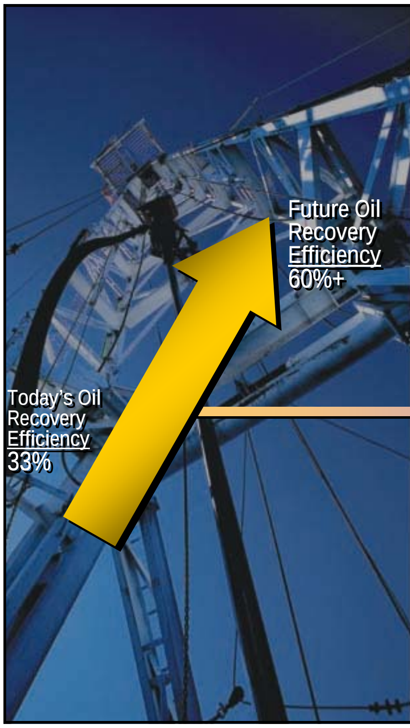

MAXIMIZING OIL RECOVERY EFFICIENCY AND SEQUESTRATION OF CO_2 WITH "NEXT GENERATION" CO_2-EOR TECHNOLOGY

Session 19 – SPE Special Session

Prepared for:
2nd Petrobras International Seminar on CO_2 Capture and Geological Storage

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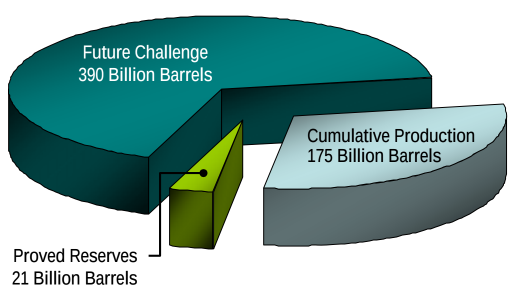
Background

1. Status and Outlook for U.S. CO_2-EOR
2. Market Demand for CO_2 from the EOR Industry
3. "Next Generation" CO_2-EOR Technology
   - Increasing Oil Recovery Efficiency
   - Integrating CO_2–EOR and CO_2 Storage
4. Summary

Large Volumes Of Oil Remain "Stranded" After Primary/Secondary Oil Recovery

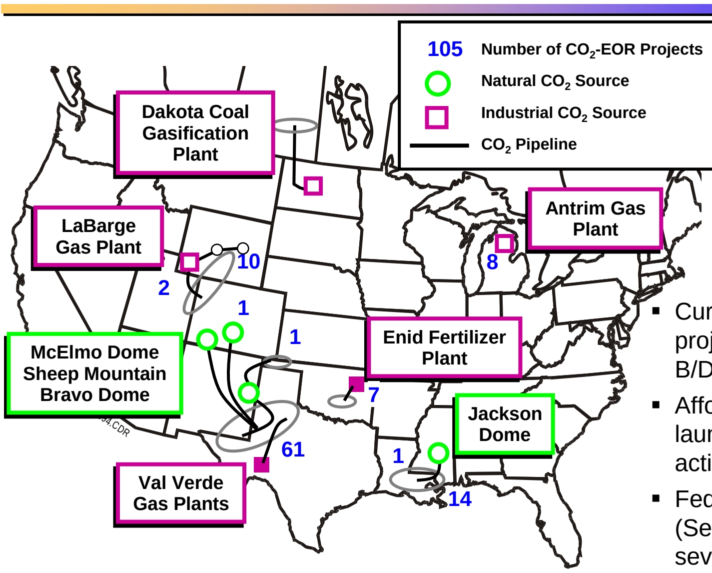
Original Oil In-Place (U.S.): 596 B Barrels*

"Stranded" Oil In-Place (U.S.): 400 B Barrels*



*All U.S. domestic basins except Deep Water GOM.
Source: Advanced Resources Int'l. (2007)

