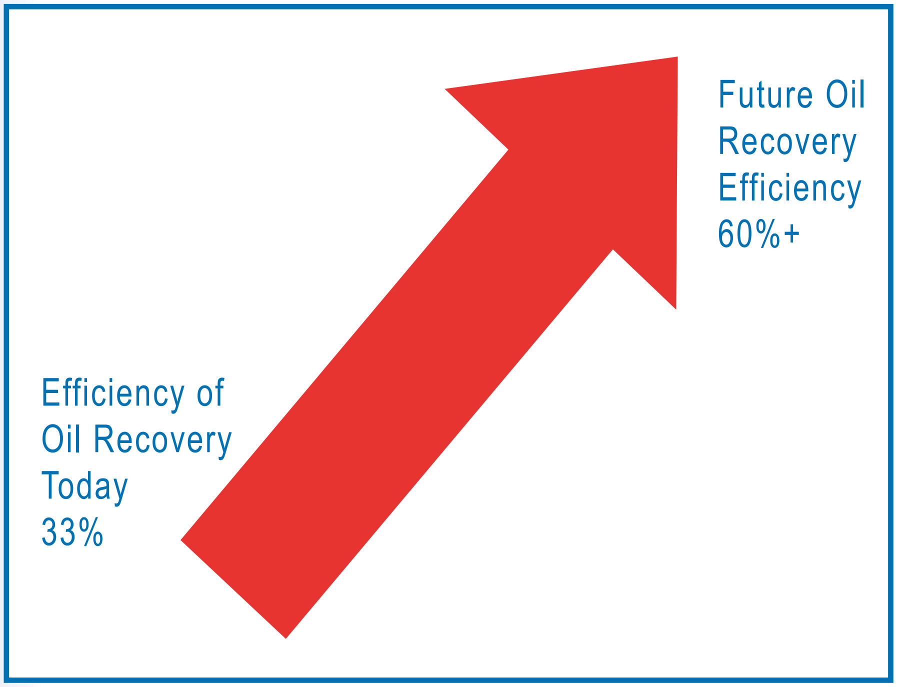
EVALUATING THE POTENTIAL FOR "GAME CHANGER" IMPROVEMENTS IN OIL RECOVERY EFFICIENCY FROM CO_2 ENHANCED OIL RECOVERY



Prepared for
U.S. Department of Energy
Office of Fossil Energy - Office of Oil and Natural Gas

Prepared by
Advanced Resources International

February 2006

Much of the analysis in this report was performed in late 2005. The domestic oil resource recovery potential outlined in the report is based on six basin-oriented assessments released by the United States Department of Energy in April 2005. These estimates do not include the additional oil resource potential outlined in the ten basin-oriented assessments or recoverable resources from residual oil zones, as discussed in related reports issued by Department of Energy in February 2006. Accounting for these, the future recovery potential from domestic undeveloped oil resources by applying EOR technology is 240 billion barrels, boosting potentially recoverable resources to 430 billion barrels.

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Prepared for

U.S. Department of Energy
Office of Fossil Energy
Office of Oil and Natural Gas

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EXECUTIVE SUMMARY

Currently available primary and secondary oil production technologies recover only about one-third of the oil in-place in domestic reservoirs, leaving behind massive volumes of oil in the ground (“stranded oil”). Scientific theory, laboratory tests, and selected field projects show that significant increases in oil recovery efficiency are possible.

This technical report examines the role that “next generation” carbon dioxide enhanced oil recovery (CO_2-EOR) technologies could provide in making “game changer” improvements in domestic oil recovery efficiency and in increasing domestic oil production. Five significant findings emerge from this study:

1. **Traditionally practiced CO_2-EOR technology will raise overall domestic oil recovery efficiency by only a few percent.** This is because: (1) CO_2-EOR is applied in only a few of our domestic oil basins, primarily the Permian Basin; (2) the traditional form of this technology is economic in a relatively small group of geologically favorable oil reservoirs; and, (3) most importantly, traditionally practiced CO_2-EOR designs provide only a modest 10 percent, recovery of the original oil in-place.

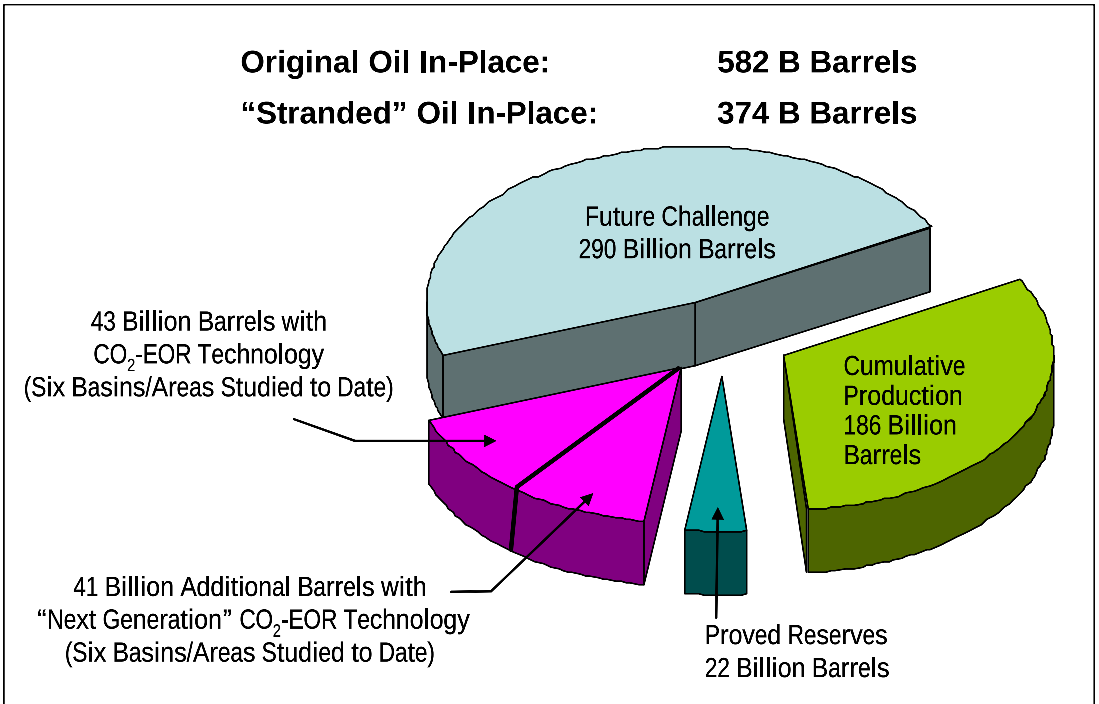
2. **Integrated application of the full suite of “next generation” technologies shows that much higher oil recovery efficiencies, two-thirds or more of the oil in-place, are feasible from an expanded group of domestic oil reservoirs.** The analysis shows that a series of “next generation” CO_2-EOR technologies could substantially increase oil recovery efficiency from geologically favorable oil reservoirs. In addition, “next generation” technology could also extend the miscible CO_2-EOR technology to a broader range of domestic oil reservoirs. For example, integrated application of three “next generation” CO_2-EOR technologies (i.e., high volume injection of CO_2, innovative process and well designs, and effective mobility control) in the Field #1oil reservoir would enable

80 percent of the original oil in-place (OOIP) to become recoverable, including 34 percent from primary and secondary recovery.

3. **<u>Successful development and integrated application of "next generation" CO_2-EOR technologies could provide 83.7 billion barrels of technically recoverable domestic oil resource (from the six basins/regions studies so far).</u>** The previously issued six basin-oriented CO_2-EOR studies reported that 43.3 billion barrels of domestic oil could become technically recoverable with "state-of-the-art" CO_2-EOR technology. Successful development and integrated application of "next generation" CO_2-EOR technology could increase this by 40.4 billion barrels, shown in Figure EX-1. This would bring the overall total from application of "next generation" CO_2-EOR technology to 83.7 billion barrels, from the six domestic oil basins/areas studied to date (Table EX-1).

4. **<u>When extrapolated to the total domestic oil resource base, "next generation" CO_2-EOR technology could add 160 billion barrels of domestic oil recovery.</u>** Integrated application of "next generation" CO_2-EOR technologies to the remaining domestic oil basins and regions still to be assessed could bring about "game changer" advances in oil recovery efficiency and domestic oil production. As a first step, we extrapolated the sample of oil reservoirs included in the study to the nation as a whole (using data on original oil in-place, provided in Figure EX-1 and Table EX-1). This extrapolation shows that the application of "state-of-the-art" CO_2-EOR technology would provide 80 billion barrels of technically recoverable resource, primarily from light oil fields. However, "next generation" CO_2-EOR technology could increase this to 160 billion barrels of technically recoverable domestic oil resource.

Figure EX-1. "Stranded" Domestic Oil Resources in Existing Oil Fields



Source: NPC Public Data Base, Maintained by DOE/FE (2004).

Table EX-1. Technically Recoverable Oil Resource From “Next Generation” CO$_2$-EOR (Six Basins/Areas Assessed to Date)

Basin/Area	Large Favorable Reservoirs (Six Areas)		All Reservoirs (Six Basins/Areas)		
	Number	Technically Recoverable	OOIP* (Billion Barrels)	ROIP** (Billion Barrels)	Technically Recoverable (Billion Barrels)
California	96	11.9	83.3	57.3	13.3
Gulf Coast	208	11.1	60.8	36.4	19.0
Oklahoma	71	12.1	60.3	45.1	20.1
Illinois	46	1.1	9.4	5.8	1.6
Alaska	33	23.1	67.3	45.0	23.8
Louisiana Offshore (Shelf)	99	4.5	28.1	15.7	5.9
Total	553	63.8	309.2	205.3	83.7

*Original Oil in-Place, in all reservoirs in basin/area; ** Remaining Oil in-Place, in all reservoirs in basin/area.
Source: Advanced Resources International, 2005.

5. **Achieving these higher oil recovery efficiencies would provide tremendous benefits to the domestic economy and for consumers.** These benefits include:
    - The energy trade balance would improve by $3.2 trillion (cumulatively), assuming one-half of the 160 billion barrels of technically recoverable resource becomes economically recoverable and oil prices average $40 per barrel.
    - State and local treasuries would gain $280 billion in revenues from future royalties, severance taxes, and state income taxes on oil production[1]. The federal budget would gain $560 billion in revenues from future royalties from production on federal lands and from corporate income taxes.[2]
    - The decline in domestic oil production would be reversed, creating new well-paying direct and indirect jobs.

---

[1] Each barrel of domestic oil provides about $7 in revenue to the Federal treasury, at an oil price of $40 per barrel.

[2] Each barrel of domestic oil provides about $3.50 in revenue to state and local treasuries, at an oil price of $40 per barrel.

