NATIONAL ENERGY TECHNOLOGY LABORATORY

Improving Domestic Energy Security and Lowering CO_2 Emissions with "Next Generation" CO_2-Enhanced Oil Recovery (CO_2-EOR)

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I. EXECUTIVE SUMMARY

This analysis, sponsored by U.S. DOE/NETL and prepared by Advanced Resources International (ARI), builds a national CO_2 EOR resource assessment from reservoir-to-reservoir simulations of CO_2 floods. ARI used a proprietary database that contains oil properties and geologic characteristics of 1,800 onshore reservoirs and over 4,000 off shore sands. The simulations were conducted using the PROPHET model. PROPHET, originally developed by Texaco for DOE in the 1980s, models stream tubes of fluid flow between injection wells and producing wells. PROPHET is a screening tool and estimates the magnitude and timing of oil production based on a user-defined CO_2 injection protocol and the porosity of the host rock, the thickness of the oil, the degree of fracturing and discontinuity within the target formation and other inputs. NETL published a similar resource assessment in February 2010; this report supersedes the earlier assessment. For this analysis, the simulation methodology was peer reviewed by industry practitioners and important refinements were made based on their input. Aggregated results indicate that CO_2-EOR can provide high value benefits to the domestic economy and the environment, as discussed below.

1. CO_2-EOR Promotes Enhanced Energy Security and Lower CO_2 Emissions

Increasing U.S. oil production and lowering domestic CO_2 emissions are two of the nation's highest priority goals. CO_2 enhanced oil recovery (CO_2-EOR), both as practiced today ("State of Art" (SOA)) and what is possible ("Next Generation"), directly addresses these two goals.

- "Next Generation" CO_2-EOR can provide 137 billion barrels of additional technically recoverable domestic oil, with about half (67 billion barrels) economically recoverable at an oil price of $85 per barrel.[1] Technical CO_2 storage capacity offered by CO_2-EOR would equal 45 billion metric tons.

- This volume of economically recoverable oil is sufficient to support nearly 4 million barrels per day of domestic oil production (1.35 billion barrels per year for 50 years), reducing oil imports by one-third. Production of oil from the ROZ (residual oil zone) would add to these totals.

- Nearly 20 billion metric tons of CO_2 will need to be purchased by CO_2-EOR operators to recover the 67 billion barrels of economically recoverable oil. Of this, about 2 billion metric tons would be from natural sources and currently operating natural gas processing plants. The remainder of the CO_2 demand (18 billion metric tons) would need to be provided by anthropogenic CO_2 captured from coal-fired power plants and other industrial sources.

- The market for captured CO_2 emissions from power plants created by economically feasible CO_2-EOR projects (projects that provide at least 20% ROR at an oil price of $85 per barrel and a CO_2 cost of $40 per metric ton) would be sufficient to permanently store the CO_2 emissions from 93 large one GW size coal-fired power plants operated for 30 years.

[1] In addition to an oil price of $85 per barrel (WTI), the economic analysis assumes a CO_2 market price of $40 per metric ton and a 20% return on investment, before tax.

2. CO_2-EOR Can Provide Large New Revenues to Federal/State Treasuries and Other Participants in the Value Chain.

The value created by applying "Next Generation" CO_2-EOR technology would be shared by numerous stakeholders. Assuming an oil price of $85 per barrel (WTI) and a CO_2 market price of $40 per metric ton, the following new revenue streams would result from recovering 67.2 billion barrels of domestic oil with "Next Generation" CO_2-EOR technology:

- Federal/state treasuries would be a large beneficiary, receiving $21.20 of the $85 per barrel oil price in the form of royalties on Federal /state lands plus severance, ad valorem and corporate income taxes. Total revenues to Federal/state treasuries would equal $1,420 billion.
- Electric power and other industrial companies would receive $10.80 of the $85 per barrel oil price from the sale of CO_2. Total revenues from sale of CO_2 at $40 per metric ton would equal $730 billion.
- The U.S. oil industry would receive $19.50 of the $85 per barrel oil price for return of and return on capital investment. Private mineral owners would receive $7.70 per barrel.
- The general U.S. economy would be the largest beneficiary, receiving $25.80 of the $85 per barrel of oil price, in the form of wages and material purchases. Total revenues would equal $1,730 billion.

With potential oil recovery of 67.2 billion barrels, $5.7 trillion of new domestic revenues and economic activity would accrue to the participants in the CO_2-EOR value chain.

Table EX-1. Distribution of Revenues from "Next Generation" CO_2-EOR

Revenue Recipient	Value Chain Function	Revenues	
		Per Barrel ($)	TOTAL ($ billion)
1. Federal/State Treasuries	Severance/Income Taxes	$21.20	$1,420
2. Power/Industrial Companies	Sale of Captured CO_2 Emissions	$10.80	$730
3. Oil Industry	Return of/on Capital	$19.50	$1,300
4. Other	Private Mineral Rights	$7.70	$520
5. U.S. Economy	Services, Materials and Sale of CO_2	$25.80	$1,730
	Total	$85.00	$5,700

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3. The Volumes of Oil Recovery and CO_2 Storage Offered by "Next Generation" CO_2-EOR are Large and Impressive.

With active use of "Next Generation" CO_2-EOR technology, large volumes of domestic oil could be produced while similarly large volumes of CO_2 could be reliably stored in domestic oil fields, Table EX-2:

Table EX-2. Oil Recovery and CO_2 Storage From "Next Generation" CO_2-EOR Technology

Reservoir Setting	Oil Recovery** (Billion Barrels)		CO_2 Demand/Storage** (Million Metric Tons)	
	Technical	Economic*	Technical	Economic*
1. Miscible CO_2-EOR				
Lower-48 Onshore	104.4	60.3	32,250	17,230
Alaska	8.8	5.7	4,110	2,330
Offshore	6.0	0.9	1,770	260
Sub-Total	119.1	67.0	38,130	19,820
2. Near Miscible CO_2-EOR	1.2	0.2	800	110
3. Residual Oil Zone***	16.3	n/a	6,500	n/a
TOTAL	136.6	67.2	45,430	19,930

*At $85 per barrel oil price and $40 per metric ton of CO_2 market price with ROR of 20% (before tax). JAF2011_030.XLS

**Includes 2.6 billion barrels already produced or being developed with miscible CO_2-EOR and 2,300 million metric tons of CO_2 from natural sources and gas processing plants.

***ROZ resources below existing oil fields in three basins; economics of ROZ resources were beyond study scope.

- The volumes of domestic oil technically recoverable with "Next Generation" CO_2-EOR technology are large: 120.3 billion barrels from the main pay zone of oil fields plus another 16.3 billion barrels from the Residual Oil Zone (ROZ).

- With an oil price of $85 per barrel and a CO_2 cost of $40 per metric ton, over 67 billion barrels will be recoverable (with ROR of 20%). An economic evaluation of oil recovery from ROZs would add to this total. As a point of reference, proved domestic oil reserves at the end of 2009 were 21 billion barrels.

- The volumes of CO_2 that could be technically stored with EOR are equally large--over 45 billion metric tons. These volumes would significantly increase as the storage potential offered by the ROZ "fairways" becomes better defined. As a point of reference, annual CO_2 emissions from domestic coal and natural gas-fired electricity production in 2009 were 2.2 billion metric tons.

- Assuming about 2 billion metric tons of CO_2 are provided to the CO_2-EOR industry from natural sources and gas processing plants, almost 18 billion metric tons of anthropogenic CO_2 could be sold to the CO_2-EOR market.

4. *"Next Generation" CO_2-EOR Provides Benefits Far Beyond Those Available from State of Art CO_2-EOR.*

The introduction of "Next Generation" CO_2-EOR technology would provide significant oil recovery and CO_2 storage benefits beyond those available from today's state of art (SOA) CO_2-EOR technology, Table EX-3:

Table EX-3. Comparison of Technically and Economically Recoverable Domestic Oil and CO_2 Storage Capacity from State of Art (SOA) and "Next Generation" CO_2-EOR Technology*

Basin/Area	Technically Recoverable Oil (Billion Barrels)		Economically Recoverable Oil** (Billion Barrels)		Economic CO_2 Demand/Storage** (Million Metric Tons)	
	SOA	"Next Generation"	SOA**	"Next** Generation"	SOA**	"Next Generation"
1. Miscible CO2-EOR						
Lower-48 Onshore	55.7	104.4	24.3	60.3	8,940	17,230
Alaska	5.8	8.8	2.6	5.7	1,490	2,330
Offshore GOM	-	6.0	-	0.9	-	260
Sub-Total	61.5	119.1	26.9	67.0	10,430	19,820
2. New Miscible CO2-EOR	n/a	1.2	n/a	0.2	-	110
3. Residual Oil Zones	n/a	16.3	n/a	***	-	***
Total	61.5	136.6	26.9	67.2	10,430	19,930

*Includes 2.6 billion barrels already produced or placed into reserves with miscible CO_2-EOR and 2,300 million metric tons of CO_2 from natural sources and gas processing plants.

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**At an oil price of $85 per barrel and a CO_2 cost of $40 per metric ton with ROR at 20% before tax.

***The economics of recovering oil from the residual oil zone were beyond study scope.

- The volumes of technically recoverable domestic oil would more than double, from 62 billion barrels with SOA technology to 137 billion barrels with "Next Generation" CO_2-EOR technology.
- Economically recoverable domestic oil would increase even more substantially, to 67 billion barrels with "Next Generation" technology compared to 27 billion barrels with SOA technology.
- The volumes of economically driven CO_2 demand by the CO_2-EOR industry would climb to nearly 20 billion metric tons from "Next Generation" technology. With about 2 billion metric tons of CO_2 provided by natural sources and gas processing plants, the net economic demand for CO_2 captured from power and industrial plants would be 18 billion metric tons (equal to 30 years of captured CO_2 emissions from 93 GWs of coal-fired power). SOA technology would create

a market demand for captured CO_2 of only about 8 billion metric tons (equal to 30 years of captured CO_2 emissions from 43 GWs of coal-fired power).[2]

5. *“Next Generation” CO_2-EOR Technologies Are Realistic and Achievable with Focused Investments in R&D.*

Before proceeding, it is useful to address the question - - just what constitutes “Next Generation” CO_2 enhanced oil recovery and how would it benefit the U.S. economy and energy security? Briefly stated, “Next Generation” CO_2-EOR incorporates four significant and, with investments in R&D plus field pilots, realistically achievable advances in technology:

- Improvements in currently practiced miscible CO_2-EOR technology,
- Advanced near miscible CO_2-EOR technology,
- Application of CO_2-EOR to residual oil zones (ROZs),[3,4,5] and
- Deployment of CO_2-EOR in offshore oil fields.

Chapter IV of the report provides a more in-depth look at these four “Next Generation” CO_2-EOR technologies. Chapter V of the report provides a more detailed explanation of the benefits of “Next Generation” CO_2-EOR technology.

The remainder of the report provides context, relevant information and details to help the reader better understand CO_2-EOR and its contribution toward improved domestic energy security and lower emissions of CO_2.

- Chapter II of the report discusses today’s CO_2-EOR activities as well as its future promise under “Next Generation” technology.
- Chapter III of the report provides a case study of the evolution in CO_2-EOR practices and performance in the Permian Basin.
- Chapter VI provides a “basin-oriented” look at the applicability of CO_2-EOR in eleven U.S. basins and regions.
- Chapter VII provides an overview of the study methodology, which is more fully discussed in Appendix A.

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[2] Assuming 85% capacity factor and 34% efficiency, a1GW power plant would generate 223 billion kWh of electricity in thirty years (1GW x 85% x 8.76 (conversion between GW and billion kWh/year) * 30 years). With a CO_2 intensity of 0.94 million metric tons CO_2/kWh (thermodynamic equivalency based on efficiency of power plant and emissions profile of average coal) and 90% capture, this power plant would supply 189 million metric tons of CO_2 in 30 years, at 6.3 million metric tons per year.

[3] “Technical Oil Recovery Potential from Residual Oil Zones: Permian Basin”, prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, Office of Fossil Energy, Office of Oil and Natural Gas, October 2005.

[4] “Technical Oil Recovery Potential from Residual Oil Zones: Big Horn Basin”, prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, Office of Fossil Energy, Office of Oil and Natural Gas, February 2006.

[5] “Technical Oil Recovery Potential from Residual Oil Zones: Williston Basin”, prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, Office of Fossil Energy, Office of Oil and Natural Gas, February 2006.

* * * * *

This report represents a significant update of the "Next Generation" CO_2-EOR technology first introduced in DOE/NETL Report -2009/135 "Storing CO_2 and Producing Domestic Crude Oil with "Next Generation" CO_2-EOR". The following major changes have been made since the previous version:

- The economic and reservoir models employed in the analysis have been thoroughly vetted by industry experts and practitioners. Based on input from these stakeholders, Advanced Resources made adjustments to how CO_2-floods are evaluated by the *PROPHET2* model and how field and pattern economics are calculated in our cashflow models.
- The current version of the report employs a significantly updated reservoir data base, incorporating current data on many important reservoir datapoints, such as cumulative production, reserves and well counts, among others.
- The economic model in the current study incorporates an economic truncation function that limits the volumes of CO_2 injection (and project life) using a marginal annual economic calculation.
- To better capture current economic conditions, we have employed new oil and CO_2 prices. The "base case" economic scenario now uses an $85/Bbl oil price and a $40/metric ton CO_2 market price. Additionally, CO_2 market prices are now calculated as a percentage of oil price. To reflect historical practices, we model CO_2 market prices at 2% to 3% of oil price (in terms of $/Mcf of CO_2) in our sensitivity analysis section of the report.
- Finally, to recognize the higher risks of introducing an emerging technology, such as "Next Generation" CO_2-EOR and its need to compete for capital with other domestic energy investments, the economics have been evaluated using a 20% return on investment, compared to a 15% return on investment in the previous study.

Advanced Resources is truly grateful for industry's participation and input and has summarized the major recommendations we received and incorporated into this updated study in Appendix B.

II. THE CURRENT AND FUTURE PROMISE OF CO_2-ENHANCED OIL RECOVERY

A. The Current Status of CO_2-EOR

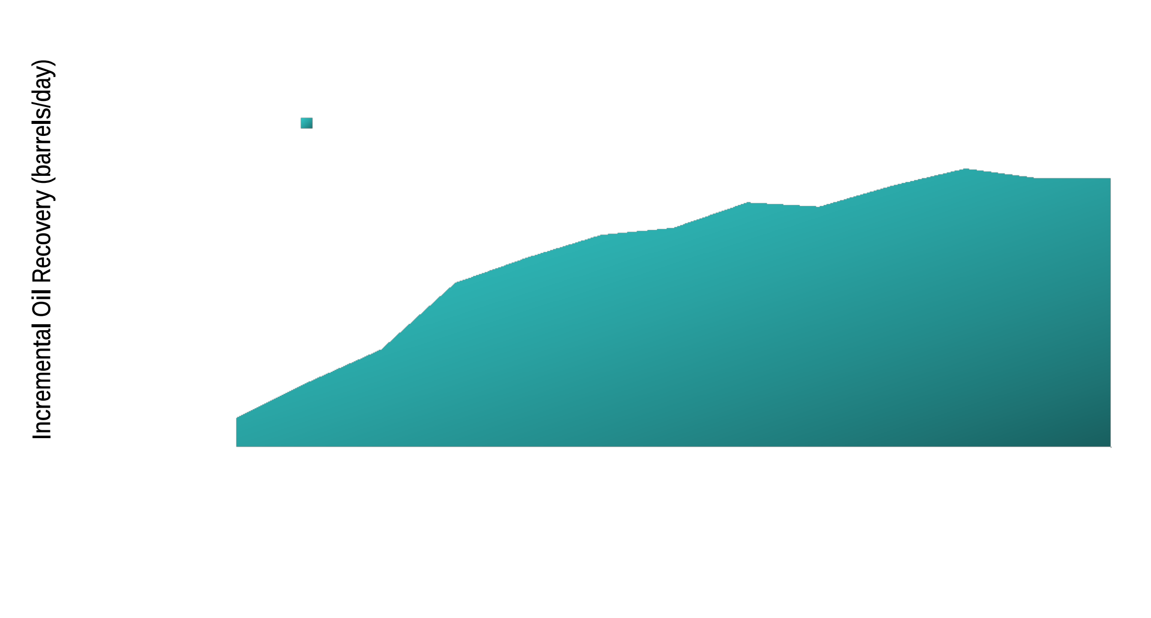
CO_2-based enhanced oil recovery, using State of Art (SOA) technology, is already being implemented, particularly in the oil fields of the Permian Basin of West Texas, the Gulf Coast and the Rockies.

- CO_2-EOR currently provides about 281,000 barrels of oil per day in the U.S.,[6] equal to 6% of U.S. crude oil production (Figure II-1). CO_2-EOR has been underway for several decades, starting initially in the Permian Basin and expanding today to 114 CO_2-EOR projects currently installed in numerous regions of the country (Figure II-2).
- Today, the great bulk of the CO_2 used for EOR comes from natural sources, such as McElmo Dome in New Mexico and Jackson Dome in Mississippi. These natural sources are supplemented by modest, but growing sources of anthropogenic CO_2 (Table II-1).
- A robust network of pipelines transport CO_2 from natural CO_2 deposits and gas processing plants to the Denver City Hub (Figure II-3). Still, the number one barrier to reaching higher levels of CO_2-EOR production is lack of access to adequate supplies of affordable CO_2.
- As shown in Table II-1, the largest single source of anthropogenic CO_2 used for EOR is the capture of 340 MMcfd (6.6 MMmt/yr) of CO_2 from the gas processing plant at La Barge in Western Wyoming. This is followed by the "poster child" for integrating large-scale CO_2-EOR with CCS - - the capture of 150 MMcfd (~3MMmt/yr) of CO_2 from the Northern Great Plains Gasification plant in Beulah, North Dakota and its transport, via a 200 mile cross-border CO_2 pipeline, to the two EOR projects at the Weyburn oil field in Saskatchewan, Canada.

New CO_2 pipelines and refurbished gas treating plants have recently been placed on-line (Figure II-2).[7] These include Denbury's 320 mile Green Pipeline along the Gulf Coast, and Occidental Petroleum's new $850 million Century natural gas/CO_2 processing plant and pipeline facilities in West Texas. The proposed Denbury (Encore) pipeline (linked to the Lost Cabin gas plant in Wyoming) is proposed to come on line as of late 2012. These new facilities will significantly expand the availability and use of CO_2 in domestic oil fields, leading to increased oil production from CO_2-EOR. For example, Occidental Petroleum expects the installation of the Century CO_2 plant to expand its Permian Basin oil production by 50,000 barrels per day within 5 years.[8]

[6] Oil and Gas Journal EOR Survey, April 2010.
[7] Various industry presentations and publications.
[8] Occidental Petroleum Investor Presentation, October, 2010.

Figure II-1. Growth CO_2-EOR Production in the U.S.



Source: Advanced Resources Int'l., based on Oil and Gas Journal, 2010.

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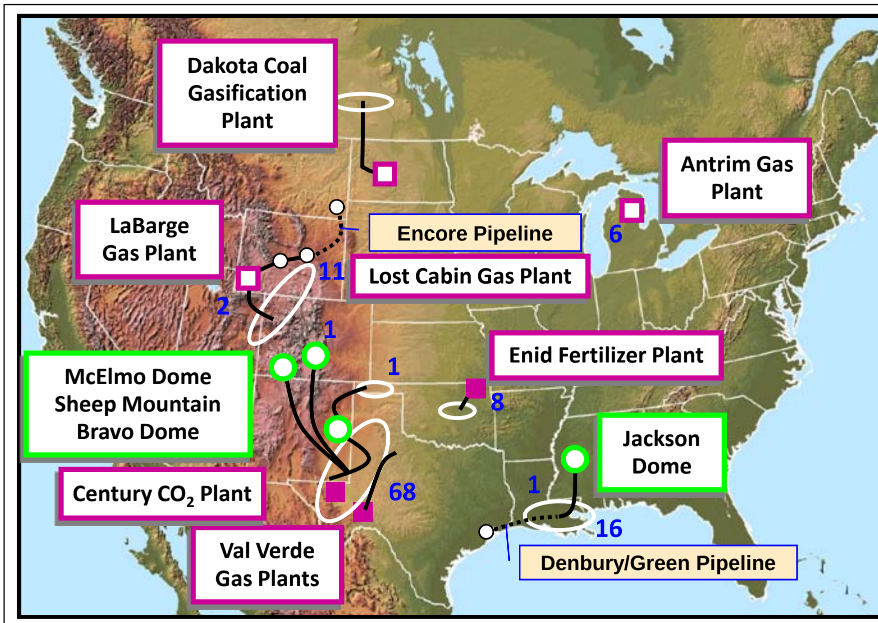
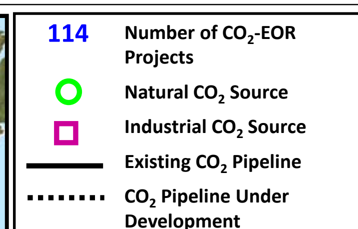
Figure II-2. Current U.S. CO_2-EOR Activity





- Currently, 114 CO_2-EOR projects provide 281,000 B/D.
- New CO_2 pipelines - - the 320 mile Green Pipeline, the 226 mile Encore Pipeline and the Century CO_2 Plant - - are expanding the use of CO_2-EOR.

Source: Advanced Resources International, Inc., based on Oil and Gas Journal, 2010 and other sources.

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Figure II-3. Existing CO_2 Pipelines (Permian Basin)

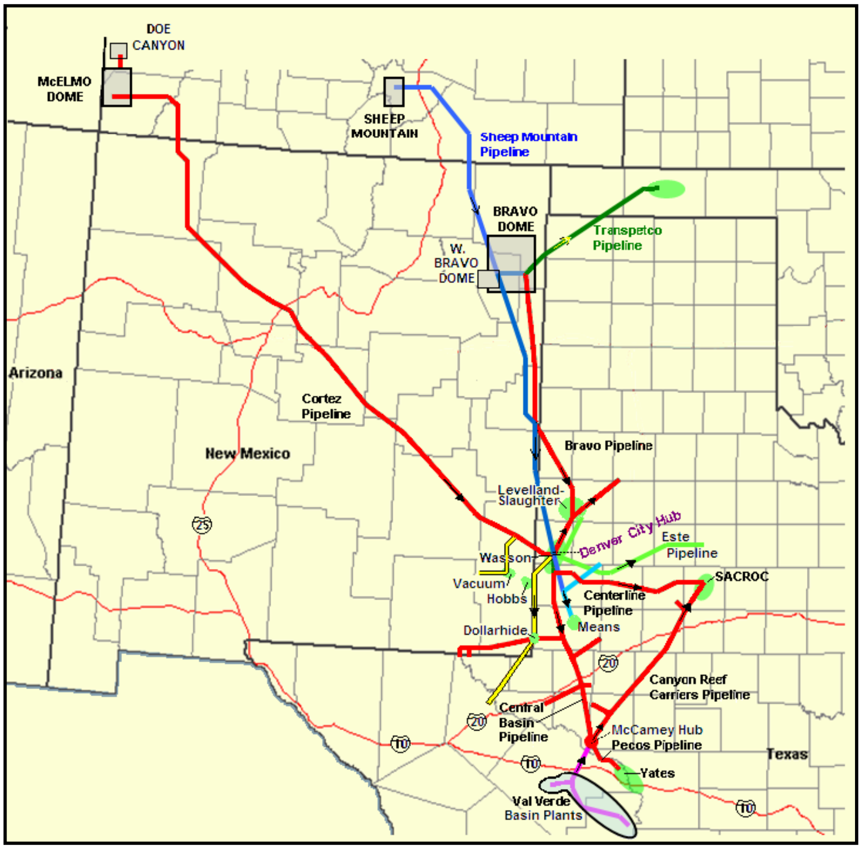

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Table II-1. Significant Volumes of Anthropogenic CO_2 Are Already Being Injected for EOR

Location of EOR / CO_2 Storage	CO_2 Sources by Type and Location	CO_2 Supply (MMcfd)*	
		Natural	Anthropogenic
Texas-Utah-New Mexico-Oklahoma	Natural CO_2 (Colorado-New Mexico)	1,730	335
New Mexico-Oklahoma	Gas Processing Plants (W. Texas)		
Colorado-Wyoming	Gas Processing Plants (Wyoming)	-	340
Mississippi/Louisiana	Natural CO_2 (Mississippi)	1,100	-
Michigan	Ammonia Plant (Michigan)	-	15
Oklahoma	Fertilizer Plant (Oklahoma)	-	30
Saskatchewan	Coal Gasification Plant (North Dakota)	-	150
TOTAL (MMcfd)		2,830	870
TOTAL (million mt/yr)**		55	17

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* Additional CO_2 supplies are anticipated in 2012 from the Lost Cabin gas processing plant in Wyoming (50 to 60 MMcfd) and from Train II of the Century gas processing plant in West Texas (180 MMcfd).
**MMcfd of CO_2 can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by 18.9 Mcf per metric ton.
Source: Advanced Resources Int'l (2011).

B. The Future Promise of CO_2-EOR

1. Oil Recovery and CO_2 Storage: Traditional ("Main") Pay Zone of Oil Fields.

The assessments of oil recovery and CO_2 storage capacity set forth in this report have been based on a database of over 6,300 domestic oil reservoirs, accounting for three-quarters of U.S. oil resources. The study identified 1,858 large oil reservoirs with 366 billion barrels of original oil in-place (487 billion barrels of original oil in-place when extrapolated to national totals) as favorable for CO_2-EOR.