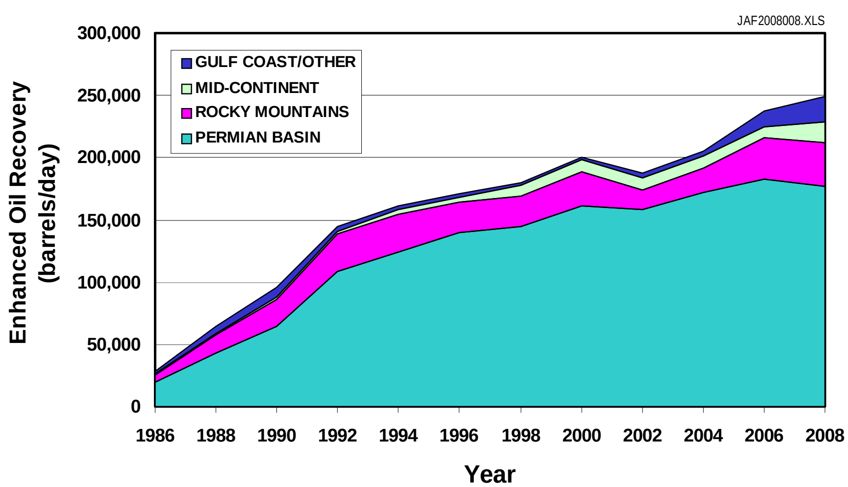
U.S. CO_2-EOR Activity



- Currently,105 CO_2-EOR projects provide 250,000 B/D
- Affordable natural CO_2 launched CO_2-EOR activity in the 1980's
- Federal tax credits (Sec.43) and state severance tax relief still encourage CO_2-EOR

Source: Oil and Gas Journal, 2008.

Growth of CO_2-EOR Production in the U.S.



Source: Oil and Gas Journal, 2008.

CO_2- EOR Activity Outside of the U.S.

		Area	Formation	Depth	Oil Gravity	Viscosity
Canada						
	Weyburn Unit	9,900	LS/Dolo	4,660’	28°	3 cp
	Joffre	6,625	Sand	4,900’	42°	1 cp
Trinidad						
	Forest Reserve	500	Sand	2,000-4,200’	17-25°	10-100+ cp
	Oropouche	175	Sand	2,400’	29°	5 cp
Turkey						
	Bati Raman	12,890	LS	4,260’	13°	590 cp

Numerous hydrocarbon miscible and nitrogen EOR projects exist in Canada, Libya, UAE, Mexico and Venezuela that would be favorable and convert to CO_2-EOR

In addition, CO_2-EOR has been discussed for oil fields in the North Sea.

Outlook For U.S. CO_2-EOR

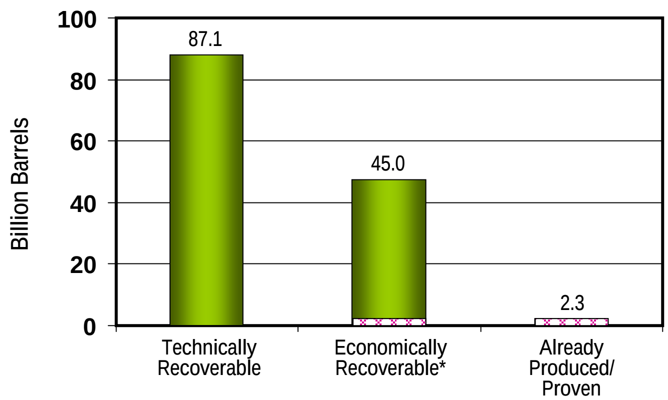
Advanced Resources, Int’l. recently updated their prior studies of U.S. CO_2-EOR, assuming use of current “best practices” technology:

- 87 billion barrels of technically recoverable resource, with 2+ billion barrels already produced or placed into reserves.
- From 39 to 48 billion barrels of economically recoverable resource: oil prices ranging from $50 to $100 per barrel, CO_2 costs ranging from $35 to $60 per metric ton.

Results are based on applying streamline reservoir simulation to 2,012 large oil reservoirs (74% of U.S. oil production).

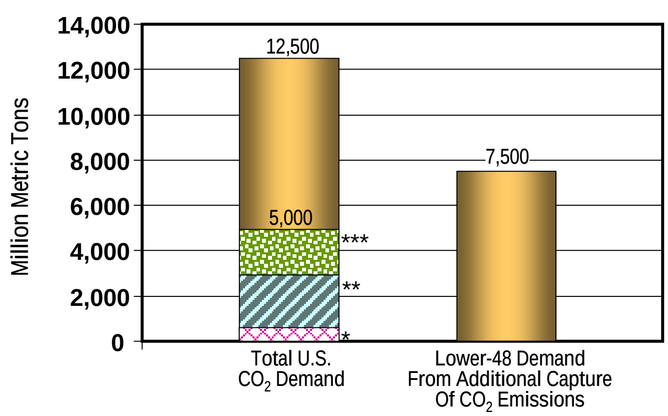
Previous version of the “basin studies” are available on the U.S. DOE web site. http://www.fe.doe.gov/programs/oilgas/eor/Ten_Basin-Oriented_CO2-EOR_Assessments.html

