource", U.S. DOE, Bartlesville Project Office, Bartlesville, OK (June 1990).

³ Brashear, J.P. et al "Effect of Well Abandonments on EOR Potential," JPT, December 1991.

Figure I-2

California Production and Reserves

A) Annual Production

B) Reserves

B. THE OPPORTUNITY: OIL RECOVERY THROUGH ADVANCED TECHNOLOGY

The remaining oil resource constitutes a huge target for future recovery operations. The 54 billion barrels of known unrecovered oil in the state of California is of two types: mobile oil and immobile oil. The mobile oil, though displaceable by water, has been uncontacted or bypassed during conventional primary production or water flooding and thus remains unrecovered. Immobile oil is trapped in the reservoir pores by viscous and capillary forces and cannot be displaced by water.

The estimated unrecovered mobile oil (UMO) resource in California is 20 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. These processes 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 34 billion barrel remaining immobile oil resource in California 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 operations, they are capable of producing substantial volumes of incremental oil with significant 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

This assessment of the benefits of RD&D in oil recovery technology is 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)⁴ for its 1984 evaluation of nationwide EOR potential. DOE has since maintained and updated the system

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

through its Bartlesville Project Office (BPO).⁵ DOE has also upgraded the capability of the system to evaluate the nation's unrecovered mobile oil through ASR techniques. In this report, the future potential of EOR and ASR techniques are examined with the following key assumptions and considerations:

- A total of 222 California reservoirs accounting for nearly 77 billion barrels of original oil-in-place (96% of the total known OOIP in the state as shown in Figure I-3), were individually analyzed for their EOR and ASR potential. No attempt is made to extrapolate the results to the remaining California resource not available in the TORIS database.
- 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 (including the FY 1991 Federal EOR tax credit) and the specific oil production tax situation in California. In addition, the effect of a state tax incentive for EOR and ASR projects was evaluated.
- 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, expansions to 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 1.6 and 4.5 billion barrels of incremental reserves across the entire oil price range. Advanced technology applied to the same resource base could stimulate an additional 0.6 to 3.7 billion barrels of incremental resources for a total of 2.1 to 8.2 billion barrels beyond currently proven reserves. In effect, improvements in process performance and application could increase potential reserves by 30% to 80%. This clearly provides a major justification for a focused RD&D and technology transfer program.

⁵ *Producing Unrecovered Mobile Oil: Evaluation of Potential Economically Recoverable Reserves in Texas, Oklahoma, and New Mexico*, DOE, May 1990.

Figure I-3

California Oil Resource

Data Coverage of EOR and ASR Analyses

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

The potential for expanded application of EOR techniques using implemented technology is limited if prices remain at or below \$16/B; incremental EOR recovery at this price would total just less than 1 billion barrels. However, implemented technology EOR potential could increase to more than 2 billion barrels of reserves at a higher oil price of \$20/B. At this oil price, advances in EOR technology could stimulate more than 1.0 billion barrels of additional incremental reserves. This means that a total of more than 3.2 billion barrels of potential EOR recovery exists under the two levels of technology for the analyzed reservoirs at a \$20/B price.

Incremental reserves attributed to ASR techniques are less substantial and are impacted much less by oil price changes than EOR. About 700 million barrels of ASR reserves could be added in the implemented technology case at an oil price of \$16/B, growing only slightly as oil prices increase to \$36/B. Research on process improvements, specifically improved polymer flooding and profile modification combined with geologically targeted infill drilling, could increase ASR potential by as much as 20%. With advances in technology, the ASR reserves could total about 900 million barrels at high prices, with incremental production yielding over 200 million barrels of reserves.

Future advanced oil recovery activities will generate revenues for California and the Federal treasury through increased production taxes, oil industry-related sales taxes, and corporate and personal income taxes. The revenue estimates in this study consider only direct revenues from recovery activities in the analyzed reservoirs, and exclude any additional indirect benefits from multiplier or "ripple" effects within the state or national economy. Under implemented technology at \$20/B, newly implemented improved oil recovery projects in California could directly generate \$2.9 billion in state revenues. At the same oil price, advanced technology could generate an additional \$1.6 billion, for a total of \$4.5 billion in state revenues (Figure I-4B). At an oil price of \$28/B, application of currently available EOR and ASR technology could contribute \$5.5 billion to the California public treasury while the application of advanced methods could increase these revenues by an additional \$5.9 billion to over \$11 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 California's contribution to reducing imports. As shown in Table I-1, this figure could total between \$17 billion and \$62 billion under the implemented technology scenario, over the \$16/B to \$28/B range. Advanced technology could further decrease imports by an *additional* \$7 billion to \$72 billion. The additional value of domestically produced EOR and ASR generates significant direct economic activities as capital spending, profits, royalties, and taxes are circulated through the U.S. economy rather than exported to buy foreign oil.

Figure I-4

Potential Impact of Advanced Technology

A) Reserve Additions

B) Direct State and Local Revenues

Table I-1

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

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	1.6	1.5	17.0	2.2
<u>Advanced Technology*</u>	<u>0.5</u>	<u>0.6</u>	<u>7.3</u>	<u>0.4</u>
Total	2.1	2.1	24.3	2.6
<u>At \$20/B</u>				
Implemented Technology	2.8	2.9	34.1	3.6
<u>Advanced Technology*</u>	<u>1.3</u>	<u>1.6</u>	<u>21.6</u>	<u>0.8</u>
Total	4.1	4.5	55.7	4.4
<u>At \$24/B</u>				
Implemented Technology	3.3	4.3	48.0	5.4
<u>Advanced Technology*</u>	<u>2.7</u>	<u>3.7</u>	<u>49.1</u>	<u>2.0</u>
Total	6.0	8.0	97.1	7.4
<u>At \$28/B</u>				
Implemented Technology	3.8	5.5	61.7	7.5
<u>Advanced Technology*</u>	<u>3.3</u>	<u>5.9</u>	<u>72.3</u>	<u>2.9</u>
Total	7.1	11.4	134.0	10.4
<u>At \$32/B</u>				
Implemented Technology	4.1	7.0	78.7	10.0
<u>Advanced Technology*</u>	<u>3.5</u>	<u>6.9</u>	<u>86.6</u>	<u>7.4</u>
Total	7.6	13.9	165.3	17.4
<u>At \$36/B</u>				
Implemented Technology	4.5	8.7	95.6	13.0
<u>Advanced Technology*</u>	<u>3.7</u>	<u>8.1</u>	<u>101.6</u>	<u>10.6</u>
Total	8.2	16.8	197.2	23.6

*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. BENEFITS DERIVED FROM A CALIFORNIA STATE TAX INCENTIVE

Instituting a state tax incentive in California which forgives state production and corporate income taxes on incremental production until project payout, would increase the reserve base of California. The tax incentive also enhances state economic activity and increases state revenues. While the impact of a state tax incentive was analyzed for both ASR and EOR processes, only EOR projects demonstrated any substantial incremental benefit. ASR processes are less sensitive to changes in oil price than EOR; therefore, the analyzed tax incentive had only a marginal impact on ASR potential.

Figure I-5 shows the potential increase in EOR and ASR reserves for implemented and advanced technology. The tax incentive could have the largest impact for EOR potential at oil prices of \$24/B and higher. Under implemented technology conditions, 200 million to 740 million barrels of incremental EOR reserves could be stimulated by the analyzed tax incentive. With technology advances, incremental reserves due to the tax incentive could increase by 200 million to 1.2 billion barrels over the advanced technology base case potential. At a moderate oil price of \$24/B, the potential reserves stimulated by the tax incentive could be substantial. Using existing EOR technology, 480 million barrels of additional reserves over the base case could be generated by the incentive. The combined effect of technology advances and the tax incentive at this price could increase the implemented technology base case potential by 3.3 billion barrels for a total of 5.9 billion barrels of incremental EOR reserves.

Table I-2 illustrates the potential economic benefits and tradeoffs which could result from the increased EOR production stimulated by the tax incentive. Using existing technology at oil prices above \$20/B, state tax revenues and economic activity could significantly increase due to the tax incentive. At \$24/B, an additional \$340 million in direct state tax revenues and an additional \$6.2 billion in state economic activity could be stimulated. Federal revenues would also increase due to the state tax incentive, but only after the Federal EOR tax credit begins to phaseout. At an oil price of \$24/B, additional EOR activity could be stimulated by the tax incentive, thereby increasing the potential amount that can be taken as a tax credit. Federal revenues at this price could therefore decrease by over \$200 million. At oil prices above \$32/B, the state tax incentive could stimulate \$250 million to \$860 million of additional direct Federal revenues.

With technology advances, there would be a trade-off between state tax revenues or overall state economic activity. At oil prices of \$24/B and \$36/B, tax revenues and economic activity could increase due to the tax incentive. At oil prices of \$28/B and \$32/B, however, state tax revenues could decrease.

Figure I-5

Impact of A State Tax Incentive on Incremental EOR and ASR Reserves

Base Case vs. Incentive Case

A) Implemented Technology

* At oil prices above \$28/B, the Federal EOR tax credit decreases by 2.5% for each \$1 over the \$28/B oil price; complete phaseout occurs at an oil price of \$34/B.

B) Advanced Technology

* At oil prices above \$28/B, the Federal EOR tax credit decreases by 2.5% for each \$1 over the \$28/B oil price; complete phaseout occurs at an oil price of \$34/B.

Table I-2

Summary of Economic Benefits and Tradeoffs of a State EOR Tax Incentive in California*

Oil Price (\$/B)	Tax Structure	Implemented Technology			Advanced Technology		
		Direct State Revenue (\$Billions)	State Economic Activity (\$ Billions)	Direct Federal Revenue (\$ Billions)	Direct State Revenues (\$ Billions)	State Economic Activity (\$ Billions)	Direct Federal Revenues (\$ Billions)
\$16	Base Incentive	0.54	6.74	0.30	0.89	10.41	0.32
		0.53	6.74	0.30	0.76	11.46	0.33
\$20	Base Incentive	1.67	18.31	1.20	3.03	32.41	1.34
		1.66	18.37	1.20	2.86	35.32	1.32
\$24	Base Incentive	2.80	25.93	2.41	6.12	59.41	3.63
		3.14	32.20	2.21	6.31	69.24	3.35
\$28	Base Incentive	3.74	32.49	3.90	9.16	80.16	5.96
		4.12	37.56	3.69	8.62	85.15	6.07
\$32	Base Incentive	5.04	40.98	5.70	11.40	94.16	11.94
		5.09	43.44	5.95	10.32	95.74	12.33
\$36	Base Incentive	6.38	49.62	7.99	13.87	109.93	17.26
		7.08	59.38	8.85	13.89	128.55	19.17

* The table entries reflect EOR potential only; as ASR is less price sensitive than EOR, the tax incentive had only a marginal impact on ASR potential.

The gains in state economic activity could more than offset the losses in state tax revenues. Policymakers in California may choose to forego state tax revenues in order to reap larger benefits for the state economy.