These large oil reservoirs were modeled for CO_2–based enhanced oil recovery using ARI's adaptation of the streamline reservoir simulator *PROPHET2*. The amount of CO_2 storage capacity offered by oil fields favorable for CO_2-EOR was then evaluated using "Next Generation" CO_2-EOR technology and economics.

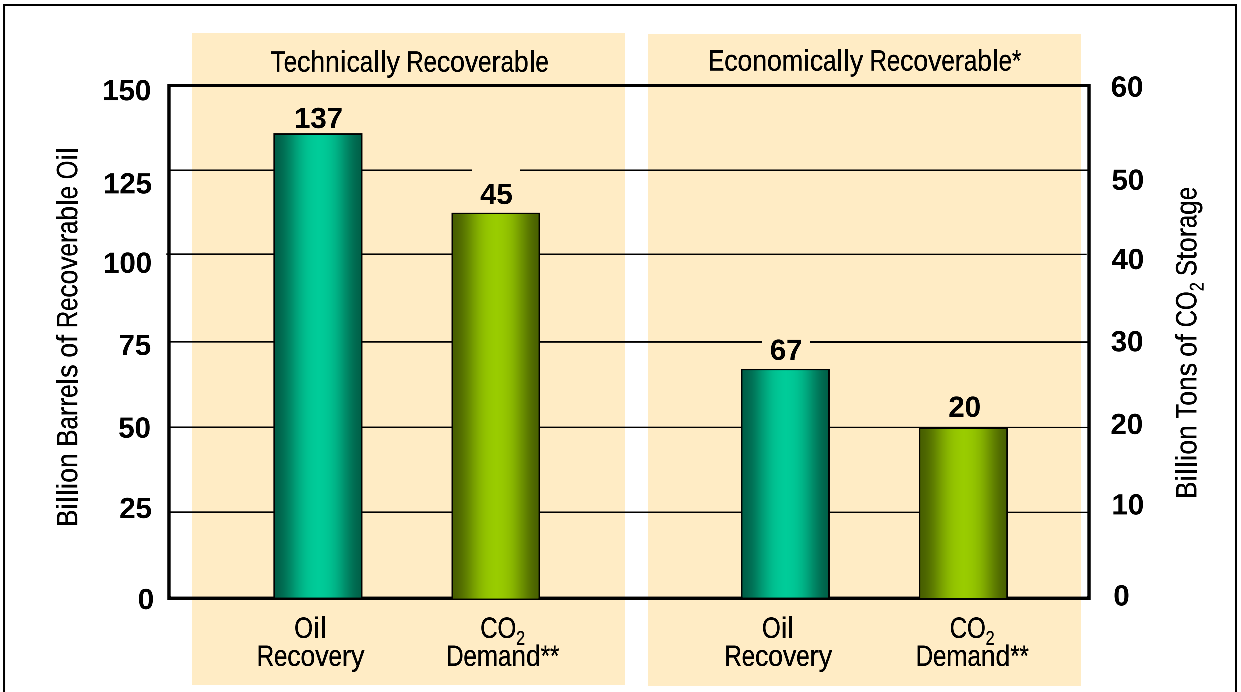
The study established two oil recovery and CO_2 storage categories -- "Technical Potential" (without consideration of prices and costs) and "Economic Potential" (the volume of oil the industry could produce and the volume of CO_2 industry could buy (and store) at a specified oil price and CO_2 market price).

As shown in Figure II-4, the volume of technically recoverable oil using "Next Generation" CO_2-EOR is 136.6 billion barrels. The CO_2 volume associated with this technically recoverable oil is 45.4 billion metric tons.

The volume of economically recoverable oil (at an oil price of $85/B, CO_2 costs of $40/Mt and a 20% before tax financial return) is 67.2 billion barrels.

The CO_2 demand associated with this economically recoverable oil is 19.9 billion metric tons. Approximately 2.3 billion metric tons of CO_2 demand for CO_2-EOR is expected to be provided from natural gas processing plants and natural sources of CO_2, providing a demand of 17.6 billion metric tons from CO_2 emissions captured by electric power and other industrial plants.

Figure II-4. Domestic Oil Supplies and CO_2 Demand (Storage) Volumes from "Next Generation" CO_2-EOR Technology**



*At an oil price of $85/B, a CO_2 market price of $40/mt and a 20% ROR, before tax.
**Includes 2,300 million metric tons of CO_2 provided from natural sources and 2.6 billion barrels already produced or being developed with miscible CO_2-EOR.
Source: Advanced Resources Int'l (2011).

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2. Oil Recovery and CO_2 Storage: Residual Oil Zone ("ROZ")

No discussion of "Next Generation" CO_2-EOR technology would be complete without at least a preliminary treatment of the major volumes of additional oil that exist in the residual oil zone (ROZ).

Our estimated oil recovery potential from using CO_2-EOR in the ROZ, below 56 large, existing Permian Basin oil fields, is 11.9 billion barrels of technically recoverable oil. This provides CO_2 storage capacity of 4.8 billion metric tons.[3] Additional technically recoverable ROZ oil resources, equal to 4.4 billion barrels and providing 1.7 billion metric tons of CO_2 storage capacity, exist underneath 13 oil fields in the Big Horn[4] and underneath 20 oil fields in the Williston[5] basins.

The scope of work for this study did not include providing an economically recoverable assessment of conducting CO_2-EOR in residual oil zones (ROZs).

C. CO_2 Market Demand and CO_2 Storage from "Next Generation" CO_2-EOR Technology: Base Case Oil Price and CO_2 Costs

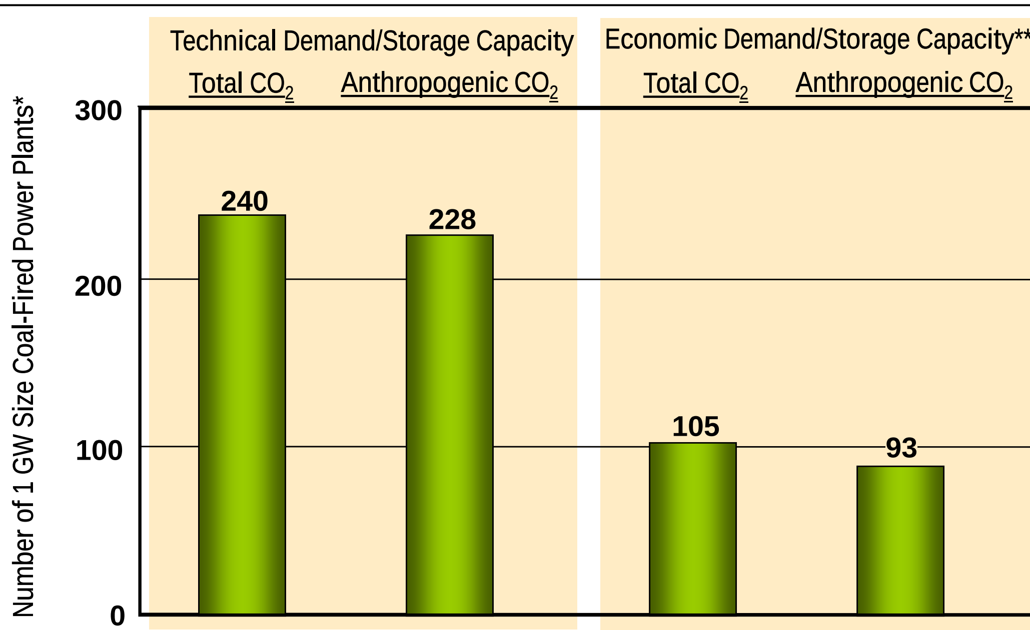
The technical CO_2 demand associated with "Next Generation" CO_2-EOR is 45.4 billion metric tons. The economic demand (and subsequent storage) for CO_2 with "Next Generation" CO_2-EOR is 19.9 billion metric tons, with about 2.3 billion metric tons of CO_2 provided by natural sources and existing natural gas processing plants.

However, large numbers such as billions of tons of CO_2 demand and storage capacity are different to grasp and thus often of limited value.

An alternative way to illustrate the CO_2 demand and storage capacity offered by "Next Generation" CO_2-EOR is to use the metric of the number of one-GW size power plants that could rely on CO_2-EOR for purchasing and storing their captured CO_2, Figure II-5:

- After subtracting out the 2.3 billion metric tons of CO_2 supply currently available, CO_2-EOR still offers sufficient technical storage capacity for all of the anthropogenic CO_2 captured from 228 one-GW size coal-fired power plants for 30 years of operation.
- Similarly, the volume of economic demand (and storage capacity) for anthropogenic CO_2 offered by CO_2-EOR, is substantial, equal to 93 one-GW size coal-fired power plants, after subtracting out the CO_2 supplies available from natural sources and natural gas processing plants.

Figure II-5. Volumes of Anthropogenic CO_2 Storage Capacity Available from "Next Generation" CO_2-EOR Technology



*Assuming 7 MMmt/yr of CO_2 emissions, 90% capture and 30 years of operations per 1 GW of generating capacity.
**At an oil price of $85/B, a CO_2 market price of $40/mt and a 20% ROR, before.
Source: Advanced Resources Int'l (2011).

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D. Impacts of Alternative Oil Prices and CO_2 Market Prices on CO_2-EOR Volumes and CO_2 Demand/Storage

The study undertook a series of sensitivity studies to gain insights on how alternative (higher and lower) oil prices and alternative (higher and lower) CO_2 market prices would impact results. Using historical ±30% bounds for future oil prices and historical ratios that relate CO_2 market prices to oil prices, the following nine cell price sensitivity matrix was constructed, Table II-2:

Table II-2. Oil and CO_2 Prices Used in Sensitivity Analysis

Oil Price	CO_2 Market Price (% of oil price, in $/Mcf)					
($/B)	Low: 2%		Base: 2.5%		High: 3%	
	($/Mcf)	($/Mt)	($/Mcf)	($/Mt)	($/Mcf)	($/Mt)
Low: $60	1.20	23	1.50	28	1.80	34
Base: $85	1.70	32	2.12	40	2.55	48
High: $110	2.20	42	2.75	52	3.30	62

The sensitivity study shows that the volumes of economic oil production and CO_2 demand (and storage) from "Next Generation" CO_2-EOR are highly sensitive to oil and CO_2 market prices, as shown on Tables II-3 and II-4 below:

Table II-3. Sensitivity Analysis of Oil Recovery (Billion Barrels): National Totals*

Oil Price	CO_2 Market Price (% oil price, $/Mcf)		
($/B)	Low: 2%	Base: 2.5%	High: 3%
Low: $60	60.4	59.1	56.6
Base: $85	69.1	67.2	65.8
High: $110	73.5	72.1	70.7

*Includes 2.6 billion barrels of oil already produced or placed in reserves with miscible CO_2-EOR.

Table II-4. Sensitivity Analysis of CO_2 Demand (Billion Metric Tons): National Totals*

Oil Price	CO_2 Market Price (% oil price, $/Mcf)		
($/B)	Low: 2%	Base: 2.5%	High: 3%
Low: $60	17.7	17.1	16.0
Base: $85	20.7	19.9	19.3
High: $110	22.3	21.7	21.0

*Includes 2,300 million metric tons of CO_2 from natural sources and natural gas processing plants.

- The high oil price ($110/B) and low CO_2 market price (2%) case adds about 6.3 billion barrels of oil recovery and 2.4 billion metric tons of CO_2 demand (and storage) compared to the Base Case (national totals).

	High Oil/Low CO_2	Base Case
Oil Recovery (B bbls)	73.5	67.2
CO_2 Demand/Storage (B mt)*	22.3	19.9

*Includes 2,300 million metric tons of CO_2 from natural sources and natural gas processing plants and 2.6 billion barrels of oil already produced or being developed with miscible CO_2-EOR.

- At a low oil price ($60/B) and high a CO_2 market price (3%), the "Next Generation" CO_2–EOR oil recovery is 10.5 billion barrels less and the CO_2 storage potential is 3.9 billion metric tons lower compared to the Base Case (national totals):

	Low Oil/High CO_2	Base Case
Oil Recovery (B bbls)	56.6	67.2
CO_2 Demand/Storage (B mt)*	16.0	19.9

*Includes 2,300 million metric tons of CO_2 from natural sources and natural gas processing plants and 2.6 billion barrels of oil already produced or being developed with miscible CO_2-EOR.

III. THE PERMIAN BASIN CO_2-EOR CASE STUDY

The purpose of the Permian Basin CO_2-EOR Case Study is to provide the reader basic information, historical context and benchmarks by which to independently assess the realism of the projections for current "State of Art" and tomorrow's "Next Generation" CO_2 enhanced oil recovery as set forth in this study and report. As such, this Chapter addresses the following three questions:

1. *What is the outlook for CO_2-EOR in the Permian Basin?*
2. *What does a successful CO_2-EOR project look like?*
3. *How closely do the results of this "Next Generation" CO_2-EOR study, match the key industry-used "benchmarks" for CO_2-EOR performance of: (a) oil recovery efficiency; (b) the net CO_2/oil ratio; and (c) costs and economic viability?*

A. Outlook for CO_2 Enhanced Oil Recovery in the Permian Basin

CO_2 enhanced oil recovery is underway in 56 Permian Basin oil fields, ranging from the field-wide CO_2 flood in the giant Wasson (San Andres) oil field to the small, 160 acre pilot CO_2 flood at Dollarhide (Clearfork). These 56 EOR projects produced about 200,000 barrels per day of incremental oil production during 2010, with five large CO_2-EOR projects accounting for the bulk of this production (Table III-1):

Table III-1. Oil Production from Major Permian Basin Fields Under CO_2-EOR (2010)

	Primary Operator	Total Field Production (B/D)	Incremental CO_2-EOR Production ** (B/D)
Wasson*	Occidental	51,100	44,600
Kelly Snider	KinderMorgan	29,600	26,500
Seminole	Hess	16,500	16,500
Slaughter**	Occidental	18,800	11,200
Means	ExxonMobil	10,000	8,700
Total		**126,000**	**107,500**

Source: Oil and Gas Journal, April 2010. JAF2011_030.XLS
*Combined production from six Wasson units.
**Combined production from nine Slaughter units.

It is notable that for these five giant oil fields, CO_2-EOR accounts for 85% of the total oil currently produced from the portions of the field under a CO_2-EOR flood. For example, without CO_2-EOR, the giant Wasson oil field, currently providing 51,100 barrels of oil per day, would only produce 6,500 barrels of oil per day.

Permian Basin oil production from CO_2-EOR has grown steadily for the past ten years. Recently, the rate of growth has been constrained by lack of CO_2 supplies. However, steps are underway that could, at least in part, help overcome the CO_2 supply constraint. For example:

- Kinder Morgan has recently expanded the CO_2 transportation capacity of its Cortez pipeline by 200 MMcfd and increased the production capacity of its SW Colorado natural CO_2 fields (Doe Canyon and McElmo Dome) by 300 MMcfd. It has plans to further increase its CO_2 production and Cortez pipeline capacity by an additional 200 MMcfd in 2011.
- OxyPermian is investing $850 million in the Century natural gas/CO_2 processing plant and associated pipeline facilities. Train I, with CO_2 capacity of 260 MMcfd, is due on line at the end of 2010. Train II, with CO_2 capacity of 180 MMcfd, is come on line in early 2012. The CO_2 will be used by Oxy to accelerate and enhance the development of its Permian Basin CO_2-EOR projects. This investment will capture 3.5 Tcf (180 million metric tons) of CO_2 for EOR and will enable Oxy to expand its Permian oil production by at least 50,000 barrels per day by 2015[9].
- Numerous planned advanced coal-based power plants equipped with CO_2 capture, such as Summit's Texas Clean Energy IGCC Project, are being located in West Texas, looking to sell their captured CO_2 to the CO2-EOR industry.

While still constrained by lack of sufficient volumes of CO_2, a number of new CO_2-EOR projects are being started or expanded:

- Kinder Morgan is planning a CO_2-EOR flood for the Katz (Strawn) oil field, looking to recover 24 million incremental barrels from the 150 million barrels of OOIP in-place in this field. By extending their SACROC CO_2 pipeline, Kinder Morgan is expecting to access an additional 100 million barrels of oil recovery from initiating CO_2 floods in the numerous other oil fields along the pipeline route to the Katz field area.
- OxyPermian has announced plans to initiate new CO_2-EOR floods at North Dollarhide (Clearfork) and SW Levelland Unit (San Andres) in 2010 and 2011.
- The most exciting news in the Permian Basin is the steady expansion of CO_2 floods in the residual oil zone (ROZ) below and beyond existing oil fields. Of particular interest are the commercial-scale (2,380 acre, 29 pattern Stage 1) ROZ flood underway by Hess at Seminole and the joint DOE/NETL and Legado ROZ field research pilot at Goldsmith.

[9] Investor presentation, October, 2010

B. A Successful CO_2-EOR Project in the Permian Basin

CO_2 injection into the Denver Unit of the giant Wasson (San Andres) oil field began in 1985, helping arrest the steep drop in oil production. Before the start of CO_2-EOR, oil production had declined from about 90,000 B/D to 40,000 B/D in 10 years. After the initiation of the CO_2 flood, oil production increased to about 50,000 B/D. Today, twenty four years after the start of the flood, the Denver Unit still produces at 30,000 B/D (Figure III-1).

At the completion of the CO_2 flood, Oxy expects the Denver Unit to recover nearly 67% of the approximately 2 billion barrels of original oil in-place, with CO_2-EOR providing 19.4% on top of an already high 47.3% recovery efficiency achieved in the Denver Unit from primary recovery and the waterflood (Table III-2).

To a significant degree, it appears that OxyPermian has been applying many of the initial features of "Next Generation" CO_2-EOR technology at the Denver Unit, including increasing the volumes of CO_2 injected, working to improve reservoir sweep efficiency, and conducting rigorous reservoir surveillance.

Figure III-1. CO_2-EOR Results at the Denver Unit of the Wasson Oil Field

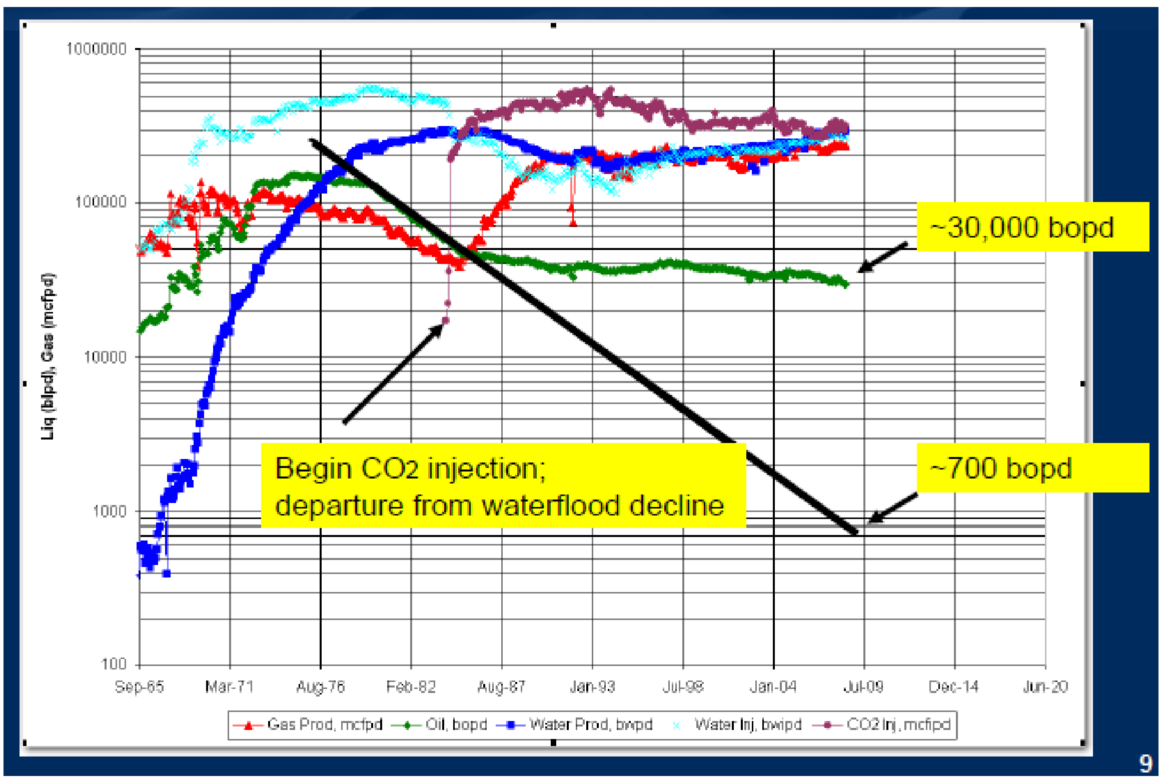
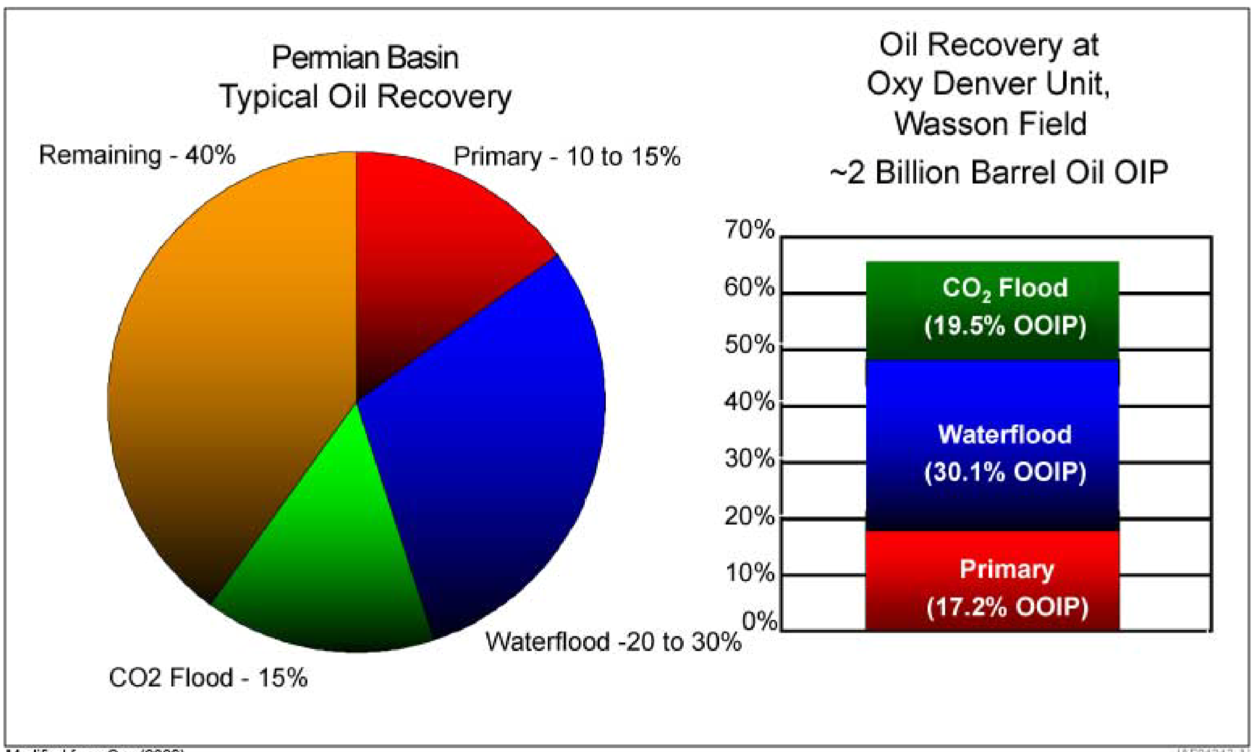


Table III-2. Oil Recovery Efficiency at the Denver Unit of the Wasson Oil Field

Recovery Method	Oil Recovery Efficiency (%OOIP)
• Primary	17.2%
• Waterflood	30.1%
• CO2 Flood	19.5%
Total Oil Recovery	66.8%

Figure III-2 compares the oil recovery performance of typical Permian San Andres Formation CO_2 floods with the CO_2 flood performance at the Denver Unit of the Wasson oil field, based on information from OxyPermian. As shown in Figure IV-2, the Wasson Denver Unit CO_2 flood has an expected oil recovery efficiency of 19.5% from the CO_2 flood, compared to an expected 15% recovery efficiency from a typical Permian Basin CO_2 flood. The extra 4.5% of recovery efficiency at the Wasson Denver Unit is equal to 90 million barrels of oil and an additional $7.6 billion dollars of revenue (at an oil price of $85 per barrel), demonstrating the value of pursuing advances in CO_2-EOR technology.