U.S Oil Resources Technically and Economically Recoverable w/CO_2-EOR



*Assuming oil price of $70/B (real); CO2 costs (delivered to field at pressure) of $45/metric ton ($2.38/Mcf); investment hurdle rate (15%, real).

Market Demand for CO_2 by the Enhanced Oil Recovery Industry(1)



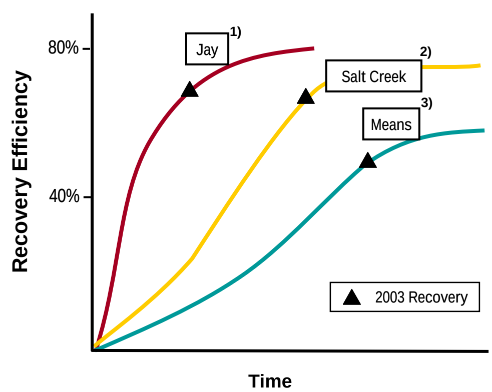
*CO_2 demand already being met by on-going CO_2-EOR projects.
**CO_2 demand in Alaska for EOR.
***CO_2 demand that can be met by natural CO_2 and already being captured CO_2 emissions.
(1) Economic CO_2 market demand for EOR at oil price of $70/B (real), CO_2 cost of $45/mt, and ROR of 15% (real, before tax).

Sources of CO_2 for EOR/ Volume of CO_2 Stored by EOR

State/ Province (storage location)	Source (location)	CO_2 Supply (MMcfd**)	
		Natural	Anthropogenic
Texas-Utah-New Mexico-Oklahoma	Geologic (Colorado-New Mexico) Gas Processing (Texas)	1,700	195/635
Colorado-Wyoming	Gas Processing (Wyoming)	-	340
Mississippi	Geologic (Mississippi)	700	-
Michigan	Gas Processing Plant (Michigan)	-	15
Oklahoma	Fertilizer Plant (Oklahoma)	-	35
Saskatchewan	Coal Gasification (North Dakota)	-	145
TOTAL MMcfd		2,400	730/1,170
TOTAL MMmt/Yr		46	14/23

* Source: 12th Annual CO2 Flooding Conference, Dec. 2007
** MMcfd of CO2 can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by 18.9 * 10^3 (Mcf per metric ton).

Is There Potential for Higher Oil Recovery Efficiencies and Greater CO_2 Demand from CO_2-EOR?



Jay:
1. Deep, light oil reservoir under nitrogen (N_2) EOR.

Salt Creek:
2. Representative light oil (39° API) West Texas carbonate oil field with 48% primary/secondary oil recovery.

Means:
3. Representative heavy oil (29° API) West Texas carbonate oil field with 25% primary/secondary oil recovery.

Source: Three ExxonMobil Oil Fields, SPE 88770 (2004)

“Next Generation” CO_2-EOR Technology

Reservoir modeling and selected field tests show that high oil recovery efficiencies are possible with innovative applications of CO_2-EOR.

So far, except for a handful of cases, the actual performance of CO_2-EOR has been less than optimum due to:

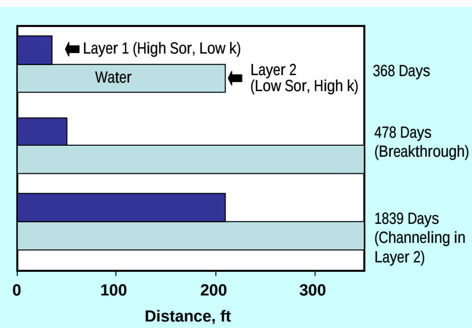
- **Geologically complex reservoirs**
- **Limited process control**
- **Insufficient CO_2 injection**

Impact of Geologic Complexity on CO_2-EOR Performance

Inability to target injected CO_2 to reservoir strata with high residual oil saturation.