E. CONCLUSIONS

The development, testing, and wide-scale application of currently available improved oil recovery technologies could stimulate incremental reserves ranging from 1.6 billion to 3.3 billion barrels from the state of California'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 0.5 billion barrels to 2.7 billion barrels of incremental reserves could be produced over this price range using EOR and ASR techniques. Even with the successful development and application of these technologies, however, about 26 billion barrels of immobile oil would still remain in the analyzed reservoirs as a long-term target for future advances in EOR, and nearly 18 billion barrels of mobile oil would remain as a long-term target for future advances in ASR processes (Figure I-6). Unfortunately, while this target is substantial it 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 oil.

The results of this analysis have important policy implications. Oil production generates significant direct revenues to California 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 the 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 California, 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 in order to help domestic EOR

Figure I-6

California Remaining Oil Resource After Advanced Technology Recovery

and ASR projects compete with foreign investment opportunities. In addition, regulatory policymakers could design regulations which reflect both the true risks to health, safety and the environment and the economic risk of resource loss through abandonment.

II. BACKGROUND AND OBJECTIVES

A. TRENDS IN CALIFORNIA OIL PRODUCTION AND RESERVES

Oil production in California has been marked by distinct periods of increase and decrease (Figure II-1). Technological advances, including the development and application of waterflooding, increased annual production to nearly 360 million barrels in 1952. As the U.S. economy struggled during the late 1950s, the state's oil output declined; between 1952 and 1962, crude oil production fell by over 17% to 297 million barrels. Over the next six years, annual production levels increased to 375 million barrels before again gradually decreasing to 322 million barrels in 1975. Beginning in 1976, with the wide-scale application of improved recovery in the form of thermal steamflooding and increased offshore activities, annual production steadily increased to a peak of 424 million barrels in 1985. A decline in the price of oil, beginning in 1982 and continuing through 1988, led to another decline in production levels. During 1991, California's production increased slightly for the first time in six years, due to the Point Arguello offshore field coming on stream in June of that year. Although oil prices have increased somewhat since 1988, the maturity of the California oil resource and the associated higher costs of improved recovery methods have stifled production increases. However, California remains the second largest producer among the lower-48 states, accounting for 17% of lower-48 production.

A significant portion of California's oil resource is comprised of heavy oil (API gravity less than 20°). In 1991, nearly 70% of the oil produced in the state was in this category. This heavy oil resource is far more difficult to produce than light oil and has a lower wellhead price. Heavy oil also requires special refining procedures, making it a less versatile, and less valuable, commodity. With increased production costs and lower market values, future recovery of this significant resource will depend on development and wide-scale application of cost-effective, thermal enhanced oil recovery techniques. Because of this heavy oil reserve, California relies on enhanced oil recovery more than any other state to maintain production levels. Over 100 thermal steamflood projects in 58 fields produce roughly 500,000 barrels of oil per day (BOPD) of incremental heavy oil. This accounts for just over half of California's production.

California's reserves levels have generally followed the same rise and fall pattern of crude oil production (Figure II-2). Between 1950 and 1963, reserves remained relatively constant between 3.5 to 4 billion barrels before dramatically increasing by over 28% between 1963 and 1966. Production

Figure II-1

California Crude Oil Production (1950 - 1991)

Figure II-2

California Crude Oil Reserves (1950 - 1991)

increases, accompanied by relatively small additions, caused reserves to fall below pre-1963 levels, to 3.5 billion barrels in 1973. After 1973, however, reserves increased sharply to 5.0 billion barrels in 1977 (the increase was largely due to a change in accounting methods). As with production, reserves levels peaked in 1985 at 5.8 billion barrels. Due to decreasing prices and a maturing resource, reserves have since fallen by over 27% to 4.2 billion barrels in 1991.

Between 1960 and 1967, the number of producing oil wells in California increased by over 3,800 wells. A period of decline in the number of producing wells between 1968 and 1973 corresponded with a decrease in production (Figure II-3). After 1973, the number of producing wells increased fairly steadily (along with the price of oil), with a small decline in 1982 and 1983, before peaking in 1985 at nearly 50,000 wells. The sharp decrease in oil price in 1986 led to a steep drop in California producing wells. Over the following years, the number of wells was between 43,000 and 46,000 wells. Reserves per producing well fluctuated widely over the 1960 to 1980 period, reaching a low of 84,000 barrels per well in 1976 and a peak of over 121,000 barrels per well in 1980. Reserves per producing well varied between 100,000 and 110,000 during the 1980s before reaching a level of 97,000 barrels per well in 1991.

Unlike many states, California's reliance on stripper wells has not increased over the last two decades. The thick, high permeability reservoirs which predominate in the state produce at high rates. Also, the higher operating costs associated with enhanced thermal recovery will not permit stripper well production rates. In 1974, stripper wells accounted for about 24% of the state's crude oil production, and the percentage fell, with only a relatively small increase in 1981, to just over 9% in 1986. Stripper wells' share of the state's production has since increased, but remains around 10% in 1990, compared to 14% nationwide (Figure II-4). Between 1980 and 1990, over 12,000 stripper wells have been abandoned in the state. The number of yearly abandonments fell during the industry boom of 1982 and early 1983 before sharply increasing during the recession of the mid-1980s. With the price collapse of 1986, California introduced measures to slow the rate of well abandonments, allowing operators to place their wells on "temporarily abandoned" status for up to one year. When prices did not make a significant recovery in the latter part of the decade, the number of stripper well abandonments rose dramatically, culminating in a twenty year high of approximately 2,500 wells lost in 1990. These wells, potential access points to key reservoirs, are now permanently lost to operators hoping to apply new recovery technologies.

Production trends in California have significant implications for industry employment, economic activity, and the state's tax base. In 1978, the oil and gas industries employed approximately 130,000 people, 20% of whom were involved in oil and gas extraction. Employment rose steadily, peaking in

Figure II-3

California Producing Wells (1960 - 1991)

Figure II-4

California Stripper Well Production and Abandonments (1970 - 1990)

1985 at over 160,000 employees, 24% of whom were in the extraction sector. After 1985, however, industry employment experienced a constant decline, falling to just over 137,000 employees in 1991 (Figure II-5).

The annual wellhead value of crude oil production was on the rise throughout the mid- and late 1970s due to increasing prices and production levels (Figure II-6). Between 1973 and 1981, the wellhead value of production, in constant 1991 dollars, increased by over 350% to more than \$12.2 billion in 1981. After 1981, the influence of sharply decreasing prices led to a drop in the wellhead value despite increased production levels. The combination of low prices and decreasing production lead to a dramatic 46% drop in wellhead value between 1985 and 1986. In 1991, the wellhead value of all petroleum production stood at \$4.7 billion. While this is a small portion of the state's overall economic activity, it still represents a significant impact on an economy adjusting to new marketplace realities.

Unlike most oil and gas producing states, California does not levy a severance tax on oil and gas production. California operators are subject to a conservation tax and must pay property taxes associated with the severance of oil and gas from the lease. The total revenues from these taxes peaked along with production in fiscal year 1985 at nearly \$495 million, an increase of over 27% from the fiscal year 1981 totals. After a sharp drop through fiscal years 1986 and 1987, the taxes associated with production have generally continued to decline and were under \$400 million in fiscal years 1990 and 1991 (Figure II-7). Revenue from the conservation tax on production, which funds the California Department of Conservation's Division of Oil and Gas, has remained fairly steady while overall production taxes fell. This was largely due to tax rate increases on the oil and gas produced. In all, taxes associated with oil and gas production in California are small relative to total state taxes paid; these taxes have never accounted for more than 2% of total state tax revenue (Figure II-8).

Even after conventional primary and secondary production is concluded, much of the California resource will remain unrecovered in currently discovered reservoirs (Figure II-9). The total known original oil-in-place (OOIP) in the state was estimated at over 80 billion barrels in 1991. Of that resource, more than two-thirds will remain unrecovered at the conclusion of conventional recovery operations. An estimated 22.6 billion barrels have been produced, and an additional 4 billion barrels remain as proved reserves as of 1991, for an ultimate recovery of 26.6 billion barrels (just 33% of the total resource). The massive remaining resource of nearly 54 billion barrels of oil is the target for newer, more efficient extraction technologies.

Figure II-5

**Total Oil and Gas Employment in California
(1978 - 1991)**

Figure II-6

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

Figure II-7

**California Oil and Gas Severance Taxes*
(FY1981 - 1991)**

Source: California Department of Finance; California Department of Conservation

* Property taxes associated with the severance of oil and gas applied to minerals from the lease and a conservation tax

Figure II-8

**California Oil and Gas Severance Taxes* as a
Percent of Total State Taxes (FY1981 - 1991)**

Source: California Department of Finance; California Department of Conservation

* Property taxes associated with the severance of oil and gas applied to minerals from the lease and a conservation tax

Figure II-9

California Oil Resource

This unrecovered resource is divided into two main components: mobile and immobile oil. In California, 20 billion barrels of unrecovered mobile oil (UMO), oil which can be displaced by water but was uncontacted or bypassed by current operations, makes up the target for a number of advanced primary and secondary recovery processes, collectively referred to as advanced secondary recovery (ASR). Nearly 34 billion barrels of remaining immobile oil, residual oil that cannot be displaced by water due to viscous and capillary forces in the reservoir, represents the target for a number of tertiary extraction techniques, defined as enhanced oil recovery (EOR). Recovery operations directed at each of these resources could play a role in sustaining California's production well into the next century and in reducing the nation's dependence on foreign oil. 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 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, either natural influx or water injection. Proven enhanced recovery processes are classified into three categories: gas-miscible, chemical, and thermal.

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 polymer-augmented waterflooding), and other reservoir management techniques is to contact the oil in the unswept zones, prior to or along with EOR applications.

1. Enhanced Oil Recovery

Gas-miscible projects in California have been mostly pilot evaluations and have not been implemented on a field-wide or commercial scale. In 1981, ARCO Oil and Gas Company began a pilot test of carbon dioxide (CO₂) miscible flooding in the North Coles Levee field, Kern county, to evaluate the potential of CO₂ flood performance. The pilot was designed to inject CO₂ continuously into two inverted five acre, five spot patterns and one ten acre, line drive pattern. The pilot test was a technical success in mobilizing oil in the CO₂ swept areas with oil recovery in the range of 15% to 20% of hydrocarbon pore volume (and increasing) and efficiency in the range of 7.4 to 31.5 thousand cubic feet of CO₂ injected per barrel of oil recovered (and dropping).¹ However, the project was discontinued in

¹ MacAllister, D.J., "Evaluation of CO₂ Flood Performance: North Coles Levee CO₂ Pilot, Kern County, California," SPE 15499.

1984.² Nine additional gas-miscible projects, six of which are located in the Wilmington field in Los Angeles county, have been conducted.³ Only one carbon dioxide injection project remains active. Fault Blk. III of the Wilmington Field was activated in 1981, stopped in 1986, and resumed in 1991. It has 7 injectors and has injected a total of 3.5 Bcf of carbon dioxide, but no incremental oil production as a direct result of the EOR effort has been reported.⁴

Immobile carbon dioxide injection as an alternative to cyclic steam injection in California reservoirs appears to hold some promise according to recent reports.^{5,6} When routinely injected in a producing well, the CO₂ acts to swell the oil and reduce viscosity, improving the productivity of the well when placed back on production. The potential for this type of carbon dioxide stimulation was not modeled in this analysis.