1. BACKGROUND

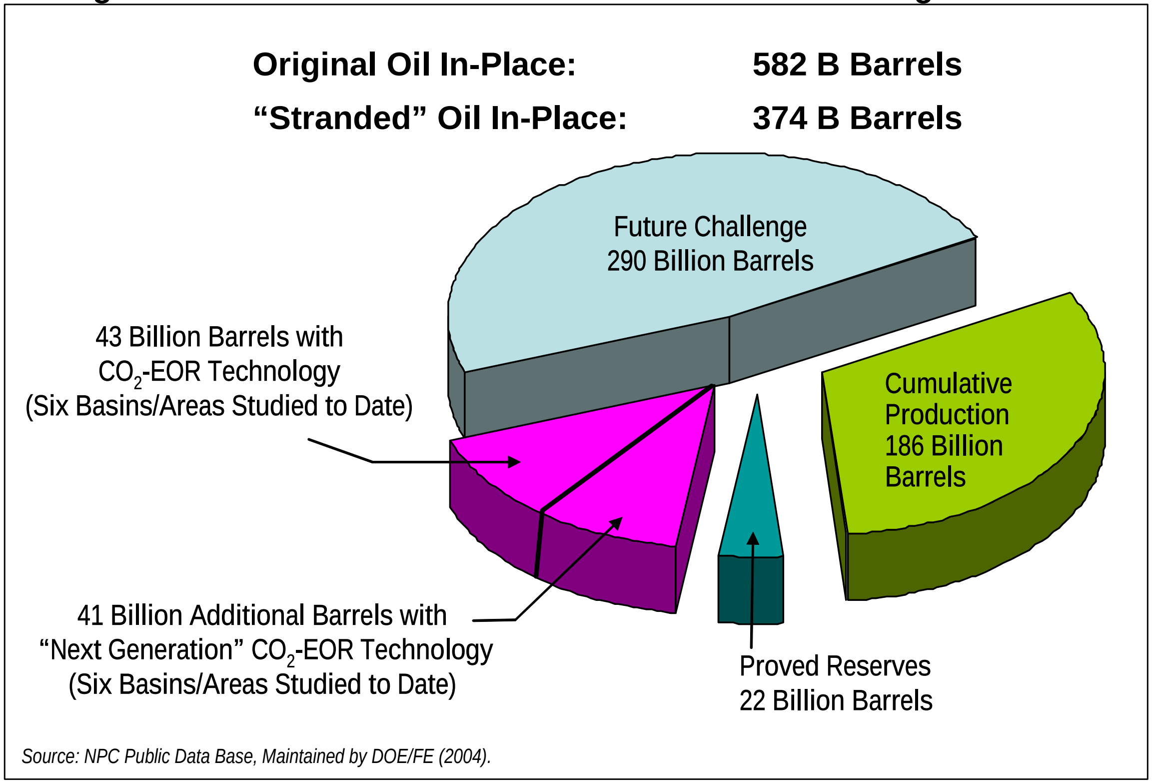
The United States has a large and bountiful storehouse of oil resources, estimated at nearly 600 billion barrels of oil in-place in already discovered oil fields. Currently used primary/secondary oil recovery methods recover only about one-third of this resource, leaving behind (“stranding”) a massive target for enhanced oil recovery.

Important steps have been taken by industry to improve the recovery efficiency in domestic oil reservoirs, notably in applying thermal enhanced oil recovery (TEOR) methods to the shallow, heavy oil fields of California and CO_2-EOR to the deeper, light oil fields of West Texas. To date, these improved oil recovery technologies have provided about 14 billion barrels of domestic oil production and reserves, adding about 3 percent to domestic oil recovery efficiency.

Even including the important steps taken so far by industry, the overall domestic oil recovery efficiency remains low. This reflects production and proving of 208 billion barrels out of a resource in-place of 582 billion barrels, in already discovered fields. (See Figure 1). These resource volumes do not include the additional oil resources that exist in domestic oil sands, in the transition zones of oil reservoirs, or in future oil discoveries. Including all these oil resources, truly massive volumes of domestic oil — a trillion barrels — remain “stranded,” after application of currently used primary/secondary oil recovery, (see Table 1), as discussed more fully below:

- Approximately 374 billion barrels of “stranded” oil remains in already discovered domestic oil fields, even after application of traditional TEOR and CO_2-EOR technology. (This consists of 582 billion barrels of discovered oil in-place, less past recovery and remaining reserves of 208 billion barrels).

Figure 1. “Stranded” Domestic Oil Resources in Existing Oil Fields



Source: NPC Public Data Base, Maintained by DOE/FE (2004).

- Undiscovered fields and reserve growth would add 380 billion to the “stranded” oil total. (This consists of 570 billion barrels of “to be discovered” oil in-place, less expected recovery of 190 billion barrels).
- An estimated 100 billion barrels of residual oil is judged to exist in the “transition zone” of discovered oil fields and 80 billion barrels exist in domestic oil sands.

Recent DOE studies have reported that widespread use of improved versions of CO_2-EOR technology could significantly increase the recovery of domestic oil. These reports show that application of “state-of-the-art” CO_2-EOR in six major domestic oil basins (containing 309 billion barrels of original oil in-place and accounting for about one-half of all domestic oil resources, could add 43.3 billion barrels of technically recoverable resource), (see Figure 2 and Table 2). This step alone would improve the oil recovery efficiency in these six basins/regions to nearly 48 percent.

Table 1. Original, Developed and Undeveloped Domestic Oil Resources

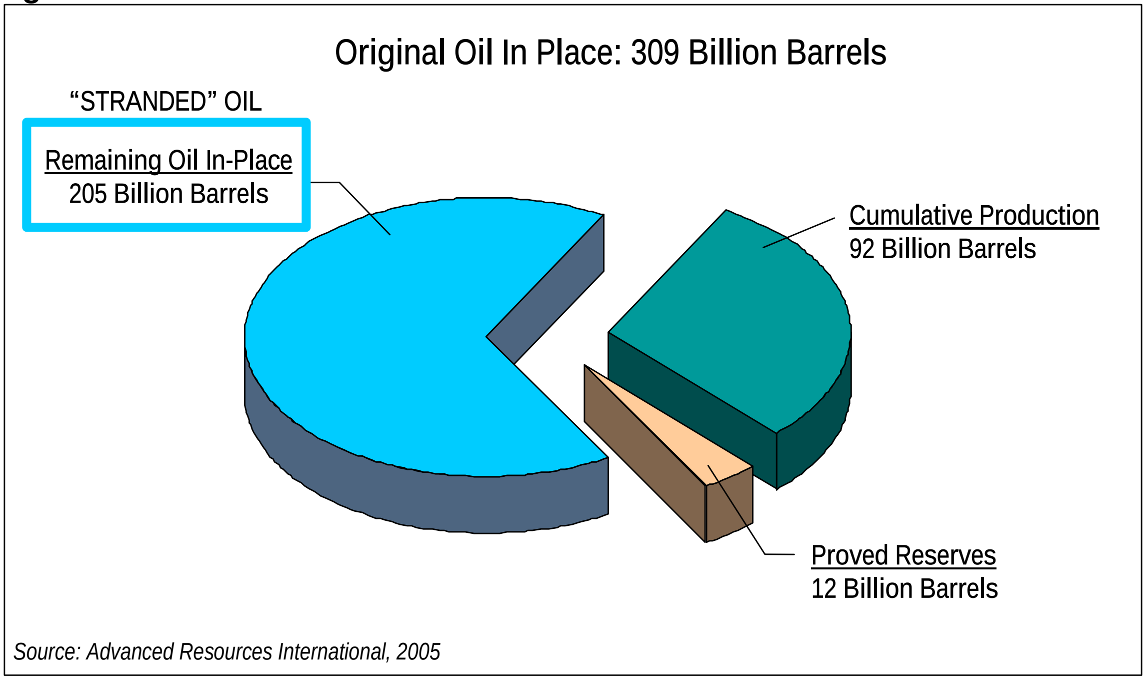
	Original Oil In- Place (BBbls)	Developed to Date		Remaining Oil In-Place (BBbls)	Future Conventional Resources (BBbls)	Target for EOR Technology (BBbls)
		Conventional Technology (BBbls)	EOR Technology (BBbls)			
I. Crude Oil Resources						
1. Discovered [1]	582	(194)	(14)	374	-	374
• Light Oil	482	(187)	(2)	293	-	293
• Heavy Oil	100	(7)	(12)	81	-	81
2. Undiscovered [2,3]	360	-		360	119	241
3. Reserve Growth [4,5]	210	-		210	71	139
4. Transition Zone [6]	100	-		100	-	100
II. Oil Sands [7]	80	-	*	80	-	80
TOTAL	1,332	(194)	(14)	1,124	190	934

*Less than 0.5 billion barrels

1. Source: DOE/FE Basin Reports, (Advanced Resources, 2005).
2. Source: USGS National Assessment of Oil and Gas Resources Update (USGS; October 2004) Conventional Oil Resources (40.43 billion barrels) and Continuous Oil Resources (2.13 billion barrels). Oil in–place estimated by assuming 33% recovery efficiency.
3. Source: Assessment of Undiscovered Technically Recoverable Oil and Gas Resources of the Nation’s Outer Continental Shelf, 2003 Update (MMS Fact Sheet, December 2004). Oil in-place estimated by assuming 33% recovery efficiency.
4. Source: Estimates of Inferred Reserves for the 1995 USGS National Oil and Gas Resource Assessment (USGS OFP 95-75L, January 1997). Oil in-place estimated by assuming 33% recovery efficiency.
5. Source: Assumptions for the Annual Energy Outlook 2004 (EIA, February 2004).
6. Source: Preliminary Estimates by Advanced Resources Int’l and Melzer Consulting (2005).
7. Source: Major Tar Sand and Heavy Oil Deposits of the United States (Lewin and Associates, Inc., July 1983).

However, “game changer” levels of improvement in oil recovery efficiency are theoretically and scientifically possible. Postulating these “next generation” technology advances and assessing their impacts is the subject of this report, *“Evaluating the Potential for “Game Changer” Improvements in Oil Recovery Efficiency for* CO_2 *Enhanced Oil Recovery.”*

Figure 2. Domestic "Stranded" Oil Resources in Six Basins/Areas Assessed



Source: Advanced Resources International, 2005

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Table 2. Technically Recoverable Oil Resource From "State-of-the-Art" CO_2-EOR (Six Areas Assessed to Date)

Basin/Area	Large Favorable Reservoirs (Six Areas)		All Reservoirs (Six Areas)		
	Number	Technically Recoverable	OOIP* (Billion Barrels)	ROIP** (Billion Barrels)	Technically Recoverable (Billion Barrels)
California	88	4.6	83.3	57.3	5.2
Gulf Coast	205	5.9	60.8	36.4	10.1
Oklahoma	63	5.4	60.3	45.1	9.0
Illinois	46	0.5	9.4	5.8	0.7
Alaska	32	12.0	67.3	45.0	12.4
Louisiana Offshore (Shelf)	99	4.5	28.1	15.7	5.9
Total	533	32.9	309.2	205.3	43.3

*Original Oil In-Place, in all reservoirs in basin/area; ** Remaining Oil in Place, in all reservoirs in basin/area.
Source: Advanced Resources International, 2005.