Figure III-2. Oil Recovery Performance From Permian Basin San Andres Formation



Modified from Oxy (2009)

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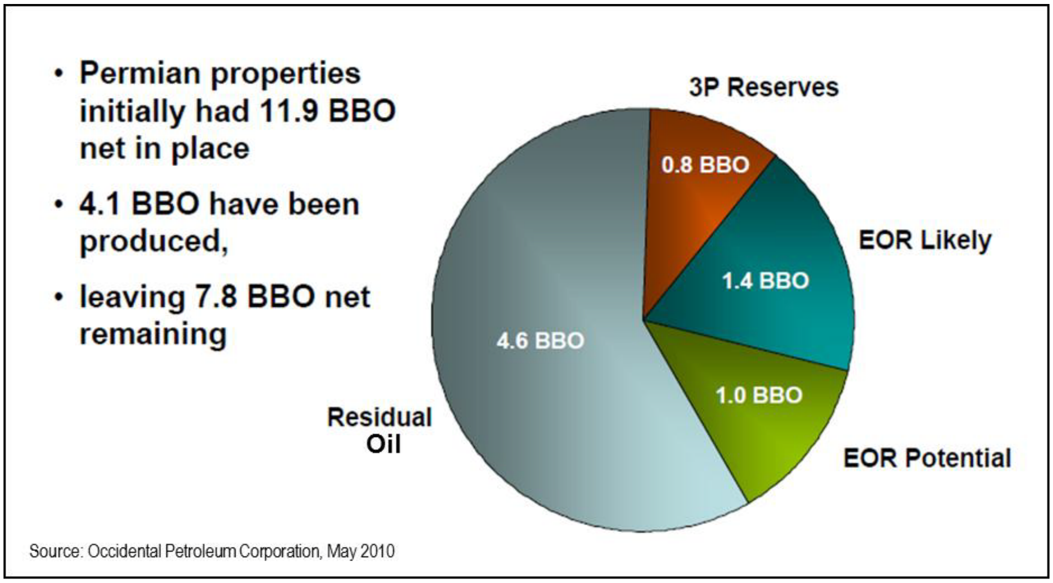
C. Applying Industry Benchmarks

1. OxyPermian's Expectations for Oil Recovery Efficiency

A most useful outlook on expected CO_2-EOR recovery efficiency is provided in the recent analyst presentations by Occidental Petroleum for its Permian Basin EOR opportunities.[10] For perspective, Occidental is the largest onshore/Lower 48 oil producer and also the largest operator of CO_2-EOR projects in the Permian Basin.

- Oxy's Permian oil properties have 11.9 billion barrels (net) of original oil in-place. Of this, 4.1 billion barrels (net) have been produced, with an estimated 0.6 billion barrels of this from past application of CO_2-EOR at Oxy's large oil fields such as Wasson (Denver Unit) (Figure III-3).

Figure III-3. Occidental Petroleum's Permian Basin EOR Opportunities



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- Of the 7.8 billion barrels (net) remaining, Oxy expects to recover 2.4 billion barrels from applying CO_2 enhanced oil recovery, with 1.4 billion barrels as likely and 1.0 billion barrels as potential (Figure III-3).

- Overall, Oxy has expectations for recovering 3 billion of the 11.9 billion barrels of original oil in-place (net) from applying CO_2-EOR in the Permian Basin. This is equal to an ultimate recovery efficiency for CO_2-EOR of over 25% of OOIP. Oxy's expectations for CO_2-EOR performance in the Permian Basin are consistent with the oil recovery efficiencies from "Next Generation" CO_2-EOR technology determined by this study.

[10] Investor presentation, October, 2010.

2. CO_2 "Slug Size" and the Net CO_2/Oil Ratio

In the past, operators used small-volume injections of CO_2 (0.4 to 0.5 hydrocarbon pore volume (HCPV)) to maximize profitability. With higher oil prices, CO_2-EOR economics favor using considerably higher volumes of CO_2. The evolution toward using higher volumes of CO_2 is illustrated by Oxy's experience at the Eastern Denver Unit of the Wasson oil field (Figure III-4).

Figure III-4. Evolution of "Industry Standard" for Volume of CO_2 Injection ("Slug Size")

Eastern Denver Unit (Wasson Oil Field) CO_2-EOR Project	Started
Start of CO_2 injection in EDU with 40% HCPV CO_2 slug size	1984
EDU WAG & start off CO_2 injection in WAC, FIA, B8 FIA	1989
Non performing FIA patterns stopped (~20% HCPV CO_2 slug size)	1992
EDU 40% to 60% HCPV CO_2 slug size increase approved	1994
EDU 60% to 80% HCPV CO_2 slug size increase approved	1996
EDU 80% to 100% HCPV CO_2 slug size increase approved	2001

Source: OXY Permian 2006

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These increased CO_2 volumes need to be managed and controlled to assure that the injected CO_2 contacts additional residual oil rather than merely re-circulates through already contacted portions of the reservoir. One of the purposes of "Next Generation" reservoir feedback, diagnostics and control ("surveillance") is to better manage the productive use of injected CO_2.

Based on using larger volumes of CO_2 injection and reservoir surveillance, OxyPermian anticipates a net CO_2 requirement of 5 Tcf for producing its next billion barrels of oil with CO_2-EOR from the Permian Basin (Table III-3).

Table III-3. Permian Reserves and CO_2 Requirements – "The Next Billion Barrels"

	Net 3P Reserves (MMBOE)	Net CO_2 Required (Tcf)
• Developed	570	2.8
• Undeveloped	430	2.2
Total	1,000	5.0

Source: OxyPermian

OxyPermian's expectations of a net 5 Mcf/BO as their future CO_2/oil ratio for their Permian Basin oil properties is consistent with our projected CO_2/oil ratio performance for "Next Generation" CO_2-EOR in the Permian Basin.

Of additional interest is a supporting set of analyses on the relationship of volumes of CO_2 injection and enhanced oil recovery as provided by Marchant (2010) in the SPE paper "Life Beyond 80 – A Look at Conventional WAG Recovery Beyond 80% HCPV Injection in CO_2 Tertiary Floods."[11] His statement -- "Tertiary oil recovery under CO_2 injection is a function of the total amount of CO_2 injected" -- is supported by the following analysis in his paper, summarized on Table III-4.

Table III-4. Relationship of Oil Recovery to CO_2 Injection Volumes

Size of CO_2 Slug	Oil Recovery from CO_2-EOR
(HCPV)	(% OOIP)
50%	15%
100%	21%
190%	26%

3. Costs and Economic Viability

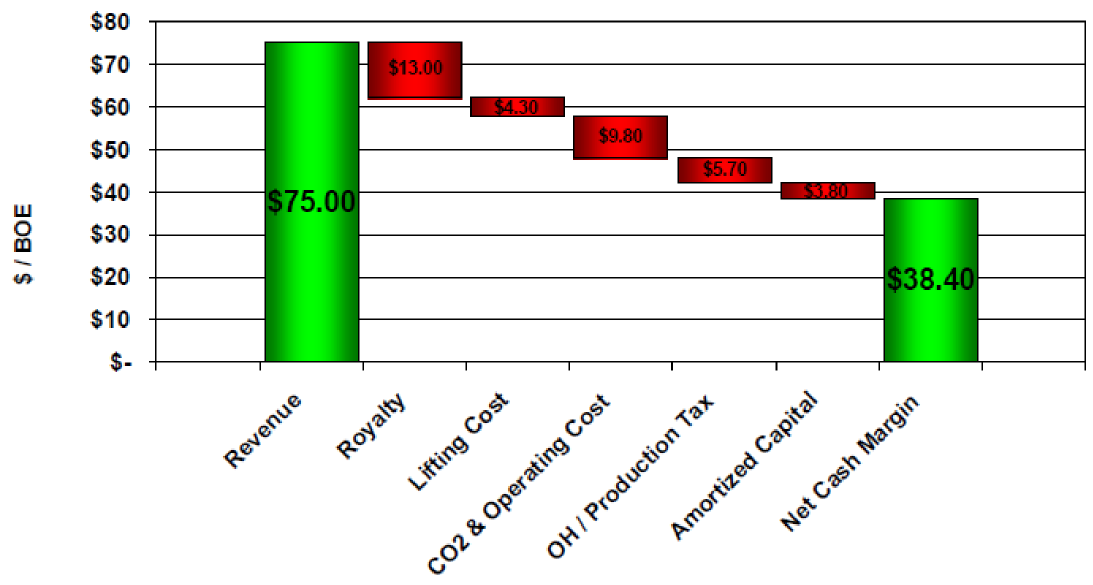
With recent higher oil prices, currently ranging from \$75 to over \$100 per barrel, and the rigorous pursuit of cost-efficiencies, the economics of CO_2-EOR have improved markedly.

Based on publicly presented information and using an oil price of \$75 per barrel, Occidental Petroleum expects its Permian Basin CO_2-EOR projects to provide a net cash margin of over \$38 per barrel, after subtraction of royalties, operating costs, CO_2 purchase and amortized capital (Figure III-5). At \$100 per barrel and including more current information on costs, Occidental Petroleum expects a net cash margin of about \$56 per barrel (Figure III-6).

Even with the costs of conducting pilot floods and the delay between investment of capital and the production of oil typical of a CO_2-EOR project, this cost analysis indicates that the CO_2-EOR projects in the Permian Basin can provide very favorable economics.

[11] Merchant, D.H., "Life Beyond 80 – A Look at Conventional WAG Recovery Beyond 80% HCPV Injection in CO_2 Tertiary Floods", SPE 139516, for presentation at the SPE International Conference on CO_2 Capture, Storage and Utilization, New Orleans, LA, 10-12 November 2010.

Figure III-5. Typical Permian Basin CO_2-EOR Project Cost Structure (Occidental Petroleum)



*$75/Bbl Marker Price
Source: Occidental Petroleum Corporation, May 2010

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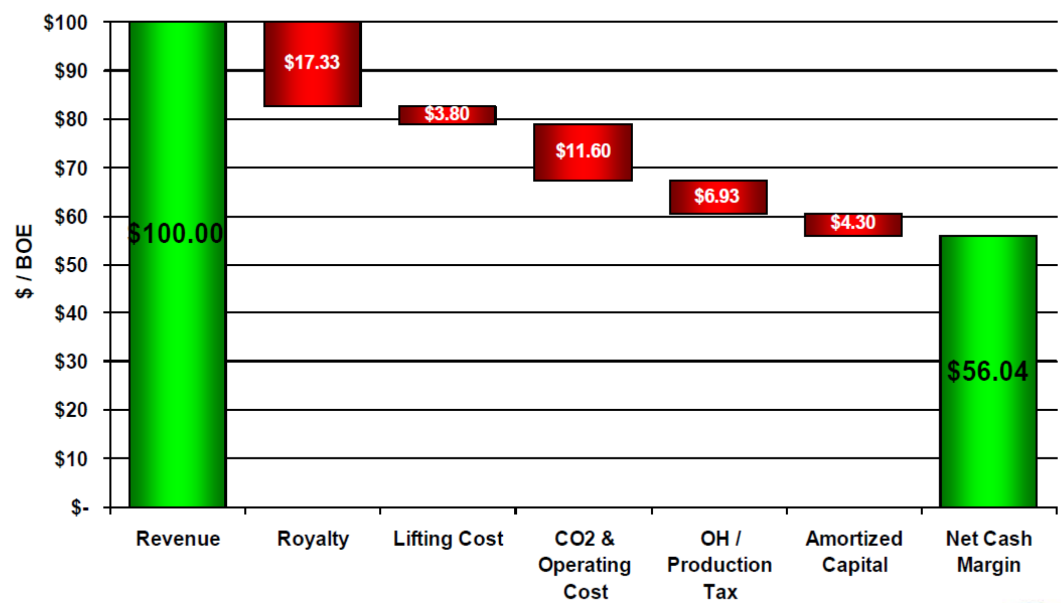
Figure III-6. Updated Typical Permian Basin CO_2-EOR Project Cost Structure (Occidental Petroleum)



*$100/Bbl Marker Price
Source: Occidental Petroleum Corporation, May 2011

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IV. "NEXT GENERATION" CO_2-EOR TECHNOLOGIES

As set forth in the Executive Summary, "Next Generation" CO_2-EOR consists of four realistically achievable advanced technologies:

1. Improvements in currently practiced CO_2-EOR technology,
2. Advanced near miscible CO_2-EOR technology,
3. Application of CO_2-EOR to residual oil zones (ROZs), and
4. Deployment of CO_2-EOR in offshore oil fields.

Each of these "Next Generation" CO_2-EOR technologies is further discussed in the sections below.

A. Improvements in Currently Practiced CO_2-EOR Technology.

The improved version of CO_2-EOR technology envisioned under "Next Generation" would address five of the opportunities for improving the performance of currently practiced State of Art (SOA) CO_2-EOR technology, namely:

- Increasing the volume of CO_2 injected,
- Capturing more of the remaining mobile and immobile oil,
- Improving sweep efficiency and mobility control (reservoir conformance),
- Improving the technology of reservoir surveillance, and
- Lowering the threshold minimum miscibility pressure (MMP).

To examine the impact on oil recovery and CO_2 storage of these improvements to currently practiced CO_2-EOR technology, we selected an "example" San Andres oil reservoir in the Permian Basin, with reservoir properties and past oil recovery performance shown in Table IV-1.

Table IV-1. Example Permian Basin San Andres Formation Oil Reservoir

Reservoir Properties	
Depth	4,200 ft
Net Pay	220 ft
Porosity	9.40%
Initial Oil Saturation	0.77
Initial FVF	1.17
Initial Pressure	1,800 psi
Temperature	99° F
Oil Gravity	35° API
Oil Viscosity	3.5 cp

Oil Resource and Recovery Data	
Original Oil In-Place	930 MMBbls
Ultimate P/S Rec.	325 MMBls
Recovery Efficiency	35%
Swept Zone Sor	0.32
Current FVF	1.07
P/S Sweep Efficiency	64%
"Unswept" Zone Sor	0.59
Min. Miscibility Pressure	1,300 psi
Dykstra-Parsons	0.78

The "example" oil reservoir is large, with 930 million barrels of original oil in-place (OOIP). The reservoir is near-depleted, with over 90% of its 325 million barrels of ultimate primary/secondary recovery already produced. The oil recovery efficiency for this "example" San Andres Formation light oil (35^o API) reservoir is 35% of OOIP. However, this still leaves a most attractive "stranded" oil target of over 600 million barrels still in-place.

Even with an oil viscosity of 3.5 cp and a Dykstra-Parsons heterogeneity co-efficient of 0.78, the waterflood sweep efficiency of this "example" oil reservoir is good at 64%. While the oil saturation in the swept zone of the reservoir has been reduced to 32%, additional mobile oil remains in its poorly swept zones.

With significant "stranded" (residual) oil and a minimum miscibility pressure of 1,300 psi, compared to an initial reservoir pressure of 1,800 psi, this "example" San Andres oil reservoir is an attractive candidate for miscible CO_2 enhanced oil recovery.

1. Applying State of Art (SOA) CO_2-EOR

As the starting point for the analysis, we modeled the "example" San Andres oil reservoir using *PROPHET2* under "State of Art" (SOA) CO_2-EOR technology.

In the "State of Art" case, using 1 HCPV of CO_2 injection and a tapered WAG, the anticipated technical oil recovery for this "example" oil reservoir is 148 million barrels, produced from 174, forty acre inverted 5-spot patterns.

- Overall technical oil recovery efficiency in the SOA case is 15.9% of OOIP, representative of a geologically favorable San Andres oil reservoir developed with current CO_2-EOR practices.

- The net (purchased) CO_2 to oil ratio is 7.6 Mcf of CO_2 per barrel of technically recovered oil (Mcf/BO), with a gross CO_2 to oil ratio of 15.7 Mcf/BO. This is reasonably representative of a somewhat higher viscosity (3.5 cp) and moderately heterogeneous (DP = 0.78) San Andres oil reservoir under a CO_2 flood.

- It is useful to note that in the SOA case, this "example" San Andres oil reservoir just barely achieves its minimum rate of return (ROR) hurdle rate of 20%, before tax, at an oil price of $85 per barrel and a CO_2 market price of $40 per metric ton ($2.11 per Mcf of CO_2). The reason is that the investment payback period is long, at 7 years.

- In addition, because ARI's economic model features an economic truncation feature that stops a project once annual costs exceed annual revenues, approximately 6 million barrels of the technically recoverable oil remains unproduced. This economic truncation reduces economic (actual) oil recovery efficiency to 15.3% and increasing the net CO_2/oil ratio to 7.9 Mcf/BO.

In the sections below, we will examine the impact on technical and economic oil recovery and CO_2 demand (storage) of applying the various "Next Generation" CO_2-EOR technologies, to this "example" oil reservoir first individually and then in combination.

2. Assessing Impacts of "Next Generation" CO_2-EOR Technology

Each of the "Next Generation" technologies has been formulated to address one or more of the major problems impeding the more efficient performance of today's "State of Art" (SOA) CO_2-EOR technology.

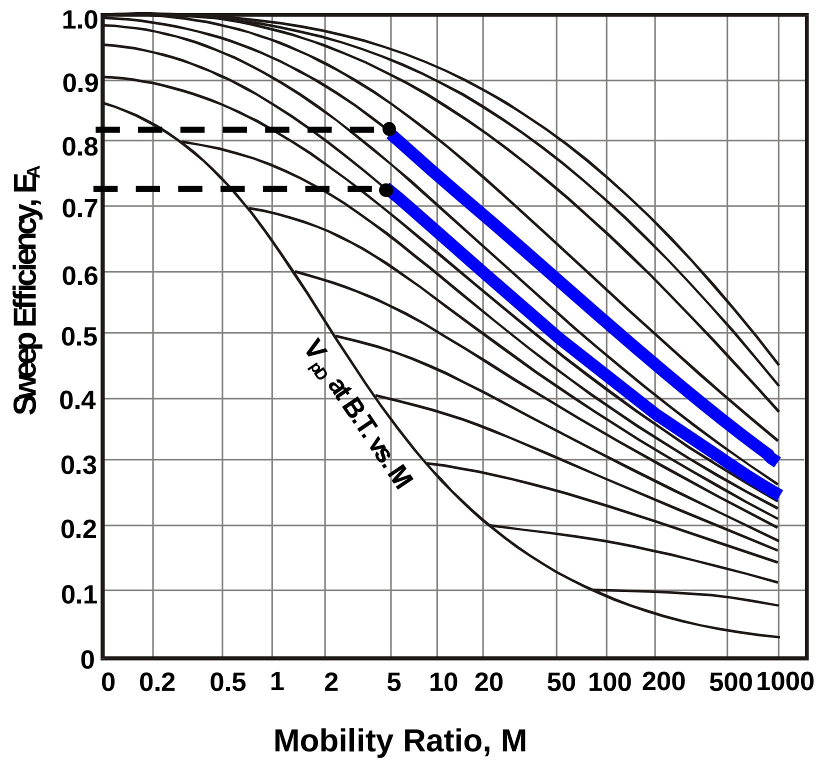
- The first problem is less than optimum reservoir contact by CO_2 due to inadequate volumes of injected CO_2. "Next Generation" technology involves injecting greater quantities of CO_2, up to 1.5 HCPV.
- The second problem is poor reservoir sweep efficiency due to a high fluid mobility ratio, particularly in cases when the viscosity of the CO_2 and water is considerably less than the viscosity of the reservoir oil. "Next Generation" technology involves improving the mobility ratio by increasing the viscosity of the displacing water in the WAG process to 2 cp.
- The third problem is inefficient reservoir contact and low sweep efficiency (poor reservoir conformance) due to high geologic complexity and reservoir heterogeneity. "Next Generation" technology involves improving reservoir contact by drilling an additional CO_2 injection well to target the mobile oil "stranded" in the reservoir.

Supporting the application of each of the three specific "Next Generation" technologies is the use of rigorous reservoir surveillance (reservoir feedback, diagnostics and control). Without rigorous reservoir surveillance, the benefits of applying these three "Next Generation" CO_2-EOR technologies would be much less.

(a). Increasing the Volume of CO_2 Injected. The first "Next Generation" technology option involves the increasing CO_2 injection volumes to 1.5 HCPV. Higher HCPVs of injected CO_2 enable more of the reservoir's residual oil to be contacted by the injected CO_2. However, higher volumes of CO_2 injection can also lead to longer overall project length and higher gross CO_2 to oil ratios. Because oil reservoirs with already high sweep efficiency may not gain sufficient benefits in relation to costs, the economic truncation algorithm within ARI's CO_2-EOR economic model limits the volume of CO_2 that is injected. This truncation algorithm works as a function of oil price and CO_2 costs.

Reservoir engineering theory and analyses argue that increasing the volume of CO_2 injected (V_{pD}), from 1.0 HCPV to 1.5 HCPV, should improve the areal sweep efficiency (E_A) from about 73% to about 82% for a 4.4 mobility ratio (M) situation, as shown by the type curves prepared by Claridge (1972) (Figure IV-1). This is equal to an increase in areal sweep efficiency of about 12%.

Figure IV-1. Areal Sweep Efficiency in Miscible CO_2 Flooding as a Function of HCPV CO_2



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

Source: Claridge, E.L., "Prediction of Recovery in Unstable Miscible Displacement", (J)SPE 12(2) 143-155 (April 1972).

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By increasing the volume of CO_2 injected from 1.0 HCPV to 1.5 HCPV, the *PROPHET2* model shows an increase in oil recovery efficiency of 20 million barrels for the "example" oil reservoir. This provides an increase of about 14% (168 MMB/148 MMB) in oil recovery over the SOA (1.0 HCPV) case. Technical oil recovery efficiency increases from 15.9% of OOIP with 1 HCPV of CO_2 injection to 18.1% of OOIP with 1.5 HCPV of CO_2 injection, Table IV-2. Advanced reservoir surveillance is essential to ensure that the increased volumes of injected CO_2 contact more of the reservoir and does not merely circulate through already swept reservoir intervals.

Interestingly, the economic benefits of injecting a higher HCPV of CO_2 are realized only with an ability to increase the CO_2 injection rate, enabling the 1.5 HCPV of CO_2 injection to be performed over the same time period as injecting the 1.0 HCPV of CO_2. With 1.5 HCPV of CO_2 and a 50% higher CO_2 injection rate, the project achieves a 29.2% ROR compared to 21.5% ROR in the SOA (1.0 HCPV, regular rate) case.

Table IV-2. Oil Recovery and Economic Impact of Increasing the Volume of CO_2 Injected

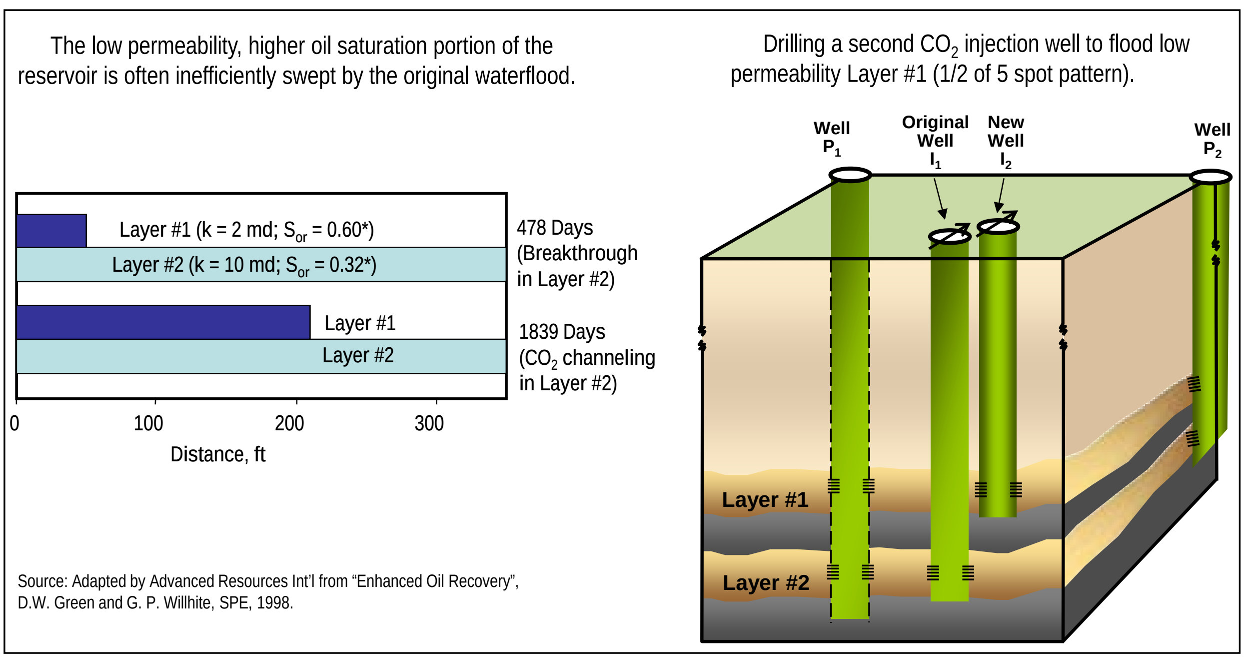
CO_2 Injection Volumes	Technical Oil Recovery		Project ROR
(HCPV/Injection Rate)	(MMBbls)	(% OOIP)	(Before Tax)
1.00/Regular Rate	148	15.9	21.5%
1.5/Regular Rate	168	18.1	20.6%
1.5/Higher Rate	168	18.1	29.2%

(b). Capturing More of the Remaining Mobile and Immobile Oil. It may be possible with optimized well design and placement to contact more of the remaining mobile oil (as well as more efficiently contact the swept zone residual oil) in a reservoir than continuing to use the existing waterflood pattern and well placement design.

The options for installing a modified CO_2 flood and well placement design include: (1) isolating the previously poorly-swept reservoir intervals (with higher residual oil) for targeted CO_2 injection; (2) drilling horizontal injection wells to target lower permeability reservoir intervals; (3) modifying the well pattern alignment; (4) using physical (or chemical) means for diverting CO_2 into previously poorly-contacted portions of the reservoir; and (5) drilling the reservoir at closer well spacing.

For the "example" oil reservoir in the "Next Generation" case, we added one new vertical CO_2 injection well to each pattern to target the previously poorly contacted portions of the reservoir, as shown in Figure IV-2.