Surfactant chemical floods have not been widely tested in California. Four projects, located in the West Coast region of the state, have been conducted. Unocal reported the largest of these projects in the Coalinga field, Fresno county. Started in 1980, the project is not currently operating and has not been reviewed in the literature.⁷ Like surfactant flooding, few alkaline floods have been implemented in California's fields. Twelve projects, eight of which are located in Los Angeles county, have been

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

³ U.S. Department of Energy, Bartlesville Project Office, *Enhanced Oil Recovery Projects Data Base*, April 1992.

⁴ 77th Annual Report of the State Oil and Gas Supervisor, California Department of Conservation Division of Oil and Gas, 1991.

⁵ Patton, J.T., et al., "Carbon Dioxide Well Stimulation: Part 2 - Design of Aminoil's North Bolsa Strip Project.", Journal of Petroleum Technology (August 1982): 1805.

⁶ Saner, W.B., and Patton, J.T., "CO₂ Recovery of Heavy Oil: Wilmington Field Test", Journal of Petroleum Technology (July 1986).

⁷ U.S. Department of Energy, Bartlesville Project Office, *Enhanced Oil Recovery Project Data Base*, April 1992.

implemented. Mobil reported the largest of these in the Torrance field, but it is not currently in operation and has not been reviewed in the literature.⁸

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. In fact, 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 fewer than 3,000 feet, like those that predominate the San Joaquin valley in central California.

Due to its large heavy oil resource, current and future California production is heavily dependent on the effective application of thermal EOR methods. Current thermal recovery in California accounts for over 75% of the EOR in the entire nation. In 1991, over 172 million barrels of California's oil production was attributable to thermal EOR methods. Seventy-seven percent of this incremental production occurred in three fields (Midway-Sunset, Kern River, and Belridge South) located in Kern county. Thermal EOR production began almost 40 years ago when Unocal instituted a steam flood in the Guadalupe field in 1955. While a variety of thermal EOR methods have been applied since that time, including hot water injection and in situ combustion, steam floods, both continuous and cyclic, have been the most prevalent and successful approaches. Currently, there are over 116 thermal EOR projects being conducted in the state of California, nearly 80% of which are located in Kern county. Over 90% of the thermal projects involve steam floods. Texaco, Shell and Mobil operate three of the most productive steam flooding projects. Texaco's steam flooding project in the Kern River field, which began in 1962, is producing over 80,000 barrels of oil per day. Shell and Mobil have steam flooding projects in the South Belridge field which are producing 65,000 and 41,000 barrels of oil per day, respectively. Twenty additional steam flooding projects were approved in 1991 by the California Department of Conservation. While low prices and environmental regulations, including restrictions on air emissions and the disposal of water and other production wastes, have kept producers from initiating many thermal projects, the nature of the oil resource ensures a continued important role for thermal EOR methods in future California oil production.^{9,10}

⁸ U.S. Department of Energy, Bartlesville Project Office, *Enhanced Oil Recovery Project Data Base*, April 1992.

⁹ Moritis, Guntis, *Oil and Gas Journal*, April 20, 1992.

2. Advanced Secondary Recovery

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

¹⁰ *77th Annual Report of the State Oil and Gas Supervisor, California Department of Conservation, Division of Oil and Gas.*

but will be modified by post-depositional diagenesis. That modification will vary from basin to basin depending on geohistory.

Recovery of remaining mobile and immobile oil from known fields is a highly cost effective method for increasing oil production. Since 1986, only two million barrels of the 11,470 million barrels in reserve additions in California have been attributed to new field discoveries. Therefore, the vast majority of these reserve additions have come from intensive development in older fields or application of improved recovery technologies. A large portion of these new reserves have resulted from implementation of waterflooding and pressure maintenance programs, drilling of additional wells to improve reservoir contact, and selective recompletion of existing wells to improve performance. Several distinct methods for producing UMO have emerged: infill drilling to tap uncontacted reservoir compartments, recompletion of production and injection wells to contact and sweep previously bypassed portions of the reservoir, polymer flooding to overcome unfavorable waterflood injection fluid characteristics, and profile modification to reduce the permeability contrast between reservoir layers. These techniques are all tested and proven methods for introducing mobile oil remaining in the reservoir.

Fourteen polymer floods have been implemented in California's fields. Three projects are being conducted in the Richfield field in Orange county by Texaco, which also operates a project in Ventura field, Ventura county. Shell has two projects in the Coalinga field in Fresno county, and Unocal has two projects in Santa Barbara county's Orcutt field. However, a Tenneco field located in the Yowlumne field of Kern county, has the most promising polymer flood, producing 3,400 barrels of oil per day.¹¹ Few infill drilling or profile modification projects were discussed in the literature.

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.

¹¹ U.S. Department of Energy, Bartlesville Project Office, *Enhanced Oil Recovery Projects Data Base*, April 1992.

There are several other processes and recovery techniques which were not included in this analysis which may have potential in California. 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 California oil recovery. In addition, improvements in reservoir management and improvements in waterflood patterns, waterflood rates of injection, and the timing of inception of waterfloods 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.

Two hundred and twenty-two reservoirs, accounting for 77 billion barrels of original oil-in-place (over 96% of the total known resource in California), were included in this analysis. These reservoirs contain 52 billion barrels of remaining oil resource (Figure II-10). Nearly 19 billion barrels of UMO is the target for application of ASR processes, and over 33 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 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

California Remaining Oil Resource After Conventional Recovery 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

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

Table III-2

Screening Criteria for EOR Candidates - Implemented Technology Case

Screening Parameters*		Units	Surfactant	Chemical Flooding	Miscible Flooding	Thermal Recovery	
Oil Gravity		°API	---	<40	<30	10 to 34	10 to 35
In-situ Oil Viscosity (μ)		cp	---	<90	---	≤15,000	≤5,000
Depth		Feet	---	---	---	≤3,000	≤11,500
Pay Zone Thickness (h)		Feet	---	---	---	≥20	≥20
Reservoir Temperature (TR)		°F	<200	<200	---	---	---
Porosity (ϕ)		Fraction	---	---	---	≥0.20***	≥0.20***
Permeability Average (k)		md	>40	>20	---	250	35
Transmissibility (kh/ μ)		md-ft/cp	---	---	---	≥5	≥5
Reservoir Pressure (PR)		psi	---	---	---	≤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 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 UMO resources in Texas, Oklahoma, and New Mexico.³ This expansion was accomplished by enlarging the system to consider the recovery potential of extended primary and secondary recovery operations in unswept portions of the reservoir, in a manner consistent with the current capabilities to analyze the tertiary recovery target (residual oil in previously swept zones). The system development and initial limited applications that were completed under the DOE UMO study are reported in detail in a topical report by the DOE.³

² *Ibid.*

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

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

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

A preliminary draft report of all developmental work is available through the U.S. Department of Energy, Bartlesville Project Office. The draft report is currently being finalized, and it will be available to the general public in 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 Flooding*</u>		<u>Profile Modification</u>	
	<u>Current</u>	<u>Advanced</u>	<u>Current</u>	<u>Advanced</u>
Reservoir Temperature (°F)	<200	<250	<180	<250
Formation Brine Salinity (ppm)	<100,000	<200,000	<100,000	<200,000
Permeability (md)	>20	>10	>20	>10
Oil Viscosity (cp)	<100	<150	<100	<150
* Source: NPC, 1984				

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

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

Table III-5

Screening and Approach for Advanced Technology Infill Drilling

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

D. SCOPE OF THE ANALYSIS

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

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

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

Table III-6

Risk Premium For Implemented and Advanced EOR and ASR Processes

	Cost of Capital	Risk Factors		Hurdle Rates	
		Implemented Technology (%)	Advanced Technology (%)	Implemented Technology (%)	Advanced Technology (%)
Alkaline	10	15	0	27	10
Surfactant	10	15	0	27	10
In-Situ	10	15	5	27	16
Polymer	10	5	0	16	10
Profile Modification	10	5	0	16	10
CO ₂ -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 RD&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 222 of the largest California reservoirs, accounting for over 96% of estimated original oil-in-place (OOIP) in California. 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 California. 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 California. A state tax incentive for EOR and ASR projects was also modeled as part of this analysis. This incentive forgave all production and corporate income taxes associated with the EOR or ASR project until the point of project payback.

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.

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

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

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 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

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

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 California state and local treasuries from advanced oil recovery processes are the additional tax revenues attributable to implementation of the projects. These taxes include production taxes, 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 improved 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 California 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's economy is defined as the sum of net revenues to the state and local treasuries (as presented above); royalties to individuals, corporations, and the state; expendable (intangible) drilling materials and services; and operating costs excluding injectant purchases. It is assumed that these funds flow predominantly to the state of California 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 California. 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 California, 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 California (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 California 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 the state of California 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 California oil resource. Direct Federal taxes total 5% to 20% of the value of each barrel of oil recovered. Each additional barrel of California oil production can replace a barrel of imported oil. 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 individual Federal income taxes are estimated to assess the direct effects of incremental oil recovery in California on the Federal treasury.

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

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 percent of any reservoir would not be developed under EOR or ASR operations.

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

A third limitation is the use of simplified process performance models. While the models used in this project are extensively calibrated, they are designed to analyze large numbers of individual reservoirs quickly and simultaneously. Therefore, while they incorporate all the relevant reservoir engineering concepts, they are relatively simplified and generalized. In this simplified state, the models cannot be as accurate as highly detailed reservoir simulators in which very specific reservoir features and process designs may be evaluated (such as assessments used in the actual design of specific projects). The present study assumes these models are appropriate for aggregate analyses but not necessarily for individual reservoirs. Further, these models are explicitly designed to estimate only incremental recovery resulting from advanced oil recovery processes after completion of conventional production operations.

Laboratory and limited field data suggest that application of some of these techniques before the economic limit of conventional recovery could yield more than the sum of conventional and advanced oil recovery, but this is not reflected in the models.

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

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

None of the above limitations invalidate the results of this analysis. Given the uncertainty of the size and combinations of the optimistic and pessimistic biases introduced by these limitations, it is assumed that the approach is valid and the resulting projections are reasonable. To avoid misinterpretation of particular reservoirs, and to respect the confidence in which some project and reservoir data were obtained, no reservoir specific 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 CALIFORNIA 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 California 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 refers to future recovery estimated for the analyzed EOR and ASR techniques. Such production and reserves are above and beyond the recovery attainable by primary and secondary recovery techniques.
- Both light oil (API > 20 degree) and heavy oil (API ≤ 20 degree) resources are considered in this analysis.
- All EOR and ASR recovery potential evaluated in this report reflect future new projects only, and they do not include incremental reserves from existing (ongoing) EOR and ASR projects. However, the expansion to the ongoing projects, if technically and economically feasible, are evaluated as part of future new projects in this report.

All reservoirs are screened for technical criteria and are analyzed in detail using the process performance and economic models described in Chapter III. The results are based on the evaluation of 222 reservoirs in California for their EOR and ASR potential. The results of this analysis were not extrapolated to the rest of the reservoirs making up the California resource.