2. STUDY OBJECTIVE AND METHODOLOGY

This report summarizes the potential for improving the recovery of domestic oil resources and sets forth a set of "next generation" CO_2-EOR technologies that would enable these resources to be efficiently developed. It has been prepared in response to language set forth in the Congressional Budget for the DOE/Fossil Energy Oil Technology Program.

The study entailed four tasks: (1) assembling an up-to-date data base on domestic oil resources in six domestic basins/areas; (2) reviewing the technical literature on advanced extraction and production technologies; (3) discussing the status of CO_2-EOR technology, particularly "next generation" technologies, with selected companies and individuals; and, (4) modeling the technical and economic oil recovery potential from using these "next generation" technologies.

This eighth report, in a series of assessments of domestic oil resources, extends the six "Basin-Oriented Assessments" released on April 20, 2005[3]. It examines alternative research and technology pathways that could provide "game changer" levels of improvement in domestic oil recovery from applying "next generation" CO_2-EOR technologies in these same six basins/regions.

It is important to note that these scientifically possible "next generation" accomplishments postulated in this report have yet to be comprehensively demonstrated in the field. Significant new investments will need to be made in research and technology development to achieve the most promising results for the domestic energy industry set forth in this report.

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[3] U.S. Department of Energy/Fossil Energy: Basin-Oriented Strategies for CO_2 Enhanced Oil Recovery: California, Onshore Gulf Coast, Offshore Louisiana, Oklahoma, Alaska, and Illinois, April 2005.

3. STATUS OF CO_2-EOR TECHNOLOGY

CO_2 injection, under the proper conditions of pressure and temperature, and in the presence of favorable crude oil composition, can become miscible with a reservoir's oil, helping remobilize and produce the oil remaining in the reservoir. The development of miscibility between the injected CO_2 and the reservoir's oil is through in-situ composition changes that occur from multiple fluid contacts and mass transfer between the reservoir's oil and the injected CO_2. Specifically, miscibility is obtained as the injected CO_2 is enriched in composition from the intermediate components in the reservoir's oil that vaporize into the CO_2, and as the injected CO_2 becomes dissolved in the reservoir's oil, ultimately eliminating the interfacial tension between these two fluids.

A review of 12 previously conducted field-scale CO_2 miscible floods shows low (8 to 10 percent) recovery of the OOIP, with a few projects with higher as well as lower recovery efficiencies, (see Table 3). At the same time, a review of 9 smaller scale CO_2 miscible pilots show 13 to 20 percent recovery of OOIP, indicating that alternative practices, such as closer well spacing and higher levels of technical involvement, may lead to higher oil recovery efficiencies (Table 4).[4]

The review of the pilot and field-scale CO_2 miscible floods also provides some insights as to the impacts on oil recovery of injecting larger hydrocarbon pore volumes (HCPVs) of CO_2. For example:

- The 7 CO_2 floods with CO_2 injection of greater than 30 percent HCPV (generally 40 percent to 60 percent HCPV) have an oil recovery efficiency of 15.0 percent.
- The 14 CO_2 floods with CO_2 injection of 30 percent HCPV (or less) have an oil recovery efficiency of only 11.9 percent.

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[4] Brock, W.R. and Bryan, L.A., "Summary Results of CO_2 EOR Tests, 1972-1987", SPE Paper No. 18977 presented at the 1990 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, April 22-25

Table 3. Summary of Selected CO_2 Miscible Flood Field-Scale Projects

Field	Oil Gravity (°API)	Viscosity (cp)	Amount Injected (% HCPV)	Incremental Recovery (% OOIP)	Gross CO_2 Utilization (Mcf/STB)	Net CO_2 Utilization (Mcf/STB)	Year Initiated
Dollarhide	40	0.4	30	14.0		2.4	1985
East Vacuum	38	1.0	30	8.0	11.1	6.3	1985
Ford Geraldine	40	1.4	30	17.0	9.0	5.0	1981
Means	29	6.0	55	7.1	15.2	11.0	1983
North Cross	44	0.4	40	22.0	18.0	7.8	1972
Northeast Purdy	35	1.5	30	7.5	6.5	4.6	1982
Rangely	32	1.6	30	7.5	9.2	5.0	1986
SACROC (17 pattern)	41	0.4	30	7.5	9.7	6.5	1972
SACROC (4 pattern)	41	0.4	30	9.8	9.5	3.2	1981
South Welch	34	2.3	25	7.6	--	--	--
Twofreds	36	1.4	40	15.6	15.6	8.0	1974
Wertz	35	1.3	60	13.0	13.0	10.0	1986

Source: Brock, W.R. and Bryan, L.A., “Summary Results of CO_2 EOR Tests, 1972-1987”, SPE Paper No. 18977 presented at the 1990 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, April 22-25.

Table 4. Summary of Selected CO_2 Miscible Flood Producing Pilots

Field	Oil Gravity (°API)	Viscosity (cp)	Amount Injected (% HCPV)	Incremental Recovery (% OOIP)	Gross CO_2 Utilization (Mcf/STB)	Net CO_2 Utilization (Mcf/STB)	Year Initiated
Garber	47	2.1	35	14.0	--	6.0	1981
Little Creek	39	0.4	160	21.0	27.0	12.6	1975
Maljamar #1	36	0.8	30	8.2	11.6	10.7	1983
Maljamar #2	36	0.8	30	17.7	8.1	6.1	1983
North Coles Levee	36	0.5	63	15.0	7.4	--	1981
Quarantine Bay	32	0.9	19	20.0	--	2.4	1981
Slaughter Estate	32	2.0	26	20.0	16.7	3.7	1976
Weeks Island	33	0.3	24	8.7	7.9	3.3	1978
West Sussex	39	1.4	30	12.9	8.9	---	1982

Source: Brock, W.R. and Bryan, L.A., “Summary Results of CO_2 EOR Tests, 1972-1987”, SPE Paper No. 18977 presented at the 1990 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, April 22-25.

3.1 CO_2-EOR RECOVERY POTENTIAL. In comparison with field projects, laboratory tests and reservoir modeling show that very high oil recovery efficiencies are theoretically possible using innovative applications of CO_2 enhanced oil recovery (CO_2-EOR). Under ideal conditions, gravity-stable laboratory core floods using high pressure CO_2 have recovered essentially all of the residual oil. Similarly, reservoir simulation models, using innovative well placement and process designs that facilitate contact of the majority of the reservoir's pore volume with CO_2, also show that high oil recovery efficiencies are possible.[5]

3.2 CO_2-EOR PERFORMANCE. While high oil recoveries are theoretically and scientifically possible, the actual performance of CO_2-EOR in the field, as presented above, has been much less. Geologically complex reservoir settings, combined with lack of reliable performance information or process control capability during the CO_2 flood, place serious barriers and constraints to achieving optimum oil recovery using CO_2-EOR.

The causes of less-than-optimum, past-performance and only modest oil recovery by CO_2-EOR include the following:

- The great majority of past-CO_2 floods used insufficient volumes of CO_2 for optimum oil recovery, due in part to high CO_2 costs relative to oil prices and the inability to control CO_2 flow through the reservoir. Figure 3 shows that low reservoir sweep efficiency results from using small volumes of CO_2 injection, particularly under conditions of high (unfavorable) mobility ratios. Table 5 provides an example of the relationship of CO_2 injection and oil recovery efficiency, where CO_2 is used as the secondary recovery process.

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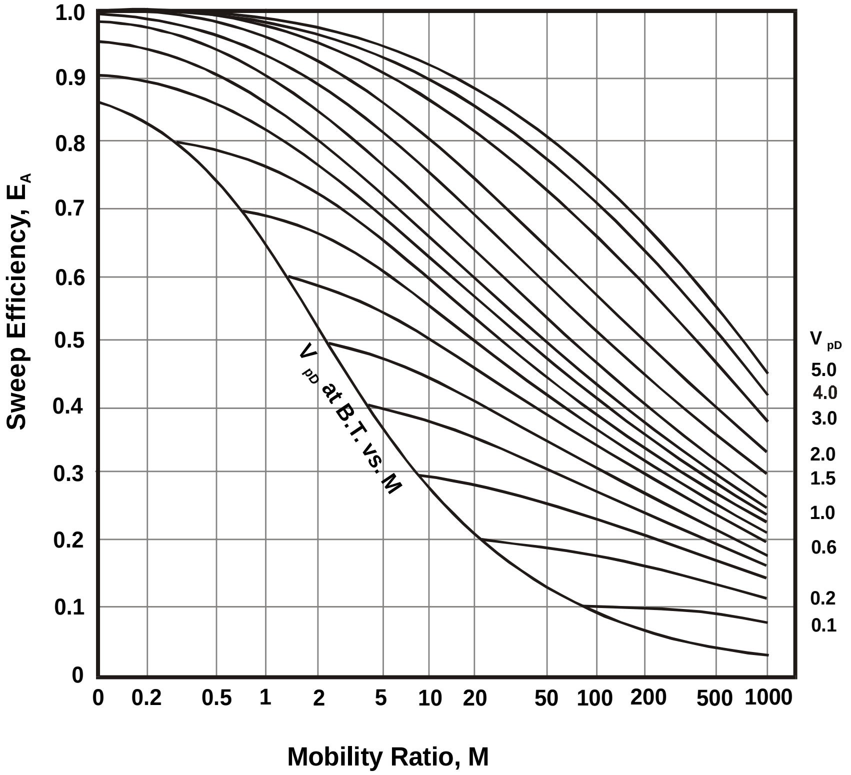
[5] See Appendix A for summary discussion of high oil recovery efficiencies from laboratory and reservoir simulation work in support of gravity stable CO_2-EOR field projects.

Figure 3. Oil Recovery in Miscible Flooding for Five-Spot Well Patterns



Note: V_{pD} is displaceable fluid pore volumes of CO_2 injected.

Source: Claridge, E.L., “Prediction of Recovery in Unstable Miscible Displacement”, SPEJ (April 1972).

