MAXIMIZING OIL RECOVERY EFFICIENCY AND SEQUESTRATION OF CO₂ WITH “GAME CHANGER” CO₂-EOR TECHNOLOGY

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BACKGROUND

1. Status and Outlook for CO$_2$-EOR
2. “Game Changer” CO$_2$-EOR Technology
   - Increasing Oil Recovery Efficiency
   - Expanding CO$_2$ Storage Capacity
3. “Early Application” of CO$_2$-EOR
4. Summary
Currently, 82 CO$_2$-EOR projects provide 237,000 B/D of production

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
GROWTH OF CO$_2$-EOR PRODUCTION IN THE U.S.

Source: Oil and Gas Journal, 2002.
LARGE VOLUMES OF DOMESTIC OIL REMAIN “STRANDED” AFTER PRIMARY/SECONDARY OIL RECOVERY

Original Oil In-Place: 582 B Barrels*
“Stranded” Oil In-Place: 390 B Barrels*

*All domestic basins except the Appalachian Basin.
Source: Advanced Resources Int'l. (2005)
OUTLOOK FOR CO₂-EOR

Recently completed “basin studies” of applying “state-of-the-art” CO₂-EOR in the U.S. indicate:

- Nearly 89 billion barrels of technically recoverable resource,
- From 4 to 47 billion barrels of economically recoverable resource.

Results are based on applying streamline reservoir simulation to 1,581 large oil reservoirs (two thirds of U.S. oil production).

ECONOMICALLY RECOVERABLE RESOURCES FROM CO₂-EOR

Assumptions:
- CO₂ Costs ($/Mcf): High = 5% oil price; Low = 2% oil price.
- Oil Price ($/Barrel): Moderate = $30; High = $40.
“NEXT GENERATION” CO₂-EOR TECHNOLOGY

Gravity-stable laboratory core floods can recover essentially all of the residual oil. Reservoir modeling and selected field tests also show that high oil recovery efficiencies are possible with innovative applications of CO₂-EOR.

Process designs that improve CO₂ contact with the reservoir can facilitate high oil recovery efficiencies.

So far, except for a handful of cases, the actual performance of CO₂-EOR has been less than optimum:

• Geologically complex reservoir settings
• Lack of “real time” information on performance
• Limited process control capacity
LIMITATIONS OF PAST PERFORMANCE

Because of high CO₂ costs and lack of information and process control, the great majority of past-CO₂ floods have used insufficient volumes of CO₂.

Sweep Efficiency in Miscible Flooding

Injected CO₂ vs Oil Recovery

Means (San Andres) @ 2:1 WAG Ratio

Note: V_{PD} is displaceable fluid pore volumes of CO₂ injected.


Source: SPE 24928 (1992)
LIMITATIONS OF PAST PERFORMANCE

In many CO₂ floods, the injected CO₂ achieved only limited contact with the reservoir:
- Viscous fingering
- Gravity override

Addition of viscosity enhancers could help improve the mobility ratio and reservoir contact.

A major barrier is the inability to target the injected CO$_2$ to reservoir strata with high residual oil saturation.

The figures show:

- Higher oil saturation/lower permeability portion of the reservoir is inefficiently swept;
- CO$_2$ channeling can be mitigated with well workover.


ARE HIGHER OIL RECOVERY EFFICIENCIES ACHIEVABLE?

Example Carbonate Field Oil Recovery Efficiencies

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

Available on the U.S. DOE web site.
“GAME CHANGER” CO$_2$-EOR TECHNOLOGY (Cont’d)

- Innovative Flood Design and Well Placement
- Viscosity and Miscibility Enhancement
- Increased Volume of CO$_2$ Injection
- Flood Performance Diagnostics and Control
  - Inter-disciplinary technical teams
  - 4-D seismic
  - Instrumented observation wells
  - Zone-by-zone performance information
ACHIEVING 60+% OIL RECOVERY EFFICIENCY WITH “GAME CHANGER” CO₂-EOR TECHNOLOGY

Original Oil In Place: 309 Billion Barrels
(Six U.S. Basins/Areas)

Cumulative Production 92 Billion Barrels

Remaining Oil In-Place 121 Billion Barrels

“Game Changer” CO₂-EOR 84 Billion Barrels

Proved Reserves 12 Billion Barrels

“State-of-the-Art” CO₂-EOR 41 Billion Barrels

Source: Advanced Resources International, 2005
INTEGRATING CO₂-EOR AND CO₂ STORAGE

Expanding CO₂ Storage Capacity: A Case Study. A Large Gulf Coast oil reservoir with 340 million barrels (OOIP) in the main pay zone. Another 100 million barrels (OIP) in the underlying 130 feet of residual oil zone and an underlying saline reservoir 195 feet thick.