B. RECOVERY OF THE REMAINING IMMOBILE OIL RESOURCE

1. Production and Reserves

Over the analyzed oil price range, EOR processes (chemical and thermal) could stimulate from 860 million to 3.8 billion barrels of incremental reserves under implemented technology (Figure IV-1A and Table IV-1A). This potential represents an increase to California's current onshore proved reserves (nearly 4.0 billion barrels) of between 21% and 95%. At an oil price of \$16/B, incremental reserves would

be relatively small. However, as the oil price rises above \$20/B, EOR processes could become increasingly prolific, and substantial incremental reserves could become economic to develop. The 2.0 billion barrels of potential EOR reserves at \$20/B could increase by 1.0 billion barrels with an \$8/B increase in the oil price. At an oil price of \$36/B, EOR techniques could generate total reserve additions of 3.8 billion barrels. Roughly 80% to 90% of the potential reserves could be attributable to expansions of existing EOR projects.

Among the EOR processes considered in this analysis, thermal (steamflooding and in situ combustion) EOR could generate the largest incremental reserves at all oil prices, and the largest contributor would be steamflooding. California has the largest volume of heavy oil in the United States. The remaining immobile heavy oil analyzed in this study is estimated at approximately 14 billion barrels, over 40% of the state's total remaining immobile oil, so the prevalence of thermal EOR is not surprising. At oil prices less than \$32/B, thermal EOR could account for all of the potential incremental reserves. At all prices, steamflooding could account for more than 92% of the potential EOR reserves.

The recovery potential of other EOR processes under the implemented technology scenario is limited in California. Chemical flooding could generate over 250 million barrels of incremental reserves at oil prices over \$28/B. Under implemented technology, no carbon dioxide-miscible flooding EOR projects were found to be economic.

Table IV-1B shows the number of EOR projects that could be initiated at different oil prices. Of the reservoirs evaluated in this analysis, only 15% could become economic to develop with current EOR technology at oil prices of \$36/B or below. In most cases, the economic projects are in the large reservoirs, but size alone is not a major determinant of EOR economics.

The timing of EOR project initiation in each reservoir that is economic at a specific price is scheduled according to that reservoir's projected conventional production decline rate. The annual incremental production resulting from EOR is determined by phasing in economic projects based on the demonstrated economic limit of conventional production, as discussed in Chapter III. Figure IV-1B shows the expected annual production from all EOR processes for oil prices of \$16/B and \$32/B. At \$16/B, EOR production could reach 47 million barrels per year in the year 2000 and could remain close to that level for ten years before declining. Annual production at \$32/B could reach over 150 million barrels in the year 2000 and could maintain that level for more than 10 years. Such steady incremental production rates and rapid declines are typical of steamflooding projects.

Table IV-1A

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

Oil Price (\$/B)	Chemical	Thermal	Total
\$16	0	861	861
\$20	0	2,033	2,033
\$24	0	2,599	2,599
\$28	0	3,022	3,022
\$32	252	3,087	3,339
\$36	252	3,518	3,770

* The analyzed California reservoirs did not exhibit any CO₂-miscible flood potential.

Table IV-1B

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

Oil Price (\$/B)	Chemical	Thermal	Total
\$16	0	9	9
\$20	0	13	13
\$24	0	20	20
\$28	0	26	26
\$32	1	29	30
\$36	1	32	33

* The analyzed California reservoirs did not exhibit any CO₂-miscible flood potential.

Figure IV-1

Reserves and Production Response from EOR Techniques

Implemented Technology

A) Incremental Reserves by EOR Process

* There was no economic miscible flooding potential in analyzed reservoirs.

B) Annual Production from EOR Reserves

2. Increases in State and Local Revenues

EOR production could also enhance state and local revenues by increased production taxes, sales taxes on purchased materials used in the analyzed EOR projects, and larger state corporate and personal income taxes on wages paid and operator profits. The revenues projected in this study are generated directly from oil production or operations in the analyzed reservoirs. State and local revenues generated over the life of the EOR projects vary considerably with oil prices, as shown in Figure IV-2. A significant portion of these revenues result from production taxes and corporate income taxes. At \$20/B, nearly \$1.7 billion in incremental revenues could be generated by implemented technology EOR. At \$28/B, nearly \$3.8 billion in additional direct state revenues could be stimulated by EOR. The percentage of total state revenues which could result from corporate income taxes increases as the price increases; at \$36/B, the contributions of corporate income and production taxes to the state treasury would be essentially equal.

Figure IV-2

Direct State and Local Revenues from EOR Production Implemented Technology

3. Effects on the State Economy

In addition to the incremental state and local revenues, enhanced oil recovery could benefit California by increasing economic activity and by creating or maintaining 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 California 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., from production on Federal lands). While the excluded elements undoubtedly aid California's citizens to some degree, a substantial portion of the benefits will be enjoyed by citizens of other states. However, to the extent that local manufacture or retail sales of these items provide economic benefits within California, injectants produced or manufactured in California are employed, or economic "multipliers" occur, the calculated economic effects are understated.

Figure IV-3 displays the total direct economic gains for the state over the oil price range analyzed. In all cases, operating costs could account for approximately 70% of these economic effects; state taxes could represent around 10%; intangible investment could be about 1% to 2%; and royalties could constitute under 20% of the total. At \$16/B, incremental benefits of the EOR projects to the state economy could exceed \$6.7 billion. A substantial increase in economic activity occurs at oil prices above \$16/B; \$18 billion and \$32 billion could be generated by EOR activities at prices of \$20 and \$28/B, respectively. At the highest oil price considered, \$36/B, almost \$50 billion of statewide direct economic activity could be stimulated by EOR projects.

Economic activity stimulated by EOR projects using implemented technology could create or maintain a substantial number of jobs statewide (Figure IV-4). The number of jobs attributable to new EOR projects during peak years could reach from 800 to over 5,000 per year, depending on the oil price. Total annual wages paid could peak between \$40 and \$230 million.

4. Effects on the National Economy and Budget

Increased oil recovery from EOR in California would also directly benefit the nation as a whole. National benefits would accrue in several ways: replacement of oil imports, increased Federal corporate

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.

Figure IV-4

Jobs and Wages from EOR Production

and personal income tax revenues, and a reduced trade deficit. The addition of as many as 3.8 billion barrels of reserves in California would expand the nation's proved reserve base. Since an additional barrel of domestic oil production could replace a barrel of imported oil, the nation's energy security would be enhanced through the implementation of EOR in California.

EOR activity in California contributes to the Federal treasury through personal and corporate income taxes. As shown in Figure IV-5A, increases in Federal revenues attributable to EOR could range from \$300 million at \$16/B to \$8 billion at \$36/B over the life of the analyzed projects. Corporate income taxes could account for between 70% and 90% of this total, depending on the oil price, and personal income taxes would make up the remainder. At moderate oil prices (\$20/B to \$28/B), \$2.0 billion to \$3.9 billion in direct Federal revenues could be generated from implemented technology EOR projects. At oil prices above \$28/B, there would be a significant increase in Federal revenues as the Federal EOR tax credit begins to phase out. It is assumed that the tax credit is used to offset other profitable operations. At \$36/B, the potential Federal revenues could be more than double the potential at \$28/B.

An increase in California oil production could directly correspond to a reduction in the trade deficit as oil imports could be replaced on a barrel-for-barrel basis by domestic production (Figure IV-5B). The trade deficit could be reduced by the direct value of the avoided imports (reserves multiplied by the effective wellhead oil price). The gains in imports avoided would represent funds that would otherwise flow to oil exporting countries to pay for U.S. oil imports. EOR in California would thus help reduce the trade deficit, enabling this money to instead circulate through the U.S. economy. At oil prices ranging from \$20/B to \$28/B, \$22 billion to \$44 billion in avoided imports could be generated by implemented technology EOR. At \$36/B, over \$73 billion could be generated.

C. RECOVERY OF THE REMAINING MOBILE OIL RESOURCE

This section will discuss the application of currently available ASR processes in analyzed reservoirs throughout the state. These two distinct recovery technologies, enhanced oil recovery and advanced secondary recovery, have been addressed separately to illustrate the potential benefits of each. However, since the resource target of these two technologies is different, both could be implemented in individual California reservoirs, and the results would be independent and additive. Given the potential synergies in the simultaneous employment of the EOR and ASR technologies, incremental reserves and economic benefits could be even greater than the sum of the two.

Figure IV-5

National Impact of EOR 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.

1. Production and Reserves

Depending on the oil price, ASR techniques applied in the analyzed reservoirs could stimulate between 700 and 750 million barrels of additions to current proved reserves in California. ASR techniques are less costly to implement than EOR recovery processes, and therefore, incremental reserves from ASR are less sensitive to changes in the oil price. The total incremental ASR potential at implemented technology levels could be much less than the potential seen for steamflooding across the analyzed price range.

This analysis evaluates three categories of ASR processes: polymer flooding and profile modification, infill drilling, and combinations of infill drilling with polymer flooding and profile modification. As shown in Figure IV-6A and Table IV-2A, polymer flooding and profile modification, applied alone and in combination with infill drilling, could play a predominant role in ASR, accounting for the bulk of the incremental reserves at all oil prices. The combination processes could contribute from 160 million to 200 million barrels of incremental reserves, while polymer flooding and profile modification could contribute 520 million barrels of incremental reserves. As oil prices increase, infill drilling could become more economic, but in this analysis, infill drilling alone did not contribute more than 3% of the total ASR reserves potential.

Table IV-2B shows the number of projects expected to be economic at each price for each recovery method. At all prices, the number of polymer flooding and profile modification projects and combination projects are higher than infill drilling. The same group of projects are essentially responsible for the potential across the entire range of analyzed prices, indicating that there is a fairly small group of reservoirs amenable to implemented technology ASR, but that they have potential at fairly low oil prices.

Figure IV-6B displays the expected annual production from all ASR processes for oil prices of \$16/B and \$32/B. Annual ASR production at an oil price of \$16/B could reach around 30 million barrels by the year 2007 and maintain that level for several years before declining gradually. At an oil price of \$32/B, annual production would be only marginally greater. To put the potential contribution of implemented technology ASR production into perspective, 30 million barrels per year would add less than 10% to current California annual production. ASR projects are undertaken as reservoirs reach their economic limit under conventional production. In this study, ASR projects are assigned initiation dates as a function of rig availability and technology transfer; projects are therefore phased in over time and some fields could be abandoned before ASR can be implemented. This abandonment, which is reflected in annual production, could be on the order of 20% of the potential resource.