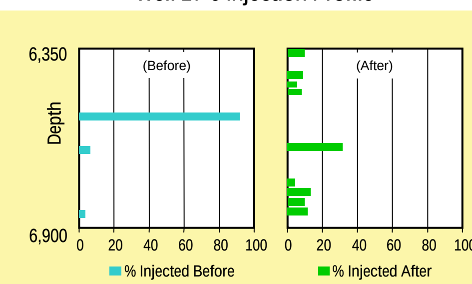
- Higher oil saturation portion of reservoir is inefficiently swept;
- CO_2 channeling reduced with well workover.

Relative Location of the Water Front



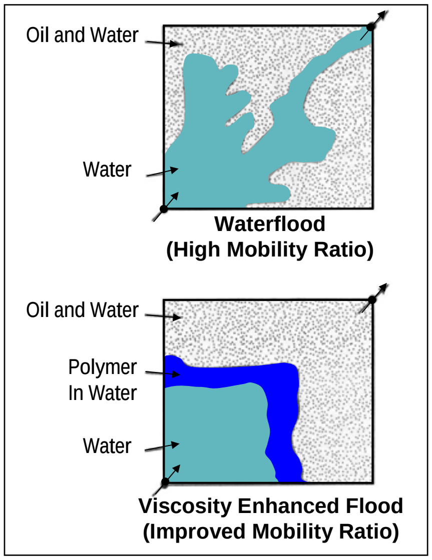
Source: Adapted by Advanced Resources Int'l from “Enhanced Oil Recovery”, D.W. Green and G. P. Willhite, SPE, 1998.

Well 27-6 Injection Profile



Source: “SACROC Unit CO_2 Flood: Multidisciplinary Team Improves Reservoir Management and Decreases Operating Costs”, J.T. Hawkins, et al., SPE Reservoir Engineering, August 1996.

Impact of Limited Process Control on CO_2-EOR Performance



Injected CO_2 achieves only limited contact with the reservoir due to:

- **Viscous fingering**
- **Gravity override**

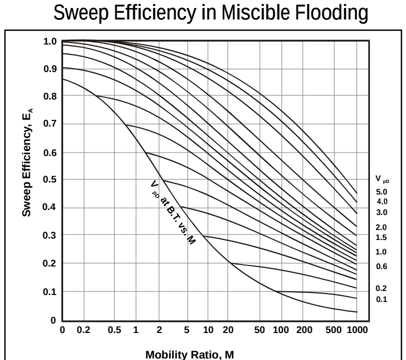
Addition of viscosity enhancers would improve mobility ratio and reservoir contact.

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

Impact of Insufficient CO_2 Injection on CO_2-EOR Performance

Because of high CO_2 costs and lack of process control, most older CO_2 floods used too little CO_2.

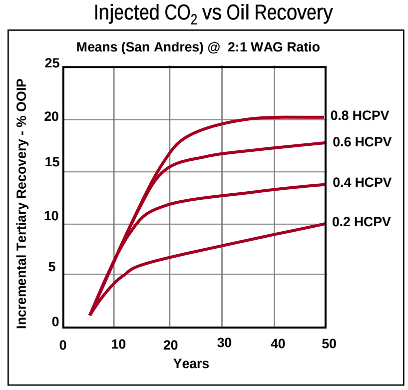
Sweep Efficiency in Miscible Flooding



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

Source: Claridge, E.L., "Prediction of Recovery in Unstable Miscible Displacement", SPE (April 1972).

Injected CO_2 vs Oil Recovery



Source: SPE 24928 (1992)

“Next Generation” CO_2-EOR Technology

Over coming these technical barriers requires “next generation” CO_2-EOR technology:

- **Innovative Flood Design and Well Placement**. Adding selectively completed wells and working over existing wells to enable injected CO_2 to contact residual oil from poorly swept portions of the reservoir.
- **Viscosity and Miscibility Enhancement**. Adding mobility control with viscosity enhancers and lowering MMP with miscibility enhancers.
- **Increased Volume of CO_2 Injection**. Injecting up to 1.5 HCPV of CO_2.
- **Flood Performance Diagnostics and Control**. Establishing fully staffed technical team. Using instrumented observation wells and downhole sensors to monitor CO_2 flood progress. Conduct periodic 4-D seismic and zone-by-zone flow tests to “manage and control” the CO_2 flood.