- **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

- **Primary/Secondary Oil Recovery:** 153 million barrels (45% of OOIP)

Theoretical CO₂ storage capacity: 2,710 Bcf (143 million tonnes)
INTEGRATING CO$_2$-EOR AND CO$_2$ STORAGE (Cont’d)

**State-of-the-Art.** Vertical wells; 1 HCPV of CO$_2$ (purchased and recycled CO$_2$); @ 1:1 WAG.

**Alternative Design.**

- Gravity-stable CO$_2$ injection with horizontal production wells.
- Targeting main pay zone, plus residual oil zone and underlying saline reservoir.
- Injecting continuous CO$_2$ (no water); continuing to inject CO$_2$ after completion of oil recovery.
- Instituting rigorous diagnostic and monitoring.
INTEGRATING CO₂-EOR AND CO₂ STORAGE (Cont’d)
With alternative CO$_2$ storage and EOR design, much more CO$_2$ can be stored and more oil becomes potentially recoverable.

The additional oil produced is “GREEN OIL”.

<table>
<thead>
<tr>
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<th>“State of the Art”</th>
<th>“Next Generation”</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ Storage (tonnes)</td>
<td>19</td>
<td>109</td>
</tr>
<tr>
<td>Storage Capacity Utilization</td>
<td>13%</td>
<td>76%</td>
</tr>
<tr>
<td>Oil Recovery (barrels)</td>
<td>64</td>
<td>180</td>
</tr>
<tr>
<td>% Carbon Neutral (“Green Oil”)</td>
<td>80%</td>
<td>160%</td>
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</table>
Weyburn Enhanced Oil Recovery Project
(An Operating Project Maximizing Oil Recovery and CO₂ Storage)

- Largest CO₂ EOR project in Canada:
  - OOIP 1.4 Bbbls
  - 155 Mbbls incremental
- Outstanding EOR response
- World’s largest geological CO₂ sequestration project
  - 2.4 MMt/year (current)
  - 7 MMt to date
  - 23 MMt with EOR
  - 55 MMt with EOR/sequestration
“EARLY APPLICATION” OF CO₂-EOR

Improving Revenues and Profits: A Case Study. Large, 2.4 billion barrels (OOIP) Permian Basin oil reservoir.

- Depth - - 5,200
- Gravity - - 33° API
- Porosity - - 12%
- Net Pay - - 141 ft.
- Initial Pressure - - 1,850 psi
- Miscibility Pressure - - 1,500 psi

First produced using traditional sequence - - primary, then secondary and finally CO₂-EOR.

Next produced with “early application” CO₂-EOR design - - primary, then CO₂-EOR (skipping the waterflood).
“EARLY APPLICATION” OF CO$_2$-EOR (Cont’d)

The economic value of this oil reservoir (after primary recovery) is much higher under “early application” of CO$_2$-EOR.

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<th>Traditional Sequence (After Primary Recovery)</th>
<th>“Early Application” (After Primary Recovery)</th>
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<tbody>
<tr>
<td></td>
<td>(Million)</td>
<td>(Million)</td>
</tr>
<tr>
<td>Gross Revenues (NPV @ 10%)</td>
<td>$9,300</td>
<td>$19,000</td>
</tr>
<tr>
<td>Oil Recovery (Barrels/Years)</td>
<td>1,060 (53 yrs)</td>
<td>1,040 (28 yrs)</td>
</tr>
<tr>
<td>Water Production (Barrels)</td>
<td>3,900</td>
<td>1,500</td>
</tr>
</tbody>
</table>
“EARLY APPLICATION” OF CO₂-EOR (Cont’d)

Traditional Sequence

“Early Application”

Years of Operation

Oil Recovery (%OOIP)
SUMMARY

1. CO₂ 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 CO₂-EOR is a technically sophisticated and challenging process, but one that can be successful if “managed and controlled”, not just “operated”.

3. “Game Changer” CO₂-EOR technologies, incorporating scientifically possible but not yet fully developed advances, could significantly increase oil recovery efficiency.
SUMMARY (Cont’d)

4. “Early application” of CO$_2$-EOR technology can significantly increase the economic value of the remaining oil resource.

5. Wide-scale application of CO$_2$-EOR is constrained by lack of sufficient “EOR-Ready” CO$_2$ supplies. A mutually beneficial link exists between CO$_2$-EOR and new industrial sources of CO$_2$.

6. Under a “carbon constrained world”, productively using industrial CO$_2$ emissions for CO$_2$-EOR will become a winning strategy.
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