Table 5. Example Oil Recovery Efficiency vs. HCPV of CO_2 Injection

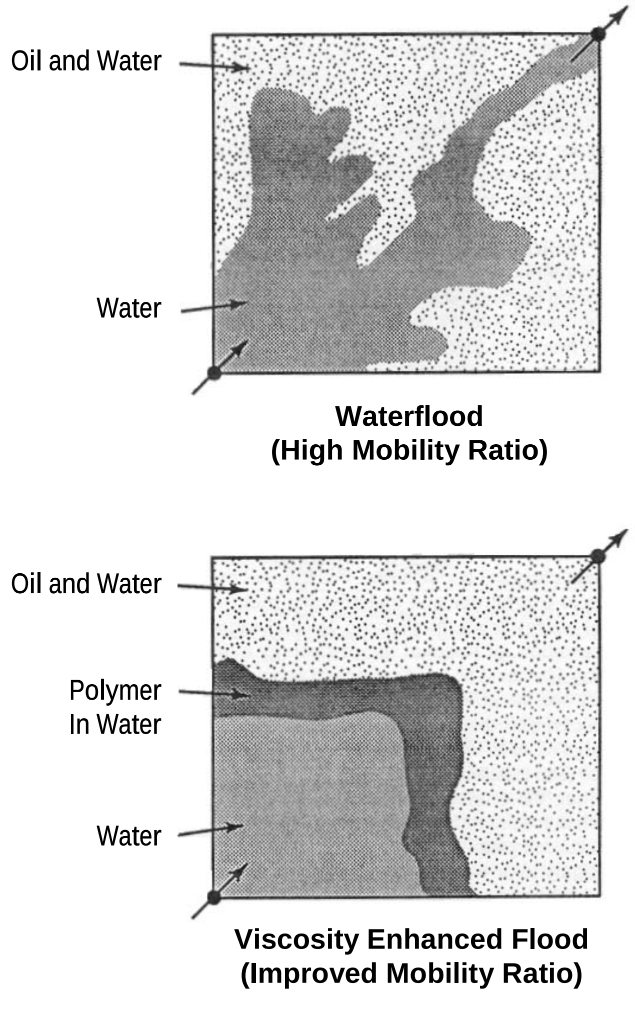
Injected CO_2 (HCPV)	Injected CO_2 (Barrels)	Reservoir Sweep Efficiency (Fraction)	Oil Recovery (Barrels)	Oil Recovery Efficiency (%)
0.40	156,400	0.345	117,300	32.2
0.60	234,600	0.440	149,600	41.1
0.80	312,800	0.515	175,100	48.1
1.00	391,000	0.570	193,800	53.2
1.50	586,500	0.670	227,800	62.6
2.00	782,000	0.725	246,500	67.7

Note: As a “rule of thumb”, 2 Mcf of CO_2 at “typical” reservoir pressure and temperature conditions occupies one reservoir barrel of CO_2.

Source: Adapted by Advanced Resources Int’l from “Enhanced Oil Recovery”, D.W. Green and G. P. Willhite, SPE, 1998.

- In many of the previous CO_2 floods, the injected CO_2 achieved only limited contact with the residual oil in the reservoir (poor sweep efficiency), due to a variety of causes, including: gravity override by the less dense CO_2; viscous fingering of the CO_2 through the reservoir's oil; and channeling of the CO_2 in highly heterogeneous reservoirs. Figure 4 shows how a high mobility ratio for the injected fluid can lead to viscous fingering and how addition of viscosity enhancers would help reduce this problem in a waterflood.

Figure 4. Schematic of Macroscopic Displacement Efficiency Improvement with Polymer-Augmented Waterflooding (Quarter of a Five-Spot Pattern)



Source: Adapted by Advanced Resources Int'l from "Enhanced Oil Recovery", D.W. Green and G. P. Willhite, SPE, 1998.

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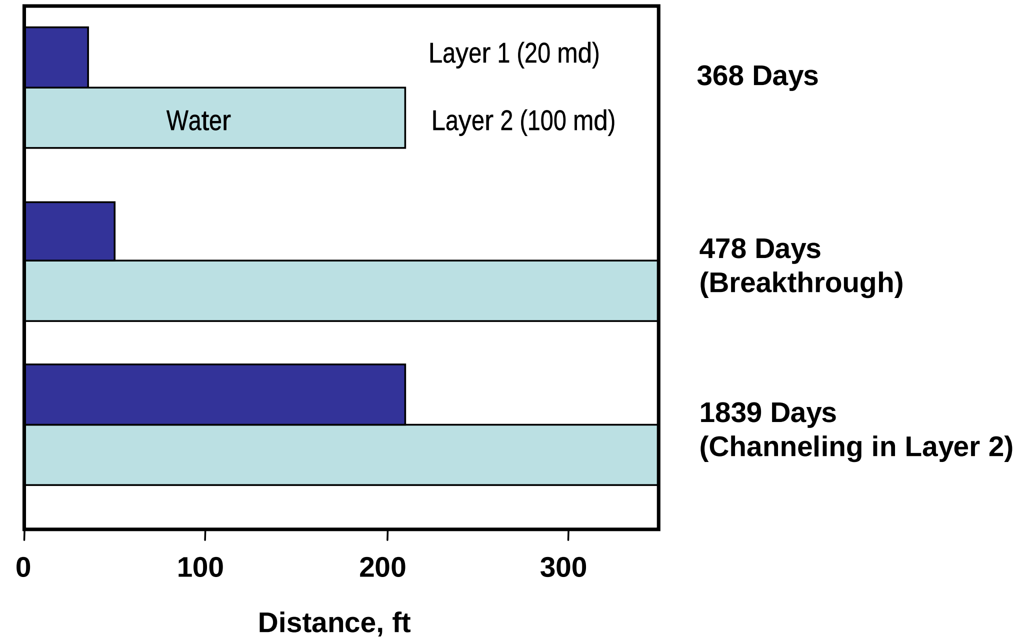
- Analysis of past CO_2 floods also shows that, in many cases, the CO_2-EOR project mobilized only a modest portion of the residual oil (poor displacement efficiency) due to lack of effective miscibility between the injected CO_2 and the reservoir's oil, caused by unexpected pressure declines in portions of the reservoir and limitations in injection and production well operating pressures.

- The final cause of less-than-optimum performance, often overlooked, has been the inability to efficiently target the injected CO_2 to preferred (high residual oil) reservoir strata and then capture and produce the mobilized oil. Figure 5 shows how the lower permeability portion of the reservoir strata is less efficiently swept by a waterflood, leaving behind higher residual oil saturations.

Figure 5. Relative Location of the Water Front in a Layered Reservoir



Source: Adapted by Advanced Resources Int'l from "Enhanced Oil Recovery", D.W. Green and G. P. Willhite, SPE, 1998.

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In addition, a variety of other operating issues have contributed toward less-than-optimum performance, such as loss of CO_2 to reservoir areas outside the pattern area and the inability to "manage and control" the CO_2 flood for lack of real-time performance information.

A number of theoretically sound "research pathways" could be pursued to address these barriers to optimum CO_2-EOR performance. This section sets forth these potential "research pathways". The next sections will examine, using analytical and reservoir modeling, just how much design improvement is possible in CO_2-EOR processes and, importantly, the impact of each of these design improvements or "research pathways" on additional oil recovery efficiency.

3.3 OPPORTUNITIES FOR IMPROVING CO_2-EOR TECHNOLOGY. To examine alternative "research pathways" that could enable the CO_2-EOR process to more closely realize its technical potential, we have set forth five potential "next generation" advances in CO_2-EOR technology, namely:

1. Increasing the volume of injected CO_2 to 1.5 hydrocarbon pore volume (HCPV), considerably beyond what has been traditionally used.

2. Examining innovative flood design and well placement options for contacting and producing the higher oil-saturated (less efficiently waterflood swept) portions of the reservoir, often containing the bulk of the "stranded" oil. This would include adding new horizontal and vertical wells targeting selected reservoir strata and using gravity-stable CO_2-EOR process designs (in steeply dipping and domed oil reservoirs) to increase overall reservoir contact and oil displacement by the injected CO_2.

3. Improving the viscosity of the injected water to reduce the mobility ratio between the injected CO_2/water and the reservoir's oil to reduce viscous fingering of the CO_2 through the mobilized oil bank.

4. Adding “miscibility enhancers” to extend miscible CO_2-EOR to additional oil reservoirs that would otherwise be produced by the less efficient immiscible CO_2-EOR process.

5. Finally, using the full combination of “next generation” CO_2-EOR technologies, which involves injecting higher volumes of CO_2, adopting innovative CO_2 flood and well design, and adding mobility control, to bring about “game changer” increases in oil recovery efficiency from favorable domestic oil reservoirs.

Appendix A provides summary presentations of a series of innovative CO_2-EOR field project and concepts that helped form the “next generation” technologies set forth in this report.

4. ALTERNATIVE RESEARCH PATHWAYS FOR “NEXT GENERATION” CO_2-EOR TECHNOLOGY

4.1 SAMPLE OIL RESERVOIRS. To evaluate the potential of “next generation” CO_2-EOR technologies for increasing oil recovery, we selected and then assembled data on three large, representative domestic oil reservoirs. Next, we applied increasingly sophisticated CO_2-EOR water-alternating-gas (WAG) process designs to examine their potential for improving the recovery efficiency in these three oil reservoirs.

The three oil reservoirs selected are: (1) Field #1 (Reservoir #1), a deep, California light oil reservoir amenable to miscible CO_2-EOR; (2) Field #2 (Reservoir #2), a deep, California heavy oil reservoir currently not amenable to miscible CO_2-EOR; and (3) Field #3 (Reservoir #3), a shallow, Illinois light oil reservoir, also currently not amenable to CO_2-EOR, Table 6. These reservoirs are each reasonably representative of a particular class of domestic oil reservoir examined in the previously cited six basins CO_2-EOR study. As such, the theoretically possible oil recovery improvements established in these three reservoirs could be projected to a substantially larger class of domestic oil reservoirs and their “stranded” oil.

Table 6. Domestic Oil Reservoirs Used to Evaluate “Next Generation” CO_2-EOR Technologies

Field	Field #1	Field #2	Field #3
Reservoir	Reservoir #1	Reservoir #2	Reservoir #3
Location	San Joaquin Basin	Los Angeles Basin	Illinois Basin
OOIP (MMBbls)	2,365	157	251
Depth (ft.)	5,500	4,500	2,940
Oil Gravity (^oAPI)	35	23	38
Oil Viscosity (cp)	3	13	6
Dykstra-Parsons	0.75	0.75	0.75

4.2 “NEXT GENERATION” CO_2-EOR TECHNOLOGIES. Four specific “next generation” CO_2-EOR technologies were evaluated with reservoir simulation, using the above three oil reservoirs. In each case, we posited an "achievable level of process performance", such as: increased injection of CO_2; an ability to contact more of the reservoir's pore volume using innovative flood and well design (including conducting a gravity-stable CO_2 flood); increasing the viscosity of the injected water used in the CO_2-WAG process; and, reducing the minimum miscibility pressure for deep, heavy oil and shallow, light oil reservoirs.

In this section, we examine how much each of these advances in CO_2-EOR technology would add to theoretically possible oil recovery efficiency when applied individually. In the next chapter we examine the integrated application of the combined set of "next generation" CO_2-EOR technologies to achieve "game changer" levels of improvement in oil recovery efficiency.