“Game Changer” CO_2-EOR Technology

The DOE report, ***“Evaluating the Potential for “Game Changer” Improvements in Oil Recovery Efficiency from CO_2-Enhanced Oil Recovery”:***

- Reviews performance of past CO_2-EOR floods.
- Sets forth theoretically and scientifically possible advances in technology for CO_2-EOR.
- Examines how much “game changer” CO_2-EOR technology would increase oil recovery and CO_2 storage capacity in the U.S.

Previous version of the “game changer” report is available on the U.S. DOE web site. http://www.fe.doe.gov/programs/oilgas/publications/eor_co2/Game_Changer_Document.pdf

U.S. Oil Resources Technically Recoverable w/"Next Generation" CO_2-EOR

Advanced Resources recently updated their study of applying "Next Generation" CO_2-EOR to U.S. oilfields, showing significant improvements in domestic oil recovery efficiency and economic resources.

State of Technology	Reservoir Favorable for CO2-EOR		Oil Recovery	
	Number	OOIP (BBbls)	Technical (MMBBbls)	Economic** (MMBBbls)
Current "Best Practices"*	1,111	430	87.1	45.0
"Next Generation"***	1,111	430	118.7	64.4

*"Storing CO2 with Enhanced Oil Recovery" Advanced Resources International, report prepared for U.S. DOE/NETL, Office of Systems, Analyses and Planning, DOE/NETL-402/1312/02-07-08, February 7, 2008. http://www.netl.doe.gov/energy-analyses/pubs/Storing%20CO2%20w%20EOR_FINAL.pdf.

**Assuming oil price of $70/B (real); CO2 costs (delivered to field at pressure) of $45/metric ton ($2.38/Mcf); investment hurdle rate (15%, real).

***Preliminary results, under DOE/NETL review.

One Example of "Next Generation" CO_2-EOR Technology: Integrating CO_2-EOR and CO_2 Storage

Expanding CO_2 Storage Capacity: A Case Study. Large Gulf Coast oil reservoir with 340 million barrels (OOIP) in the main pay zone.

- Primary/Secondary Oil Recovery: 153 million barrels (45% of OOIP)
- Main Pay Zone:
  - Depth - - 14,000 feet
  - Oil Gravity - - 33ºAPI
  - Porosity - - 29%
  - Net Pay - - 325 feet
  - Initial Pressure - - 6,620 psi
  - Miscibility Pressure - - 3,250 psi

Another 100 million barrels (OIP) in the underlying 130 feet of residual oil zone and an underlying saline reservoir 195 feet thick.

Theoretical CO_2 storage capacity: 2,710 Bcf (143 million tonnes)

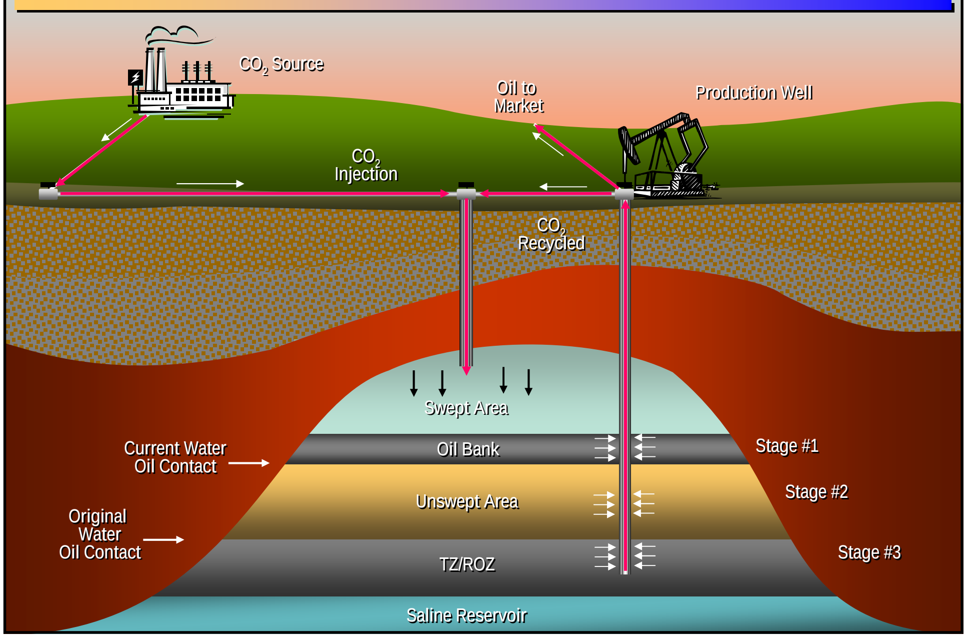
Integrating CO_2-EOR and CO_2 Storage

First, produce using current "best practices" - - vertical wells, 1 HCPV of CO_2 and a 1:1 WAG.