Figure IV-2. Using Modified Pattern and Well Placement Design to Capture Mobil Oil



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To properly model the addition of a second injection well in each pattern, the reservoir is split into "fully swept" and "partially swept" zones. Adding a CO_2 injection well and modifying the flow pattern of the reservoir to contact the mobile oil left after the waterflood improves oil recovery by 5.1 % for the "example" oil reservoir. This improves technical oil recovery efficiency to 21% in the "modified pattern and well placement" case versus 15.9% in the SOA case. Adding a second CO_2 injection well also enables the project to increase CO_2 injectivity in a pattern area by 50%. Advanced reservoir surveillance is a key enabling technology for implementing changes in patterns and well placement designs for targeting left behind mobile oil.

While the drilling of the new CO_2 injection well adds $1.2 million of CAPEX per pattern for the "example" oil reservoir and increase O&M costs, the overall economics are significantly improved. The recovery of the additional 47 million barrels of oil and its earlier production (in the "modified pattern and well placement" case), increases the ROR to 77%, Table IV-3.

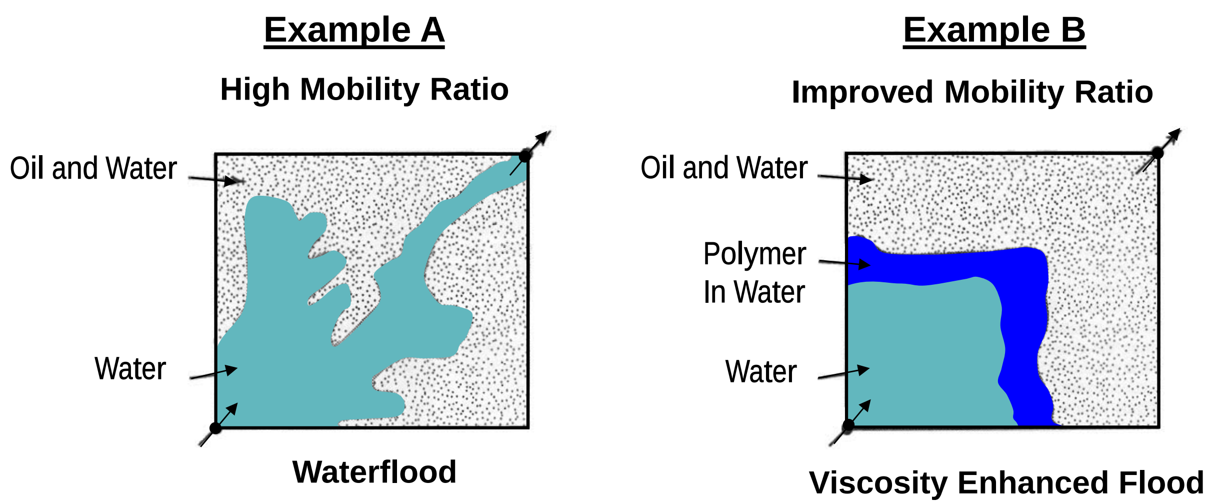
Table IV-3. Oil Recovery and Economic Impact of Modified Pattern and Well Placement

Pattern/Well Design	Technical Oil Recovery		Project ROR
	(MMBbls)	(% OOIP)	(Before Tax)
Existing Design (SOA)	148	15.9	21.5%
Modified Design ("Next Generation")	195	21.0	77.2%

(c). Improving Sweep Efficiency and Mobility Control (Reservoir Conformance). Often the viscosities of the injected fluids (CO_2 and water) are considerably lower than the viscosity of the reservoir oil, leading to viscous fingering of the CO_2 through the reservoir's oil and thus inefficient macroscopic displacement (sweep efficiency) in the reservoir, Figure IV-3. The extent of viscous fingering (and sweep efficiency) is governed by the mobility ratio -- the viscosity of the reservoir oil divided by the viscosity of the displacing fluids.

The "example" oil reservoir has a mobility ratio of 4.4, based on an oil viscosity of 3.5 cp and a water viscosity (in the reservoir) of 0.8 cp. (The mobility ratio between the reservoir's oil and the injected CO_2 is considerably higher.) Reservoir engineering theory and analysis argue that improving the oil/water mobility ratio from 4.4 to 1.7 (by increasing the viscosity of the water to 2 cp) should improve the areal sweep efficiency (E_A) from about 73% to about 81%, as shown by the type curves prepared by Claridge (1972), Figure III-4. This is equal to an increase in the areal sweep efficiency of about 11%.

Figure IV-3. Example of Viscous Fingering of CO_2 Due to Unfavorable Mobility Ratio*



*The mobility ratio is the viscosity of the reservoir oil divided by the viscosity of the displacing fluid.

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

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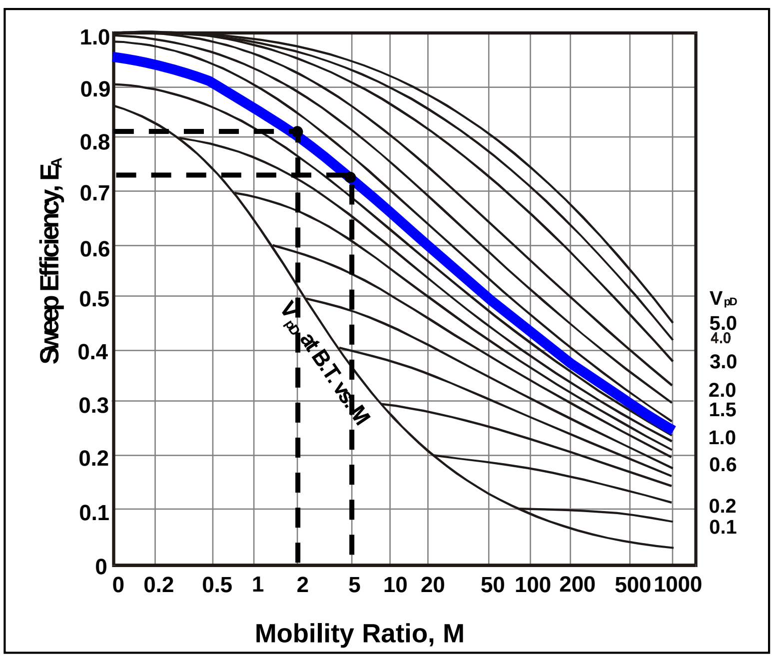
Figure IV-4. Areal Sweep Efficiency in Miscible CO_2 Flooding as a Function of Mobility Ratio

(Five-Spot Well Pattern)



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

Source: Claridge, E.L., "Prediction of Recovery in Unstable Miscible Displacement", (J)SPE 12(2) 143-155 (April 1972).

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After adding a polymer or other viscosity increasing agents to the drive water in the WAG CO_2 flood to change the mobility ratio from 4.4 to 1.7, the *PROPHET2* model shows an increase in the oil recovery of 10 million barrels for the "example" oil reservoir. Technical oil recovery efficiency increases to 17.0% with a 2 cp water WAG compared to 15.9% recovery efficiency with an 0.8 cp water in the WAG, Table IV-4. Again, rigorous reservoir surveillance is important for capturing the full benefits of improving sweep efficiency (reservoir conformance) with improved mobility control.

Table IV-4. Oil Recovery and Economic Impact of Improving the Mobility Ratio

Water Viscosity	Mobility Ratio	Technical Oil Recovery		Project ROR
(cp)	(M)	(MMBbls)	(% OOIP)	(Before Tax)
0.8	4.4	148	15.9	21.5%
2	1.7	158	17.0	27.0%

Importantly, improving the mobility ratio helps improve early time oil production, reducing the investment payback period to 5 years in the "Next Generation" case from 7 years in the SOA case and achieve a higher rate of return. (at a $85 per barrel of oil price and a $40 per metric ton of CO_2 cost), Table IV-4.

(d). Assessing Impact of the Combined Application of "Next Generation" Technologies. Not surprisingly, the integrated application of all three of the "Next Generation" technologies, combined with a rigorous program of reservoir feedback, diagnostics and control ("reservoir surveillance"), provides the largest impact:

- Economically feasible oil recovery increases to 244 million barrels (26.2% of OOIP) in the "Next Generation" case from 142 million barrels (15.3% of OOIP) in the SOA case.
- Even though the volume of purchased CO_2 is 50% larger, the net CO_2/oil ratio (due to higher oil recovery and improved control of the injected CO_2) is lower at 5.7 Mcf per barrel of oil in the "Next Generation" case versus 7.9 Mcf per barrel of oil in the SOA case.
- While overall CAPEX for the "Next Generation" CO_2 flood is higher (due to drilling more wells and increasing the size of the CO_2 recycle equipment) and the overall OPEX is higher (due to the costs of adding polymers to the injected water and conducting reservoir surveillance), the economics are significantly better. As shown in Table IV-5, the "Next Generation" CO_2-EOR project achieves a rate of return (ROR) of nearly 94% compared to 21.5% in the SOA case.

Table IV-5. Impact of Integrated Application of "Next Generation" CO_2-EOR Technology

Technology Case	Economic Oil Recovery		Net CO_2/Oil Ratio	Project ROR
	(MMBBbls)	(% OOIP)	(Mcf/BO)	(Before Tax)
State of Art	142	15.3	7.9	21.5%
"Next Generation"	244	26.2	5.7	93.8%

A particularly important finding emerges from the assessment of individual versus integrated application of "Next Generation" CO_2-EOR technology in the "example" oil reservoir:

- The sum of the individual (technology by technology) applications of "Next Generation" CO_2-EOR technology is 77 million barrels of increased oil recovery.
- The integrated application of the three "Next Generation" CO_2-EOR technologies provide 102 million barrels of increased oil recovery, about a third more than the sum from applying these technologies individually. Integrated application of "Next Generation" CO_2-EOR captures the beneficial synergistic interactions of these three improved technologies and provides a "sum that is greater than the parts."

(e). Lowering the Threshold Minimum Miscibility Pressure (MMP). A significant number of oil reservoirs, particularly in Appalachia, the Mid-Continent and the Illinois Basin, have reservoir pressures somewhat below MMP, relegating these oil reservoirs to use of less efficient near miscible or even immiscible CO_2-EOR technology. "Next Generation" CO_2-EOR technology, through use of miscibility enhancing additives, has a goal of reducing the MMP of oil reservoirs by 250 psi, enabling a larger number of oil reservoirs to be processed with miscible and near miscible CO_2-EOR. (The "example" oil reservoir was already favorable for miscible CO_2-EOR and thus would not benefit from this specific "Next Generation" technology.)

B. Advanced Near Miscible CO_2 Enhanced Oil Recovery Technology

1. Background

As discussed previously, a large number of oil reservoirs, particularly in Appalachia, the Illinois Basin and the Mid-Continent, have depths and oil properties unsuitable for achieving miscible CO_2 and its efficient oil displacement. However, recent laboratory and analytical work indicate that if the achievable reservoir pressure is close to minimum miscibility pressure (MMP), the oil reservoir can achieve reasonable oil recovery using near miscible CO_2-EOR technology.

While the exact parameters of the pressure range for near miscible CO_2-EOR have yet to be defined, we have established for this study a near miscibility reservoir pressure range of 75% to 99% of MMP. Reservoirs with achievable pressures of less than 75% of MMP would be assigned to immiscible CO_2 flooding, the analysis of which is beyond the scope of work of this study.

2. Resource Target

Various investigators have identified attractive targets for applying near miscible CO_2-EOR technologies to domestic oil fields. For example:

- The Illinois Geological Survey identified a large number of oil fields holding 3.8 billion barrels of OOIP in the Illinois Basin that would be attractive for near miscible CO_2-EOR technology. These reservoirs could provide 0.3 billion barrels of oil recovery and about 100 million metric tons of CO_2 storage capacity.[12]

- Work by the Chemical and Petroleum Engineering Department of the University of Kansas identified the Arbuckle Formation in Kansas as a large target for near miscible CO_2-EOR. To date, the Arbuckle Formation in Kansas has produced 2.2 billion barrels from about 8 billion barrels of OOIP. Most of the Arbuckle oil fields are close to abandonment, with 90% of the wells producing less than 5 barrels of oil per day. The Kansas study noted that near miscible CO_2-EOR offered the potential for recovery of up to 1 billion barrels from these Arbuckle Formation reservoirs.[13]

3. Mechanisms of Near Miscible CO_2-EOR

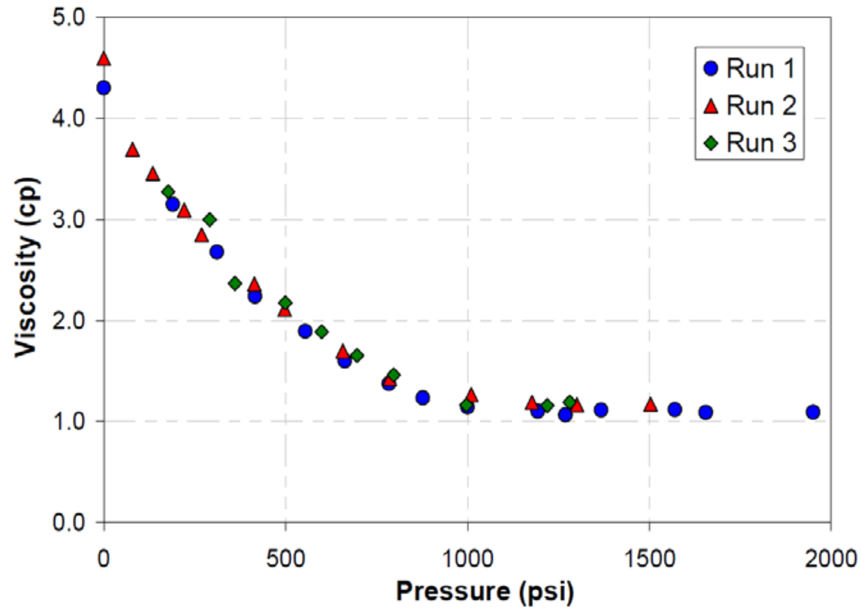
Three oil displacement mechanisms are important for near miscible CO_2-EOR:

- First, the injection of CO_2 and its dissolution into the oil phase, reduces the viscosity of the oil/CO_2 mixture providing a more favorable mobility ratio and thus improved sweep efficiency. Figure IV-5 shows the sharp reduction in oil viscosity, achieved by injecting CO_2 at 1,100 psig, from an initial 4.5 cp to about 1 cp, based on work by Kansas, for a 33^o API oil at 110^oF.

- Second, the dissolution of CO_2 into the oil phase causes the oil to swell, with the volume above residual oil saturation becoming mobile and displaceable with CO_2 and water. Figure IV-6 shows the increase (swelling) of the oil volume by about 30% due to dissolution of 0.7 mole fraction of CO_2 into the oil phase, in the near miscible region of 1,150 psig, as reported by the Kansas study,[13] for a 33^o API oil at 110^oF.

[12] Frailey, S.M., "CO_2 Flood Pilots in the Illinois Basin", PTTC IOR/EOR Illinois Basin Workshop, CO_2 Enhanced Oil Recovery, Illinois Basin Pilot Projects, Midwest Geological Sequestration Consortium, March 2, 2011, Evansville, IN.
[13] Bui, L.H., Tsau, J.S., and G.P. Willhite, "Laboratory Investigations of CO_2 Near-Miscible Application in Arbuckle Reservoir", SPE 129710, paper prepared and presented at the 2010 SPE Improved Oil Recovery Symposium, Tulsa, OK 24-28 April, 2010.

Figure IV-5. Effect of CO_2 Dissolution in Crude Oil on Viscosity.



Source: Bui, L.H., Tsau, J.S., and G.P. Willhite, "Laboratory Investigations of CO2 Near-Miscible Application in Arbuckle Reservoir", SPE 129710, paper prepared and presented at the 2010 SPE Improved Oil Recovery Symposium, Tulsa, OK 24-28 April, 2010.

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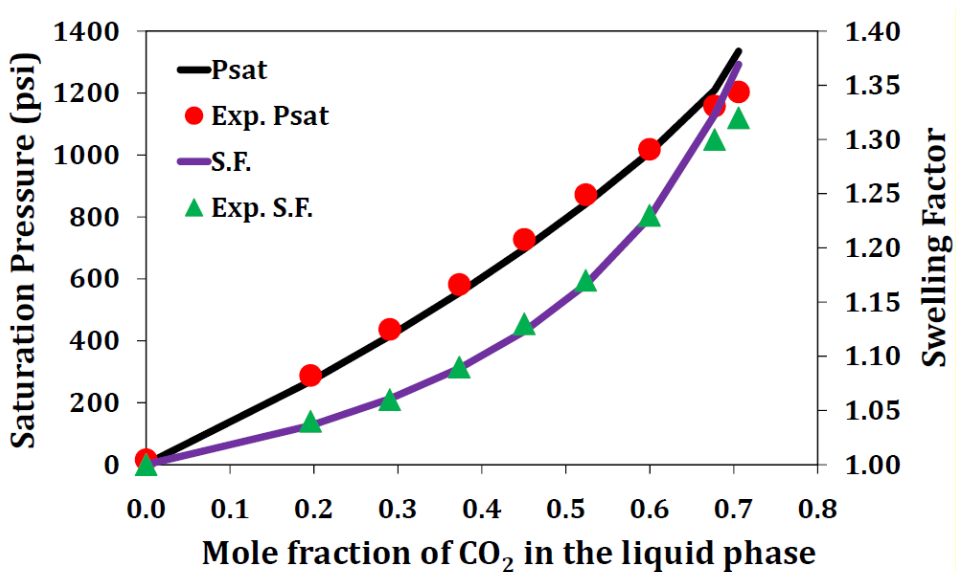
Figure IV-6. Saturation Pressure/Swelling Factor for Near Miscible CO_2-EOR



Source: Bui, L.H., Tsau, J.S., and G.P. Willhite, "Laboratory Investigations of CO2 Near-Miscible Application in Arbuckle Reservoir", SPE 129710, paper prepared and presented at the 2010 SPE Improved Oil Recovery Symposium, Tulsa, OK 24-28 April, 2010.

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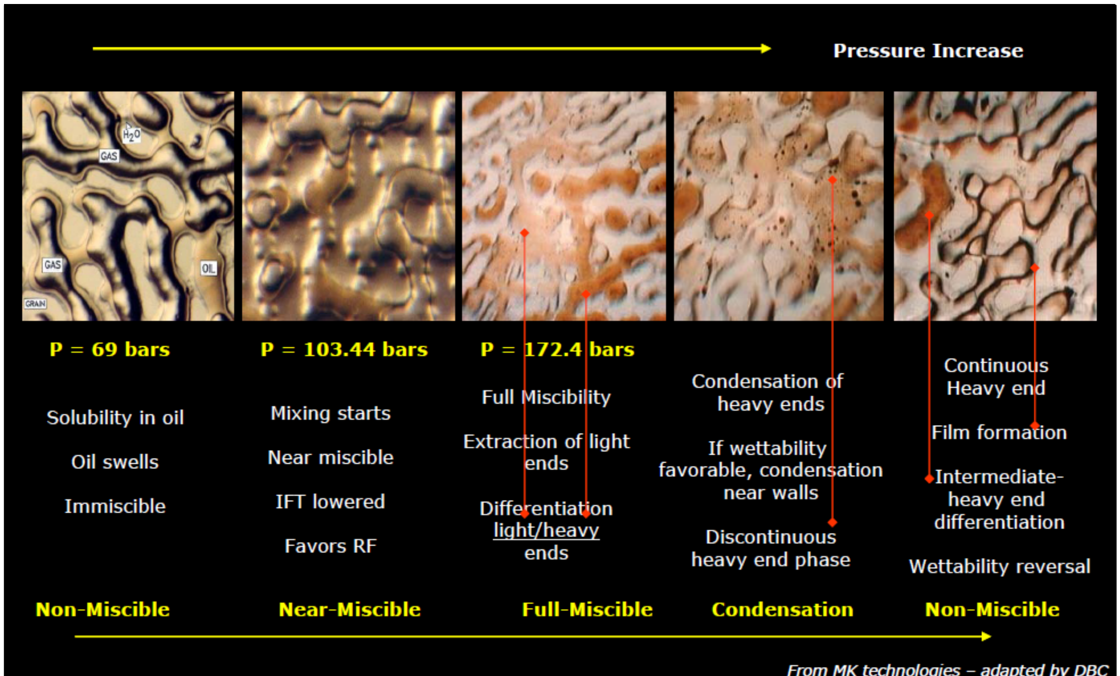
- Third, as reservoir pressure enters the near miscible pressure response range, the extraction and vaporization of light hydrocarbon components from the crude oil into the CO_2 vapor phase begins, the mixing of the CO_2 and oil phases progresses, and the interfacial tension (IFT) of the system is lowered, promoting improved oil recovery. Figure IV-7 shows that the onset of this mixing and lower IFT begins at about 60% of minimum miscibility pressure for the oil composition examined by IFP.[14]

Figure IV-7. Mechanisms of Near Miscible CO_2-EOR



Source: Bossie-Codreanu, IFP – March 2009

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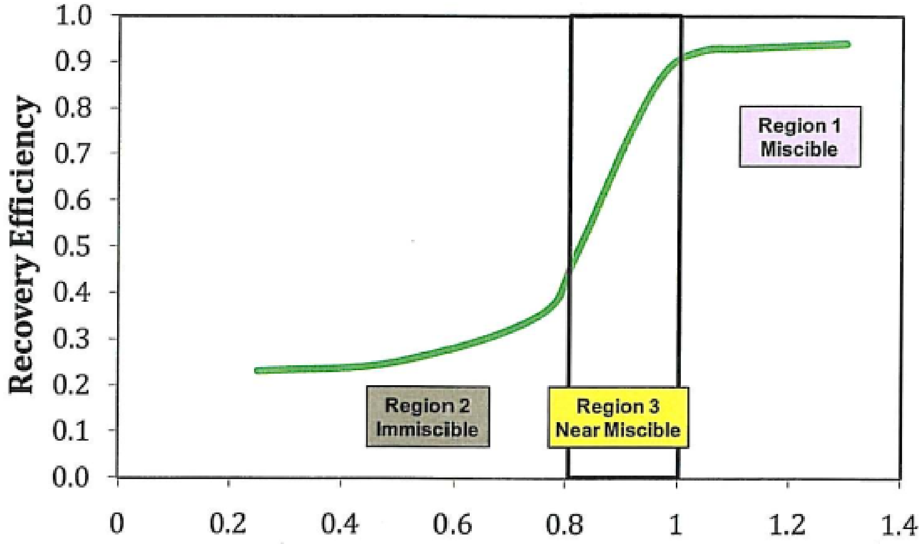
4. Oil Recovery with Near Miscible CO_2-EOR

Figure IV-8 provides the classical oil recovery versus pressure for a slim tube experiment of CO_2 injection. It shows that the efficiency of oil recovery begins to increase sharply in the near miscible pressure region, defined in the figure as 80% of minimum miscibility pressure (MMP).

A somewhat more representative experiment is to conduct a core flow test of oil recovery with pressure in the near miscible region. The Kansas study and laboratory tests determined that oil recovery in the near miscibility pressure region (80% to 99% MMP) recovered 65% to 80% of the water flood residual oil in dolomite cores and 45% to 60% of the water flood residual oil in sandstone cores.[13]

[14] Bossie-Codreanu, IFP – March 2009.

Figure IV-8. Relative Miscible Pressure, Pres/MMP



5. Application of Near Miscible CO_2-EOR Technology by This Study

To capture the performance of near miscible CO_2-EOR, the ARI study identified 67 oil reservoirs holding 12 billion barrels of OOIP that had pressures of 75% to 99% of MMP. It then performed *PROPHET2* streamtube reservoir simulations to calculate oil recovery and CO_2 requirements for each of these oil reservoirs. In general, the results were consistent with the above laboratory findings that the closer the reservoir pressure is to MMP, the higher and more efficient is the oil recovery.

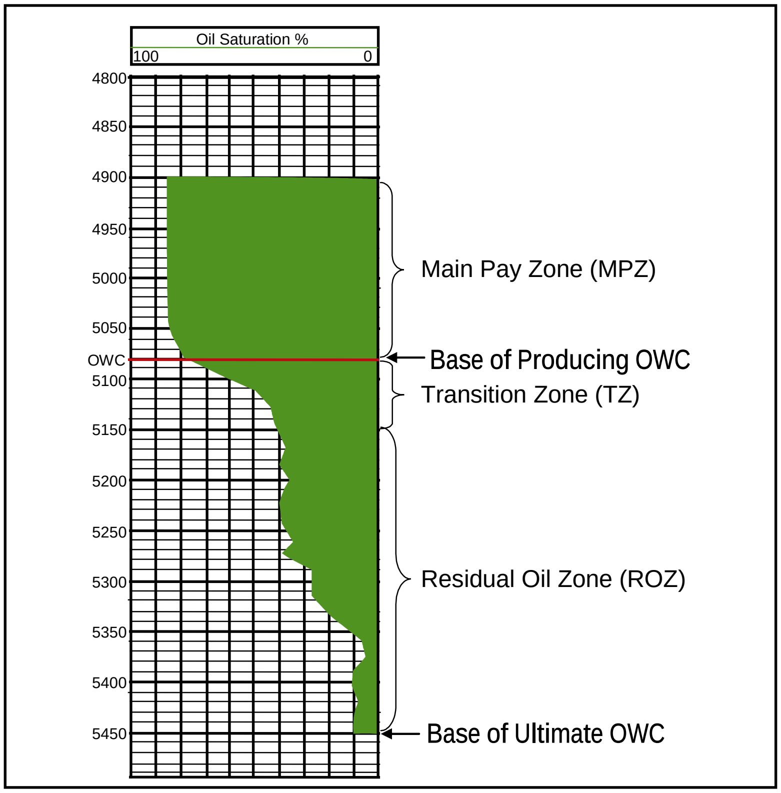
The near miscible reservoirs in the "Next Generation" CO_2-EOR case were flooded with 1 HCPV of CO_2. The residual oil to CO_2 was set at 80% of the residual oil in the reservoir after water flooding to incorporate the extraction/vaporization and lower IFT oil recovery mechanisms inherent within near miscible CO_2-EOR.