While we describe alternative ways that these advances in technology might be achieved, each of these improved levels of process design and field performance represents a topic for substantial future R&D in CO_2-EOR.

Research Pathway #1. Increasing CO_2 Injection. The giant Field #1 oil reservoir, described above, serves as the setting for examining the impact of the "increasing CO_2 injection" research pathway for "next generation" CO_2-EOR technology.

To examine improvement in oil recovery efficiency possible from this "research pathway", we progressively increased the volume of CO_2 injection (using reservoir simulation) from 0.4 HCPV (hydrocarbon pore volume) in the "traditional practices" case to 2.0 HCPV in the "next generation" CO_2-EOR technology cases. Higher HCPV's of injected CO_2 enable more of the reservoir's residual oil to be contacted (and even multiply contacted) by the injected CO_2. However, progressively longer CO_2 injection periods, longer overall project length and higher gross CO_2 to oil ratios are involved in the higher volume CO_2 injection cases.

In the past, the combination of high CO_2 costs and low oil prices led operators to use small-volume injections of CO_2 to maximize profitability. This strategy was also selected because field operators had very limited capability to observe and then control the sub-surface movement of the injected CO_2 in the reservoir. With adequate volumes of lower cost CO_2 and higher oil prices, CO_2-EOR economics would favor using higher volumes of CO_2. However, these increased CO_2 volumes would need to be "managed and controlled" to assure that they contact, displace, and recover additional residual oil rather than merely circulate through a high permeability, high CO_2-saturated interval of the reservoir.

Modeling of the Field #1 oil reservoir (using *PROPHET*) shows that "increasing CO_2 injection" can significantly increase oil recovery efficiency. Increasing the volume of CO_2 injection would provide 258 million (at 1 HCPV) to 539 million (at 2 HCPV) additional barrels of oil recovery (beyond traditional CO_2-EOR practices of 0.4 HCPV) from Field #1, raising overall oil recovery efficiency to a range of 55–67 percent, Table 7. (Analysis of the costs and economics of increasing CO_2 injection is provided in a subsequent chapter of this report.)

Table 7. Comparison of Traditional Practices vs. Increasing CO_2 Injection

	Traditional Practices	Increasing CO_2 Injection		
	0.4 HCPV CO_2 (10^6 Bbls/%OOIP)	1.0 HCPV CO_2 (10^6 Bbls/%OOIP)	1.5 HCPV CO_2 (10^6 Bbls/%OOIP)	2.0 HCPV CO_2 (10^{6}Bbls/%OOIP)
OOIP*	2,365	2,365	2,365	2,365
Primary/Secondary Recovery	808 (34%)	808 (34%)	808 (34%)	808 (34%)
"Stranded" Oil	1,557	1,557	1,557	1,557
CO_2-EOR Oil Recovery	234 (10%)	492 (21%)	727 (31%)	773 (33%)
Total Oil Recovery	1,042 (44%)	1,300 (55%)	1,535 (65%)	1,581 (67%)

* OOIP = Original Oil In-Place

Research Pathway #2. Innovative Flood Design and Well Placement. The giant Field #1 oil reservoir (discussed above) also serves as the geologic setting for examining the impact of the “innovative CO_2 flood design and well placement” research pathway for “next generation” CO_2-EOR technology.

To examine the level of improvement in oil recovery efficiency possible from this “research pathway”, we set forth an alternative well design and placement configuration (using reservoir simulation). This well design and placement configuration ensured that both the previously highly waterflood-swept (with low residual oil) portions of the oil reservoir and the poorly waterflood-swept (with higher residual oil) portions of the oil reservoir were equally contacted by the injected CO_2.

Examples of such innovative well design and placement options include: (1) isolating the previously poorly-swept reservoir intervals (with higher residual oil) for targeted CO_2 injection; (2) drilling horizontal injection and production wells to target bypassed or poorly produced reservoir areas or intervals; (3) altering the injection and production well pattern alignment; (4) using physical or chemical diversion materials to divert CO_2 into previously poorly-contacted portions of the reservoir; and (5) placing the injection and production wells at closer spacings.

Analytical modeling of the Field #1 oil reservoir (using *PROPHET*) shows that the use of innovative flood design and well placement can significantly increase oil production, particularly when combined with the higher volume (1 HCPV) injection of CO_2. Application of “innovative flood design and well placement” with higher volume (1 HCPV) injection of CO_2 could provide an additional 426 million barrels of oil recovery (beyond traditional CO_2-EOR practices) from the Field #1 oil reservoir, raising overall oil recovery efficiency to 62 percent of OOIP, Table 8.

Table 8. Comparison of Traditional Practices vs. Innovative Wells

	Traditional Practices	Innovative Flood Design and Well Placement
	(10^6Bbls/ %OOIP)	(10^6Bbls/ %OOIP)
OOIP*	2,365	2,365
Primary/Secondary Recovery	808 (34%)	808 (34%)
"Stranded" Oil	1,557	1,557
CO_2-EOR Oil Recovery	234 (10%)	660 (28)
Total Oil Recovery	1,042 (44%)	1,467 (62%)

* OOIP = Original Oil In-Place

Research Pathway #3. Improving the Mobility Ratio. The giant Field #1 oil reservoir serves as the setting for examining the impact of "improving the mobility ratio" research pathway for "next generation" CO_2-EOR technology.

To examine the level of improvement in oil recovery efficiency possible for this "research pathway", we assumed an increase in the viscosity of the injected water (as part of the CO_2-WAG process) to 3 cp, equal to the viscosity of the Field #1 reservoir oil. (The viscosity of the CO_2 itself was left unchanged, although increasing the viscosity of CO_2 with CO_2-philic agents, such as those being pursued in the joint DOE/University of Pittsburgh research program, could theoretically further improve performance.) Examples of ways to increase the viscosity of the injected water would be to add polymers or other viscosity-enhancing materials.

Analytic modeling of the Field #1 oil reservoir (using *PROPHET*) shows that the use of viscosifiers for improving the mobility ratio of the CO_2-EOR process can provide an important addition to oil recovery efficiency. Application of an improved mobility ratio CO_2-EOR design with higher volume (1 HCPV) injection of CO_2 could provide an additional 356 million barrels of oil recovery (beyond traditional CO_2-EOR practices) from Field #1 oil reservoir, raising overall recovery efficiency to 59 percent of OOIP, Table 9.

Table 9. Comparison of Traditional Practices vs. Improving Mobility Ratio

	Traditional Practices	Improving Mobility Ratio
	(10^6Bbls/ %OOIP)	(10^6Bbls/ %OOIP)
OOIP*	2,365	2,365
Primary/Secondary Recovery	808 (34%)	808 (34%)
"Stranded" Oil	1,557	1,557
CO_2-EOR Oil Recovery	234 (10%)	590 (25%)
Total Oil Recovery	1,442 (44%)	1,398 (59%)

* OOIP = Original Oil In-Place

Research Pathway #4. Extending Miscibility. Two distinctly different oil reservoirs, the deep, heavy oil Field #2 (Reservoir #2) and the shallow, light oil Field #3 (Reservoir #3) (both previously described) serve as the setting for examining the impact of the "extending miscibility" research pathway for "next generation" CO_2-EOR technology.

To examine the level of improvement in oil recovery efficiency possible from this "research pathway", we added "miscibility extenders" to the CO_2-EOR process such that the minimum miscibility pressure requirements were reduced by 500 (pounds per square inch (psi). This enabled the above two oil reservoirs, which had previously been processed using immiscible CO_2-EOR, to attain higher oil recovery by using miscible CO_2-EOR.

Examples of miscibility enhancing agents would include: addition of LPG to the CO_2, although this would lead to a more costly injection process; addition of H_2S or other sulfur compounds, although this may lead to higher cost operations; and, use of other (to be defined) miscibility pressure or interfacial tension reduction agents.

Analytical modeling (using *PROPHET)* shows that extending the range of oil reservoirs applicable for miscible CO_2-EOR would significantly increase oil recovery efficiency, particularly when combined with higher volume (1 HCPV) injection of CO_2.

Application of "miscibility extenders" with higher volume injection of CO_2 (1 HCPV) would provide an additional 12 million barrels of oil recovery (beyond traditional immiscible application of CO_2-EOR) from the Field #2 (Reservoir #2), raising overall oil recovery efficiency to 48 percent, Table 10. Similarly, this research pathway would provide an additional 11 million barrels of oil recovery (beyond traditional immiscible application of CO_2-EOR) from the Field #3 (Reservoir #3), raising overall oil recovery efficiency to 63 percent, Table 10.

Table 10. Comparison of Traditional Practices vs. Extending Miscibility

	Field #2 (Deep Heavy Oil)		Field #3 (Shallow Light Oil)	
	Immiscible CO_2-EOR	Extending Miscibility	Immiscible CO_2-EOR	Extending Miscibility
	(10^6Bbls/%OOIP)	(10^6Bbls/%OOIP)	(10^6Bbls/%OOIP)	(10^6Bbls/%OOIP)
OOIP*	157	157	251	251
Primary/Secondary Recovery	49 (31%)	49 (31%)	112 (44%)	112 (44%)
"Stranded" Oil	108	108	139	139
CO_2-EOR Oil Recovery	15 (10%)	27 (17%)	35 (14%)	46 (19%)
Total Oil Recovery	64 (41%)	76 (48%)	147 (58%)	158 (63%)

* OOIP = Original Oil In-Place

5. ACHIEVING “GAME CHANGER” RESULTS

The previous chapter showed that each of the “next generation” CO_2-EOR technologies could provide increased oil recovery and improved oil recovery efficiency over “traditional practices”. This chapter discusses how optimum oil recovery efficiency from CO_2-EOR technology could result from applying these “next generation” technologies in an integrated, combined fashion. As shown below, and further reported in the following sections, using an optimum combination of “next generation” CO_2-EOR technologies could provide “game changer” levels of improvement in domestic oil recovery efficiency.

The same three sample oil fields—Field #1, Field #2, and Field #3—were selected to evaluate the impact of using the combination of “next generation” technologies research pathways for radically improving oil recovery efficiency with CO_2-EOR technology.

5.1 APPLYING THE COMBINATION OF “NEXT GENERATION” TECHNOLOGIES: CASE #1. To examine the upside level of improvement in oil recovery efficiency theoretically possible for CO_2-EOR technology, we examined the integrated application of a combination of three “next-generation” technologies—(1) higher volume CO_2 injection (1.5 HCPV); (2) innovative CO_2 flood and well placement design; and, (3) improved mobility control. These three “next generation” technologies were applied to the Field #1 oil reservoir. (The performance specifications of these three “next generation” technologies, when applied individually, were discussed previously.)

Analytic modeling of the Field #1 oil reservoir (using *PROPHET*) shows that the use of this combination set of technologies could provide an additional 973 million barrels of oil recovery (beyond traditional CO_2-EOR practices) from the Field #1 oil reservoir. This would raise the overall oil recovery efficiency from this reservoir to 81 percent of OOIP, (see Table 11).

