The Wyoming Enhanced Oil Recovery Institute’s
2008 Wyoming EOR/IOR Conference
“CO₂ EOR, Reservoir Sweep and CO₂ Storage”
Steve Melzer
Melzer CO2 Consulting
CO₂ EOR, Reservoir Sweep and CO₂ Storage

• Background and Growth of CO₂ EOR

• The Concept of and Experience with Reservoir Sweep

• Incidental Storage of CO₂ in EOR

• The Converging Worlds of CO₂ EOR and CO₂ Storage
BACKGROUND
(OF CO₂ EOR PROJECT GROWTH*)

GROWTH OF PERMIAN BASIN & WORLDWIDE CO₂ PROJECTS
1984 - 2008

* Ref: O&GJ Biennial EOR Editions & UTPB

* Includes Only CO₂ Miscible Floods
…..and Growth Even with Languishing Oil Pricing

GROWTH OF PERMIAN BASIN & WORLDWIDE CO2 PROJECTS
1984 - 2004

WW Projects | PB Projects

Year | No. of Projects
--- | ---
1988 | 60
1990 | 70
1992 | 80
1994 | 90
1996 | 100
1998 | 110
2000 | 120

Average Growth > 2 Projects/Yr

WTI Posted Oil Prices - 1988-2000

Year | Oil Prices in $/bbl
--- | ---
1988 | $20
1989 | $22
1990 | $24
1991 | $26
1992 | $28
1993 | $30
1994 | $32
1995 | $34
1996 | $36
1997 | $38
1998 | $40
1999 | $42
2000 | $44

Average Price = $18.80 (U.S.)
BACKGROUND
(OF CO₂ EOR PRODUCTION GROWTH*)

WW & PERMIAN BASIN CO₂ EOR PRODUCTION
1986 - 2008

* Ref: O&GJ Biennial EOR Editions & UTPB
* Includes both CO₂ Miscible & Immiscible Floods
HOW BIG IS THE CO$_2$ EOR BUSINESS?

** Does not take into account the NGLs produced from the recycle volumes
ENHANCED OIL RECOVERY AND \text{CO}_2 \text{ EOR}
BEYOND PRIMARY (AND WATERFLOODS)

• IMPROVE SWEEP
  – INFILL DRILLING
  – PATTERN MODIFICATION
  – AUGMENTED WATERFLOODING (POLYMER, ETC)
  – LOW SALINITY WATERFLOODING

• REDUCE WATERFLOOD RESIDUAL
  – THERMAL (CYCLIC STEAM, STEAM DRIVE, SAGD, FIRE)
  – CHEMICAL (ALKALINE/POLYMER/SURFACTANT)
  – MISCIBLE GAS INJECTION
    • HYDROCARBON MISCIBLE FLOODING (HCMF)
    • NITROGEN
    • CO₂
EOR METHODS

ENHANCED OIL RECOVERY METHODS

GAS (Miscible/Immiscible)
- CO₂ (Drive, Soak)
- Hydrocarbon
- Nitrogen
- Flue Gas
- Air

THERMAL
- Steam (Soak, Drive)
- Combustion (In-situ)
- Hot Water

CHEMICAL
- Polymer
- Alkaline/Caustic
- Micellar/Polymer
- Surfactant (foam)

OTHER
- Microbial
TODAY’S VIEW THE PRODUCING LIFE OF A RESERVOIR

IDEALIZED OIL PRODUCTION CURVE*

Primary Stage
Typically Water Flooding

Secondary Stage

EOR

~15%
~20-25%
~10-20%

Oil Recovered (bbls)

Recovery % of Original Oil in Place

TIME

‘IN-FILL’ DRILLING

* Average for San Andres Dolomites (PB)

Melzer Consulting
The Concept of and Experience with Reservoir Sweep
WATERFLOODING & SWEEP EFFICIENCY