C. Application of CO_2-EOR to Residual Oil Zones (ROZs).

The third "Next Generation" CO_2-EOR technology is the application of miscible CO_2-EOR to the oil resource in residual oil zones. Residual oil zones exist below and beyond the main oil reservoir pay zone, below the traditional oil-water contact, Figure IV-9.

Our own detailed log work and extensive work by others, notably, Mr. L. Stephen Melzer of Melzer Consulting and Dr. Robert Trentham of UT Permian Basin, have confirmed that ROZs hold a massive, previously overlooked oil resource in the Permian and numerous other domestic oil basins.

Figure IV-9. Oil Saturation Profile in the TZ/ROZ: Adapted from a Wasson Denver Unit Well.

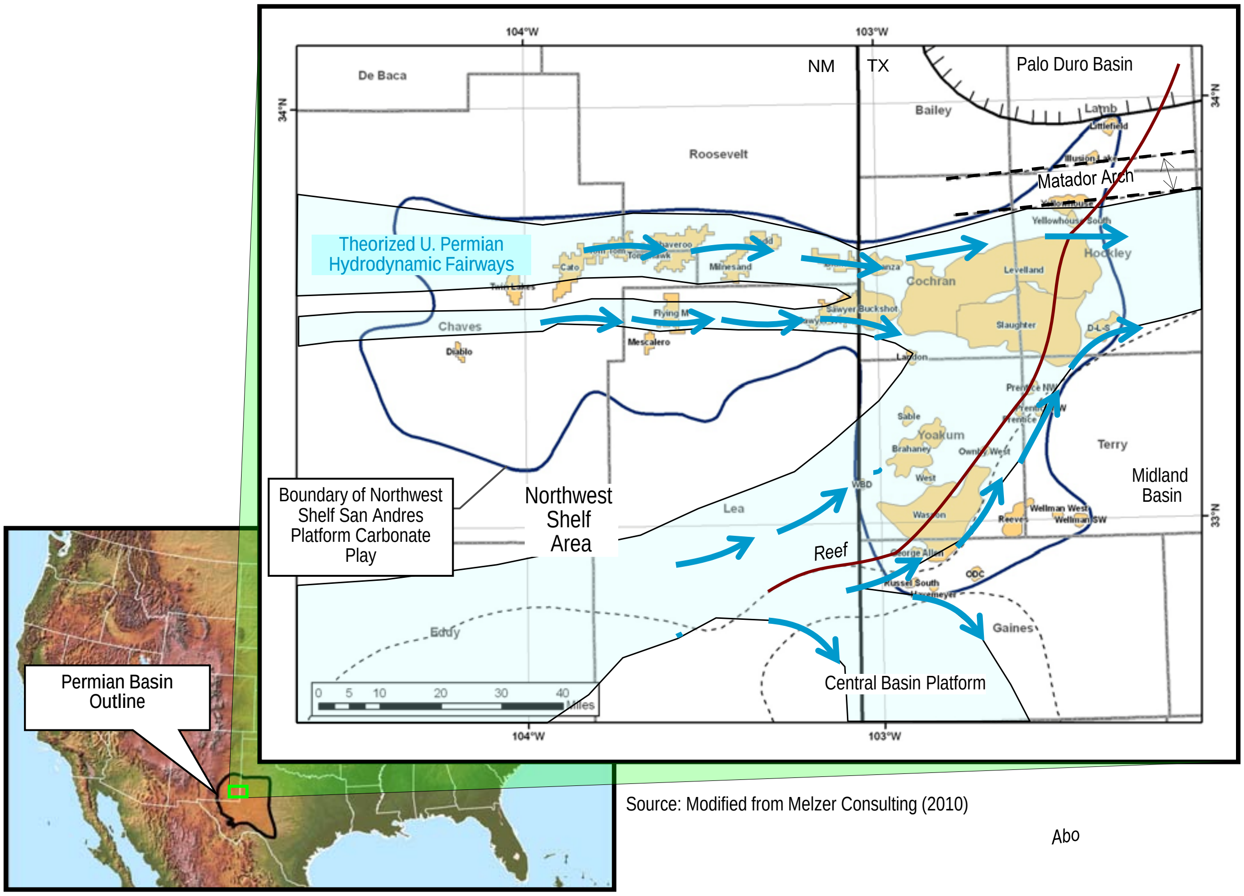


Briefly, residual oil zones exist in the portions of oil reservoirs that have been hydro-dynamically swept by the movement of water from outcrop to deeper horizons over a time period of millions of years. One may wish to label this movement of water and its displacement of oil as “nature’s waterflood”. Because residual oil saturation is low in the naturally water flooded ROZ, CO_2-EOR is required to re-mobilize and recover this oil.

Information from previous reports prepared by Advanced Resources and Melzer Consulting for U.S. DOE/NETL and more recent work by Melzer Consulting for RPSEA show that the ROZ resource occurs well beyond the outlines of existing oil fields and actually exists as a series of areally extensive “ROZ fairways”, as illustrated in Figure IV-10. However, because of limitations of scope, the current study only addresses the ROZ resource below the main pay zone within the structural confinement of existing oil fields and does not capture the much larger oil resource within the “ROZ fairways”.

While the viability of recovering oil from ROZs is being demonstrated by a series of ROZ field projects (at Seminole by Hess, at Wasson Denver Unit by Occidental, at Goldsmith by Legado, among others), a number of important technical issues remain to be addressed and solved before one can expect optimally efficient oil recovery from ROZs using miscible CO_2-EOR. Some of the technical challenges are discussed in the three ROZ basin studies cited previously.[3,4,5]

Figure IV-10. Map of ROZ Fairways.



Source: Modified from Melzer Consulting (2010)

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D. Deployment of CO_2-EOR in Offshore Oil Fields

The deep, light oils common to Gulf of Mexico (GOM) offshore oil fields are particularly amenable to miscible CO_2-EOR technology. And, with the continued discovery and development of oil fields in the deep waters of the Outer Continental Shelf, the size of this resource target continued to grow.

However, the deployment of CO_2-EOR technology in offshore oil fields faces many barriers and challenges, including inadequate platform space for CO_2 recycling equipment, the expense of drilling new CO_2 injection wells, and the need to transport of CO_2 from onshore sources to offshore platforms. While these barriers and challenges can be addressed, they add substantial costs to the oil recovery process.

While CO_2-EOR projects have been undertaken, in a small handful of offshore oil fields near to shore and in shallow GOM waters, none are currently operating. As such, the fourth "Next Generation" CO_2-EOR technology involves undertaking the challenge of deploying innovative designs and advanced CO_2-EOR technology for offshore oil fields.

V. USING CO_2 ENHANCED OIL RECOVERY (CO_2-EOR) TO INCREASE DOMESTIC OIL PRODUCTION AND TO ACCELERATE DEPLOYMENT OF CCS

A. Overview of Benefits

Numerous benefits stem from using captured CO_2 emissions from power and industrial plants for enhanced oil recovery. The most compelling of the numerous benefits include:

- ***Improved Domestic Energy Security***. The implementation of "Next Generation" CO_2-EOR technology, including productively using captured CO_2 emissions from power plants, would enable an additional 67 billion barrels of domestic oil to be economically recovered. This would support 4 million barrels per day of additional oil production by year 2030, greatly improving domestic energy security.

- ***Increased Revenue Streams***. The sale and use of captured CO_2 would provide revenue streams to the capturer of CO_2 emissions and to other entities involved in the CO_2 value chain.

- ***Accelerated Deployment of CCS***. Selection of EOR as the CO_2 storage option would enable major CCS projects to be implemented in the near-term (next ten years) while the "thorny issues" surrounding using saline formations for storing CO_2 (e.g., pore space rights, regulatory approval, public acceptance) are resolved.

These three benefits of integrating CO_2-EOR with CO_2 capture and storage are further discussed below.

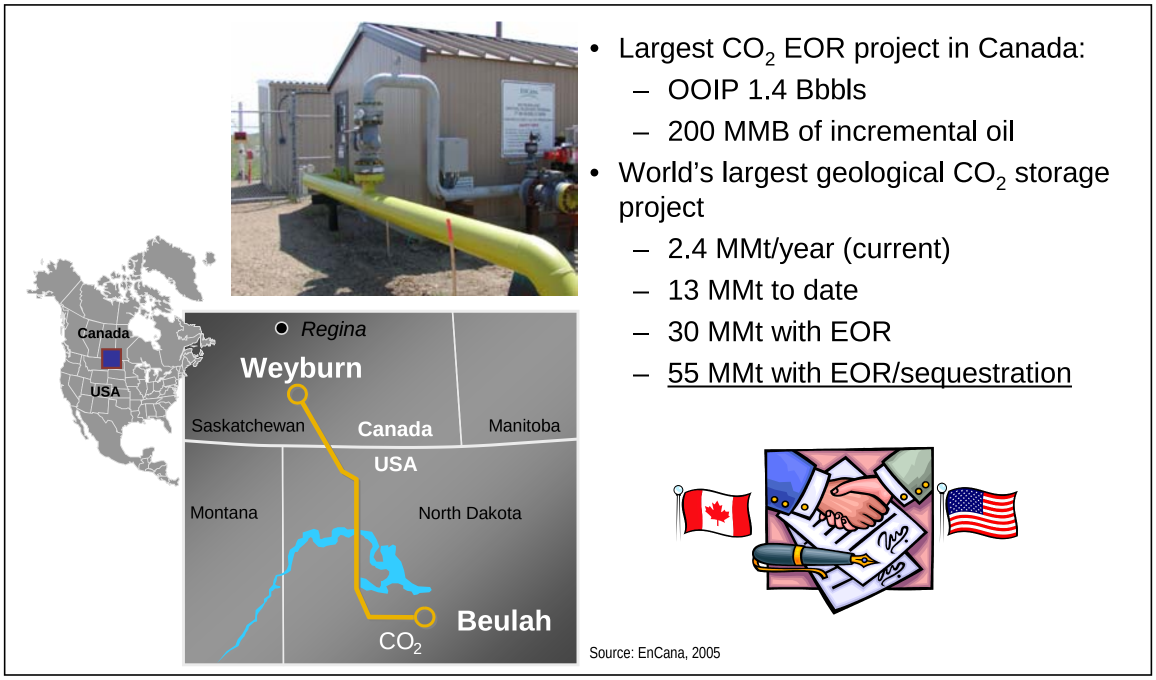
The "poster child" for integrating CO_2-EOR and CO_2 storage, the Weyburn oil field, provides a real world demonstration of the oil recovery and CO_2 storage benefits offered by integrated CO_2-EOR and CO_2 sequestration, Figure V-1. For example:

- The volume of oil recovery is estimated at 200 million barrels, adding to Canadian energy security.

- The purchase of CO_2 by EnCana (now Cenovus) is providing valuable revenues to the Coal Gasification Plant at Beulah, North Dakota. The production of oil is providing royalties and economic activity for the Province of Saskatchewan.

- The storage of CO_2 while recovering the 200 million barrels of oil is estimated at 55 million metric with integrated EOR and CO_2 sequestration.

Figure V-1 "Poster Child" for Integrating CO_2-EOR and CO_2 Storage



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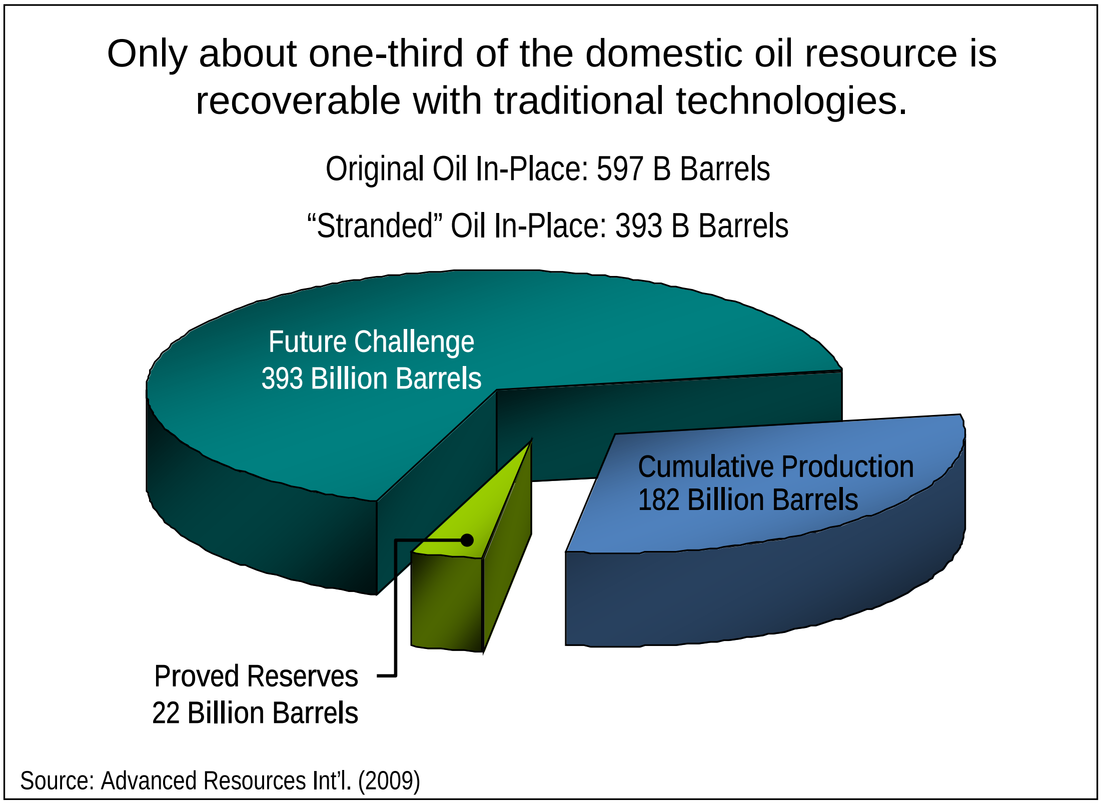
1. Improving Energy Security by Using CO_2-EOR to Increase Domestic Oil Production.

The U.S. uses 19 million barrels of oil per day (about 7 billion barrels per year) primarily to power its massive transportation fleet. Nearly two-thirds of this oil is imported, from countries such as Canada, Mexico, the Middle East and other sources. These large and growing imports impact our energy security, the size of our trade deficit, and the health of our economy.

While still a significant oil producer -- the U.S. produced about 7 million barrels of oil per day (including crude oil, condensate and natural gas liquids) last year -- domestic oil production has been steadily declining. (The recent development of the Bakken Shale has helped stem the oil production decline.)

Yet, the nation has a vast resource of nearly 400 billion barrels of oil still left in the ground ("stranded") that is unrecoverable with existing primary and secondary oil recovery technologies, Figure V-2. Recovering a portion of this "stranded" oil is the goal of the CO_2-EOR technologies clustered under the "Next Generation" technology umbrella.

Figure V-2. The Domestic Oil Resource Base



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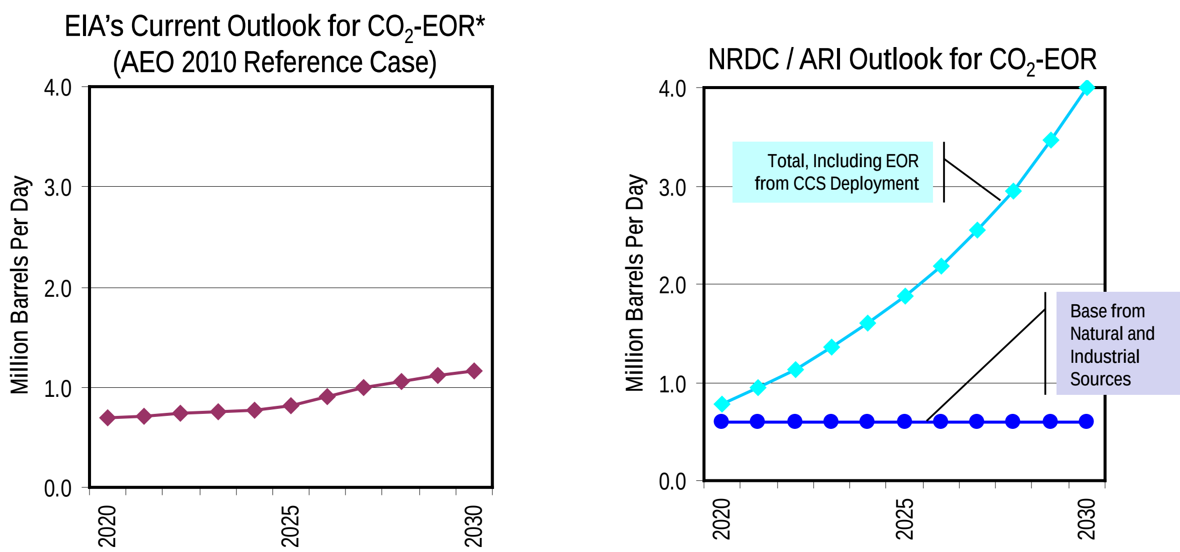
A recent report, prepared for the Natural Resources Defense Council by Advanced Resources International, entitled "U.S. Oil Production Potential from Accelerated Deployment of Carbon Capture and Storage[15], states that combining CCS with enhanced oil recovery could boost U.S. oil production by 3.4 million barrels per day by year 2030, Figure V-3. This would be in addition to CO_2-EOR production of about 0.6 million barrels per day from use of currently available CO_2 supplies from natural sources and gas processing plants.

Achieving the total of 4 million barrels per day of oil production from CO_2-EOR, with 3.4 million barrels per day directly linked to use of CO_2 from CCS, would significantly reduce oil imports. It would also reduce annual CO_2 emissions by nearly 400 million metric tons in year 2030.

[15] Advanced Resources International, Inc., "U.S. Oil Production Potential from Accelerated Deployment of Carbon Capture and Storage", prepared for the Natural Resources Defense Council, March 2010. This report draws heavily from the U.S. DOE/NETL-sponsored report, also prepared by Advanced Resources "Storing CO_2 and Producing Domestic Crude Oil with Next Generation CO_2-EOR Technology: An Update" Publication Number: DOE/NETL-2010/1417, April 2010.

Figure V-3. Comparison of NRDC/ARI and EIA's Outlook for CO_2-EOR



*Discussions are underway among the U.S. EIA, U.S. DOE/NETL and the NRDC staff on how to represent the integration of CO_2–EOR and CCS in energy market forecasts.

Source: Advanced Resources International, Inc. (2011).

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2. Providing Revenue Streams from Sale of CO_2 and Production of Oil.

A most important benefit from integrating CO_2-EOR and CO_2 storage is that use of CO_2 for oil recovery would provide new revenue streams to a series of notable stakeholders, Table V-1:

- An important revenue stream accrues to the capturers of CO_2 emissions, helping lower the overall cost of conducting CCS. In this report, we assume a price for CO_2 of $40/metric ton, delivered to the oil field at pressure. At 0.3 metric tons of purchased (net) CO_2 per barrel of recovered oil, this results in a transfer of $12 of the $85 per barrel oil to entities selling the CO_2 to the oil industry. Power and other industries involved with CO_2 capture would need to provide nearly 90% of the future CO_2 demand, gaining $730 billion dollars of revenues.
- A second revenue stream accrues to local and state governments and the Federal Treasury from royalties, severance and ad valorem taxes and income taxes. Our analysis shows that, at an oil price of $85 per barrel, $21.20 of this oil price is transferred directly to state and local governments and the Federal Treasury. With 67.2 billion barrels of economically recoverable oil from applying "Next Generation" CO_2-EOR, this equals $1,420 billion of revenues transferred to domestic public treasuries rather than to foreign treasuries. These revenues, in states such as Texas, Wyoming and others, are a primary source of funds for school systems and other valuable public services.

Table V-1. Distribution of Economic Value of Incremental Oil Production from CO_2-EOR

Notes		Oil Industry	Private Minerals	Federal/ State	Power Plant/Other	U.S. Economy
1	Domestic Oil Price ($/B)	$85.00				
2	Less: Royalties	($14.90)	$12.40	$2.50		
3	Production Taxes	($3.50)	($0.60)	$4.10		
4	CO2 Purchase Costs	($12.00)			$10.80	$1.20
5	CO2 Recycle Costs	($9.60)				$9.60
6	O&M/G&A Costs	($9.00)				$9.00
7	CAPEX	($6.00)				$6.00
	Total Costs	($55.00)			-	
	Net Cash Margin	$30.00	$11.80	$6.60	$10.80	**$25.80**
8	Income Taxes	($10.50)	($4.10)	$14.60	?	**?**
	Net Income ($/B)	$19.50	$7.70	$21.20	-	
						JAF2011_030.XLS

1 Assumes $85 per barrel of oil.
2 Royalties are 17.5%; 1 of 6 barrels produced are from federal and state lands.
3 Production and ad valorem taxes of 5%, from FRS data.
4 CO_2 market price of $40/tonne, including transport; 0.3 tonne of purchased CO_2 per barrel of oil; CCS would provide about 90% of CO_2 demand.
5 CO_2 recycle cost of $16/tonne; 0.6 tonnes of recycled CO_2 per barrel of oil.
6 O&M/G&A costs from ARI CO_2-EOR cost models.
7 CAPEX from ARI CO_2-EOR cost models.
8 Combined Federal and state income taxes of 35%, from FRS data.

- A third revenue stream accrues to the general domestic economy from successful application of CO_2-EOR technology. With $25.80 of the $85 barrel oil price being spent on domestic wages and purchases, this provides $1.7 trillion dollars of gross revenues to the domestic economy.
- A fourth revenue stream accrues to a variety of entities holding private mineral rights from royalty payments ($7.70 per barrel) and to the U.S. oil industry ($19.50 per barrel) for return of and return on capital investment. The Texas economic model shows that every dollar of direct investment in oil development has a multiplier of 4 in terms of supporting economic activity.
- Finally, the domestic trade balance (foreign debt) from producing 67.2 billion barrels of domestic oil rather than importing this oil would be reduced by $5.7 trillion.

3. Accelerating the Application of CO_2 Storage.

The integration of CO_2-EOR and CCS would greatly help accelerate the regulatory acceptance and implementation of CO_2 storage:

- Oil fields provide CO_2 storage options that can be permitted under existing (or slightly modified) regulatory guidelines, thereby avoiding the large delays inherent when waiting on new regulations and permitting for large-scale storage of CO_2 in saline formations.
- The pore space, mineral rights and long-term liability issues of oil fields are already well established and thus would not be impediments to an integrated CO_2 storage and CO_2-EOR project.
- Oil fields generally have existing subsurface data and often possess usable infrastructure such as injection wells and gathering systems, enabling more accurate assessment of CO_2 storage capacity and substantial cost savings.

Beyond these three benefits, a number of other conditions favor the use of oil fields for injecting and storing CO_2. First, oil fields are located in areas with an accepted history of subsurface field activities contributing to public acceptance for storing CO_2. Second, oil fields provide an existing "brown field" storage site versus having to establish a new "green field" site when preparing a saline formation for CO_2 storage. Third, the footprint of the CO_2 plume within an oil field would be several times smaller than within a saline formation. Finally, the early reliance on EOR for storing CO_2 would help build the regional pipeline infrastructure for future CO_2 storage projects in saline formations.

B. Proposed Use of Oil Fields for Storing CO_2

To a large extent, industrial operators of proposed coal-to-liquids (CTL) plants, integrated gasification combined cycle (IGCC) facilities, and other carbon conversion projects have already "voted with their feet" for first turning to oil fields for storing CO_2. Three such projects are discussed below[16]:

- Hydrogen Energy's (BP/Rio Tinto) pet-coke gasification plant in Kern County, California plans to deliver 2 MMt/yr of CO_2 to the giant Elk Hills oil field for CO_2-EOR, Figure V-4.
- Southern Company's Kemper County IGCC plant plans to provide 1.1 to 1.5 MMt/yr to Denbury Resources for CO_2-EOR in oil fields in Louisiana and Mississippi, Figure V-5.
- Summit Energy's Texas Clean Energy IGCC project plans to sell 3 MMt/yr for CO_2-EOR in West Texas, Figure V-6.

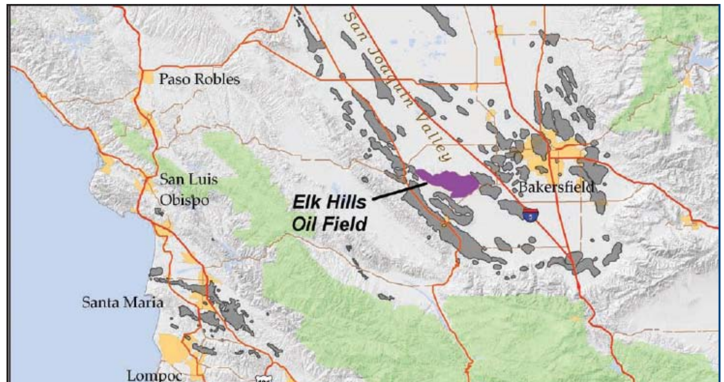
[16] Various industry presentations and publications.