Table 11. Comparison of Traditional Practices vs. Combination of "Next Generation" Technologies (Field #1)

	Traditional Practices	Combination of "Next Generation" Technologies
	(10^6Bbls/ %OOIP)	(10^6Bbls/ %OOIP)
OOIP*	2,365	2,365
Primary/Secondary Recovery	808 (34%)	808 (34%)
"Stranded" Oil	1,557	1,557
CO_2-EOR Oil Recovery	234 (10%)	1,107 (47%)
Total Oil Recovery	1,042 (44%)	1,915 (81%)

* OOIP = Original Oil In-place

5.2 APPLYING THE COMBINATION OF "NEXT GENERATION" TECHNOLOGIES: CASE #2. Next, we examined applying the same combination of three next generation CO_2-EOR technologies plus "miscibility enhancement" to Field #2 (Reservoir #2) and Field #3 (Reservoir #3).

Analytic modeling (using *PROPHET*) shows that the use of this combination of "next generation" technologies could provide an additional 51 million barrels of oil recovery (beyond "traditional" immiscible CO_2-EOR) from the Field #2 reservoir, raising overall oil recovery efficiency to 73 percent of OOIP, (see Table 12).

Similarly, the application of this combination of "next generation" CO_2-EOR technologies to the Field #3 reservoir could provide an additional 56 million barrels of oil recovery (beyond "traditional" immiscible CO_2-EOR), raising overall oil recovery efficiency to 81 percent of OOIP, (see Table 13).

Table 12. “Traditional” vs. Combination of “Next Generation” Technologies (Field #2)

	Traditional Immiscible CO_2-EOR	Combination of “Next Generation” Technologies
	(10^6Bbls/ %OOIP)	(10^6Bbls/ %OOIP)
OOIP*	157	157
Primary/Secondary Recovery	49 (31%)	49 (31%)
“Stranded” Oil	108	108
CO_2-EOR Oil Recovery	15 (10%)	66 (42%)
Total Oil Recovery	64 (41%)	115 (73%)

* OOIP = Original Oil-In-place

Table 13. “Traditional” vs. Combination of “Next Generation” Technologies (Field #3)

	Traditional Immiscible CO_2-EOR	Combination of “Next Generation” Technologies
	(10^6Bbls/ %OOIP)	(10^6Bbls/ %OOIP)
OOIP*	251	251
Primary/Secondary Recovery	112 (44%)	112 (44%)
“Stranded” Oil	139	139
CO_2-EOR Oil Recovery	35 (14%)	91 (36%)
Total Oil Recovery	147 (58%)	203 (81%)

* OOIP = Original Oil-In-place

6. ECONOMICS OF “NEXT GENERATION” CO_2-EOR TECHNOLOGY

In the previous sections of this report, we presented the additional technically recoverable oil resources that could be gained from the application of “next generation” CO_2-EOR technology. In this section, we examine, using the three oil reservoirs previously introduced—Field #1, Field #2, and Field #3—how “next generation” in CO_2-EOR technology could impact economically recoverable oil resources.

6.1 BASIC ECONOMIC MODEL. The economic model used in the analysis draws on the previously published economic models in the six state/region reports. This basic economic model was modified to incorporate the additional costs associated with applying “next generation” CO_2-EOR technology in the field. The specific process and cost changes incorporated into the “next generation” CO_2-EOR version of the economic model are set forth below.

- **Oil and Water Production.** The oil production and CO_2 injection rates from applying “next generation” CO_2-EOR technology and the increase in the life of the CO_2-EOR project were estimated using *PROPHET*. This involved assembling the reservoir properties for each of the three oil reservoirs and then placing them into the *PROPHET* stream-tube reservoir model to calculate CO_2 injection and oil and water production versus time. In each case, the project life of the “next generation” CO_2-EOR flood increased substantially beyond the project life in the “traditional practices” case.

- **CO_2 Injection.** The costs of injecting CO_2 were estimated using the same pricing formula assumed in the six basins/region reports:
  - Cost of Purchased CO_2 (per Mcf): 5 percent of oil price ($/Bbl)
  - Cost of Recycled CO_2 (per Mcf): 1 percent of oil price ($/Bbl)

  The capital investment costs for the CO_2 recycle plant were scaled to reflect the higher peak recycled CO_2 volumes in the "next generation" technology cases.

- **Additional Costs for Applying Advanced CO_2-EOR Technology.** Five additional modifications were made to the cost and economics model to account for the higher costs of applying each of the "next generation" CO_2-EOR technologies, as set forth below:

  - *Increased Volume of CO_2 Injection.* The costs for purchasing, recycling, and injecting 1.5 HCPV of CO_2 are included in the "next generation" economic model, using the cost formulas set forth above.

  - *Innovative Flood Design and Well Placement.* The "next generation" economic model assumes that one additional new horizontal production well and one new vertical CO_2 injection well would be added to each pattern. These wells would enable CO_2 to contact and capture residual oil from previously bypassed or poorly contacted portions of the reservoir. (The model assumes that each pattern already has or drills one production and one injection well.)

  - *Viscosity Enhancement.* The economic model assumes that the water injection costs for the CO_2-WAG process are increased by $0.25 per barrel of injected water to account for the addition of viscosity enhancers.

- *Extending Miscibility.* The economic model assumes that the costs of purchased and recycled CO_2 are increased by $0.25 per Mcf for additives to extend miscibility, for reservoirs requiring this option.

- *Flood Performance Diagnostics and Control.* The economic model assumes that the "next generation" CO_2-EOR project is supported by a fully staffed technical team (geologists, reservoir engineers, and economic analysts), uses a series of observation wells and downhole sensors to monitor the progress of the flood, and conducts periodic 4-D seismic plus pressure and residual oil saturation measurements to "optimize, manage, and control" the CO_2 flood. The "next generation" economic model adds 10 percent to the initial capital investment and 10 percent to the annual operating costs of the CO_2 flood to cover these extra costs.

6.2 "NEXT GENERATION" CO_2-EOR TECHNOLOGY COSTS. Insights on the costs and benefits of conducting a "next generation" CO_2-EOR flood may be gained by examining the changes in oil production, capital investment, CO_2 requirements, and operating costs between using "traditional practices" and using the combination of "next generation" technologies in Field #1, Table 14A.

- **Oil Recovery.** Oil recovery from the example Field #1 (Reservoir #1) oil field (with 2,365 million barrels of original oil in-place) is estimated at 1,106 million barrels in 37 years under combination "next generation" technology versus 234 million barrels in 19 years under "traditional practices".

Table 14A. Economic Comparison of Alternative CO_2-EOR Technologies Applied to the Field #1 (Reservoir #1)

	"Traditional Practices"	Combination Application of "Next Generation" CO_2-EOR Technologies
Oil Recovery (10^6 Bbls)	234	1,107
% OOIP	10%	47%
Project Life (years)	19	37
Capital Investment (10^6\$)		
Basic Cap Ex	\$553	\$553
Additional Wells	-	\$1,002
Larger CO_2 Recycle Plant	-	\$318
Information	-	\$187
Total	\$553	\$2,060
CO_2 Costs (10^6\$)		
Purchased CO_2	\$1,561	\$2,626
Recycled	\$362	\$2,003
Total	\$1,923	\$4,629
Operating and Maintenance Costs (10^6\$)		
Basic Op Ex	\$1,930	\$1,930
Additional Wells and Fluid Lifting	-	\$3,000
Viscosity Enhancement	-	\$944
"Management and Control"	-	\$1,060
Total	\$1,930	\$6,934

- **Capital Investment.** Capital investment in the example Field #1 oil field is four-fold higher, at \$2,060 million dollars under combination application of "next generation" technologies versus \$553 million dollars under "traditional practices". The extra costs are due to:

  - An extra \$1,002 million for drilling, completing, and equipping additional horizontal and vertical wells,
  - A larger CO_2 recycle plan, adding \$318 million, and
  - An allocation of \$187 million for instrumented observation wells, 4-D seismic and downhole testing to provide real-time information with which to “manage and control” the “next generation” CO_2 flood.

- **CO_2 Costs**. CO_2 costs for the example Field #1 oil field are more than twice as high, at \$4,629 million under combination application of “next generation” technologies versus \$1,923 million under “traditional practices”. The extra costs are due to:
  - Somewhat larger volumes of higher cost purchased CO_2 of 2,101 Bcf under combination “next generation” technology versus 1,249 Bcf under “traditional practices”.
  - Significantly larger volumes of lower cost recycled CO_2 of 8,011 Bcf under combination “next generation” technology versus 1,448 Bcf under “traditional practices”.

- **Operating and Maintenance Costs (O&M)**. O&M costs in the example Field #1 oil field are more than three times higher, at \$6,934 million (for 37 years) under combination application of “next generation” technologies versus \$1,930 million for (19 years) under “traditional practices”. The extra costs are due to:
  - An extra \$3,000 million for operating a larger number of wells for 18 additional years and lifting volumes of additional oil and water,
  - An extra \$944 million for purchase and injection of viscosity enhancing materials, and
  - An additional allocation of \$1,060 million (about \$29 million per year) for “managing and controlling” the “next generation” CO_2 flood.

6.3 EXAMPLE ECONOMIC RESULTS. The economic comparison of using "traditional practices" CO_2-EOR (0.4 HCPV of CO_2) and a combination of "next generation" CO_2-EOR technologies (with 1.5 HCPV of CO_2) are provided below for the Field #1 reservoir, Table 14B.

Appendix B-1 provides the detailed economic model runs that underlie the summary performance cost information presented in Tables 14A and 14B.

Table 14B. Economic Comparison of Alternative CO_2-EOR Technologies – Applied to Field #1 (Reservoir #1)

	Traditional Practices	Combination Application of "Next Generation" CO_2-EOR Technologies*
Oil Recovery (10^6 Bbls)	234	1,107
% OOIP	10%	47%
Project Life (years)	19	37
CapEx ($/Bbl)	$2.36	$1.86
CO_2 Costs ($/Bbl)	$8.22	$4.18
OpEx ($/Bbl)	$8.25	$6.26
Rate of Return (%)**	Below Minimum Threshold	Above Minimum Threshold

*Includes extra costs for applying "next generation" CO_2-EOR technology.
**Assumes long-term oil price of $25 per barrel, adjusted for gravity and location differentials; minimum threshold rate of return of 15% (real), before tax.

A similar economic comparison is made for the deep, heavy oil Field #2 (Reservoir #2) that was previously produced with "traditional" immiscible CO_2–EOR technology, Table 15. The final economic comparison is made for Field #3 (Reservoir #3) shallow, light oil reservoir that was also previously produced with "traditional" immiscible CO_2-EOR technology, Table 16.

Appendices B-2 and B-3 provide the detailed economic model runs that underlie the summary information presented in Tables 15 and 16.