- ▲ Injection Well
- ● Production Well
SWEEP EFFICIENCY

WF Swept Area

△ Injection Well
● Production Well
WATERFLOOD RECOVERY

\[ R = E_s \times (S_{Oi} - S_{ORwf}) / S_{Oi} \]

\[ S_{Oi} = 0.80 \]
\[ S_{ORwf} = 0.35 \]
\[ E_s = 0.70 \]

\[ R = 0.70 \times (0.80 - 0.35) / 0.80 = 0.39 \]

ROIP (Swept Region)\] = 0.70 * (0.45) / 0.80 = 0.39

ROIP (Unswept Region)\] = 0.30 * (0.80) / 0.80 = 0.30

ROIP (Total)\] = 0.69
SWEEP EFFICIENCY

WF Swept Area

CO₂ Swept Area

Injection Well

Production Well

Melzer CO₂ Consulting
CO₂ FLOOD RECOVERY CALCULATIONS
MISCIBLE PROJECTS

\[ R = E_t \times (S_{OS} - S_{ORM}) \]

where: \( R \) = Recovery Factor
\( S_{OS} \) = Oil Saturation at Flood Start
\( S_{ORM} \) = Miscible Residual Oil Saturation

\( E_s > E_t \)

\[ R = E_t \times (S_{ORWF} - S_{ORM}) \]

where: \( S_{ORWF} \) = Waterflood Residual Oil Saturation
PRIMARY + WATERFLOOD AND CO₂ SWEEP EFFICIENCY

• PRIMARY + WATERFLOOD RECOVERY

\[ R = E(p+s) \times (S_{Oi} - S_{ORwf}) \]
\[ E(p+s) = \frac{R}{(S_{Oi} - S_{ORwf})} \]
CO₂ MISCIBLE FLOODING

EXPECTED RECOVERY

\[ R = E_T \times \frac{(S_{ORwf} - S_{ORm})}{S_{Oi}} \]

\[ S_{ORwf} = 0.38 \quad S_{Oi} = 0.85 \]
\[ S_{ORm} = 0.10 \quad E_T = 0.35 \]

\[ R = 0.35 \times \frac{(0.38 - 0.10)}{0.85} = 0.115 \]
PHASE I RESERVOIR SCREENING
RULES OF THUMB: CO₂ MISCIBLE INJECTION

• PERCENT OF OOIP
  8 TO 18 (12)

• RATIO – TERTIARY / (P + S)
  20 TO 35 (25)

• SWEEP EFFICIENCY
  25 TO 50 (35)

• RATIO – \( E_t / E(P+S) \)
  50 TO 60 (50)
### RULE OF THUMB EXAMPLES (1)
#### EUR FROM CO₂ INJECTION

<table>
<thead>
<tr>
<th></th>
<th>FIELD A</th>
<th>FIELD B</th>
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</thead>
<tbody>
<tr>
<td>( S_{Wi} ) (% PV)</td>
<td>15.0</td>
<td>23.7</td>
</tr>
<tr>
<td>( S_{Oi} ) (% PV)</td>
<td>85.0</td>
<td>76.3</td>
</tr>
<tr>
<td>( S_{ORwf} ) (% PV)</td>
<td>38.0</td>
<td>26.0</td>
</tr>
<tr>
<td>(P+S) Target (% PV)</td>
<td>47.0</td>
<td>50.3</td>
</tr>
<tr>
<td>(P+S) (% OOIP)</td>
<td>41.8</td>
<td>55.2</td>
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<tr>
<td>(P+S) (% PV)</td>
<td>35.5</td>
<td>42.1</td>
</tr>
<tr>
<td>( E(P+S), % )</td>
<td>75.6</td>
<td>83.7</td>
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</table>
**RULE OF THUMB EXAMPLES (2)**