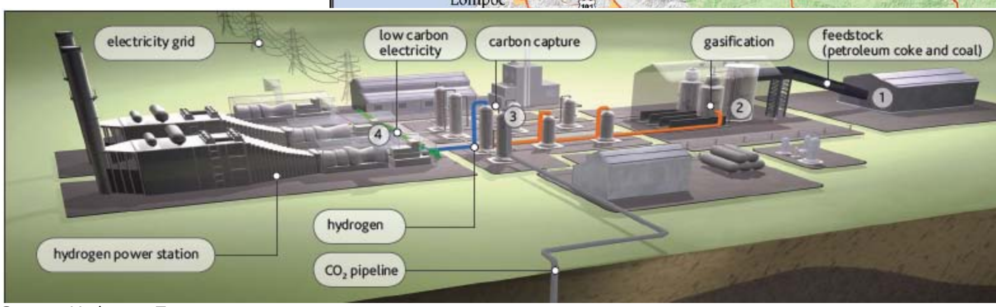
Figure V-4. Advanced Power Plants and Use of EOR for CO_2 Storage

Elk Hills Oil Field near Bakersfield, CA

Hydrogen Energy's (Rio Tinto/BP) Pet-coke Gasification Plant

- 250MW gasification of pet-coke
- Capture 90% of CO_2; over 2 million tons of CO_2 per year
- Oxy will take CO_2 for EOR at Elk Hills oil field
- Operational by 2015





Source: Hydrogen Energy

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Figure V-5. Advanced Power Plants Using EOR for Storage

Southern Company's Kemper County IGCC Plant

- 582 MW IGCC fueled by Mississippi lignite
- Capture 65% of CO_2
- Negotiating to sell 1.1 to 1.5 million tons of CO_2 per year for EOR
- Cost $2.4 B; operational by 2014

*Source: Mississippi Power, Denbury Resources

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Figure V-6. Advanced Power Plants Using EOR for Storage

Summit's Texas Clean Energy IGCC Project

- 400 MW IGCC with 90% capture
- Located near Odessa in Permian Basin
- Sell 3 million tons of CO_2 per year to EOR market
- Expected cost $1.75 B; $350 MM award under CCPI Round 3.

Source: Siemens Energy

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* * * * *

Clearly, many of the proposed new IGCC and coal to gas/liquids plants are looking to CO_2-EOR as their primary CO_2 storage option. Because of this, some power companies have expressed concerns that these initial plants will "use up" all of the available EOR market and CO_2 storage capacity, leaving little for subsequent use.

As such, the key questions are: (1) How much CO_2 could be sold to and stored with "Next Generation" CO_2 enhanced oil recovery, and (2) Where are the potential CO_2 demand (and storage) centers? These key questions are addressed in the following chapter.

VI. A REGIONAL ("BASIN-ORIENTED STRATEGY") LOOK AT THE CO_2-EOR/STORAGE POTENTIAL

The CO_2-EOR potential, for both storing CO_2 and producing oil, varies significantly across the regions and basins of the U.S. For example, the great Permian Basin of West Texas and New Mexico, while the "birth place" of CO_2-EOR, still offers major opportunities for applying "Next Generation" CO_2-EOR technology.

Other regions of the country offer similar promise but still face constraints. California, currently locked out of natural CO_2 sources, has a host of deep, light oil reservoirs, such as the giant Elk Hills, ready for development with CO_2-EOR. The giant oil fields in East and South Texas, now with access to supplies of CO_2, are being evaluated for CO_2-EOR as the Green Pipeline beings to deliver CO_2 to the region.

The oil fields in the offshore Gulf of Mexico, while technically attractive for CO_2-EOR miscible flooding, face serious infrastructure and cost constraints. Alaska, with large declining oil fields that could be revitalized with CO_2-EOR, would need to see the launch of the Alaska Natural Gas Pipeline or the installation of a "world scale" energy processing and petrochemicals facility to create sufficient supplies of CO_2.

Chapter VII of the report provides a more detailed look at the oil production and CO_2 storage potential offered by the following eleven regions:

1. Appalachia
2. California
3. East and Central Texas
4. Michigan/Illinois
5. Mid-Continent
6. Permian Basin
7. Rockies
8. Southeast Gulf Coast
9. Williston Basin
10. Alaska
11. Offshore Gulf of Mexico

1. Appalachia

a. Background. The Appalachia Basin, the origin of the U.S. oil industry, provided much of the petroleum used by the U.S. during World War II. Currently, oil production is 12 million barrels per year (about 33,000 barrels per day) from a series of very mature fields (Table V1-1.1).

Table VI-1.1. Crude Oil Production from the Appalachian Basin (MM Bbls/Yr)

Year	New York	Ohio	Pennsylvania	West Virginia	TOTAL
2000	*	7	2	1	10
2001	*	6	2	1	9
2002	*	6	2	1	9
2003	*	6	2	1	9
2004	*	6	3	1	10
2005	*	6	4	2	12
2006	*	5	4	2	11
2007	*	5	4	2	11
2008	*	6	4	2	12
2009	*	6	4	2	12

*less than 0.5 million barrels. Source: EIA Crude Oil Production by State (March 2011).

b. Reservoirs Favorable for CO_2-EOR. Advanced Resources' Big Oil Fields Database for the Appalachian Basin contains 84 oil reservoirs that screen favorably for miscible CO_2-EOR plus 19 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 103 reservoirs contain 9.4 billion barrels of OOIP out of a data base of 171 reservoirs with 10.2 billion of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 84 Appalachian Basin oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	8.6 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	1.5 billion barrels
Primary/Secondary Oil Recovery Efficiency	17%
Remaining Oil In-Place	7.1 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR applied to these 84 oil reservoirs offers the potential for technically recovering 2.4 billion barrels of the remaining oil in-place, equal to 28% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 48 of the 84 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. These 48 reservoirs have an economically feasible oil recovery of 1.3 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 84 Appalachian Basin oil fields technically favorable for miscible CO_2-EOR is 790 million metric tons (15 Tcf). The volume of purchased CO_2 for the 48 Appalachian Basin oil reservoirs economically favorable for miscible CO_2-EOR is 290 million metric tons (5 Tcf).

(5) Summary Table. Table VI-1.2 provides a summary of the oil recovery and CO_2 demand (and storage) potential from the application of miscible "Next Generation" CO_2-EOR in the Appalachian Basin for the data base and extrapolated regional totals.

Table VI-1.2. Appalachian Basin Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	2.4	1.3	790	290
2. Regional Totals	3.3	1.3	1,080	290

*Database totals extrapolated to regional totals using a dividing factor of 0.73.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 19 Appalachian Basin oil reservoirs technically favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	0.78 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.16 billion barrels
Primary/Secondary Oil Recovery Efficiency	20%
Remaining Oil In-Place	0.62 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR applied to these 19 oil reservoirs offers the potential for technically recovering 0.1 billion barrels of the remaining oil in-place, equal to 8% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), none of the 19 oil reservoirs provide a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 19 Appalachian Basin oil fields technically favorable for near miscible CO_2-EOR is 60 million metric tons (1 Tcf).

(5) Summary Table. Table VI-1.3 provides a summary of the oil recovery and CO_2 demand (and storage) potential from the application of near miscible "Next Generation" CO_2-EOR in the Appalachian Basin for the database and extrapolated regional totals.

Table VI-1.3. Appalachian Basin Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.1	-	60	-
2. Regional Totals	0.1	-	80	-

*Database totals extrapolated to regional totals using a dividing factor of 0.73.

e. Miscible and Near Miscible CO_2-EOR. Table VI-1.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in the Appalachian Basin.

Table VI-1.4. Appalachian Basin Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	2.5	1.3	850	290
2. Regional Totals	3.4	1.3	1,160	290

*Database totals extrapolated to regional totals using a dividing factor of 0.73.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Using "Next Generation" CO_2-EOR in the Appalachian Basin would provide significantly more oil recovery and CO_2 storage potential than would be realized from applying State of Art CO_2-EOR technology, Table VI-1.5.

- Economic oil recovery would be 1.3 billion barrels with "Next Generation" technology compared to essentially zero with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 290 million metric tons with "Next Generation" technology compared to about 10 million metric tons with State of Art technology.

Table VI-1.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Appalachian Basin (Regional Totals)

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	1.1	3.4
	▪ Economic	0.0	1.3
CO_2 Demand (Million Metric Tons)			
	▪ Technical	520	1,160
	▪ Economic	10	290

2. Onshore California

a. Background. While much of the oil production from California is due to steam injection for heavy oil recovery, California (particularly the San Joaquin Basin) does have large, deep light oil reservoirs (such as Elk Hills) that account for an important part of California's oil production. In 2009, California produced 194 million barrels (530,000 barrels per day) of heavy and light oil (Table VI-2.1).

Table VI-2.1. Oil Production from Onshore California (MM Bbls/Yr)

Year	Coastal	Los Angeles	San Joaquin	TOTAL
2000	18	16	215	249
2001	18	16	220	238
2002	18	17	205	240
2003	17	16	197	230
2004	17	16	191	224
2005	15	16	184	215
2006	15	16	176	207
2007	15	17	173	205
2008	16	16	175	207
2009	18	15	161	194

Sources: EIA Proved Reserves and Production (December, 2010) and EIA Crude Oil Production by State (March 2011).

b. Reservoirs Favorable for CO_2-EOR. Advanced Resources' Big Oil Fields Database for California contains 76 oil reservoirs that screen favorably for miscible CO_2-EOR plus 13 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 89 reservoirs contain 31.9 billion barrels of OOIP out of a data base of 187 reservoirs with 74.6 billion of OOIP.

c. ***Miscible CO_2-EOR.***

(1). Database. The data for the 76 California oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	28.2 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	8.8 billion barrels
Primary/Secondary Oil Recovery Efficiency	31%
Remaining Oil In-Place	19.4 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 76 oil reservoirs offers the potential for technically recovering 6.9 billion barrels of the remaining oil in-place, equal to 25% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 69 of the 76 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 6.5 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 76 California oil fields technically favorable for miscible CO_2-EOR is 1,940 million metric tons (37 Tcf). The volume of purchased CO_2 for the 69 California oil reservoirs economically favorable for miscible CO_2-EOR is 1,690 million metric tons (32 Tcf).

(5) Summary Table. Table VI-2.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in California and extrapolated to regional totals.

Table VI-2.2. Onshore California Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	6.9	6.5	1,940	1,690
2. Regional Totals	7.7	6.5	2,160	1,690

*Database totals extrapolated to regional totals using a dividing factor of 0.90.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 13 California oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	3.7 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	1.1 billion barrels
Primary/Secondary Oil Recovery Efficiency	31%
Remaining Oil In-Place	2.6 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 13 oil reservoirs offers the potential for technically recovering 0.2 billion barrels of the remaining oil in-place, equal to 5% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 2 of the 13 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 0.2 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 13 California oil fields technically favorable for near miscible CO_2-EOR is 140 million metric tons (3 Tcf). The volume of purchased CO_2 for the 2 California oil reservoirs economically favorable for near miscible CO_2-EOR is 70 million metric tons (1Tcf).

(5) Summary Table. Table VI-2.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in California.

Table VI-2.3. Onshore California Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.2	0.2	140	70
2. Regional Totals	0.2	0.2	160	70

*Database totals extrapolated to regional totals using a dividing factor of 0.90.

e. Miscible and Near Miscible CO_2-EOR. Table VI-2.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in California.

Table VI-2.4. Onshore California Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	7.1	6.7	2,080	1,760
2. Regional Totals	7.9	6.7	2,320	1,760

*database totals extrapolated to regional totals using a dividing factor of 0.90.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology.
Applying "Next Generation" CO_2-EOR in California would provide valuable additional oil recovery and CO_2 storage, Table VI-2.5.

- Economic oil recovery would be 6.7 billion barrels with "Next Generation" technology compared to 1.2 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 1,760 million metric tons with "Next Generation" technology compared to 480 million metric tons with State of Art technology.

Table VI-2.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Onshore California (Regional Totals)

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	3.1	7.9
	▪ Economic	1.2	6.7
CO_2 Demand (Million Metric Tons)			
	▪ Technical	1,340	2,320
	▪ Economic	480	1,760

3. *East and Central Texas*

a. Background. East Texas ushered in the “oil boom” at historic oil fields such as Spindletop and Conroe. Today, this area provides 114 million barrels of oil per year (about 310,000 barrels per day) (Table VI-3.1).

Table VI-3.1. Oil Production from East and Central Texas (MM Bbls/Yr)

Year	East Texas (RR #1-6)	Central Texas (RR 7B/7C and 9-10)	TOTAL
2000	93	56	149
2001	78	53	131
2002	71	48	119
2003	67	48	115
2004	66	46	112
2005	64	45	109
2006	66	49	115
2007	64	49	113
2008	61	55	116
2009	55	59	114

Source: EIA Proved Reserves and Production (December, 2010).

b. Summary of Results. Advanced Resources’ Big Oil Fields Database for East and Central Texas contains 186 oil reservoirs that screen favorably for miscible CO_2-EOR plus 7 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 193 reservoirs contain 61.1 billion barrels of OOIP out of a data base of 213 reservoirs with 66.4 billion barrels of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 186 East and Central Texas oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	59.4 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	21.2 billion barrels
Primary/Secondary Oil Recovery Efficiency	36%
Remaining Oil In-Place	38.2 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 186 oil reservoirs offers the potential for technically recovering 15.3 billion barrels of the remaining oil in-place, equal to 26% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 162 of the 186 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 13.5 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 demand for the 186 East and Central Texas oil fields technically favorable for miscible CO_2-EOR is 4,390 million metric tons (83 Tcf). The volume of purchased CO_2 demand for the 162 East and Central Texas oil reservoirs economically favorable for miscible CO_2-EOR is 3,620 million metric tons (68 Tcf).

Subtracting out the 400 million metric tons (8 Tcf) of CO_2 expected to be delivered to East Texas from natural sources still leaves a near- to mid-term economic market for purchase (and storage) of anthropogenic CO_2 of 3,220 million metric tons (60 Tcf).

(5) Summary Table. Table VI-3.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in East and Central Texas.

Table VI-3.2. East and Central Texas Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)**	
	Technical*	Economic	Technical*	Economic
1. Database Totals	15.3	13.5	4,390	3,620
2. Regional Totals	20.7	13.5	5,930	3,620

*Database totals extrapolated to regional totals using a dividing factor of 0.74.
**Includes 580 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 7 East and Central Texas oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	1.8 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.5 billion barrels
Primary/Secondary Oil Recovery Efficiency	26%
Remaining Oil In-Place	1.3 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 7 oil reservoirs offers the potential for technically recovering 0.12 billion barrels of the remaining oil in-place, equal to 7% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), none of the oil reservoirs provide at least a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 7 East and Central Texas oil fields technically favorable for near miscible CO_2-EOR is 80 million metric tons (2 Tcf).

(5) Summary Table. Table VI-3.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in East and Central Texas.

Table VI-3.3. East and Central Texas Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.1	-	80	-
2. Regional Totals	0.2	-	110	-

*Database totals extrapolated to regional totals using a dividing factor of 0.74.

e. Miscible and Near Miscible CO_2-EOR. Table VI-3.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in East and Central Texas.

Table VI-3.4. East and Central Texas Oil Recovery and CO_2 Storage from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)**	
	Technical*	Economic	Technical*	Economic
1. Database Totals	15.4	13.5	4,470	3,620
2. Regional Totals	20.9	13.5	6,040	3,620

*Database totals extrapolated to regional totals using a dividing factor of 0.74.
**Includes 400 million metric tons of CO_2 demand provided from natural sources.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in East and Central Texas would provide valuable additional oil recovery and CO_2 storage (Table VI-3.5).

- Economic oil recovery would be 13.5 billion barrels with "Next Generation" technology compared to 5.9 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 3,620 million metric tons with "Next Generation" technology compared to 2,120 million metric tons (gross) with State of Art technology.

Table VI-3.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: East and Central Texas

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	11.1	20.9
	▪ Economic	5.9	13.5
CO_2 Demand (Million Metric Tons)			
	▪ Technical	4,210	6,040
	▪ Economic		
	– Gross*	2,120	3,620
	– Net	1,720	3,220

* Includes 400 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

4. *Michigan/Illinois Basin*

a. Background. The mature Michigan and Illinois oil basins have seen a steady decline in production in recent years, reaching 20 million barrels per year (about 55,000 barrels per day) in 2009 (Table VI-4.1).

Table VI-4.1. Oil Production from Michigan and Illinois Basins (MM Bbls/Yr)

Year	Michigan	Illinois/Indiana	Kentucky	TOTAL
2000	8	14	3	25
2001	7	12	3	22
2002	7	14	3	24
2003	7	14	3	24
2004	6	12	3	21
2005	6	12	2	20
2006	5	12	3	20
2007	5	11	3	19
2008	6	11	3	20
2009	6	11	3	20

Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for Michigan/Illinois Basin contains 140 oil reservoirs that screen favorably for miscible CO_2-EOR plus 8 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 148 reservoirs contain 9.8 billion barrels of OOIP out of a data base of 190 reservoirs with 10.2 billion barrels of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 140 Michigan/Illinois Basin oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	8.4 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	3.2 billion barrels
Primary/Secondary Oil Recovery Efficiency	38%
Remaining Oil In-Place	5.2 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 140 oil reservoirs offers the potential for technically recovering 2.1 billion barrels of the remaining oil in-place, equal to 25% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 122 of the 140 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 1.8 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 140 Michigan/Illinois Basin oil fields technically favorable for miscible CO_2-EOR is 710 million metric tons (13 Tcf). The volume of purchased CO_2 for the 122 Michigan/Illinois Basin oil reservoirs economically favorable for miscible CO_2-EOR is 570 million metric tons (11 Tcf).

(5) Summary Table. Table VI-4.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in Michigan/Illinois Basin.

Table VI-4.2. Michigan/Illinois Basin Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	2.1	1.8	710	570
2. Regional Totals	2.8	1.8	960	570

*Database totals extrapolated to regional totals using a dividing factor of 0.74.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 8 Michigan/Illinois Basin oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	1.3 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.4 billion barrels
Primary/Secondary Oil Recovery Efficiency	32%
Remaining Oil In-Place	0.9 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 8 oil reservoirs offers the potential for technically recovering 0.1 billion barrels of the remaining oil in-place, equal to 10% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), none of the oil reservoirs provide at least a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 8 Michigan/Illinois Basin oil fields technically favorable for near miscible CO_2-EOR is 70 million metric tons (1 Tcf).

(5) Summary Table. Table VI-4.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in the Michigan/Illinois Basin.

Table VI-4.3. Michigan/Illinois Basin Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.1	-	70	0
2. Regional Totals	0.2	-	90	0

*Database totals extrapolated to regional totals using a dividing factor of 0.74.

e. Miscible and Near Miscible CO_2-EOR. Table VII-4.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in the Michigan/Illinois Basin.

Table VI-4.4. Michigan/Illinois Basin Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	2.2	1.8	780	570
2. Regional Totals	3.0	1.8	1,050	570

*Database totals extrapolated to regional totals using a dividing factor of 0.74.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying Next Generation CO_2-EOR in the Michigan/Illinois Basin would provide valuable additional oil recovery and CO_2 storage (Table VI-4.5).

- Economic oil recovery would be 1.8 billion barrels with "Next Generation" technology compared to 1.1 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 570 million metric tons with "Next Generation" technology compared to 390 million metric tons with State of Art technology.

Table VI-4.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Michigan/Illinois Basin

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	1.8	3.0
	▪ Economic	1.1	1.8
CO_2 Demand (Million Metric Tons)			
	▪ Technical	660	1,050
	▪ Economic	390	570

5. Mid-Continent

a. Background. After years of steady decline, oil production in the Mid-Content area, particularly in Oklahoma, has begun to rebound reaching 115 million barrels per year (315,000 barrels per day) in 2009 (Table VI-5.1).

Table VI-5.1. Oil Production from the Mid-Continent (MM Bbls/Yr)

Year	Oklahoma	Kansas/Nebraska	Arkansas	TOTAL
2000	70	37	7	114
2001	69	37	8	114
2002	67	36	7	110
2003	65	37	7	109
2004	62	36	7	105
2005	62	36	6	104
2006	63	38	6	107
2007	61	39	6	106
2008	64	42	6	112
2009	67	42	6	115

Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Mid-Continent contains 174 oil reservoirs that screen favorably for miscible CO_2-EOR plus 9 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 183 reservoirs contain 46.0 billion barrels of OOIP out of a database of 246 reservoirs with 53.1 billion of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 174 the Mid-Continent oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	43.7 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	12.0 billion barrels
Primary/Secondary Oil Recovery Efficiency	27%
Remaining Oil In-Place	31.7 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 174 oil reservoirs offers the potential for technically recovering 13.1 billion barrels of the remaining oil in-place, equal to 30% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 154 of the 174 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery from these reservoirs is 11.9 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 174 Mid-Continent oil fields technically favorable for miscible CO_2-EOR is 3,740 million metric tons (71 Tcf). The volume of purchased CO_2 for the 154 Mid-Continent oil reservoirs economically favorable for miscible CO_2-EOR is 3,240 million metric tons (61 Tcf).

(5) Summary Table. Table VI-5.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in Mid-Continent.

Table VI-5.2. Mid-Continent Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	13.1	11.9	3,740	3,240
2. Regional Totals	22.2	11.9	6,340	3,240

*Database totals extrapolated to regional totals using a dividing factor of 0.59.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 9 Mid-Content oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	2.3 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.6 billion barrels
Primary/Secondary Oil Recovery Efficiency	28%
Remaining Oil In-Place	1.7 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 9 oil reservoirs offers the potential for technically recovering 0.17 billion barrels of the remaining oil in-place, equal to 7% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 2 of the 9 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 0.1 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 9 Mid-Continent oil fields technically favorable for near miscible CO_2-EOR is 110 million metric tons (2 Tcf). The volume of purchased CO_2 for the 2 Mid-Continent oil reservoirs economically favorable for near miscible CO_2-EOR is 30 million metric tons (1 Tcf).

(5) Summary Table. Table VI-5.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in the Mid-Content.

Table VI-5.3. Mid-Content Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.2	0.1	110	30
2. Regional Totals	0.3	0.1	190	30

*Database totals extrapolated to regional totals using a dividing factor of 0.59.

e. Miscible and Near Miscible CO_2-EOR. Table VI-5.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in the Mid-Continent.

Table VI-5.4. Mid-Continent Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	13.3	12.0	3,850	3,270
2. Regional Totals	22.5	12.0	6,530	3,270

*Database totals extrapolated to regional totals using a dividing factor of 0.59.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in the Mid-Continent would provide valuable additional oil recovery and CO_2 storage (Table VI-5.5).

- Economic oil recovery would be 12.0 billion barrels with "Next Generation" technology compared to 6.6 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 3,270 million metric tons with "Next Generation" technology compared to 2,120 million metric tons with State of Art technology.

Table VI-5.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Mid-Continent (Regional Totals)*

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)*			
	▪ Technical	12.9	22.5
	▪ Economic	6.6	12.0
CO_2 Demand (Million Metric Tons)			
	▪ Technical	4,220	6,530
	▪ Economic	2,120	3,270

*Includes 0.1 billion barrels already produced or proven with miscible CO_2-EOR technology.

6. Permian Basin

a. Background. The Permian Basin, located in West Texas (Texas Railroad Districts 8 and 8A) and East New Mexico, is still one of the largest oil producing regions of the world. In 2009, this area with 289 million barrels of oil production (790 thousand barrels per day) ranked first for U.S. oil production. To date, the Permian Basin has produced 32 billion barrels of oil with 4.8 billion barrels of remaining proved reserves. (These values include production and proved reserves from applying CO_2-EOR). Table VI-6.1 provides a tabulation of recent oil production rates for the Permian Basin as well as separately for West Texas and East New Mexico.

Table VI-6.1. Oil Production from the Permian Basin (MM Bbls/Yr)

Year	West Texas [1]	East New Mexico [2]	TOTAL
2000	259	66	325
2001	258	67	325
2002	248	66	314
2003	248	65	313
2004	245	63	308
2005	245	60	305
2006	240	59	299
2007	237	58	295
2008	232	58	290
2009	229	60	289

Sources: [1] EIA Proved Reserves and Production (December, 2010); [2] EIA Crude Oil Production by State (March, 2011)

The Permian Basin contains numerous large, deep, light oil fields and reservoirs attractive for CO_2 enhanced oil recovery. The oil fields are mature and, except for those under CO_2 enhanced oil recovery, are in steep decline.

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Permian Basin contains 215 oil reservoirs that screen favorably for miscible CO_2-EOR plus 2 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 217 reservoirs contain 72.2 billion barrels of OOIP out of a database of 228 reservoirs with 72.5 billion OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 215 Permian Basin oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	71.0 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	23.3 billion barrels
Primary/Secondary Oil Recovery Efficiency	33%
Remaining Oil In-Place	47.7 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 215 oil reservoirs offers the potential for technically recovering 18.2 billion barrels of the remaining oil in-place, equal to 26% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 151 of the 215 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. Because most of the giant oil fields in this basin, such as Wasson, Slaughter and Seminole, meet the 20% rate of return hurdle, the great bulk of the original oil in-place resource in this basin is in oil fields economic for CO_2-EOR. The economically feasible oil recovery is 14.6 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 215 Permian Basin oil fields technically favorable for miscible CO_2-EOR is 6,490 million metric tons (123 Tcf). The volume of purchased CO_2 for the 151 Permian Basin oil reservoirs economically favorable for miscible CO_2-EOR is 4,750 million metric tons (90 Tcf).

(5) Summary Table. Table VI-6.2 provides a summary of the oil recovery and CO_2 demand from the application of miscible "Next Generation" CO_2-EOR in Permian Basin for the 215 oil reservoirs in the data base and for regional totals.