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 and Polymer Flooding or Profile Modification	Total
\$16	523	13	166	702
\$20	516	13	192	721
\$24	519	13	194	726
\$28	522	24	195	741
\$32	522	24	195	741
\$36	524	24	196	744

Table IV-2B

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

Oil Price (\$/B)	Polymer Flooding and Profile Modification	Infill Drilling	Infill Drilling and Polymer Flooding or Profile Modification	Total
\$16	14	3	12	29
\$20	13	3	15	31
\$24	13	3	15	31
\$28	15	4	15	34
\$32	15	4	15	34
\$36	17	4	15	36

Figure IV-6

Reserves and Production Response from ASR Techniques

Implemented Technology

A) Incremental Reserves by ASR Process

B) Annual Production from ASR Reserves

2. Increases in State and Local Revenues

Figure IV-7 shows the expected growth in state revenues from ASR production and the proportional contributions of production, sales, and state income taxes to the total. State corporate income tax receipts could account for the largest portion of total state revenues from ASR over all prices considered. Corporate taxes could generate \$600 million of the \$940 million in direct state revenues at an oil price of \$16/B. At moderate oil prices (\$20/B to \$28/B), \$1.2 billion to \$1.8 billion in additional direct state revenues could be stimulated by implemented technology ASR activities. At \$36/B, \$2.3 billion could be generated for the state through ASR activities, with 70% of that amount from state corporate taxes.

Figure IV-7

Direct State and Local Revenues from ASR Production Implemented Technology

3. Effects on the State Economy

Figure IV-8 displays the total state economic activity associated with potential implemented technology ASR production. Total state economic activity could range from \$3.6 billion at \$16/B to \$7.6 billion at \$36/B. Between \$4.6 billion and \$6.2 billion of economic activity could be generated by implemented technology ASR at oil prices ranging from \$20/B to \$28/B. State tax revenues and royalties would be the largest components of these increases in state economic activity, each accounting for roughly 30% of the total. Together these could total \$5 billion at the \$36/B oil price. Operating costs would be the next largest component of increased economic activity, averaging about 20% to 30% of the total activity across all oil prices. Intangible investments would contribute the remaining 10%.

The implementation of ASR techniques could also contribute to employment in the state of California. Figure IV-9 displays the annual number of jobs that could be created or maintained by ASR projects. The annual trends in jobs created or maintained closely match the production trends. At an oil price of \$16/B, jobs directly resulting from new ASR projects could rise to over 400 per year in 2008 and then decline over the next 12 years. At \$32/B, the number of jobs created or maintained annually could reach 600. At this price, as much as \$27 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 ASR production in California. Federal revenues from ASR production could range from about \$1.9 billion to \$5.0 billion over the oil price range analyzed. Figure IV-10A shows that nearly all of these revenues could stem from increased corporate income taxes. Implemented technology ASR activity could stimulate an additional \$2.4 billion to \$3.6 billion in direct Federal revenues at oil prices ranging from \$20/B to \$28/B.

As the increased California production replaces oil imports, the U.S. trade deficit could be reduced and national security would be enhanced as the nation's vulnerability to future supply disruptions is diminished. At moderate oil prices, \$12 billion to over \$17 billion in imports avoided could result from implemented technology ASR activities. At \$36/B, over \$22 million in avoided imports could be generated (Figure IV-10B).

Figure IV-8

Direct State Economic Activity* from ASR Production

Implemented Technology

* 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

Implemented Technology

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.

D. CONCLUSIONS

At implemented technology levels, EOR and ASR processes could make substantial contributions to the reserve base and the California and national economies, as well as to domestic energy security. At a \$24/B oil price, EOR processes could add 2.6 billion barrels of oil to California reserves while ASR techniques could add over 720 million barrels of incremental reserves. The application of current EOR and ASR technologies, in concert, could potentially add over 3.3 billion barrels of reserves at this price, nearly replacing California's current onshore 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 California and its citizens stand to gain significantly from the increased production resulting from incremental reserves. Production increases could generate \$2.9 billion to \$7.0 billion in additional state and local revenues over the life of the analyzed projects assuming oil prices of \$20/B to \$32/B. Total state economic activity could be boosted by \$23 billion to \$48 billion over the same price range. Jobs would be created or maintained, and state economic activity would increase. The national economy would benefit through decreased oil imports, reductions in the trade deficit, and increased Federal corporate and personal income tax revenues. Maximizing recovery of the known oil resource in California should therefore be an important goal for state and Federal policymakers. 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.

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 a large resource target for improved recovery technologies. Of the 33 billion barrels of immobile oil resource analyzed in this study, implemented technology EOR practices as defined in this report could produce an estimated 3.8 billion barrels at an oil price of \$36/B, leaving over 29 billion barrels of remaining immobile oil in these reservoirs. Of the nearly 19 billion barrels of UMO in the analyzed California reservoirs, implemented technology practices could produce an estimated 740 million barrels at \$36/B, leaving nearly 18 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

California Remaining Oil Resource After Implemented Technology Recovery

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

A. INTRODUCTION

While currently available enhanced oil recovery (EOR) and advanced secondary recovery (ASR) techniques could contribute substantially to the California reserve base, technological advances in these processes resulting from a concerted RD&D effort would have far more dramatic effects on the state's oil production. Development and wide-scale application of improved recovery 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 the impact of advanced technology on oil recovery and the associated economic benefits. Evaluations of advanced technology EOR and ASR potential in the state of California are presented separately. Given that the modeled advances in technology are conservatively defined, improvements in recovery processes resulting from RD&D not envisioned in this report could add substantially to the estimated reserve potentials. However, well abandonments could limit access to the resource and increase project costs if EOR and ASR are not applied before conventional production ceases. Immediate actions are therefore necessary to realize the economic benefits of these advanced processes.

B. RECOVERY OF THE REMAINING IMMOBILE OIL RESOURCE

1. "Advanced" Technology Defined

Enhanced oil recovery processes, as currently applied, have severe limitations. Some current EOR techniques can only be applied in a limited number of reservoirs with properties which fall within a narrow range of suitable values (temperature, salinity, oil viscosity, etc.). The sweep efficiency of EOR processes is often relatively poor; only a small portion of the residual oil remaining in the previously waterflooded zone is contacted. Injectants are expensive, often approaching the value of the oil they are designed to recover, which places a burden on project economics. The National Petroleum Council (NPC) predicted gradual improvements in EOR performance and project economics as current processes are improved and tested in the lab and field. These advanced processes are predicted to gain operator acceptance as the research and development efforts of oil companies, universities, 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 most likely to impact California oil production will be advances in chemical EOR applications. 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. 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 would result in improvements in injection rate, interfacial tension, chemical retention, and lower costs, thereby improving the recovery and economics of these relatively prolific processes. Additionally, the risk factors associated with current chemical and gas-miscible flooding are assumed to be substantially reduced by an RD&D effort.

2. Production and Reserves

Under advanced technology, EOR could potentially stimulate incremental reserves of 1.2 billion to 7.2 billion barrels over the price range analyzed in this study (\$16/B to \$36/B). Nearly 390 million to 3.4 billion barrels of the potential incremental reserves could be attributed to advances in technology over the price range analyzed. Figure V-1 and Table V-1A show the comparison between the incremental reserves potentially generated through the application of advanced technology EOR processes and implemented technology EOR processes. The greatest increase in incremental reserves due to advanced technology would occur in the higher end of the analyzed price range, at oil prices of \$24/B and greater. At \$20/B, incremental reserves due to EOR technology advances could be 1.2 billion barrels for a total advanced technology potential of 3.2 billion barrels. At \$28/B, advanced technology could stimulate an additional 6.2 billion barrels of incremental reserves. Over the \$24/B to \$36/B price range, advanced technology EOR processes could double the potential reserves from implemented technology EOR processes at the same oil price. The difference between the potentials would be the increment resulting from successful RD&D and technology transfer efforts.

The potential incremental reserves contributed by each of the advanced EOR processes considered in this analysis are also shown in Figure V-1. Advanced chemical flooding is the primary source of incremental reserves over the implemented technology potential at all but the highest oil price. At \$20/B, advanced technology chemical flooding could recover 963 million barrels of oil due to advances in technology. At \$28/B, advanced chemical flooding could recover 1.8 billion barrels from California reservoirs that could not have been economically producible with implemented technologies.

Advances in thermal EOR technology, primarily steamflooding, produce little incremental potential over implemented technology reserves until oil prices reach \$24/B. At that price, advanced thermal processes could contribute 3.8 billion barrels versus 2.6 billion barrels from implemented technology thermal EOR. The difference, 1.2 billion barrels, would be attributable to advances in steamflooding technology. This increment could increase to 1.8 billion barrels at \$36/B. Total advanced technology thermal EOR reserves at this price could reach 5.3 billion barrels of incremental oil.

Figure V-1

Incremental Reserves by EOR Process Implemented Technology vs. Advanced Technology

* There was no economic miscible flooding potential in analyzed reservoirs.

As under implemented technology conditions, advanced miscible flooding processes do not generate any potential reserves over the analyzed oil price range. While there may be some limited potential for CO₂-miscible flooding in California, it is not apparent from this analysis. Such unrecognized potential may exist in reservoirs which are not part of the TORIS database, or in reservoirs where unique economic criteria hold. Immiscible carbon dioxide injection as an alternative to cyclic steam injection in California reservoirs appears to hold some promise according to recent reports.^{1,2} When routinely injected in a producing well, the CO₂ acts to swell the oil and reduce viscosity, improving the productivity of the well when placed back on production. The potential for this type of carbon dioxide stimulation was not modeled in this analysis.

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 chemical projects increases dramatically (by 30 at prices above \$24/B) indicating that technology enhancements to chemical processes are the key to bringing many more California fields over the EOR economic or technical threshold. The number of thermal projects under advanced technology could be 50% higher than the number in the implemented technology case at prices above \$20/B. This increase is roughly proportional to the increase in incremental reserves, indicating that the bulk of the reserves due to advances in thermal processes result from improved applicability or enhanced project economics; the additional reserves due to advanced technology are coming from reservoirs that were not technically or economically viable to develop under implemented technology conditions.

Figure V-2 shows the expected annual EOR production for oil prices of \$16/B and \$32/B for both the implemented and advanced technology cases. Even at \$16/B, up to 70 million barrels per year could be added to California oil production by the years 2000 to 2005 as a direct result of advanced technology EOR. The peak under advanced technology could be over 22 million barrels per year more than the implemented technology peak. At \$32/B, advanced technology EOR could generate more than 200 million barrels by the year 2010, nearly 50 million barrels per year more than the production estimated under implemented technology at this oil price.

¹ Patton, J.T, et al., "Carbon Dioxide Well Stimulation: Part 2 - Design of Aminoil's North Bolsa Strip Project", Journal of Petroleum Technology (August 1982): 1805.

² Saner, W.B. and Patton, J.T., "CO₂ Recovery of Heavy Oil: Wilmington Field Test", Journal of Petroleum Technology (July 1986).

Table V-1A

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

Oil Price (\$/B)	Chemical		Thermal		Total	
	Implemented	Advanced**	Implemented	Advanced**	Implemented	Advanced**
\$16	0	378	861	869	861	1,247
\$20	0	965	2,033	2,252	2,033	3,217
\$24	0	1,273	2,599	3,821	2,599	5,094
\$28	0	1,816	3,022	4,361	3,022	6,177
\$32	252	1,878	3,087	4,799	3,339	6,677
\$36	252	1,925	3,518	5,288	3,770	7,213

* The analyzed California reservoirs did not exhibit any CO₂-miscible flooding potential.