**EUR FROM CO₂ INJECTION**

<table>
<thead>
<tr>
<th></th>
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<th>FIELD B</th>
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<tbody>
<tr>
<td>$S_{Oi}$ (% PV)</td>
<td>85.0</td>
<td>76.3</td>
</tr>
<tr>
<td>$S_{ORwf}$ (% PV)</td>
<td>38.0</td>
<td>26.0</td>
</tr>
<tr>
<td>$S_{ORm}$ (% PV)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Tertiary Target (% PV)</td>
<td>28.0</td>
<td>16.0</td>
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<tr>
<td>Tertiary, % OOIP</td>
<td>14.6</td>
<td>10.0</td>
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<tr>
<td>Tertiary, (% PV)</td>
<td>12.4</td>
<td>7.6</td>
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<tr>
<td>$E_{T}$</td>
<td>44.3</td>
<td>47.7</td>
</tr>
<tr>
<td>$E_{T} / E(P+S)$, %</td>
<td>58.6</td>
<td>57.0</td>
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RULE OF THUMB EXAMPLE (3)
EUR FROM CO$_2$ INJECTION

TERTIARY SUMMARY

<table>
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<tr>
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<th>FIELD A</th>
<th>FIELD B</th>
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</thead>
<tbody>
<tr>
<td>%OOIP ($S_{ORwf}$)</td>
<td>38.0</td>
<td>26.0</td>
</tr>
<tr>
<td>$E_T$</td>
<td>44.3</td>
<td>47.7</td>
</tr>
<tr>
<td>$T / (P+S)$</td>
<td>35.4</td>
<td>18.1</td>
</tr>
<tr>
<td>$E_T / E(p+s)$, %</td>
<td>58.6</td>
<td>57.0</td>
</tr>
<tr>
<td>Tertiary, % OOIP</td>
<td>14.6</td>
<td>10.0</td>
</tr>
</tbody>
</table>
PRIMARY, WF AND TERTIARY RECOVERY FROM THE W. TX SAN ANDRES EXPERIENCE

WITH A RANGE OF VALUES OF 8-18%
CO$_2$ FLOODING: MISCIBILITY

- FIRST CONTACT
- DYNAMIC OR MULTIPLE CONTACT
- RESIDUAL OIL FOR CO$_2$ FLOODING
- IMMISCIBLE CHARACTERISTICS OF CO$_2$
- WHY CO$_2$?
- OIL RECOVERY FROM CO$_2$ INJECTION
DEFINITIONS OF MISCIBILITY

- Two fluids are "first-contact miscible" if they form only one phase when mixed in any proportions.

- A process that relies on "Developed" or "Multiple-Contact" miscibility is based on the transfer of components between phases to generate mixtures that avoid the two-phase region. Such processes really involve chromatographic separations of components as phases with different compositions flowing at different rates. Displacement processes may be described as:
  - Vaporizing Gas Drives
  - Condensing Gas Drives
  - Condensing/Vaporizing Gas Drives
MISCIBILITY CONCEPTS

MINIMUM MISCIBILITY PRESSURE
SLIMTUBE TEST

OIL RECOVERY - % OOIP

PRESSURE - PSIG

Nitrogen

Melzer CO2nsulting
CORRELATIONS FOR MINIMUM MISCIBILITY PRESSURE
CO\textsubscript{2} AND CRUDE OIL MIXTURES
(Selected References)


WHY CO₂?

• MISCIBLE AT LOWER PRESSURES THAN NITROGEN OR METHANE

• CHEAPER AND MORE PLENTIFUL THAN LPG/ENRICHED HYDROCARBON GAS

• DENSITY (IN DENSE PHASE) CLOSER TO RESERVOIR FLUIDS – OIL/WATER
KEY (MINIMUM) REQUIREMENTS FOR CO₂ MISCIBLE PROJECTS

• RESERVOIR CHARACTERISTICS
  – CARBONATES / SANDSTONES
  – GRAVITY SEGREGATION
  – STRATIFICATION/FRACTURES
  – CONTINUITY – WELL SPACING
  – POROSITY / PERMEABILITY
  – RESERVOIR THROUGHPUT (INJECTIVITY)
  – WATERFLOOD PERFORMANCE
IDEALIZED FLOODING
Fluid Mobility Issues Can Reduce Recoveries And Increase CO₂ Recycling

Areal “Breakthrough”

- Initial Radial Flow at Injector, Mobile Oil Bank Develops
- Preferential Flow Paths Encountered, Recovery Diminished