Then produce using "next generation" CO_2-storage and CO_2-EOR project design:

- Gravity-stable, vertical CO_2 injection with horizontal wells.
- Targeting the main pay zone, plus the transition/residual oil zone and the underlying saline aquifer.
- Injecting continuous CO_2 (no water) and continuing to inject CO_2 after completion of oil recovery.

Integrating CO_2-EOR and CO_2 Storage (Cont'd)



Integrating CO_2-EOR and CO_2 Storage

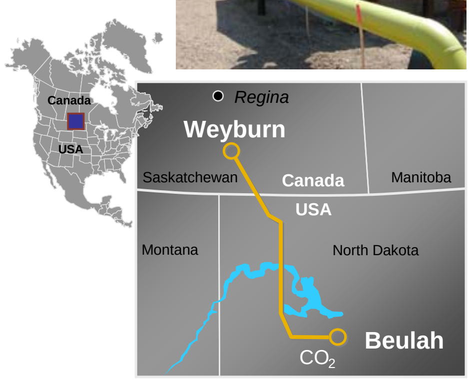
Integrating CO_2-EOR and CO_2 Sequestration shows that much more CO_2 can be stored, making the additional oil produced “GREEN OIL”*.

	Current “Best Practices”	“Next Generation”		
	(millions)	EOR	Seq.	Total
CO_2 Storage (tonnes)	19	76	33	109
Storage Capacity Utilization	13%	52%	24%	76%
Oil Recovery (barrels)	64	180	-	180
% Carbon Neutral (“Green Oil”)	70%	100%	-	160%

*”Green Oil” means that more CO_2 is injected and stored underground than the volume of CO_2 contained in the produced oil, once burned.

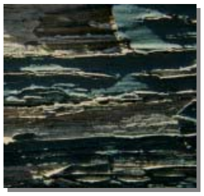
Weyburn Enhanced Oil Recovery Project

(An Operating Project Maximizing Oil Recovery and CO_2 Storage)



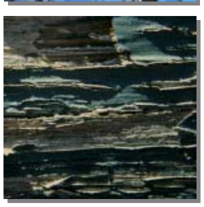
Source: EnCana, 2005

- **Largest CO_2 EOR project in Canada:**
  - **OOIP 1.4 Bbbls**
  - **155 Mbbls incremental**
- **World’s largest geological CO_2 sequestration project**
  - **2.4 MMt/year (current)**
  - **7 MMt to date**
  - **23 MMt with EOR**
  - **<u>55 MMt with EOR/sequestration</u>**



Summary

1. CO_2 enhanced oil recovery, while still an emerging industry, has the potential to add significant volumes of future oil supply, in the U.S. and worldwide.
2. Thirty years of experience shows that CO_2-EOR is a technically sophisticated and challenging process, but one that can be successful if "managed and controlled", not just "operated".
3. "Next Generation" CO_2-EOR technologies, incorporating scientifically possible but not yet fully developed advances, could significantly increase oil recovery efficiency and CO_2 storage capacity.



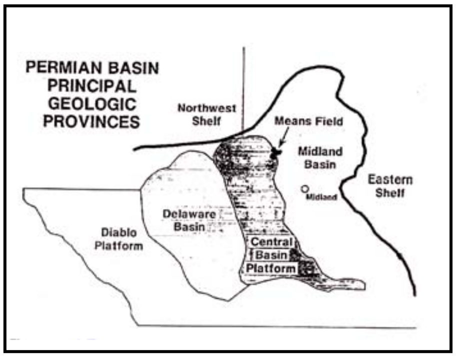
Summary (Cont'd)

4. Wide-scale application of CO_2-EOR is constrained by lack of sufficient "EOR-Ready" CO_2 supplies.
5. Under current "best practices" CO_2-EOR Technology, the U.S. CO_2-EOR market provides a demand for 7.5 Gt of CO_2*
6. In a "carbon constrained world", productively using industrial CO_2 emissions for CO_2-EOR will become a winning strategy.