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

Table V-1B

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

Oil Price (\$/B)	Chemical		Thermal		Total	
	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced
\$16	0	7	9	9	9	16
\$20	0	20	13	18	13	38
\$24	0	24	20	29	20	53
\$28	0	31	26	33	26	64
\$32	1	30	29	43	20	73
\$36	1	34	32	48	33	82

* The analyzed California reservoirs did not exhibit any CO₂-miscible flooding potential.

Figure V-2

Annual Production from EOR

Implemented Technology vs. Advanced Technology

A) At \$16/B

B) At \$32/B

3. Effects on State Revenues and Economic Activity

At all analyzed oil prices, the direct revenues to the state of California from EOR activities could significantly increase with advanced technology (Figure V-3A). Similar to the implemented technology case, production taxes and state corporate income taxes in the advanced technology case would make up over 75% of the state's total direct revenues and sales tax receipts would contribute most of the remaining 25%. At \$20/B, advanced technology could generate incremental revenues from EOR of nearly \$3.0 billion, \$1.4 billion of which could be stimulated by EOR technology advances. At an oil price of \$28/B, advances in EOR technology could stimulate \$5.4 billion in state revenues, for a total of \$9.2 billion in potential direct state revenues from advanced technology EOR.

Direct state economic activity generated by California EOR would also grow due to advanced technology. Figure V-3B displays the total potential incremental direct economic benefits to the state for both the implemented and advanced technology cases. The distribution of total economic benefits among the contributing components under advanced technology would be similar to the distribution shown in the implemented technology case. At \$20/B, the incremental state economic gain due to advanced EOR technology is estimated at \$32 billion, an increase of \$14 billion over implemented technology potential. At \$28/B, the direct state economic gain could increase to over \$80 billion with full advanced EOR technology development. The differences between the implemented and advanced technology potential would be attributable to advances in technology. Clearly, the state of California could accrue substantial benefits from the development and application of advanced EOR technology at all analyzed oil prices.

Advanced technology also has a substantial impact on the state's employment. Even at a relatively low oil price of \$16/B, the development of advanced technology could create or maintain over 2,400 jobs annually by the year 2001, more than twice the potential under implemented technology (not illustrated). At the higher oil price of \$32/B, up to 4,000 jobs per year more than those created or maintained under implemented technology could result from development and implementation of advanced EOR technology processes. Peak wages at \$16/B and \$32/B with advanced technology EOR could total at \$110 and \$375 million per year, respectively.

4. Effects on the National Economy and Budget

As discussed in Chapter IV, increased oil recovery in the state of California through EOR processes would significantly benefit the nation in the areas of enhanced energy security, import

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.

replacement, a reduced trade deficit, and expanded direct revenues to the Federal treasury. The potential benefits could be even more pronounced with the development of advanced technology. Over 7.0 billion barrels of crude oil could be recovered with advanced EOR technology, 3.4 billion barrels of which are the incremental reserves over implemented technology. These reserves could offset oil imports and enhance U.S. energy security.

Revenues to the Federal treasury, in the form of corporate and personal income taxes, could grow along with reserves as a result of advances in technology (Figure V-4A). Technology advances could increase implemented technology potential by \$140 million to over \$2.0 million in direct Federal revenues at oil prices ranging from \$20/B to \$28/B. The total direct Federal revenues stimulated by advanced technology EOR could total \$1.3 billion to nearly \$6.0 billion at these prices. At oil prices above \$28/B, additional direct Federal revenues could become more substantial as the Federal EOR tax credit begins to phase out. At \$36/B, after a complete phaseout of the tax credit, advanced technology EOR could stimulate over \$17 billion in direct Federal revenues, over 53% of which could be due to advances in EOR technology.

As imports are replaced, the trade deficit could be reduced and money, formerly flowing to oil exporting countries, could be recirculated within the U.S. economy. Only the direct value of the avoided imports (potential reserves multiplied by the effective wellhead oil price) is considered in this analysis. Economic multipliers could stimulate indirect effects within the economy and further enhance the benefits from advanced technology EOR activities. At oil prices ranging from \$20/B to \$28/B, an additional \$19 billion to \$67 billion in avoided imports could be stimulated by technology advances, for a total of \$41 billion to over \$110 billion (Figure V-4B). At \$36/B, nearly \$95 billion (56%) of the \$170 billion in total avoided imports could be attributable to advances in EOR technology.

C. RECOVERY OF THE REMAINING MOBILE OIL RESOURCE

1. "Advanced" Technology Defined

The ASR advanced technology analysis, designed to reflect the potential technological improvements possible from a focused RD&D program in geological reservoir characterization, is conducted in a manner consistent with the implemented technology analysis. A major assumption is that RD&D will allow geologic reservoir characterization techniques to be widely applied, resulting in infill

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.

drilling that is targeted only into those portions of the reservoir where project economics will allow drilling to closer well and pattern spacings. This will improve the project economics of ASR, resulting in more activity and much greater recovery under advanced technology than would be possible under the reservoir-wide, blanket drilling program assumed in the implemented technology case. Heterogeneous portions of reservoirs contain a proportionally larger amount of unrecovered mobile oil that is trapped in isolated compartments or bypassed by the injection fluids in conventional recovery operations. By contrast, the more homogenous portions of reservoirs exhibit more efficient conventional recovery and require less intensive drilling. In this study, infill drilling potential is evaluated by dividing each reservoir into two parts: a more continuous (homogeneous) segment and a less continuous (heterogeneous) segment. The economic recovery potential is evaluated independently in each segment, and the closest economic well spacing for each segment is independently selected.

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

2. Production and Reserves

The development of advanced technology ASR methods through RD&D could further increase California's oil reserves. The incremental reserves from advanced technology ASR could range from 870 million to 960 million barrels in the analyzed California reservoirs (Figure V-5 and Table V-2A). ASR is less sensitive than EOR to increases in oil price. Thus, a similar increase in reserves due to advances in technology can be seen across the analyzed oil price range, between 170 million and 215 million barrels.

Table V-2A shows the distribution of incremental reserves by ASR process. Essentially the same effects are reflected in the advanced technology case as were seen under the implemented technology case: polymer flooding and profile modification could have the most potential, followed by combination

processes and then infill drilling applied alone. On a percentage basis, infill drilling would have the largest increase, but the largest reserves increase with advanced technology, an increment of 170 million barrels, would occur for polymer flooding and profile modification over the entire price range analyzed.

Table V-2B shows the estimated number of economic ASR projects for both the implemented and advanced technology cases. At all oil prices, the number of infill drilling projects is essentially unchanged under advanced technology, although the incremental reserves associated with these projects increase dramatically. This increase in recovery from projects that were already economic under implemented technology emphasizes the effectiveness of targeting infill wells to the more prolific portions of the reservoir. Table V-2B also shows that the number of economic polymer flooding and profile modification projects could increase significantly from the implemented case; this increase is roughly proportional to the rise in reserve additions at all oil prices considered. The number of economic projects increases as a result of assumed improvements in the chemical composition of polymer solutions that allow these solutions to withstand more severe reservoir conditions. Such technological advances would make more

Figure V-5

Incremental Reserves by ASR Process Implemented Technology vs. Advanced Technology

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 and Polymer Flooding or Profile Modification		Total
	Implemented	Advanced*	Implemented	Advanced*	Implemented	Advanced*	
\$16	523	693	13	29	166	150	872
\$20	516	691	13	30	192	171	892
\$24	519	690	13	33	194	195	918
\$28	522	691	24	36	195	214	941
\$32	522	693	24	50	195	201	944
\$36	524	693	24	50	196	216	959

* This is the total reserves under advanced technology plus the increment due to technology advances.

Table V-2B

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

Oil Price (\$/B)	Polymer Flooding and Profile Modification		Infill Drilling		Infill Drilling and Polymer Flooding or Profile Modification		Total
	Implemented	Advanced	Implemented	Advanced	Implemented	Advanced	
\$16	14	24	3	3	12	12	39
\$20	13	24	3	3	15	15	42
\$24	13	23	3	3	15	18	44
\$28	15	24	4	3	15	18	45
\$32	15	25	4	4	15	18	47
\$36	17	25	4	4	15	19	48

reservoirs technically and economically amenable to the application of chemical treatment processes. The additional projects would be undertaken in reservoirs which were not economic to develop under implemented technology.

Figure V-6 displays the projected annual production that could result from ASR technology advances for oil prices of \$16/B and \$32/B from the analyzed California reservoirs. At both oil prices, a relatively small amount of oil could be added to the state's production over the next 25 years from the implementation of advanced ASR techniques. A substantial portion of the incremental production attributable to advanced technology could occur in the years beyond the year 2010. At \$16/B, production from advanced technology ASR reserves could peak at over 34 million barrels per year in the year 2008, a 2 million barrel per year increase over the implemented technology peak. At \$32/B, advanced technology ASR could produce nearly 37 million barrels per year in the year 2008, a 3 million barrel per year increase over the implemented technology peak at this oil price.

3. Effects on State Revenues and Economic Activity

Advances in technology could result in significant increases to direct state and local revenues from production taxes, sales taxes, and state corporate and personal income taxes (Figure V-7A). At oil prices between \$20/B and \$28/B, technology advances could stimulate \$300 million to \$465 million over implemented technology potential, for a total of \$1.5 billion to \$2.2 billion in state revenues stimulated by advanced technology ASR. At \$36/B, \$625 million (22%) of the \$2.9 billion in state revenues generated by advanced technology ASR could be attributed to advances in technology. As in the implemented technology scenario, the revenues would be mostly from corporate income taxes (which could account for 60% to 70% of the total potential across the analyzed oil price range).

In addition to increases in state and local revenues, the application of advanced technology ASR could significantly increase economic activity within the state of California. At oil prices between \$20/B and \$28/B, \$1.1 billion to \$2.2 billion in additional state economic activity could be stimulated by the application of ASR technology advances. At these prices, advanced technology ASR could generate a total of \$5.6 billion to \$8.4 billion of additional economic activity within the state. At an oil price of \$36/B, nearly \$11 billion of in-state economic activity could be stimulated by advanced technology ASR, 28% of which would be attributable to technology advances (Figure V-7B).

Annual production of advanced ASR reserves could also create or maintain a substantial number of jobs in California (not illustrated). Advanced ASR technology could result in an increase of about 50

Figure V-6

Annual Production from ASR

Implemented Technology vs. Advanced Technology

A) At \$16/B

B) At \$32/B

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.

to 100 jobs annually over the 2005 to 2020 time period at an oil price of \$16/B, and 100 to 200 jobs per year at an oil price of \$32/B. Even at lower prices, the number of jobs created or maintained by advanced technology ASR processes could be beneficial to the California economy.

4. Effects on the National Economy and Budget

The development of advanced technology for the recovery of the known UMO resource in the state of California could also benefit the nation. Figure V-8A shows a small, but significant, increase in the incremental revenues to the Federal treasury from personal and corporate income taxes due to technology advances. Total Federal revenues from advanced technology ASR could range from \$2.3 billion at the \$16/B oil price to \$6.3 billion at \$36/B. Essentially all of these revenues would stem from increased corporate income taxes. Over \$470 million to \$1.3 billion of the additional Federal revenues could be attributed to advances in ASR technology.