Table 15. Economic Comparison of Alternative CO_2-EOR Technologies Applied to Field #2 (Reservoir #2)

	"Traditional" Immiscible CO_2-EOR Technology	Combination Application of "Next Generation" CO_2-EOR Technologies*
Oil Recovery (10^6 bbls)	15	66
% OOIP	10%	42%
Project Life (years)	23	29
CapEx ($/Bbl)	$2.76	$2.06
CO_2 Costs ($/Bbl)	$5.41	$5.58
OpEx ($/Bbl)	$10.69	$6.17
Rate of Return (%)**	Negative	Above Minimum Threshold

*Includes extra costs for applying "next generation" CO_2-EOR technology.

**Assumes long-term oil price of $25 per barrel, adjusted for gravity and location differentials; minimum threshold rate of return of 15% (real), before tax.

Table 16. Economic Comparison of Alternative CO_2-EOR Technologies Applied to Field #3 (Reservoir #3)

	"Traditional" Immiscible CO_2-EOR Technology	Combination Application of "Next Generation" CO_2-EOR Technologies*
Oil Recovery (10^6 bbls)	35	91
% OOIP	14%	36%
Project Life (years)	18	39
CapEx ($/Bbl)	$2.65	$1.71
CO_2 Costs ($/Bbl)	$3.96	$7.09
OpEx ($/Bbl)	$9.34	$7.90
Rate of Return (%)**	Above Minimum Threshold	Above Minimum Threshold

*Includes extra costs for applying "next generation" CO_2-EOR technology.

**Assumes long-term oil price of $25 per barrel, adjusted for gravity and location differentials; minimum threshold rate of return of 15% (real), before tax.

7. STATE-BY-STATE RESULTS

Examining the application of the combination of “next generation” CO_2-EOR technologies to the six basins/regions previously assessed -- California, Gulf Coast, Oklahoma, Illinois, Alaska, and Louisiana Offshore (Shelf) -- shows that significant improvements are possible in domestic oil recovery and oil recovery efficiency.

7.1 CALIFORNIA. Because of its geologically complex reservoirs and large volumes of deep heavy oil, the overall oil recovery efficiency in the California on-shore oil fields is low, at 31 percent of the original oil in-place (OOIP), Table 17. (This relatively low oil recovery efficiency includes the successful application of steam-based enhanced oil recovery in California’s large, shallow heavy oil fields.)

Table 17. California: Original Oil In-Place, Cumulative Production, Proved Reservoirs and Recovery Efficiency (Currently Used Oil Recovery Methods)

	OOIP (B Bbls)	Cumulative Recovery (B Bbls)	Proved Reserves (B Bbls)	Total Recovery (B Bbls)	Recovery Efficiency %
Data Base	74.8	21.3	2.2	23.5	31
State Total	83.3	23.1	2.9	26.0	31

Screening the California large oil fields data base identified 96 reservoirs that would be favorable for miscible or immiscible CO_2-EOR. Application of the combination of “next generation” CO_2-EOR technologies to these reservoirs shows that oil recovery efficiency could be significantly improved, raising recovery efficiency in oil reservoirs favorable for CO_2-EOR by 32 percent and raising the overall oil recovery efficiency in California oil fields by 16 percent, Table 18.

Table 18. California: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (“State-of-the-Art” and “Next Generation” CO_2-EOR Technology)

	OOIP	Oil Recovery from Applying CO_2-EOR Technology			
		“State-of-the-Art”	Incremental from “Next Generation”	Total	Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base					
• Favorable Reservoirs	37.5	4.6	7.3	11.9	32
• Unfavorable Reservoirs	37.3	--	--	--	--
Total	74.8	4.6	7.3	11.9	16
State Total	83.3	5.2	8.1	13.3	16

The use of the combination of “next generation” CO_2-EOR technologies would add 11.9 billion barrels of technically recoverable resource (13.3 billion barrels when extrapolated to the state as a whole). Combining the oil recovery from currently used (primary, secondary and thermal) recovery methods and the additional oil recovery from applying the combination “next generation” CO_2-EOR technologies would raise the overall recovery efficiency in California oil fields to 47 percent, Table 19.

Table 19. California: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (Currently Used Oil Recovery Methods and “Next Generation” CO_2-EOR Technology)

	OOIP	Past and Future Oil Recovery			
		Current Methods	“Next Generation” CO_2-EOR	Total	State-Wide Oil Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base	74.8	23.5	11.9	35.4	47
State Total	83.3	26.0	13.3	39.3	47

7.2 GULF COAST.

The great bulk of the onshore oil reservoirs in the Gulf Coast region (Louisiana on-shore, Mississippi, and East Texas RR#3) have light oil, are moderately deep and often have a favorable bottom water drive. As such, the overall oil recovery efficiency in the Gulf Coast oil fields is high, at 40 percent, Table 20. (A limited number of new CO_2-EOR floods, primarily in Mississippi, are included in the totals.)

Table 20. Gulf Coast: Original Oil In-Place, Cumulative Production, Proved Reservoirs and Recovery Efficiency (Currently Used Oil Recovery Methods)

	OOIP (B Bbls)	Cumulative Recovery (B Bbls)	Proved Reserves (B Bbls)	Total Recovery (B Bbls)	Recovery Efficiency (%)
Data Base	35.1	14.0	0.3	14.3	40
State Total	60.8	23.7	0.8	24.5	40

Screening the Gulf Coast large oil fields data base identified 208 reservoirs that would be favorable for miscible or immiscible CO_2-EOR. Application of the combination of “next generation” CO_2-EOR technologies to these reservoirs shows that oil recovery efficiency could be significantly improved, raising recovery efficiency in oil reservoirs favorable for CO_2-EOR by 35 percent and the overall oil recovery efficiency in Gulf Coast onshore oil fields by 32 percent, Table 21.

Table 21. Gulf Coast: Original Oil In-Place, Recoverable Resources, and Recovery Efficiency – ("State-of-the-Art" and "Next Generation" CO_2-EOR Technology)

	OOIP	Oil Recovery from Applying CO_2-EOR Technology			
		"State-of-the-Art"	Incremental from "Next Generation"	Total	Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base					
• Favorable Reservoirs	32.2	5.9	5.2	11.1	35
• Unfavorable Reservoirs	2.9	--	--	--	--
Total	35.1	5.9	5.2	11.1	32
State Total	60.8	10.1	8.9	19.0	32

The use of the combination of "next generation" CO_2-EOR technologies would add 11.1 billion barrels of technically recoverable resource (19.0 billion barrels when extrapolated to the state or as a whole). Combining the oil recovery from currently used (primary and secondary) recovery methods and the additional oil recovery from applying the combination "next generation" CO_2-EOR technologies would raise the overall recovery efficiency in Gulf Coast oil fields to 72 percent, Table 22.

Table 22. Gulf Coast: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (Currently Used Oil Recovery Methods and "Next Generation" CO_2-EOR Technology)

	OOIP	Past and Future Oil Recovery			
		Current Methods	"Next Generation" CO_2-EOR	Total	State-Wide Oil Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base	35.1	14.3	11.1	25.4	72
State Total	60.8	24.5	19.0	43.5	72

7.3 OKLAHOMA. Many of the Oklahoma oil fields were discovered and produced before modern reservoir engineering practices began to be routinely applied. In addition, a large number of the older Oklahoma oil fields depleted their reservoir drive and have yet to undertake comprehensive secondary oil recovery. As a result, the overall oil recovery efficiency in the Oklahoma oil fields is low, at 25 percent, Table 23. (A small number of CO_2-EOR and polymer floods are included in the totals.)

Table 23. Oklahoma: Original Oil In-Place, Cumulative Production, Proved Reservoirs and Recovery Efficiency (Currently Used Oil Recovery Methods)

	OOIP (B Bbls)	Cumulative Recovery (B Bbls)	Proved Reserves (B Bbls)	Total Recovery (B Bbls)	Recovery Efficiency %
Data Base	36.5	8.9	0.3	9.2	25
State Total	60.3	14.5	0.7	15.2	25

Screening the Oklahoma large oil fields data base identified 71 reservoirs that would be favorable for miscible or immiscible CO_2-EOR. Application of the combination of “next generation” CO_2-EOR technologies to these reservoirs shows that oil recovery efficiency could be significantly improved, raising recovery efficiency in oil reservoirs favorable for CO_2-EOR by 44 percent and the overall oil recovery efficiency in Oklahoma oil fields by 33 percent, Table 24.

Table 24. Oklahoma: Original Oil In-Place, Recoverable Resources, and Recovery Efficiency – ("State–of-the-Art" and "Next Generation" CO_2-EOR Technology)

	OOIP	Oil Recovery from Applying CO_2-EOR Technology			
		"State-of-the-Art"	Incremental from "Next Generation"	Total	Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base					
• Favorable Reservoirs	27.3	5.4	6.7	12.1	44
• Unfavorable Reservoirs	--	--	--	--	--
Total	36.5	5.4	6.7	12.1	33
State Total	60.3	9.0	11.1	20.1	33

The use of the combination of "next generation" CO_2-EOR technologies would add 12.1 billion barrels of technically recoverable resource (20.1 billion barrels when extrapolated to the state or as a whole). Combining the oil recovery from currently used (primary and secondary) recovery methods and the additional oil recovery from applying the combination "next generation" CO_2-EOR technologies would raise the overall recovery efficiency in Oklahoma oil fields to 58 percent, Table 25.

Table 25. Oklahoma: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (Currently Used Oil Recovery Methods and "Next Generation" CO_2-EOR Technology)

	OOIP (B Bbls)	Past and Future Oil Recovery			
		Current Methods	"Next Generation" CO_2-EOR	Total	State-Wide Oil Recovery Efficiency
		(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base	36.5	9.2	12.1	21.3	58
State Total	60.3	15.2	20.1	35.3	58

7.4 ILLINOIS. The Illinois Basin has a large number of relatively shallow, light oil reservoirs that have been successfully produced with primary and secondary oil recovery methods. As a result, the recovery efficiency in Illinois oil fields is moderately high, at 39 percent of the original oil in-place (OOIP), Table 26.

Table 26. Illinois: Original Oil In-Place, Cumulative Production, Proved Reservoirs and Recovery – Efficiency (Currently Used Oil Recovery Methods)

	OOIP (B Bbls)	Cumulative Recovery (B Bbls)	Proved Reserves (B Bbls)	Total Recovery (B Bbls)	Recovery Efficiency %
Data Base	6.5	2.4	0.1	2.5	39
State Total	9.4	3.6	0.1	3.7	39

Screening the Illinois large oil fields data base identified 46 reservoirs that would be favorable for miscible or immiscible CO_2-EOR. Application of the combination of "next generation" CO_2-EOR technologies to these reservoirs shows that oil recovery efficiency could be significantly improved, raising recovery efficiency in oil reservoirs favorable for CO_2-EOR by 35 percent and raising the overall oil recovery efficiency in Illinois oil fields by 17 percent, Table 27.