*7.5 Gt of CO2 is equal to 30 years of captured CO2 emissions from 100 large (500 MW) coal-fired power plants.

Appendix 1

Background



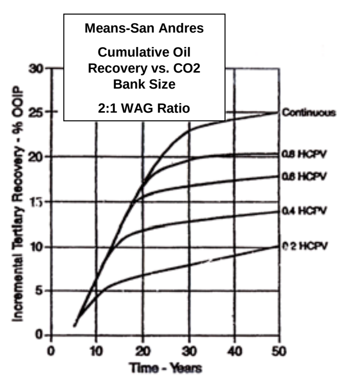
- The Means oil field is located in the West Texas portion of the Permian Basin, near Midland (Andrews County) Texas.
- The field is located along the eastern edge of the Central Basin Platform.
- The field was discovered in 1934 and developed on 40-acres well spacing in the 1950s. Water injection began in 1963, using an 80-acre inverted nine-spot pattern.
- A full-scale CO_2 miscible flood was initiated in 1983 in the upper zones of the Means San Andres Unit, encompassing 8,500 acres and holding 230 MMB of OOIP.

Reservoir Properties

Reservoir Depth, ft*	4,400
Area, acres	
- Field	14,300
- Unit	8,500
Net Pay, Ft	
- Upper San Andres	54
- Total	120(e)
Average Porosity, %	9%
Average Permeability, md	1
Initial Water Saturation	0.29
Initial Formation Volume Factor	1.04
Initial Reservoir Pressure, psig	1,850
Current Reservoir Pressure, psig	2,000
Reservoir Temperature, °F	105
Oil Gravity, °API	29
Oil Viscosity, cp	6

- The Grayburg/San Andres formations are at depths ranging from 4,200 to 4,800 feet.
- Significantly, the reservoir's oil is 29° API with a viscosity of 6 cp. The minimum miscibility pressure (MMP) is 2,000 psi.
- The reservoir has a net pay of 54 feet in the Upper San Andres Flow Unit (within a 300 foot gross interval), a porosity of 9% and a permeability of 1 to 20 md.

CO_2-EOR Development



Effect of Solvent Bank Size on Oil Recovery

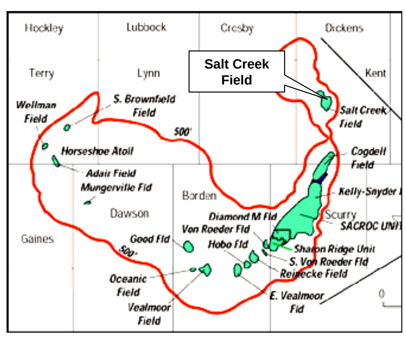
- The CO_2-EOR WAG process was implemented as part of an integrated reservoir development plan which included infill drilling improved waterflooding, and pattern modification:
  - 205 new producers
  - 158 new injectors
- Currently, the project produces 10,000 B/D of oil and148,000 B/D of water:
  - 1,300 B/D (infill/secondary)
  - 8,700 B/D (CO2-EOR)
- The initial plan was to inject 250 Bcf of CO_2, equal to 55% HCPV, at a 2:1 WAG ratio.
- Latest CO_2 injection volumes, assuming injection of 60 to 70 MMcfd (88% CO_2), will be 450 to 500 Bcf (~1 HCPV).

Summary

- The Means case study is an example of effectively applying CO_2-EOR to a high viscosity, low API gravity oil reservoir with an underlying weak aquifer.
- An integrated infill drilling and CO_2 WAG flood has raised oil recovery efficiency from about 25% under primary/secondary to an expected 50% with CO_2-EOR.
- Of the 25% of OOIP increase in recovery efficiency, 15% OOIP is due to CO_2-EOR and 10% OOIP is due to infill development associated with CO_2-EOR.

Background

The Salt Creek Field is located in the Permian Basin of West Texas (Kent County, Texas). With 700 million barrels of OOIP, it is one of the major oil fields located on the northeast end of the Horseshoe Atoll oil play.



The field produces from a Pennsylvanian-age Canyon Reef carbonate at a depth of 6,300 feet.

The 12,100-acre field contains two limestone build-ups, not in pressure communication.

Oil production at Salt Creek began in 1950. A centerline waterflood was started in 1953.