The nation would also benefit from increased ASR in California through enhanced energy security as the domestic resource base expands. Each barrel of reserves added through advanced ASR techniques in California could replace a barrel of imported oil and reduce the nation's trade deficit by the direct value of the avoided imports. At oil prices of \$20/B to \$28/B, the application of technology advances could result in \$3.0 billion to \$4.9 billion in avoided imports over implemented technology, for a total of \$15 billion to \$22 billion of avoided imports due to advanced technology ASR. At an oil price of \$36/B, over \$29 billion in imports avoided could be generated by advanced technology ASR, 23% of which could be due to advances in technology (Figure V-8B).

D. CONCLUSIONS

As discussed in Chapter IV, 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 application.

Advances in technology could significantly increase the potential reserves and associated economic benefits which are possible using implemented technology EOR and ASR. At an oil price of \$20/B, implemented technology EOR and ASR processes could contribute nearly 2.8 billion barrels to California's

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.

reserves base. At \$28/B, potential incremental reserves could reach almost 3.8 billion barrels of oil. Technology advances could increase implemented technology potential reserves by nearly 1.4 billion barrels of oil at an oil price of \$20/B. The total potential reserves at this price, about 4.1 billion barrels, would more than replace California's 1991 onshore proved reserves. At an oil price of \$28/B, technology advances could add nearly 3.4 billion barrels of incremental reserves for a total EOR and ASR reserves potential of over 7.1 billion barrels of incremental oil. If this potential were to be realized, advanced technology EOR and ASR would be nearly double California's onshore proved reserves.

The activities associated with advanced technology EOR and ASR could generate substantial direct state tax revenues. At \$20/B, \$1.7 billion of the \$4.5 billion of potential direct state revenues are attributable to technology advances. At an oil price of \$28/B, over 51% (\$59 billion) of the \$11 billion in total potential state revenues are 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 those classes of reservoirs with the largest potential resource and greatest threat of abandonments. Near- and mid-term RD&D efforts, jointly funded by the Federal government and private industry, are directed towards the producing problems of these reservoirs. The results, once successfully developed and demonstrated, are to be transferred to other operators facing similar producing conditions. While they are a start, efforts like the PON process are not enough. A more aggressive and focused, collaborative RD&D effort will greatly

increase domestic production, enhance national energy security, reduce imports, and increase economic benefits associated with oil recovery.

Even after application of advanced technology EOR and ASR, a substantial portion of the oil resource will remain unrecovered in the analyzed reservoirs (Figure V-9). At the improbably high oil price of \$36/B, total ASR reserves potential would be 960 million barrels while EOR reserves potential would total 7.2 billion barrels. If this reserves potential were realized, nearly 18 billion barrels of mobile oil (95% of the mobile oil target) and 26 billion barrels of immobile oil (78% of the immobile oil target) would remain in analyzed reservoirs. In addition, over 1.7 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 about 44 billion barrels is the target for further advances in EOR and ASR technologies.

Figure V-9

California Remaining Oil Resource After Advanced Technology Recovery

VI. AN EVALUATION OF CALIFORNIA STATE TAX INCENTIVES

A. INTRODUCTION

Previous studies sponsored by the IOGCC and various states have indicated that focused state tax incentives can be simultaneously beneficial to operators and the state economy. Relief of state production and corporate income taxes on incremental EOR and ASR production could enhance the profitability of marginal improved oil recovery projects, thus significantly increasing state-wide reserves potential. The resulting higher level of investments and production could stimulate new state tax revenues and statewide economic activity, more than offsetting the foregone revenues on improved recovery projects that would have been implemented without the incentive. Therefore, appropriately designed tax incentives offer the promise of "non-zero-sum" gains, where producers, state treasuries, and the national economy benefit due to the resulting increased oil production from known reservoirs.¹

California's oil operators are not subject to an explicit severance tax, but they are subject to other production-related taxes. A conservation tax of \$0.015223 per barrel of oil produced is levied; these revenues fund the California Department of Conservation's Division on Oil and Gas. In addition, operators are subject to local taxes which average approximately 2.7% of the revenue from production, and California's 9.6% state corporate income tax rate. This chapter assesses the impact of one state tax incentive option for California — relief of production and corporate income taxes on incremental production until project payback (i.e., until cumulative cash flow from the project exceeds zero).

This incentive design was shown to be effective in previous IOGCC studies for the states of Oklahoma and New Mexico.^{1,2} Further, this incentive is self-limiting, directing economic stimulus to projects that require tax relief and away from projects that would be profitable without the incentive. The size and term of the incentive is directly related to the magnitude of each project's initial investment and early operating costs. The proposed incentive provides for lower costs and risks to the state while providing operators with early benefits that are critically important to marginal projects.

¹ Interstate Oil and Gas Compact Commission, *The Potential of Enhanced Oil Recovery in Oklahoma*, April 1987.

² Interstate Oil and Gas Compact Commission, *The Potential of Enhanced Oil Recovery by Carbon Dioxide Flooding in New Mexico*, December 1986.

Any proposed state tax incentive must take into account the FY91 Federal EOR tax credit. This provides a credit against Federal income tax equal to 15% of all qualified EOR costs (tangible property investments, intangible drilling and development costs, and purchase costs of tertiary injectant) on projects that began or were significantly expanded after December 31, 1990. The tax credit is contingent upon prior professional certification 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, the incentive is gradually phased out at oil prices above \$28/B. For every \$1/B that the average bench mark price for the preceding year exceeds \$28/B, the incentive is reduced 2.5 percentage points for the subsequent year, completely phasing out the incentive at an oil price of \$34/B.

The analysis considers three key factors important to the state of California:

- Incremental reserves and production;
- Direct state tax revenues from production, sales, and corporate and personal income taxes; and
- Overall in-state economic activity, including wages and benefits paid.

Other economic benefits which accrue to citizens of other states, Federal tax revenues and overall gains in domestic economic activity, are also assessed.

B. RESERVES AND PRODUCTION

Under the implemented technology case, the proposed tax incentive could increase recovery from known California reservoirs by as much as 743 million barrels over the reserves potential possible with the current tax structure (base case) (Table VI-1 and Figure VI-1A). Because ASR projects are less sensitive to price changes than EOR projects, the incentive has more impact on EOR than ASR. The effect of the tax incentive would be concentrated at oil prices of \$24/B and higher. At \$20/B, the 9 million barrels of incremental reserves stimulated by the tax incentive would be marginal relative the potential at higher prices; at \$16/B, the tax incentive would have no impact. At \$24/B, over 480 million barrels of oil could be added to proved reserves as a direct result of a state tax incentive for EOR projects. At oil prices of \$28/B and \$32/B, between 200 million and 280 million barrels of incremental reserves could be stimulated by the analyzed tax incentive. At \$36/B, after the complete phaseout of the Federal

EOR tax credit, a state tax incentive could have a larger impact; over 740 million barrels of EOR reserves over the base case potential could be generated by the tax incentive. Higher oil prices would be necessary to see an impact from a tax incentive due to the nature of the California oil resource. As discussed in earlier chapters, the large volumes of heavy oil are more difficult to produce and have less value than light oil. As a result, higher oil prices are required before significant incremental EOR reserves become economically producible. ASR reserves potential could increase by less than 10 million barrels of oil over the current tax structure potential across the range of analyzed oil prices.

Tax incentives combined with technology advances could generate much more substantial benefits in terms of additional oil recovery (Figure VI-1B). Tax incentives would be most effective in stimulating EOR reserves at oil prices above \$20/B. At oil prices of \$20/B and lower, tax incentives could stimulate an additional 125 million to 277 million barrels of EOR reserves over base case potential. At \$24/B, nearly 810 million barrels of incremental reserves could be stimulated by the tax incentive. At oil prices of \$28/B and \$32/B, 200 million to 360 million barrels of incremental reserves could be stimulated by the analyzed tax incentive. At \$36/B, nearly 1.2 billion barrels could be stimulated. Over the oil price range of \$24/B to \$36/B, the combination of technology advances and a state tax incentive could stimulate an additional 3.3 billion to 4.6 billion barrels of incremental reserves over the implemented technology base case potential. At these oil prices, a total potential of 5.9 billion to 8.4 billion barrels of incremental EOR reserves could be possible with technology advances and the analyzed state tax incentive. As with implemented technology, the tax incentive does not have as significant an impact on advanced technology ASR reserves. Less than 15 million barrels of incremental reserves could be added to base case reserves due to the tax incentive across the range of analyzed oil prices.

C. DIRECT STATE TAX REVENUES AND ECONOMIC ACTIVITY

As discussed in previous chapters, EOR and ASR projects could contribute significant revenues to the state treasury in the form of production taxes, sales taxes on materials and equipment purchased, and state corporate and personal income taxes on wages and operator profits. With a focused state tax incentive, incremental revenues from marginally economic projects could also flow to the state, however, at the cost of some revenues foregone in projects already economic at the respective oil price. Production and corporate income tax revenues could be lost on those projects which would have been profitable without the tax incentive. In some cases, then, the increase in tax revenues from new projects which may

Table VI-1

Effect of Tax Incentives on Incremental Reserves
(Million Barrels)

Oil Price (\$/B)	Tax Structure	Implemented Technology			Advanced Technology*		
		EOR	ASR	Total	EOR	ASR	Total
\$16	Base	861	702	1,563	1,247	872	2,119
	Incentive	861	707	1,568	1,372	882	2,254
\$20	Base	2,033	721	2,754	3,217	892	4,109
	Incentive	2,042	727	2,769	3,494	895	4,389
\$24	Base	2,599	726	3,325	5,094	918	6,012
	Incentive	3,081	731	3,812	5,901	918	6,819
\$28	Base	3,022	741	3,763	6,177	941	7,118
	Incentive	3,302	744	4,046	6,536	943	7,479
\$32	Base	3,339	741	4,080	6,677	944	7,621
	Incentive	3,543	745	4,288	6,874	958	7,832
\$36	Base	3,770	744	4,514	7,213	959	8,172
	Incentive	4,513	749	5,262	8,371	959	9,330
Increment due to Financial Incentives							
\$16		0	5	5	125	10	135
\$20		9	6	15	277	3	280
\$24		482	5	487	807	0	807
\$28		280	3	283	359	2	361
\$32		204	4	208	197	14	211
\$36		743	5	748	1,158	0	1,158

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

Figure VI-1

Impact of Tax Incentives on EOR and ASR Reserves

Base Case vs. Incentive Case

A) Implemented Technology

* At oil prices above \$28/B, the Federal EOR tax credit decreases by 2.5% for each \$1 over the \$28/B oil price; complete phaseout occurs at an oil price of \$34/B.

B) Advanced Technology

* At oil prices above \$28/B, the Federal EOR tax credit decreases by 2.5% for each \$1 over the \$28/B oil price; complete phaseout occurs at an oil price of \$34/B.

be stimulated by the incentive would not be sufficient to offset revenues that may be lost. However, it is possible to design the tax incentive to stimulate the maximum incremental reserves at the minimum cost to California's taxpayers.