Table 27. Illinois: Original Oil In-Place, Recoverable Resources, and Recovery Efficiency – ("State–of-the-Art" and "Next Generation" CO_2-EOR Technology)

		Oil Recovery from Applying CO_2-EOR Technology			
	OOIP	"State-of-the-Art"	Incremental from "Next Generation"	Total	Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base					
• Favorable Reservoirs	3.1	0.5	0.6	1.1	35
• Unfavorable Reservoirs	3.4	--	--	--	--
Total	6.5	0.5	0.6	1.1	17
State Total	9.4	0.7	0.9	1.6	17

The use of the combination of "next generation" CO_2-EOR technologies would add 1.1 billion barrels of technically recoverable resource (1.6 billion barrels when extrapolated to the state as a whole). Combining the oil recovery from currently used (primary and secondary) recovery methods and the additional oil recovery from applying the combination "next generation" CO_2-EOR technologies would raise the overall oil recovery efficiency in Illinois oil fields to 56 percent, Table 28.

Table 28. Illinois: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (Currently Used Oil Recovery Methods and "Next Generation" CO_2-EOR Technology)

		Past and Future Oil Recovery			
	OOIP	Current Methods	"Next Generation" CO_2-EOR	Total	State-Wide Oil Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base	6.5	2.5	1.1	3.6	56
State Total	9.4	3.7	1.6	5.3	56

7.5 ALASKA. Oil recovery efficiency in Alaska is dominated by performance in a small number of very large oil fields, such as Prudhoe Bay and Kuparuk River. An aggressive program of water injection, reinjection of the produced natural gas (which contains a significant percent of CO_2), and hydrocarbon miscible CO_2-EOR has led to an overall oil recovery efficiency in the Alaska oil fields of 33 percent of the original oil in-place (OOIP), Table 29.

Table 29. Alaska: Original Oil In-Place, Cumulative Production, Proved Reservoirs and Recovery Efficiency (Currently Used Oil Recovery Methods)

	OOIP (B Bbls)	Cumulative Recovery (B Bbls)	Proved Reserves (B Bbls)	Total Recovery (B Bbls)	Recovery Efficiency %
Data Base	65.3	14.9	6.7	21.6	33
State Total	67.3	15.3	6.9	22.2	33

Screening the Alaska large oil fields data base identified 33 reservoirs that would be favorable for miscible or immiscible CO_2-EOR. Application of the combination of “next generation” CO_2-EOR technologies to these reservoirs shows that oil recovery efficiency could be significantly improved, raising recovery efficiency in oil reservoirs favorable for CO_2-EOR by 36 percent and raising the overall oil recovery efficiency in Alaska oil fields by 35 percent, Table 30.

Table 30. Alaska: Original Oil In-Place, Recoverable Resources, and Recovery Efficiency – ("State–of-the-Art" and "Next Generation" CO_2-EOR Technology)

	OOIP	Oil Recovery from Applying CO_2-EOR Technology			
		"State-of-the-Art"	Incremental from "Next Generation"	Total	Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base					
• Favorable Reservoirs	64.5	12.0	11.1	23.1	36
• Unfavorable Reservoirs	0.8	--	--	--	--
Total	65.3	12.0	11.1	23.1	35
State Total	67.3	12.4	11.4	23.8	36

The use of the combination of "next generation" CO_2-EOR technologies would add 11.1 billion barrels of technically recoverable resource (11.4 billion barrels when extrapolated to the state or as a whole). Combining the oil recovery from currently used (primary, secondary and hydrocarbon miscible) recovery methods and the additional oil recovery from applying the combination "next generation" CO_2-EOR technologies would rase the overall recovery efficiency in Alaska oil fields to 68 percent, Table 31.

Table 31. Alaska: Original Oil In-Place, Recoverable Resources and Recovery Efficiency – (Currently Used Oil Recovery Methods and "Next Generation" CO_2-EOR Technology)

	OOIP	Past and Future Oil Recovery			
		Current Methods	"Next Generation" CO_2-EOR	Total	State-Wide Oil Recovery Efficiency
	(B Bbls)	(B Bbls)	(B Bbls)	(B Bbls)	(%)
Data Base	65.3	21.6	23.1	44.7	68
State Total	67.3	22.2	23.8	46.0	68

7.6 LOUISIANA OFFSHORE (SHELF). Conducting CO_2-EOR in offshore areas, even with the best of currently available technology, will encounter barriers and constraints beyond those experienced in onshore operations. Given the very limited past experience in operating CO_2-EOR in the offshore, the already favorable primary/ secondary oil recoveries from these high permeability, strong water drive reservoirs, and expectations of nearly 6 billion barrels of technically recoverable oil resource from application of “state-of-the-art” CO_2-EOR technology to the Louisiana Offshore (Shelf) reservoirs, the application of “next generation” CO_2-EOR technology may not be feasible for this basin/region. As such, no further analysis of increasing oil recovery or oil recovery efficiency has been conducted for the Louisiana Offshore (Shelf) oil fields.

8. SUMMARY

The results from this study indicate that domestic oil recovery efficiency could be improved significantly with “next generation” CO_2-EOR technology. Domestic oil recovery (in the six basins/regions examined so far) could be increased by 83.7 billion barrels of technically recoverable resource (over current primary/secondary methods) and overall oil recovery efficiency (in these six basins/regions) would be increased to 61 percent of original oil in-place.

However, the reader should note that significant new investments are required in research and technology development for CO_2-EOR to provide the increased domestic oil resources and to realize the higher oil recovery efficiencies set forth in this report.

The four major findings from this study are as follows:

1. **Demonstration of “state-of-the-art” CO_2-EOR practices and development of “next generation” CO_2-EOR technologies could greatly increase the recovery efficiency from domestic oil reserves.** Domestic oil recovery efficiency, even including “traditionally practiced” thermal and CO_2-EOR technologies, is low – less than 36 percent of the original oil in-place. “State-of-the-art” CO_2-EOR technology can raise this to nearly 48 percent. Development and successful application of “next generation” CO_2-EOR technologies can further increase domestic oil recovery efficiency, raising this critical value to 61 percent overall (and in geologically favorable reservoirs to over 80 percent) in the six basins/regions addressed by this study.

2. **With “state-of-the-art” CO_2 enhanced oil recovery technology, an estimated 43.3 billion barrels of “stranded” oil (in the six basins and areas studied to date) could become technically recoverable.** Of the 895 oil reservoirs in the data base, 533 large reservoirs screen favorably for “state-of-the-art” CO_2-EOR, providing 32.9 billion barrels of technically recoverable resource. When the CO_2-EOR potential in these 533 large favorable oil reservoirs is extrapolated to the “stranded” oil resources in each of the six basins/areas, the CO_2-EOR potential becomes 43.3 billion barrels of technically recoverable resource, as reported in previous DOE/FE studies[6], Table 32. Extrapolated to all domestic light oil reservoirs, “state-of-the-art” CO_2-EOR technology could provide 80 billion barrels of technically recoverable domestic oil resource, as reported in the DOE/FE study, *Undeveloped Oil Resources: The Foundation for Increased Oil Production and a Viable Domestic Oil Industry*.[7]

Table 32. Technically Recoverable Oil Resource From “State-of-the-Art” CO_2-EOR (Six Basins/Areas Assessed to Date)

Basin/Area	Large Favorable Reservoirs (Six Areas)		All Reservoirs (Six Basins/Areas)		
	Number	Technically Recoverable	OOIP* (Billion Barrels)	ROIP** (Billion Barrels)	Technically Recoverable (Billion Barrels)
California	88	4.6	83.3	57.3	5.2
Gulf Coast	205	5.9	60.8	36.4	10.1
Oklahoma	63	5.4	60.3	45.1	9.0
Illinois	46	0.5	9.4	5.8	0.7
Alaska	32	12.0	67.3	45.0	12.4
Louisiana Offshore (Shelf)	99	4.5	28.1	15.7	5.9
Total	533	32.9	309.2	205.3	43.3

*Original Oil In-Place, in all reservoirs in basin/area; ** Remaining Oil In-Place, in all reservoirs in basin/area.
Source: Advanced Resources International, 2005.

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[6] U.S. Department of Energy/Fossil Energy: “Basin-Oriented Strategies for CO2 Enhanced Oil Recovery: California, Onshore Gulf Coast, Offshore Louisiana, Oklahoma, Alaska and Illinois”, April 2005.

[7] U.S. Department of Energy/Fossil Energy: “Undeveloped Oil Resources: The Foundation for Increased Oil Production and a Viable Domestic Oil Industry” February 2006.

3. **With integrated application of the full set of "next generation" CO_2 enhanced oil recovery technologies, 83.7 billion barrels of "stranded" oil (in the six basins and areas studied to date) could become technically recoverable.** Of the 895 oil reservoirs in the data base, 553 large reservoirs screen favorably for CO_2-EOR, with 63.8 billion barrels of technically recoverable resource when using the full set of "next generation" CO_2-EOR technologies. When the CO_2-EOR potential in these 553 large favorable oil reservoirs is extrapolated to the "stranded" oil resources in each of the six state/areas, the CO_2-EOR potential becomes 83.7 billion barrels of technically recoverable resource, Table 33.

Table 33. Technically Recoverable Oil Resource From "Next Generation" CO_2-EOR (Six Basins/Areas Assessed to Date)

	Large Favorable Reservoirs (Six Areas)		All Reservoirs (Six Basins/Areas)		
Basin/Area	Number	Technically Recoverable	OOIP* (Billion Barrels)	ROIP** (Billion Barrels)	Technically Recoverable (Billion Barrels)
California	96	11.9	83.3	57.3	13.3
Gulf Coast	208	11.1	60.8	36.4	19.0
Oklahoma	63	12.1	60.3	45.1	20.1
Illinois	46	1.1	9.4	5.8	1.6
Alaska	32	23.1	67.3	45.0	23.8
Louisiana Offshore (Shelf)	99	4.5	28.1	15.7	5.9
Total	553	63.8	309.2	205.3	83.7

*Original Oil In-Place, in all reservoirs in basin/area; ** Remaining Oil In-Place, in all reservoirs in basin/area.
Source: Advanced Resources International, 2005.

4. **When extrapolated to all domestic oil fields, the integrated application of "next generation" CO_2-EOR technologies could provide 160 billion barrels of technically recoverable resource.** Integrated application of "next generation" CO_2-EOR technologies to the remaining domestic oil basins and regions still to be assessed could bring about truly "game changer" advances in oil recovery efficiency and domestic oil production. Extrapolating the sample of oil reservoirs included in the study to the

nation as a whole (using data on original oil in-place, provided in Figures EX-1 and Table EX-1) shows that the integrated application of “next generation” CO_2-EOR technologies could provide 160 billion barrels of technically recoverable resource from domestic oil fields.