Tertiary oil recovery (CO_2 WAG) began in 1993 in the main pay zone (MPZ) and later expanded to the residual oil zone (ROZ) in 2000.

Reservoir Properties

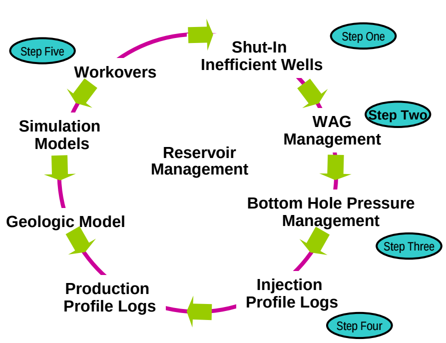
Reservoir Interval, ft*	6,200-6,700
Area, acres	12,100
Net Pay, Ft	100
Average Porosity, %	11
Average Permeability, md	20
Initial Water Saturation	0.19
Initial Formation Volume Factor	1.2
Initial Reservoir Pressure, psig	2,915
Current Reservoir Pressure, psig	3,150
Reservoir Temperature, ºF	129
Oil Gravity, ºAPI	39
Oil Viscosity, cp	0.53

*Includes ROZ interval from 6,500' to 6,700'.

- The Salt Creek Canyon Reef formation is a multi-layered reservoir, with a gross interval of 250 to 300 feet, thickening to over 600 feet in the northern portion of the main area.
- The oil is light (39º API, 0.53 cp viscosity) with a miscibility pressure of 1,800 psi.
- The field averages 100 feet of net pay, 11% porosity and 20 md permeability (with 1 to 2,000 md of permeability in individual flow units).

CO_2-EOR Reservoir Management

Schematic of Salt Creek Reservoir Management Process



- Assure reservoir pressure exceeds MMP (of 1,800 psi) in all areas of the field.
- Assure fluid injection (I) rates balance (or exceed) fluid withdrawal (W) rates, on both pattern and field levels.
- Stimulate wells to improve injectivity; convert producers to injectors to assure I/W fluid balance.
- Start WAG process when first breakthrough of CO_2 is observed (almost immediately at Salt Creek).
- Reduce CO_2 injection and increase the WAG ratio as the flood matures.
- Hold weekly meetings with field operations staff to update and optimize the WAG process at a pattern level.

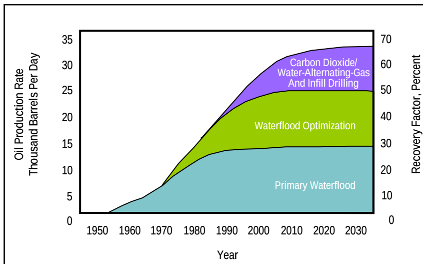
Production History and Expectations

Actual and Expected Oil Recovery (MMB)

	Total	Primary/ Secondary	CO_2-EOR
OOIP	700		
Cum. Recovery (2003)	370	328	42
EUR	460	340	120
%OOIP	66%	48%	17%

- Primary and secondary oil recovery, has produced and proven 336 million barrels, 48% of OOIP.
- The CO_2-EOR project is expected to recover an additional 120 million barrels, 18% of OOIP.
- Production is currently 7,700 B/D oil, plus gas plant liquids.

Salt Creek Field Oil Recovery Factor, by Process



Source: Wilkinson, J.R., ExxonMobil Production Company; et. al., SPE paper 88770,"Lessons Learned from Mature Carbonates for Application to Middle East Fields", presented at the SPE 11th Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, 10-13 October 2004.

- The EOR project plans to inject about 1,200 Bcf of CO_2, equal to 0.8 HCPV for a gross CO_2/oil ratio of 13 Mcf/B.

Summary

- The Salt Creek case study demonstrates that high oil recovery efficiencies, in excess of 60% of OOIP, are achievable from a multi-layer, highly heterogeneous carbonate reservoir using optimized water flooding, infill drilling and CO_2-EOR.
- The CO_2-EOR project is expected to recover 17% of OOIP (in addition to a high, 48% of OOIP with P/S recovery) at a gross CO_2 to oil ratio of 13 Mcf/B and a net ratio estimated at about 5 Mcf/B.
- A formal CO_2 flood tracking system (Zonal Allocation Program) and weekly team meetings are used to alter CO_2 injection volumes, improve vertical conformance and optimize oil production.

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