Table VI-6.2. Permian Basin Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	18.2	14.6	6,490	4,750
2. Regional Totals	23.9	14.6	8,540	4,750

*Database totals extrapolated to regional totals using a dividing factor of 0.76.
** Includes 1,730 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 2 Permian Basin oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	1.1 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.4 billion barrels
Primary/Secondary Oil Recovery Efficiency	31%
Remaining Oil In-Place	0.8 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 2 oil reservoirs offers the potential for technically recovering 0.1 billion barrels of the remaining oil in-place, equal to 9% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), none of the oil reservoirs provide at least a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 2 Permian Basin oil fields technically favorable for near miscible CO_2-EOR is 60 million metric tons (1 Tcf).

(5) Summary Table. Table VI-6.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in the Permian Basin.

Table VI-6.3. Permian Basin Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	0.1	-	60	-
2. Regional Totals	0.1	-	80	-

*Database totals extrapolated to regional totals using a dividing factor of 0.76.

e. Miscible and Near Miscible CO_2-EOR. Table VI-6.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in the Permian Basin.

Table VI-6.4. Permian Basin Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	18.3	14.6	6,550	4,750
2. Regional Totals	24.0	14.6	8,620	4,750

*Database totals extrapolated to regional totals using a dividing factor of 0.76
**Includes 1,540 million metric tons of CO_2 demand expected to be provided from natural sources and gas processing plants.

Of the 4,750 million metric tons (90 Tcf) of economic CO_2 demand in the Permian Basin, 1,540 million metric tons (29 Tcf) is expected to be provided from natural sources and existing gas processing plants, leaving a net demand of 3,210 million metric tons (61 Tcf) as the market of anthropogenic CO_2, primarily from power plants.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology (Regional Totals). Applying "Next Generation" CO_2-EOR in the Permian Basin would provide significant additional oil recovery and CO_2 storage capacity, Table VI-6.5:

- Economic oil recovery would be 14.6 billion barrels with "Next Generation" CO_2-EOR technology compared to 6.4 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 4,750 million metric tons gross and 3,210 million metric tons net, with "Next Generation" technology compared to 2,690 million metric tons gross and 1,150 million metric tons net with State of Art technology.

Table VI-6.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Permian Basin Regional Totals**

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	13.6	24.0
	▪ Economic	6.4	14.6
CO_2 Demand (Million Metric Tons)			
	▪ Technical	6,070	8,620
	▪ Economic		
	– Gross*	2,690	4,750
	– Net	1,150	3,210

* Includes 1,540 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.
**Includes 2.2 billion barrels already produced or proven with miscible CO_2-EOR technology.

In addition, with “Next Generation” CO_2-EOR technology, the massive oil resource in the ROZs of the Permian Basin below 56 existing oil fields became feasible to be pursued, providing 11.9 billion barrels of technically recoverable resource and 4.8 million metric tons of CO_2 demand and storage capacity.

Expanding the understanding of ROZs beneath existing oil fields (reflected in the above resource number) to regionally extensive ROZ “fairways” would significantly increase the oil resource available from residual oil zones. This represents a major opportunity for “Next Generation” CO_2-EOR R&D.

7. Rockies

a. Background. The pursuit of new oil plays as well as the liquids-rich shale plays such as the Niobrara and Mancos shales have increased the rate of oil production in this region to 103 million barrels per year (280,000 barrels per day) in 2009 (Table VI-7.1).

Table VI-7.1. Oil Production from the Rockies (MM Bbls/Yr)

Year	Colorado*	Utah	Wyoming	TOTAL
2000	19	16	61	96
2001	18	15	57	90
2002	19	14	55	88
2003	22	13	52	87
2004	23	15	52	90
2005	24	17	52	93
2006	24	18	53	95
2007	24	20	54	98
2008	25	22	53	100
2009	29	23	51	103

*Includes New Mexico West. Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Rockies contains 142 oil reservoirs that screen favorably for miscible CO_2-EOR plus 4 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 146 reservoirs contain 22.5 billion barrels of OOIP out of a database of 172 reservoirs with 24.7 billion of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 142 the Rockies oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	21.9 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	7.1 billion barrels
Primary/Secondary Oil Recovery Efficiency	33%
Remaining Oil In-Place	14.7 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 142 oil reservoirs offers the potential for technically recovering 5.8 billion barrels of the remaining oil in-place, equal to 26% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 120 of the 142 oil reservoirs provide at least a 20% rate of return (before tax) and thus are deemed to be economically feasible. The economically feasible oil recovery is 4.7 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 142 Rockies oil fields technically favorable for miscible CO_2-EOR is 1,650 million metric tons (31 Tcf). The volume of purchased CO_2 for the 120 Rockies oil reservoirs economically favorable for miscible CO_2-EOR is 1,270 million metric tons (24 Tcf).

(5) Summary Table. Table VI-7.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in Rockies.

Table VI-7.2. Rockies Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	5.8	4.7	1,650	1,270
2. Regional Totals	9.6	4.7	2,750	1,270

*Database totals extrapolated to regional totals using a dividing factor of 0.6.
** Includes 330 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the Rockies oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	0.6 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.2 billion barrels
Primary/Secondary Oil Recovery Efficiency	24%
Remaining Oil In-Place	0.5 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 4 oil reservoirs offers the potential for technically recovering less than a tenth of one billion barrels of the remaining oil in-place, equal to 4% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2, none of the oil reservoirs provide at least a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 4 Rockies oil fields technically favorable for near miscible CO_2-EOR is 30 million metric tons (<1 Tcf).

(5) Summary Table. Table VI-7.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in the Rockies.

Table VI-7.3. Rockies Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	<1	-	30	-
2. Regional Totals	<1	-	40	-

*Database totals extrapolated to regional totals using a dividing factor of 0.6.

e. Miscible and Near Miscible CO_2-EOR. Table VI-7.4 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in Rockies.

Table VI-7.4. Rockies Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	5.8	4.7	1,670	1,270
2. Regional Totals	9.7	4.7	2,790	1,270

*Database totals extrapolated to regional totals using a dividing factor of 0.6.
** Includes 230 million metric tons of CO2 demand expected to be provided by natural sources and gas processing plants.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in the Rockies would provide valuable additional oil recovery and CO_2 storage (Table VI-7.5).

- Economic oil recovery would be 4.7 billion barrels with "Next Generation" technology compared to 1.9 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 1,270 million metric tons with "Next Generation" technology compared to 710 million metric tons (gross) with State of Art technology.

Table VI-7.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Rockies (Regional Totals)

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)**			
	▪ Technical	4.5	9.7
	▪ Economic	1.9	4.7
CO_2 Demand (Million Metric Tons)			
	▪ Technical	1,930	2,790
	▪ Economic		
	– Gross*	710	1,270
	– Net	480	1,040

* Includes 230 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.
**Includes 0.3 billion barrels already produced or proven with miscible CO_2-EOR technology.

In addition, with "Next Generation" CO_2-EOR technology, the residual oil zone (ROZ) resources in the Big Horn would provide 1.1 billion barrels of technically recoverable resources below 13 existing oil fields and would provide 0.4 million metric tons of CO_2 demand and storage capacity.

8. Southeast Gulf Coast

a. Background. The recent introduction of CO_2-EOR in Mississippi and Louisiana has helped stem the decline in oil production in this area. Oil production from the Southeast Gulf Coast was 100 million barrels (270,000 barrels per day) in 2009 (Table VI-8.1).

Table VI-8.1. Oil Production from the Southeast Gulf Coast (MM Bbls/Yr)

Year	Louisiana	Mississippi	Alabama/Florida	TOTAL
2000	105	20	15	140
2001	105	20	14	139
2002	93	18	12	123
2003	90	17	11	118
2004	83	17	10	110
2005	75	18	10	103
2006	74	17	10	101
2007	77	20	9	106
2008	73	22	10	105
2009	69	23	8	100

Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Southeast Gulf Coast contains 204 oil reservoirs that screen favorably for miscible CO_2-EOR plus 5 oil reservoirs that screen favorably for near miscible CO_2-EOR. These 209 reservoirs contain 23.8 billion barrels of OOIP out of a database of 298 reservoirs with 26.4 billion of OOIP.

c. Miscible CO_2-EOR.
(1). Database. The data for the 204 Southeast Gulf Coast oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	23.3 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	9.1 billion barrels
Primary/Secondary Oil Recovery Efficiency	39%
Remaining Oil In-Place	14.2 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 204 oil reservoirs offers the potential for technically recovering 6.0 billion barrels of the remaining oil in-place, equal to 26 % of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 146 of the 204 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 4.8 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 204 Southeast Gulf Coast oil fields technically favorable for miscible CO_2-EOR is 2,010 million metric tons (38 Tcf). The volume of purchased CO_2 for the 146 Southeast Gulf Coast oil reservoirs economically favorable for miscible CO_2-EOR is 1,440 million metric tons (27 Tcf).

Subtracting out the 130 million metric tons (3 Tcf) of CO_2 expected to be delivered to the Gulf Coast from natural sources (at 0.3 Bcfd for 30 years), still leaves a near- to mid-term market for purchase (and storage) of anthropogenic CO_2 of 1,310 million metric tons (24 Tcf).

(5) Summary Table. Table VI-8.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible Next Generation CO_2-EOR in Southeast Gulf Coast for the database and extrapolated to regional totals.

Table VI-8.2. Southeast Gulf Coast Oil Recovery and CO_2 Demand from Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	6.0	4.8	2,010	1,440
2. Regional Totals	10.1	4.8	3,350	1,440

*Database totals extrapolated to regional totals using a dividing factor of 0.60.
** Includes 130 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

d. Near Miscible CO_2-EOR.

(1). Database. The data for the 5 Southeast Gulf Coast oil reservoirs favorable for near miscible CO_2-EOR are as follows:

Original Oil In-Place	0.54 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	0.16 billion barrels
Primary/Secondary Oil Recovery Efficiency	30%
Remaining Oil In-Place	0.38 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 5 oil reservoirs offers the potential for technically recovering less than a tenth of one billion barrels of the remaining oil in-place, equal to 7% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), none of the oil reservoirs provide at least a 20% rate of return (before tax) and thus none are economically feasible.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 5 Southeast Gulf Coast oil fields technically favorable for near miscible CO_2-EOR is 30 million metric tons (1 Tcf).

(5) Summary Table. Table VI-8.3 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of near miscible "Next Generation" CO_2-EOR in Southeast Gulf Coast.

Table VI-8.3. Southeast Gulf Coast Oil Recovery and CO_2 Demand from Near Miscible "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	<0.1	-	30	-
2. Regional Totals	0.1	-	40	-

*Database totals extrapolated to regional totals using a dividing factor of 0.6.

e. Miscible and Near Miscible CO_2-EOR. Table VI-8.4 provides a summary of the oil recovery and CO_2 demand storage potential available from the application of "Next Generation" CO_2-EOR in Southeast Gulf Coast.

Table VI-8.4. Southeast Gulf Coast Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand** (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	6.1	4.8	2,040	1,440
2. Regional Totals	10.1	4.8	3,390	1,440

*Database totals extrapolated to regional totals using a dividing factor of 0.60.
**Includes 130 million metric tons of CO_2 demand provided by natural sources and gas processing plants.

f. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in the Southeast Gulf Coast would provide valuable additional oil recovery and CO_2 storage (Table VI-8.5).

- Economic oil recovery would be 4.8 billion barrels with "Next Generation" technology compared to 0.9 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 1,440 million metric tons (gross) with "Next Generation" technology compared to 290 million metric tons (gross) with State of Art technology.

Table VI-8.5. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Southeast Gulf Coast (Regional Totals)

		State of Art	Next Generation
Oil Recovery (Billion Barrels)			
	▪ Technical	5.4	10.1
	▪ Economic	0.9	4.8
CO_2 Demand (Million Metric Tons)			
	▪ Technical	2,590	3,390
	▪ Economic		
	– Gross*	290	1,440
	– Net	160	1,310

* Includes 130 million metric tons of CO_2 demand expected to be provided by natural sources and gas processing plants.

9. Williston Basin

a. Background. With the discovery and aggressive development of the Bakken Shale, oil production from the Williston Basin has more than doubled during this decade, reaching 109 million barrels per year (300,000 barrels per day), Table VI-9.1.

Table VI-9.1. Oil Production from the Williston Basin (MM Bbls/Yr)

Year	N/S Dakota	Montana	TOTAL
2000	34	15	49
2001	33	16	49
2002	32	17	49
2003	31	19	50
2004	33	25	58
2005	37	33	70
2006	41	36	77
2007	47	35	82
2008	64	32	96
2009	81	28	109

Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Williston Basin contains 86 oil reservoirs that screen favorably for miscible CO_2-EOR. These 86 reservoirs contain 9.3 billion barrels of OOIP out of a database of 95 reservoirs with 9.4 billion of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 86 Williston Basin oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	9.3 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	2.6 billion barrels
Primary/Secondary Oil Recovery Efficiency	28 %
Remaining Oil In-Place	6.7 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 86 oil reservoirs offers the potential for technically recovering 2.8 billion barrels of the remaining oil in-place, equal to 30% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 40 of the 86 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 1.3 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 demand for the 86 Williston Basin oil fields technically favorable for miscible CO_2-EOR is 820 million metric tons (15 Tcf). The volume of purchased CO_2 demand for the 40 Williston Basin oil reservoirs economically favorable for miscible CO_2-EOR is 360 million metric tons (7 Tcf).

(5). Summary. Table VI-9.2 provides a summary of the oil recovery and CO_2 demand storage potential from the application of "Next Generation" CO_2-EOR in Williston Basin.

Table VI-9.2. Williston Basin Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	2.8	1.3	820	360
2. Regional Totals	4.0	1.3	1,150	360

*Database totals extrapolated to regional totals using a dividing factor of 0.71.

d. Near Miscible CO_2-EOR. At this time, no oil reservoirs in the Williston Basin screen favorably for near miscible CO_2-EOR.

e. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in the Williston Basin would provide valuable additional oil recovery and CO_2 storage (Table VI-9.3).

- Economic oil recovery would be 1.3 billion barrels with "Next Generation" technology compared to 0.3 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 360 million metric tons with "Next Generation" technology compared to 130 million metric tons with State of Art technology.

Table VI-9.3. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Williston Basin (Regional Totals)

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	2.1	4.0
	▪ Economic	0.3	1.3
CO_2 Demand (Million Metric Tons)			
	▪ Technical	820	1,150
	▪ Economic	130	360

In addition, with "Next Generation" CO_2-EOR technology, the residual oil zone (ROZ) resources below 20 existing oil fields in the Williston Basin would provide 3.3 billion barrels of technically recoverable resources and would provide 1.3 million metric tons of CO_2 demand and storage capacity.

10. Alaska

a. Background. From a peak of 738 million barrels (2 million barrels per day) in 1988, oil production from Alaska's North Slope and Cook Inlets declined steadily -- 355 million barrels (1 million barrels per day) in 2000 and has 219 million barrels (600,000 barrels per day) in 2010 (Table VI-10.1).

Table VI-10.1. Oil Production from Alaska (MM Bbls/Yr)

Year	TOTAL
2000	355
2001	351
2002	359
2003	356
2004	332
2005	315
2006	270
2007	266
2008	250
2009	236
2010	219

Source: EIA Crude Oil Production by State (March 2011).

b. Reservoirs Favorable for CO_2-EOR. Advanced Resources' Big Oil Fields Database for Alaska contains 36 oil reservoirs that screen favorably for miscible CO_2-EOR. These 36 reservoirs contain 50.1 billion barrels of OOIP out of a data base of 43 reservoirs with 50.7 billion of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 36 Alaska oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	50.1 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	21.7 billion barrels
Primary/Secondary Oil Recovery Efficiency*	43%
Remaining Oil In-Place	28.4 billion barrels

*Includes oil recovery from hydrocarbon miscible EOR.

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 36 oil reservoirs offers the potential for technically recovering 8.7 billion barrels of the remaining oil in-place, equal to 17% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 19 of the 36 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 5.7 billion barrels

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 36 Alaska oil fields technically favorable for miscible CO_2-EOR is 4,070 million metric tons (77 Tcf). The volume of purchased CO_2 for the 19 Alaska oil reservoirs economically favorable for miscible CO_2-EOR is 2,330 million metric tons (44 Tcf).

(5). Summary Table . Table VI-10.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of miscible "Next Generation" CO_2-EOR in Alaska.

Table VI-10.2. Alaska Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	8.7	5.7	4,070	2,330
2. Regional Totals	8.8	5.7	4,110	2,330

*Database totals extrapolated to regional totals using a dividing factor of 0.99.

d. Near Miscible CO_2-EOR. At this time, no oil reservoirs in Alaska screened favorably for near miscible CO_2-EOR.

e. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Applying "Next Generation" CO_2-EOR in Alaska would provide valuable additional oil recovery and CO_2 storage (Table VI-10.3).

- Economic oil recovery would be 5.7 billion barrels with "Next Generation" technology compared to 2.6 billion barrels with State of Art technology.
- Economic CO_2 demand (and storage capacity) would be 2,330 million metric tons with "Next Generation" technology compared to 1,490 million metric tons with State of Art technology.

Table VI-10.3. Summary Table of Comparison of State of Art and "Next Generation" CO_2-EOR Technology: Alaska (Regional Totals)

		State of Art	"Next Generation"
Oil Recovery (Billion Barrels)			
	▪ Technical	5.8	8.8
	▪ Economic	2.6	5.7
CO_2 Demand (Million Metric Tons)			
	▪ Technical	3,320	4,110
	▪ Economic	1,490	2,330

11. Offshore Gulf of Mexico

a. Background. With the onset of new oil fields from deep waters, oil production from the Federal Offshore Gulf of Mexico and the state waters rebounded to 576 million barrels in 2009 (1,580,000 barrels per day) (Table VI-11.1).

Table VI-11.1. Oil Production from the Offshore Gulf of Mexico (MM Bbls/Yr)

Year	Federal Offshore	Louisiana State Offshore	Texas State Offshore	TOTAL
2000	523	13	1	537
2001	560	13	1	574
2002	568	11	1	580
2003	569	11	1	581
2004	532	10	1	543
2005	468	8	1	477
2006	474	8	*	482
2007	466	8	1	475
2008	422	6	1	429
2009	569	6	1	576

*Less than 0.5 million barrels. Source: EIA Crude Oil Production by State (March 2011).

b. Summary of Results. Advanced Resources' Big Oil Fields Database for the Offshore Gulf of Mexico contains 646 oil reservoirs (in 146 fields) that screen favorably for miscible CO_2-EOR. These 646 reservoirs contain 29.5 billion barrels of OOIP.

c. Miscible CO_2-EOR.

(1). Database. The data for the 646 Offshore Gulf of Mexico oil reservoirs favorable for miscible CO_2-EOR are as follows:

Original Oil In-Place	29.5 billion barrels
Expected Ultimate Primary/Secondary Oil Recovery	12.1 billion barrels
Primary/Secondary Oil Recovery Efficiency	41 %
Remaining Oil In-Place	17.4 billion barrels

(2). Technically Recoverable. "Next Generation" CO_2-EOR technology applied to these 646 oil reservoirs offers the potential for technically recovering 6.0 billion barrels of the remaining oil in-place, equal to 20% of OOIP.

(3). Economically Recoverable. Using an oil price of $85 per barrel (WTI) and $40 per metric ton of CO_2 (delivered at pressure to the basin), 123 oil reservoirs provide at least a 20% rate of return (before tax) and thus are economically feasible. The economically feasible oil recovery is 0.9 billion barrels.

(4). Purchase and Storage of CO_2. The volume of purchased CO_2 for the 146 Offshore Gulf of Mexico oil fields (646 reservoirs) technically favorable for miscible CO_2-EOR is 1,770 million metric tons (33 Tcf). The volume of purchased CO_2 for the 123 Offshore Gulf of Mexico oil reservoirs economically favorable for miscible CO_2-EOR is 260 million metric tons (4 Tcf).

(5). Summary Table. Table VI-11.2 provides a summary of the oil recovery and CO_2 demand and storage potential from the application of "Next Generation" CO_2-EOR in Offshore Gulf of Mexico.

Table VI-11.2. Offshore Gulf of Mexico Oil Recovery and CO_2 Demand from "Next Generation" CO_2-EOR

	Oil Recovery (Billion Barrels)		CO_2 Demand (Million Metric Tons)	
	Technical*	Economic	Technical*	Economic
1. Database Totals	6.0	0.9	1,770	260
2. Regional Totals	6.0	0.9	1,770	260

*Regional totals equal data base totals.

d. Near Miscible CO_2-EOR. At this time, no oil reservoirs in the Offshore Gulf of Mexico screened favorably for near miscible CO_2-EOR.

e. Comparison of State of Art and "Next Generation" CO_2-EOR Technology. Given the barriers, complexities and economic challenges of initiating CO_2-EOR in the Offshore Gulf of Mexico oil fields, this region, only feasible with "Next Generation" technology.

VII. OVERVIEW OF METHODOLOGY

A. Six Step Methodology

A six part methodology was used to assess the CO_2 storage potential of applying "Next Generation" CO_2-EOR technology to domestic oil reservoirs. The six steps were: (1) assembling and updating the Major Oil Reservoirs Database containing over 6,300 large domestic oil reservoirs; (2) calculating the minimum miscibility pressure for applying CO_2 -EOR; (3) using minimum miscibility pressure and other criteria to screen reservoirs favorable for miscible and near miscible CO_2-EOR; (4) calculating oil recovery from applying "Next Generation" CO_2-EOR technology; and (5) applying the updated cost and economic model. Step 6 was to incorporate the prior work conducted by Advanced Resources and Melzer Consulting on residual oil zones (ROZs) into this study and report.

B. Cost Model

The cost model includes costs for: (1) drilling new wells or reworking existing wells; (2) providing surface equipment for new wells; (3) installing the CO_2 recycle plant; (4) constructing a CO_2 spur-line from the main CO_2 trunkline to the oil field; and (5) other capital investment costs. The cost model also accounts for normal well operation and maintenance (O&M), for lifting costs of the produced fluids, and for costs of capturing, separating and reinjecting the produced CO_2.

C. Economic Model

The economic model used by the study is an industry standard cash flow model run on either a pattern or a field-wide basis. The key inputs and assumptions of the economic model include the following: (1) Oil Price - - $85 per barrel (WTI reference price); (2) CO_2 Purchase Costs - - $40 per metric ton (delivered at pressure to the oil field); (3) Financial Hurdle Rate - - 20% ROR (before tax); (4) Royalties - - 17.5%; (5) State Severance/Ad Valorem Taxes - - State specific; (6) CO_2 Reinjection Cost ($/Mcf) - - 1% of oil price ($/barrel) (for compression and treatment); and (7) CAPEX and OPEX - - state and depth specific.

D. Regional Scaling Factors

A series of scaling factors are used to extrapolate the technical oil recovery from the sample of oil fields in the Big Oil Fields Database to regional totals, as shown in Chapter 6 for each region. For two of the regions, Alaska and the Offshore Gulf of Mexico, the Big Oil Fields Database contains essentially all of the past oil production and proved reserves for these two regions. For other regions, the scaling factors range from 59% to 99%.

The scaling factor for technically recoverable oil for each region is based on the volume of oil production and proved reserves represented by the oil fields in the data base to total oil production and proved reserves reported for the region.

No scaling factors are used for extrapolating economically recoverable oil from the oil fields in the data base to regional totals. The economic results from the large oil fields in the data base, which tend to have more favorable economics due to resource size and scale, may not be representative of the economics of the thousands of smaller oil fields in a given region.

E. Additional "Next Generation" Model Features

The study incorporated the following additional features into this version of the "Next Generation" CO_2-EOR Model:

- The analysis assumes that the thinner, edge areas of the oil field, accounting for 20% of and reservoir area and 10% of the OOIP, will not be feasible for application of CO_2-EOR.

- The oil recovery model assumes that the residual oil left in the pore space after CO_2 injection (S_{orm}) is 8%. This compares to the previous analysis that used a more complex algorithm that related the S_{orm} to volumes of CO_2 injected.

- The model currently uses tapered WAG ratios starting with an initial large slug of CO_2 before introducing water for mobility control. The previous analysis used a consistent ("simple") WAG ratio. An economic truncation algorithm (comparing annual revenues with annual costs) halts project operation and CO_2 injection once annual cash flow becomes negative.

- The analysis assumes that 25% of the injected CO_2 is dissolved in the reservoirs water or is lost outside the pattern area and thus is not available as recycled CO_2 for meeting total CO_2 injection needs.

Additional detail on the "Next Generation" CO_2-EOR study methodology is provided in Appendix A.

APPENDIX A
Discussion of Study Methodology

STUDY METHODOLOGY

A five part methodology was used to assess the CO_2 storage and EOR potential of domestic oil reservoirs. The six steps were: (1) assembling and updating the Major Oil Reservoirs Database; (2) calculating the minimum miscibility pressure for applying CO_2 -EOR; (3) using minimum miscibility pressure and other criteria to screen reservoirs favorable for CO_2-EOR; (4) calculating oil recovery from applying "Next Generation" CO_2-EOR technology; and (5) applying the updated cost and economic model.

A. Assembling The Major Oil Reservoirs Database

Overall, the Major Oil Reservoirs Database contains over 6,300 reservoirs, accounting for 75% of the oil expected to be ultimately produced in the U.S. by primary and secondary oil recovery processes. Figure A-1 illustrates a portion of the reservoir data included in the Major Oil Reservoirs Database.