OPTIONS:
- WAG Injection Design
- Thickening Agents
- Selective Injection
- Profile Modification
  - Cement
  - Liners

Re: T. Bradley, EOR CM Workshop, Dec 2006
HETEROGENEITY* IN A VERTICAL SENSE

* Re: T. Bradley, EOR CM Workshop, Dec 2006
HETEROGENEITY IN A HORIZONTAL (AREAL) SENSE
Fractured Reservoir Model
Naturally Fractured Reservoirs

• Can Prove Difficult for Flooding (i.e., “short-circuiting” injector-producer pairs)

• Can be Useful to establish line drive pattern flooding if unidirectional
Naturally Fractured Reservoirs
Increased Sweep Efficiency from Line Drive Patterns

5-SPOTS

LINE DRIVE
Atypical CO₂ Flooding
IMMISCIBLE CO\textsubscript{2} FLOODING

• CO\textsubscript{2} Solubility and Oil Swelling
  – Oil Volume Increase (can be \textasciitilde 50%)
  – Oil From Dead End Pores
  – Incremental Oil Below MMP

• Viscosity Reduction (Over that of Water)
  – Better Injection Rates
  – Reduces Mobility Ratio
  – Improves Relative Permeability
  – Improves Sweep Efficiency
CO₂ SECONDARY FLOODING

- Poor Waterflood Performance (e.g., Clay Swelling)
- Stratification / Continuity
- Poor Water Injectivity
- High Connate Water
- Viscous Oil
- Attic Drive

RULES OF THUMB NOT WELL ESTABLISHED
Residual Oil Zones
aka Transition Zones

- Conventionally Productive Oil Zone
- Residual Oil Zone (ROZ)
- Average Saturation profile

Water Saturation (%)

Height

Melzer Consulting
Hess’ Seminole Field
Gaines County, West Texas

Seminole Sentinel

12 Pages, 1 Insert  Sunday, May 20, 2007  Volume 98, Number 064

Hess to Expand

CORP. ANNOUNCES $300 MILLION PROJECT PLANS

By Dustin Wright Managing Editor

The Hess Corp. has recently announced a large-scale development project in Gaines County, which is expected to enhance oil production from the Seminole Oil Zone (ROZ).

We have executed a pilot program on this property since 1994 and a second program since 2004, and we have moved to be successful, so the producers have agreed to move ahead with a larger scale development in this zone,” said Pete Johnson, Manager of Production Operations for Hess Floyd Peterson, Operations Manager for Hess Corp.

According to Peterson, the SOZ is a field with a proven oil production of 20 million barrels of unconventional oil that must be mixed with carbon dioxide for future production into the field.

The first stage of the development will include the deepening of the ROZ. Additional development will include the mixing of CO2 to enhance oil production.

Sen. Hess Page 3

Sen. Hess Page 3
BALANCING THE PATTERNS

• With CO₂, substantial oil can be trapped because the producing well may become uneconomic before the oil bank from the other injectors arrives. Pattern balancing is difficult and conflicts with other stated goals such as maximizing injection.

• In a waterflood, we were able to live with more unbalanced patterns because of the favorable mobility ratio and the relatively low cost of the water.

• Of course, practical compromises must be made.
BALANCED INJECTION
THE INACHIEVABLE IDEAL (5-SPOT EXAMPLE)
PATTERN BALANCING

‘REAL’ EXAMPLE
MAINTAINING A CONTINUOUS OPTIMIZATION PROGRAM

Regardless of the detail or the quality of the pre-deployment study and the thoroughness of the plan of operation, performance will indicate changes that will be needed. Opportunities may range from the small and simple to major breakthroughs as the result of new learnings and new technology.