Figure VI-2A shows the total state revenues that could accrue from economically viable, implemented technology EOR and ASR projects under the analyzed state tax incentive compared to the current tax structure. At oil prices above \$20/B, implementing a tax incentive could increase the direct state revenues resulting from EOR activities. Base case state revenue potential could be increased by \$54 million to nearly \$700 million due to the tax incentive over this price range, with the largest increases occurring at \$24/B and \$36/B. At lower oil prices, the incentive could result in a decrease from the base case potential revenues. For the analyzed oil prices, the tax incentive could result in a decrease in state revenues from implemented technology ASR activities. This decrease could range from \$31 million to \$80 million, depending on oil price. A state tax incentive for EOR projects could actually increase state tax revenues while also stimulating an increase in incremental reserves over the implemented technology base case potential. This focused incentive would be particularly effective at higher oil prices.

With advances in technology, productivity and project economics tend to improve; fewer projects, therefore, would require the tax incentive to be profitable. As a result, combined application of a tax incentive with technology advances could lead to a decrease in state and local revenues at nearly all analyzed oil prices range for advanced technology EOR and ASR activities (Figure VI-2B and Table VI-2). At \$24/B, a tax incentive applied to EOR could increase state revenues by nearly \$200 million as the impact of the increased incremental reserves from previously uneconomic projects outweighs the potential losses in state tax revenues from already profitable operations. At an oil price of \$36/B, state revenues could marginally increase due to a state EOR tax incentive. For ASR, the decrease in state revenues due to the analyzed incentive could range from \$35 million to \$147 million over the analyzed price range.

The tax incentive could increase the general level of economic activity (as defined in Chapters IV and V) within California, even when a decrease in state tax revenues may occur. In those instances, California may wish to "invest" in a better economic future by foregoing some tax revenues in order to generate business activity within the state. Table VI-2 shows the increased California economic activity that could result from the analyzed tax incentive.

Figure VI-2

Impact of Tax Incentives on Direct State and Local Revenues

Base Case vs. Incentive Case

A) Implemented Technology

B) Advanced Technology

Table VI-2

**Summary of the Benefits to the State of California
from a Focused EOR Tax Incentive***

Oil Price (\$/B)	Tax Structure	Implemented Technology		Advanced Technology	
		State Tax Revenues (\$ Billions)	Economic Activity (\$ Billions)	State Tax Revenues (\$ Billions)	Economic Activity (\$ Billions)
\$16	Base Incentive	0.54	6.74	0.89	10.42
		0.53	6.74	0.76	11.46
\$20	Base Incentive	1.67	18.31	3.03	32.41
		1.66	18.37	2.86	35.32
\$24	Base Incentive	2.80	25.95	6.12	59.41
		3.14	32.20	6.31	69.24
\$28	Base Incentive	3.74	32.49	9.16	80.16
		4.12	37.56	8.62	85.15
\$32	Base Incentive	5.04	40.99	11.40	94.15
		5.09	43.44	10.32	95.74
\$36	Base Incentive	6.38	49.62	13.87	109.93
		7.08	59.38	13.89	128.54

* Entries are for EOR only; as ASR is less sensitive to price than EOR, the state tax incentive would have a marginal impact on the benefits from ASR.

As noted before, the incentive could be much more effective with EOR than ASR. There could be a considerable payoff in terms of state economic activity from EOR at oil prices of \$24/B and higher. Under implemented technology, the increase in state economic activity due to a tax incentive for EOR could range from \$2.5 billion to \$9.8 billion with the largest increases occurring at oil prices of \$24/B and \$36/B. With technology advances at higher oil prices, \$1.6 billion to nearly \$19 billion in additional state economic activity could be stimulated by a focused tax incentive for EOR. At \$28/B and \$32/B, where a decrease in state revenues could occur, California could choose to forego some tax revenues in order to benefit the overall state economy. At \$28/B, a tax incentive for advanced technology EOR could stimulate an additional \$5 billion in state economic activity by incurring a \$540 million decrease in

revenues. At \$32/B, \$1.6 billion in economic activity could be gained at the cost of \$1.1 billion in state tax revenues.

D. DIRECT FEDERAL REVENUES AND NATIONAL ECONOMIC ACTIVITY

The analyzed tax incentives on incremental EOR and ASR production from California reservoirs could add substantially to the Federal treasury and the national economy. The stimulated projects could increase Federal income tax payments by operators and their employees. Further, the additional spending for drilling, field equipment, and injectants provides new incremental spending in the United States, payments that otherwise would have been made to purchase and import foreign oil.

Direct Federal revenues from EOR could increase as the Federal EOR tax credit begins to phaseout. The state tax incentive could stimulate additional EOR activities, particularly steamflooding. Increased EOR project activity would increase the value of the available Federal EOR tax credit, potentially resulting in a decrease in Federal revenues as the credit can be applied against other profitable operations (Table VI-3). Under implemented technology conditions, Federal revenues could increase as the tax credit phases out at oil prices over \$28/B; \$250 million to nearly \$860 million in additional direct Federal revenues could be stimulated by a state tax incentive at oil prices of \$32/B and \$36/B. At oil prices over \$20/B, total public sector revenues (state revenues plus Federal revenues) could increase over the base case potential as a result of the state tax incentive. Under advanced technology, Federal revenues could increase by \$110 million to \$1.9 billion at oil prices of \$28/B and higher. The impact of the tax incentive would be larger on EOR activities than on ASR activities, as ASR potential is less sensitive to changes in oil price. At all analyzed oil prices, direct Federal revenues could increase by \$15 million to nearly \$50 million with a state tax incentive for implemented technology ASR. With technology advances, a state tax incentive for ASR could generate an additional \$16 to \$40 million in direct Federal revenues.

Overall national economic activity, as measured by the direct value of the avoided imports (reserves multiplied by the effective wellhead price of oil), could increase as a direct result of the analyzed state tax incentive (Table VI-3). Incremental domestic production could offset payments that would be made for imported oil and therefore could result in large gains to the nation's economy. Once again, the most significant increases would be seen with a state EOR tax incentive with oil prices of \$24/B and higher.

Table VI-3

**Summary of the Benefits to the Nation
from a Focused EOR Tax Incentive***

Oil Price (\$/B)	Tax Structure	Implemented Technology		Advanced Technology	
		Federal Tax Revenues (\$ Billions)	National Economic Activity (\$ Billions)	Federal Tax Revenues (\$ Billions)	National Economic Activity (\$ Billions)
\$16	Base Incentive	0.30	7.57	0.32	12.49
		0.30	7.57	0.33	14.02
\$20	Base Incentive	1.20	22.02	1.34	40.64
		1.20	22.15	1.32	44.34
\$24	Base Incentive	2.41	33.42	3.63	78.48
		2.21	41.03	3.35	92.32
\$28	Base Incentive	3.90	44.35	5.96	111.78
		3.69	50.96	6.07	120.18
\$32	Base Incentive	5.70	58.79	11.94	139.76
		5.95	61.95	12.33	144.19
\$36	Base Incentive	7.99	73.20	17.26	168.05
		8.85	84.94	19.14	192.32

* Entries are for EOR only; as ASR is less sensitive to price than EOR, the state tax incentive would have a marginal impact on the benefits from ASR.

E. CONCLUSIONS

Large quantities of heavy oil remain in California's known reservoirs. Application of EOR processes, particularly thermal EOR, is necessary to contact and produce this significant resource. Heavy oil is therefore more costly to produce than light oil, yet it has a lower market value and higher refining costs. As such, higher oil prices are necessary in order to stimulate production and reserves. Given the nature of the California oil resource, a tax incentive for operators in the state, in the form of production and corporate income tax relief on incremental production for EOR projects, could significantly improve the economic viability of EOR projects and thus increase reserves, production, and the associated economic benefits. Because ASR is less sensitive (than EOR) to changes in oil price, a tax incentive for ASR would stimulate only a marginal increase in reserves at a significant cost to the state and Federal treasuries.

Under implemented technology at higher oil prices (\$24/B and above), a focused state tax incentive could stimulate 200 million to 700 million barrels of incremental reserves while potentially increasing state tax revenues and state economic activity. The national economy could also benefit with substantial increases in Federal revenues (at oil prices above \$28/B as the Federal EOR tax credit phases out) and overall national economic activity (across the entire range of analyzed oil prices). More substantial reserves increases are possible under advanced technology although California may have to tradeoff decreased state tax revenue for increases in economic activity at some oil prices.

The results indicate a significant potential synergy between tax incentives and advances in technology. The combined effects of the analyzed incentives and attainable improvements in the recovery techniques could result in significant incremental reserves and a cost-effective method for stimulating economic activity in California (Table VI-4). At \$24/B, advances in EOR technology combined with a focused state tax incentive could lead to additional incremental reserves of over 3.3 billion barrels and an additional \$43 billion in state economic activity and \$3.5 billion in state tax revenues. A well-formulated policy of RD&D combined with economic incentives for field application of resulting technologies holds the best opportunity for maximizing recovery from known California fields.

Further, the national treasury and economy could benefit substantially from such a focused program in California, particularly after the phaseout of the Federal EOR tax credit. The results indicate that sharing the costs and benefits between the state and Federal levels could maximize reserves and production, to the benefit of operators and the entire public sector. State level tax incentives in California should therefore remain as an option to stimulate operator response to new technologies which require wide-scale field testing and application to be viable. Coordinated, focused economic policies and continued private and public RD&D to improve oil recovery techniques holds the potential to maximize the recovery potential of the critically important California oil resource. The benefits will be realized in sustained oil production levels, stronger domestic industries, lower foreign energy imports, larger public sector revenues, and increased domestic economic activity.

As previously discussed, the impact of the FY91 Federal EOR tax credit somewhat reduces the effect of state tax incentives. The inclusion of the EOR tax credit in the analytical system used in this study leads to a conservative estimate of impact of the state tax incentive. To the extent that the amount of the EOR tax credit is limited by the alternative minimum tax (AMT), the potential impact of the EOR tax credit may be overstated. Therefore, the impact of the state tax incentive presented here could be understated.

Table VI-4

The Combined Impact of Technology Advances and State Tax Incentives on Potential Reserves and State Economic Activity from EOR Activities

Oil Price (\$/B)	Incremental Reserves (Million Barrels)			State Economic Activity (\$ Billions)		
	Implemented Base	Advanced Incentive	Difference*	Implemented Base	Advanced Incentive	Difference*
\$16	861	1,372	511	6.74	11.46	4.72
\$20	2,033	3,494	1,461	18.31	35.32	17.01
\$24	2,599	5,901	3,302	25.95	69.24	43.29
\$28	3,022	6,536	3,514	32.49	85.15	52.66
\$32	3,339	6,874	3,535	40.98	95.74	54.76
\$36	3,770	8,371	4,601	49.62	128.55	78.93

*Reflects the combined impact of technology advances and the proposed tax incentive.

State incentives could stimulate substantial incremental reserves; oil that would otherwise be left in the reservoir and abandoned after conventional production ends can be recovered economically by operators with tax incentives. As discussed in Chapter V, advances in technology can also stimulate relatively large additions to California reserves and production. The application of focused tax incentives and attainable improvements in recovery technologies result in even greater increases in incremental reserves and production potential. The results of this analysis therefore indicate that the potential exists for significant benefits to the state of a coordinated RD&D and tax incentive policy to encourage operators to increase recovery from known California fields.