Considerable effort has been invested to construct an up-to-date, volumetrically consistent database that contained all of the essential data, formats and interfaces to enable the study to: (1) develop an accurate estimate of the size of the original and remaining oil in-place; (2) reliably screen the reservoirs as to their amenability for miscible and immiscible CO_2-EOR; and, (3) provide the *CO_2-PROPHET* Model the essential input data for calculating CO_2 injection requirements and oil recovery.

Figure A-1. Reservoir Data Format: Major Oil Reservoirs Database

Basin Name	**Area:**	
State		To change Basin, click on cell above
Field Name	**Reservoir Number**	
	Manual	
Reservoir	**Total Reservoirs**	

Reservoir Parameters:	**Oil Production**	**Volumes**
Area (A)	Producing Wells (active)	OOIP (MMbl)
Net Pay (ft)	Producing Wells (shut-in)	Cum P/S Oil (MMbl)
Depth (ft)	2008 Production (MMbbl)	EOY 2008 P/S Reserves (MMbl)
Lithology	Daily Prod - Field (Bbl/d)	Ultimate P/S Recovery (MMbl)
Dip (*)	Cum Oil Production (MMbbl)	Remaining (MMbbl)
Gas/Oil Ratio (Mcf/Bbl)	EOY 2008 Oil Reserves (MMbbl)	Ultimate P/S Recovered (%)
Salinity (ppm)	Water Cut	P/S Sweep Efficiency (%)
Gas specific Gravity		**OOIP Volume Check**
Historical Well Spacing (Acres)	**Water Production**	Reservoir Volume (AF)
Current Pattern Acreage (Acres)	2008 Water Production (Mbbl)	Bbl/AF
Permiability (mD)	Daily Water (Mbbl/d)	OOIP Check (MMbl)
Porosity (%)		
Reservoir Temp (deg F)	**Injection**	**SROIP Volume Check**
Initial Pressure (psi)	Injection Wells (active)	Reservoir Volume (AF)
Pressure (psi)	Injection Wells (shut-in)	Swept Zone Bbl/AF
	2008 Water Injection (MMbbl)	SROIP Check (MMbbl)
B_{oi}	Daily Injection - Field (Mbbl/d)	
B_o @ S_o, swept	Cum Injection (MMbbl)	
S_{oi}	Daily Inj per Well (Bbl/d)	**ROIP Volume Check**
S_{or}		ROIP Check (MMbl)
S_{wi}	**EOR**	
S_w	Type	
	2009 EOR Production (MMbbl)	
API Gravity	Cum EOR Production (MMbbl)	
Viscosity (cp)	EOR 2009 Reserves (MMbbl)	
	Ultimate Recoverery (MMbbl)	
Dykstra-Parsons	**OGJ Data**	
Miscibility:	2009 Enhanced Production (B/d)	
C5+ Oil Composition	2009 Total Production (B/d)	
Min Required Miscibility Press(psig)	Project Acreage	
Depth > 3000 feet	Scope	
API Gravity >= 17.5	# Projects	
Pr > MMP		
Flood Type		

B. Calculating Minimum Miscibility Pressure

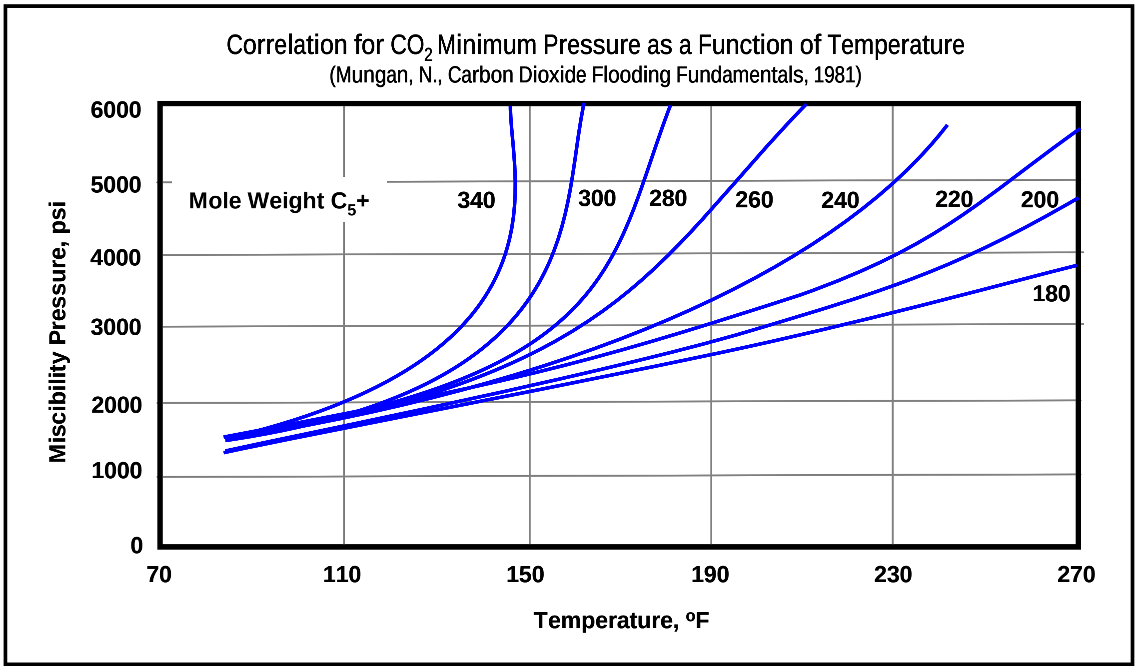
The miscibility of a reservoir's oil with injected CO_2 is a function of pressure, temperature and the composition of the reservoir's oil. The study's approach to estimating whether a reservoir's oil will be miscible with CO_2, given fixed temperature and oil composition, is to determine whether the reservoir would hold sufficient pressure to attain miscibility. To determine the minimum miscibility pressure (MMP) for any given reservoir, the study used the Cronquist correlation. This formulation determines MMP based on reservoir temperature and the molecular weight (MW) of the pentanes and heavier fractions of the reservoir oil, as set forth below:

$$MMP = 15.988 * T^{(0.744206+0.0011038*MW\ C5+)}$$

Where: T is Temperature in °F, and MW C5+ is the molecular weight of pentanes and heavier fractions in the reservoir's oil.

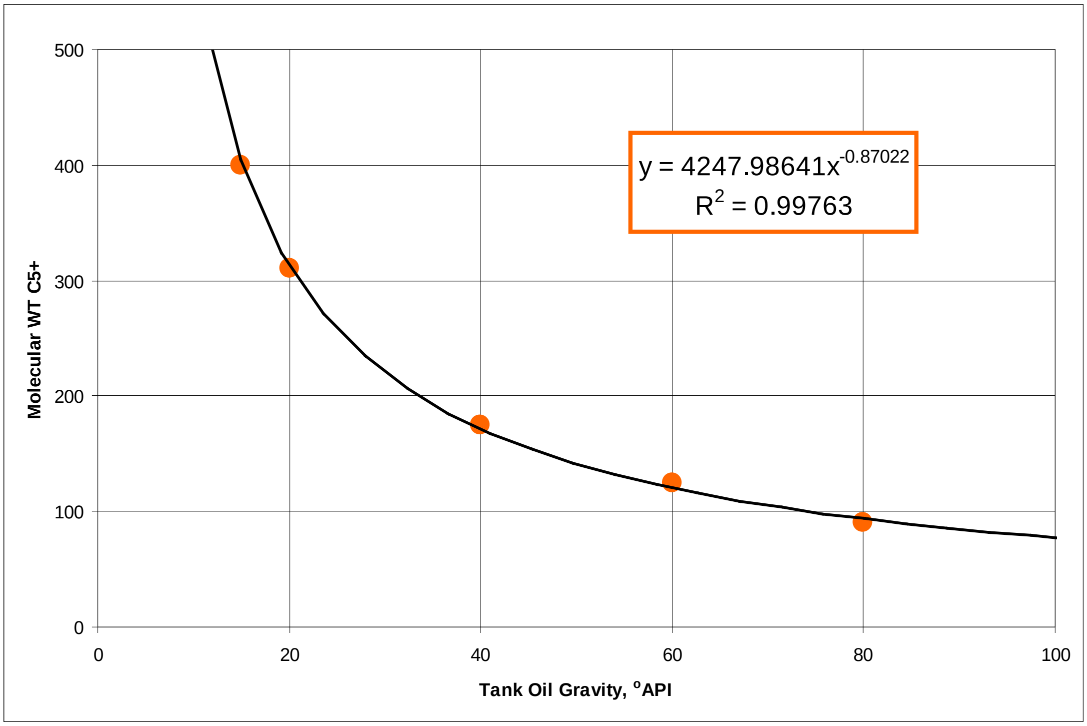
A similar approach to estimating minimum miscibility pressure, prepared by Mungan (1981), is shown on Figure A-2.

Figure A-2. Estimating CO_2 Minimum Miscibility Pressure



The temperature of the reservoir was taken from the database or estimated from the thermal gradient in the basin. The molecular weight of the pentanes and heavier fraction of the oil was obtained from the database or was estimated from a correlative plot of MW C5+ and oil gravity, shown in Figure A-3.

Figure A-3. Correlation of MW C5+ to Tank Oil Gravity



C. Screening Reservoirs for CO_2-EOR

The preliminary screening steps involved selecting the deeper oil reservoirs that had sufficiently high oil gravity. A minimum reservoir depth of 2,500 to 3,000 feet, at the mid-point of the reservoir, was used to ensure the reservoir could accommodate high pressure CO_2 injection. A minimum oil gravity of 17.5 ^{o}API was used to ensure the reservoir's oil had sufficient mobility, without requiring thermal injection.

The next step was comparing the minimum miscibility pressure (MMP) to the maximum allowable pressure. The maximum pressure was determined using a pressure gradient of 0.6 to 0.7 psi/foot, depending on the region. If the minimum miscibility pressure was below the maximum injection pressure, the reservoir was classified as a miscible flood candidate. Oil reservoirs that did not screen positively for miscible CO_2-EOR were selected for consideration by near miscible CO_2-EOR.

D. Calculating Oil Recovery

The study utilized *CO_2-PROPHET* to calculate incremental oil produced using "Next Generation" CO_2-EOR technology.

- *CO_2-PROPHET* generates streamlines for fluid flow between injection and production wells, and
- The model performs oil displacement and recovery calculations along the established streamlines. (A finite difference routine is used for oil displacement calculations.)

Even with these features, it is important to note the *CO_2-PROPHET* is still primarily a "screening-type" model, and lacks some of the key features, such as gravity override and compositional changes to fluid phases, available in more sophisticated reservoir simulators. More detailed assessments of CO_2-EOR would need to use a compositional, 3D reservoir simulator.

E. Assembling The Cost and Economics Models

A detailed, up-to-date CO_2-EOR Cost Model was developed for the study. The model includes costs for: (1) drilling new wells or reworking existing wells; (2) providing surface equipment for new wells; (3) installing the CO_2 recycle plant; (4) constructing a CO_2 spur-line from the main CO_2 trunkline to the oil field; and (5) other costs.

The cost model also accounts for normal well operation and maintenance (O&M), for lifting costs of the produced fluids, and for costs of capturing, separating and reinjecting the produced CO_2.

The economic model used by the study is an industry standard cash flow model that can be run on either a pattern or a field-wide basis. The economic model accounts for royalties, severance and ad valorem taxes, as well as any oil gravity and market location discounts (or premiums) from the "marker" oil price.

The key inputs and assumptions of the economic model include the following:

- Oil Price - - $85 per barrel (WTI reference price). The oil price selected for the analysis is consistent with EIA's Annual Energy Outlook oil price for years 2012 and 2013.
- CO_2 Purchase Price - - $40 per metric ton (delivered at pressure to the oil field). The CO_2 purchase price selected is consistent with historical ratios relating to CO_2 purchase to oil price using a value of 2.5% (with a range of 2% to 3%) of the oil price to calculate the CO_2 purchase price in $/Mcf. For example at an $85 per barrel oil price, the CO_2 purchase price would be $2.12/Mcf equal to about $40 per metric ton.
- Financial Hurdle Rate - - 20% ROR (before tax)
- Royalties - - 17.5%
- State Severance/Ad Valorem Taxes - - State specific
- CO_2 Reinjection Cost - - 1% of oil price (for compression and treatment)
- CAPEX and OPEX - - State and depth specific.

G. Other Considerations

Based on discussions with operators, the study incorporated the following additional features into this version of the "Next Generation" CO_2-EOR Model:

- The analysis assumes that the thinner, edge areas of the oil field, accounting for 20% of the field and reservoir area and 10% of the OOIP, will not be feasible for application of CO_2-EOR.
- The oil recovery model assumes that the residual oil left in the pore space after CO_2 injection is 8%.
- The quantity of CO_2 injected is up to 1.5 HCPV. The tapered WAG ratios includes an initial large slug of CO_2 plus water for mobility control.
- An economic truncation algorithm (comparing annual revenues with annual costs) halts project operation and CO_2 injection once annual cash flow becomes negative.
- The analysis assumes that 25% of the injected CO_2 is dissolved in water or is lost outside the pattern area.

APPENDIX B
A Summary of the Meetings with Industry Practitioners

Background

A series of "field" visits and meetings were held with industry experts active in applying CO_2-EOR technology. The purpose of the visits and meetings were to: (1) obtain industry feedback on the methodology and results of the NETL/ARI studies of CO_2-EOR; and (2) to discuss observations and recommendations for conducting an updated assessment of "Next Generation" CO_2-EOR and CO_2 storage.

Three specific industry review meetings were held in September 2010 involving Don Remson of NETL, Vello Kuuskraa, Robert Ferguson and Tyler Van Leeuwen of Advanced Resources International and Bob Blaylock of BAH.

- The first meeting was on September 9, 2010 in Houston, Texas with Kinder Morgan. This meeting involved two Kinder Morgan staff - - Lanny Schoeling, Vice President, Engineering & Technical Development and Steve Pontious, Staff Engineer.
- The second meeting was during the afternoon of September 9, 2010 in Houston, Texas with Hess Corporation. This meeting involved four staff - - Manuel De Jesus Valle, Geological Advisor, Americas Onshore Subsurface; Ed De Zabala, Senior Reservoir Engineering Advisor, EOR Exploration and Production Technology; Alvaro Grijalba, Subsurface Team Lead, Americas Technical – Permian; and Paul Carmody, Facilities Engineering Advisor, Americas Production Excellence.
- The third meeting was on September 16, 2010 in Midland, Texas with a number of industry experts from eight companies. The meeting involved:
  - Steve Melzer, President of Melzer Consulting
  - Barry Schneider of Denbury Resources
  - Scott Wehner, Manager – Engineering; Andrew Parker, Geoscientists – Permian Basin; and Tom Beebe, Sr. Reservoir Engineer of Whiting Petroleum Corporation
  - Mike Moore, Vice President, External Affairs & Business Development CCS of Blue Source
  - Dr. Robert Trentham, Director, Center for Energy and Economic Diversification, University of Texas of the Permian Basin
  - Brian Hargrove and Barry Petty, Trinity CO_2
  - Michael Rushing, CO_2/EOR Manager, Apache Corporation, and
  - Tom Thurmond, Engineering Manager, Legado Resources

Overall Industry Observations

The industry experts found that the methodology and results of the CO_2-EOR studies of NETL/ARI were reasonable. While a number of excellent suggestions were made as to how specific areas of the methodology could be improved (e.g., current higher costs of CO_2 pipelines), the overall response, as stated by one respondent was "if we were asked to do this, we probably would have done it the same way."

The industry reviewers found the oil recovery efficiencies of 15% to 20% of OOIP for oil reservoirs geologically favorable for CO_2 to be reasonable. (Overall, the NETL/ARI results for "state of art" CO_2-EOR provides 17.5% recovery of OOIP, after eliminating oil reservoirs not favorable for miscible CO_2-EOR.) The industry experts cited examples of CO_2-EOR projects that were recovering 17% to 18% of OOIP and, with additional reservoir surveillance and technology, were looking to push this over 20% of OOIP.

Two specific observations were made with respect to observed oil recovery efficiencies in actual CO2-EOR floods:

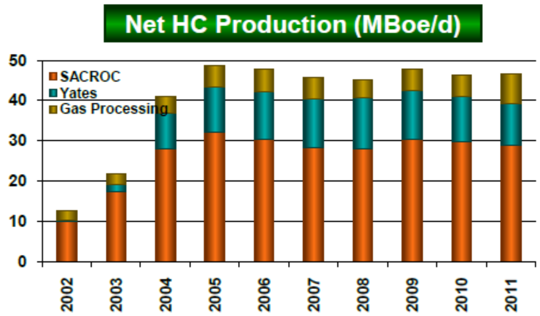
- Whiting noted that their Postle CO_2-EOR project is currently expected to recover 17% to 18% of OOIP and, with application of cross-well seismic and increased use of CO_2 in selected patterns, the company looks to push up the recovery efficiency to the mid-twenties.
- Denbury noted that their oil recovery expectations are for 17% to 18% of OOIP for straight CO_2 flooding. With incorporation of a WAG process at the end of the straight CO_2-flood, Denbury looks to boost oil recoveries to 20% OOIP. Denbury specifically cited the West Heidelberg oil field which already has an expected 18% recovery of OOIP from CO_2-EOR (60% OOIP overall recovery). They are considering converting this field to a WAG process to further increase oil recovery.

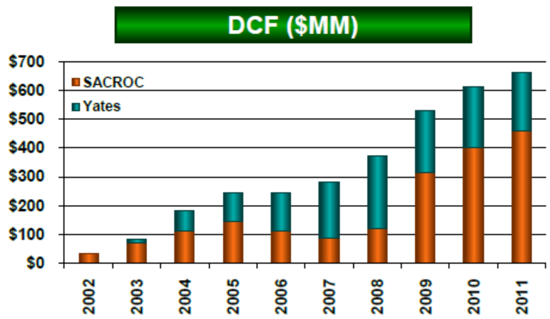
The exclusion of NGL production from the liquids production reported for CO_2-EOR projects is one reason reported oil recovery efficiencies are lower than actual total liquids recoveries. (A barrel of NGLs has about two-thirds of the Btu content and sales value of crude oil.) For example:

- The SACROC CO_2-EOR project operated by Kinder Morgan reports (for 2010) about 29,000 barrels per day of oil production and about 16,000 barrels per day of NGL production from the SACROC gas plant. (A small portion of the input stream to the gas plant is from other nearby oil fields.) Adding the NGL production (after adjusting for Btu content) would increase the reported liquids production value by 37 %, see Table B-1.
- Whiting reports that their long-term observation is that CO_2-EOR strips the light ends from the crude oil (the propane, butane, etc.) leading to significantly higher incremental NGL production volumes after the initiation of a CO_2 flood.

Future assessments of the performance of CO_2-EOR would benefit from the incorporation of NGL production into overall oil recovery estimates and economics.

Table B-1. Oil and Gas Segment: Production and DCF





Original Oil in Place (billion Bbls)	
SACROC	2.8
Yates	5.0
Katz	0.23

Gross Production (Bbl/d)	2010	2011
SACROC oil	29,222	29,374
SGP NGLs	15,921	17,001
Yates	24,046	22,500
Katz	284	1,451

DCF ($MM)	2010	2011
SACROC Unit-only	$400	$459
Yates	$213	$203
Katz	$1	$17

Notes: Yates DCF does not include contribution from MKM
Boe: Oil and NGL =1:1, Residue gas sales = 6:1
Gas Processing includes net Boe attributable to our plant interests and processing agreements but excluded from reserve report

Source: KinderMorgan, 2011

Major Recommendations

The industry experts made ten significant recommendations for improving the modeling of "Next Generation" CO_2-EOR.

Recommendation #1. Consider modifying the injected CO_2 to water ratio, including using a larger initial slug of CO_2 or even straight CO_2 in low permeability oil reservoirs, to increase the processing rate and reduce the need to "drill down" the pattern.

Currently, the model uses the same WAG ratio, independent of the permeability (and thus injectivity) of the reservoir, often causing the model to use closer well spacing than currently exists to achieve a 15 to 30 year flood (per pattern).

Modifying the WAG ratio or eliminating the use of water would enable the model to use larger well spacing, reducing the need to drill additional wells and thus improving economics.

The *PROPHET2* model has been revised to set the minimum pattern size to 40 acres, to increase minimum CO_2 injectivity, and to incorporate a larger initial CO_2 slug, as part of a tapered WAG.

Recommendation #2. Consider applying the CO_2 flood to only 80% of the reservoir area to eliminate the low quality edge of the reservoir from being flooded. The exact factor could be related to field size, with large fields having a higher factor of developable acreage.

Currently, the model selects one type pattern and applies the results from this type pattern to the entire reservoir. A key input is the average reservoir net thickness which includes both the thicker central area and the thinner edge area. Reducing the CO_2 flood to the higher quality, thicker pay central area of the oil reservoir would provide somewhat higher recovery per pattern and enable fewer patterns to flood the bulk of the OOIP.

The PROPHET model has been revised to flood only 80% of the field area containing 90% of the OOIP.

Recommendation #3. Consider allowing higher gravity oils to become miscible or near miscible CO_2 candidates due to achieving multi-contact miscibility with time. Currently, lower gravity oil reservoir, say 18^o to 20^o API, are generally categorized as immiscible floods, relegated to low recovery of the OOIP.

Certain lower gravity floods in relatively shallow oilfields, such as the Eucutta oil field, are achieving higher oil recovery efficiency than would be realized from an immiscible model. A similar lower oil gravity CO_2 flood with higher expected performance is in planning stages for the shallower Wall reservoir in the Salt Creek field in Wyoming. Applying near miscible CO_2 flooding to these lower oil gravity oil reservoirs would provide higher oil recovery efficiencies.

This recommendation has been incorporated, in a preliminary way, into the model, but requires further analytical work.

Recommendation #4. Incorporate the oil resources and production from the Residual Oil Zones (ROZs) into "Next Generation" ROZ. Currently the model only floods the MPZ (main pay zone of the oil reservoir). However, evidence is mounting that the San Andres ROZ in the Permian Basin is of high quality, with a thick pay and favorable oil saturation.

Adding the ROZ of the San Andres formation in the Permian Basin would increase the size of the target oil producible with CO_2-EOR. It would also significantly increase the storage volume for CO_2.

The already performed study of the Permian, Big Horn and Williston basins' ROZ resources (beneath existing fields) will be incorporated into this "Next Generation" study. Further study of ROZ resources, with a particular emphasis on the oil resources held in ROZ "fairways" and on the economic feasibility of producing oil from ROZs would significantly improve the understanding of this important domestic oil resource.

Recommendation #5. Use marginal oil productivity and costs to set the maximum HCPV of CO_2 to be injected.

Currently, the *PROPHET2* model uses 1.0 HCPV for the "State of Art" CO_2-EOR case and uses 1.5 HCPV for the "Next Generation" CO_2-EOR case. Making the volume of CO_2 injected in the "Next Generation" CO_2-EOR case a function of marginal costs would provide a more realistic representation of current EOR operations.

This feature has been incorporated into this "Next Generation" study.

Recommendation #6. Consider including a "combination technology case", involving injection of CO_2 and surfactant, for improving oil recovery from immiscible CO_2-EOR projects, such as Yates.

Currently, oil reservoirs categorized as immiscible are not included in this study. Adding a low-concentration of surfactant slug followed by CO_2 could substantially increase oil recovery efficiency in shallower, immiscible flooded CO_2-EOR projects.

This feature is being investigated for use in subsequent model updates.

Recommendation #7. Increase the size of the initial CO_2 slug to 0.4 HCPV before starting a CO_2 WAG.

Currently, the CO_2 flooding design is to conduct a 1 to 3 WAG for the first 0.4 HCPV of injected CO_2, followed by a 1 to 2.5 WAG for the remaining 0.6 HCPV of injected CO_2. Increasing the volume of the CO_2 slug at the start of the project will provide a quicker oil response and potentially help promote miscibility, helping improve the economics of the CO_2 flood.

The tapered WAG feature has been incorporated into this "Next Generation" study.

Recommendation #8. Modify the CO_2 injection and production algorithm in PROPHET2 to reflect a higher net CO_2 to oil ratio, to account for dead-end pores and loss of CO_2 outside the pattern.

Currently, the model does not include dead-end pore space or loss of CO_2 outside the pattern, thus providing a relatively favorable CO_2 material balance. Reducing the production of CO_2 to about 75% of what would otherwise occur, to account for dead-end pore space and CO_2 losses, would raise the required purchase volumes of CO_2.

This feature has been incorporated into this "Next Generation" CO_2-EOR study.

Recommendation #9. Consider incorporating the higher NGL production achieved from CO_2-EOR floods in the overall economics.

Currently, only the oil production from a CO_2 flood is included in the recovery efficiency and economic calculation. Past experience shows that implementation of CO_2-EOR significantly improves the stripping of light ends from the crude oil.

This feature is being investigated for use in subsequent model updates.

Recommendation #10. Consider using basin-by-basin criteria for establishing the maximum pressure gradient for MMP (minimum miscibility pressure).

Currently, the screening criteria for miscibility use a maximum pressure gradient of 0.6 psi/ft. for all basins. Increasing the pressure gradient to a higher, say 0.7 psi/ft. for the Illinois Basin would enable a shallower, 2,700 reservoir with a MMP of 1,800 psi to be a miscible CO_2 flood (maximum pressure of 1,890 psi) instead of being processed as an immiscible CO_2 flood (maximum pressure of 1,620 psi).

This feature has been incorporated into the "Next Generation" analysis of the Illinois Basin.