Many companies feel “the plan” is fixed and never have learned this lesson.
MONITORING PROGRAM GOES HAND-IN-HAND WITH THE OPERATING PLAN

- Strong communication between field and office
- Pattern injectors and producers in same pay – DA! But…..
- Metering and documentation system for injected and produced fluids
- Periodic pressure measurements (falloffs and buildups)
- Initial and (possibly) followup step-rate tests
- Fluid level program for pumping wells
- Water quality monitoring
- Periodic profile measurements
- Pattern balancing program
- Program to monitor and adjust WAG ratio and WAG cycles
TOOLS (1)

• GRAPHICAL

e.g., DIMENSIONLESS PLOTS CAN ID PROBLEM PATTERNS
TOOLS (2)
TOOLS (3)

• SIMULATORS
  – SOME COMMERCIAL
  – SOME PROPRIETARY IN-HOUSE
CO₂ FLOODING RECAP (1)

• PROVEN TO BE TECHNICALLY VIABLE IN MISCIBLE AND IMMISCIBLE RESERVOIR CONDITIONS

• MOST PROVEN OF THE PROCESSES FOR LIGHT OILS

• LOW RELATIVE COST OF CO₂ (EXCLUDING TRANSPORTATION - MORE ON THIS LATER)
CO₂ FLOODING RECAP (2)

- REDUCES REMAINING OIL IN PLACE VERY EFFECTIVELY BUT SWEEPS SMALLER VOLUME DUE TO GAS-LIKE VISCOSITY

- A POOR WATERFLOOD (POOR SWEEP EFFICIENCY) WILL MAKE A POOR CO₂ FLOOD

- IF PROLIFERATION OF CO₂ SOURCES ARE COMING AND REMOVE (TO A DEGREE) THE OBSTACLES OF DEVELOPMENT OF A PIPELINE NETWORK, THIS WILL COMMERCIALIZE THE:
  - DEVELOPMENT OF LESS EFFICIENT FLOODS
  - IMPLEMENTATION OF SLOWER RESPONDING FLOODS
KEY REFERENCES
The CO₂ Conference

Week of Dec 8th 2008

with Houston and Midland Venues

WHAT A COMBINATION.

SIXTH ANNUAL EOR CARBON MANAGEMENT WORKSHOP IN HOUSTON

+  

14TH ANNUAL CO₂ FLOODING CONFERENCE IN MIDLAND

Mark your calendar, because once again CO₂ Conference Week will offer you a mix of information not found elsewhere. This conference brings leaders in the growing carbon capture and storage industry with oil industry personnel actively conducting CO₂ processing, compression, injection and reservoir surveillance.

- Business opportunities in carbon capture and storage
- Policy and legislative updates, including CCS
- International project showcase
- Network with the actual practitioners
- Field trip to Vacuum Field in SE New Mexico
- Case histories covering current flood operations, technologies and developments
Key Reference Work (1)
The Annual CO₂ Flooding Conference

• Held Each December in Midland, Texas – Home to 53 Active CO₂ Floods
• Concentrates on Actual Case Histories
• Includes a CO₂ Flood Field Visit
• Includes a CO₂ Shortcourse
• Includes an EOR Carbon Management Workshop
• Great Networking Opportunity

Visit: www.spe-pb.org or call 432-552-2430
Key Reference Work (2)

THE CO\(_2\) FLOODING CONFERENCE SHORTCOURSES

2. Is My Field a Candidate for CO\(_2\) Flooding?, September 1995
4a. CO\(_2\) Flood Surveillance and Monitoring, December 2004
5. How to Put Together a CO\(_2\) Flood, December 1996
6. CO\(_2\) Measurements and Metering, December 1997
7. CO\(_2\) Facilities and Plants, December 1998
8. CO\(_2\) Flooding: Sandstones vs. Carbonate Reservoirs, December 1999
10. Reservoir Modeling and Simulation for CO\(_2\) Flooding, December 2001
11. Wellbore Management in CO\(_2\) Floods, December 2002
12. Carbon Dioxide Health And Safety, December 2004

(http://www.utpb.edu/ceed/co2/shortcourses.html) or phone 432-552-2430
Key Reference Work (3)

- Practical Aspects of CO₂ Flooding, Society of Petroleum Engineers Monograph Volume 22, 2002

Thank you

Questions?