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The Society gratefully acknowledges those companies that support the program by allowing their professionals to participate as Lecturers.

And special thanks to The American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) for their contribution to the program.
Low Cost Methods for Improved Oil and Gas Recovery
Presentation Objective

- It is perceived that IO&G recovery is a costly proposition
- Several low cost IO&G recovery processes have been tested in the field
- Objective of this presentation is to make these methods and their concepts known
- Detailed discussions are available in SPE publications
Processes

- The Double Displacement Process of Improved Oil Recovery Using Air Injection
- Co-Production of Gas & Water from Water-Drive Gas Reservoirs
- Water Flooding of Low Pressure Gas Reservoirs
- LSU researchers participated in the conceptual definition of these methods
The Double Displacement (DDP) Process

SPE 35360 & SPE 39462
AFTER WATER INFLUX

- Attic Oil
- Current OWC
- Water-swept Oil Zone
- Aquifer

Oil Producer
DDP EXTENSION - SCWD

Producer

Residual oil

Oil bank

Second contact Water Displacement
OIL FILM FORMATION

Immobile Oil to Water

Gas Invades Pore

Pore after Gas Invasion

\[ S'_{o/w} = \sigma'_{wg} - \sigma'_{og} - \sigma'_{ow} \]
CONSORTIATED CORE OIL PRODUCTION

Before Gas BT

57% of water $S_{or}$ was mobilized

Shut-In

SCWD 50%
West Hackberry Air Injection Project
Reservoir A
Four Producers

Bopd: % water, air inj. rate, Mscf/d/10

Air inj. rate

% water cut

Single-Well Cyclic Carbon Dioxide Injection

$CO_2$ Huff & Puff
Steps of Cyclic CO2 Injection

The cycle may be repeated
Recovery Mechanisms

*Three major mechanisms:*
- Swelling of the oil
- Reduction of oil viscosity
- Decreasing water saturation near the well bore

*ALSO*
- At high pressure, oil components may vaporize
- Injection increase BHP which increases rate when the well is brought back on production
Attractiveness of Cyclic CO$_2$ Injection

- Economically attractive because of its shorter project life
- Use a smaller amount of CO$_2$ compared to full scale CO$_2$ flooding
- In reservoirs with poor inter-well communication, Huff & Puff may offer the only feasible process for incremental recovery
Typical Performance of a cyclic Treatment

- **Rapid Decline**
- **Significant Stimulation**

![Graph showing typical performance of a cyclic treatment with data points and lines indicating rapid decline and significant stimulation.](image-url)
Factors Affecting Huff & Puff Performance

- Field implementation of cyclic CO$_2$ has been successful in diverse reservoir environment
- A database was evaluated to determine the key factors affecting Huff & Puff performance (LSU 1989)
- An approximate predictive method was also derived using the database
Characteristics of the Database

- Total of 106 Huff & Puff projects in 12 fields
- 87 projects deemed successful (82%)
- All drive mechanism are represented:
  - Depletion (3)
  - Depletion followed by Water-flooding (2)
  - Gravity drainage (1)
  - Gas Cap/Water drive (1)
  - Weak to moderate water drive (3)
  - Strong water drive (2)
Characteristics of the Database

- Implementation Pressure, psia: 100 to 4450
- Depth, ft: 1,200 to 13,000
- Permeability, md: 0.1 to 3000
- Porosity, %: 15 to 32
- Initial water saturation, %: 13 to 55
- Oil API gravity: 23 to 38
Effect of Injected CO$_2$ Volume

- The more CO$_2$ is injected, the higher the incremental oil production.
- The volume of CO$_2$ injected is designed to limit undesirable interference with other wells specially those on other leases.
Offset Production

Although Huff & Puff is a single well process, injection of CO₂ in one well can affect the production in adjacent wells.

The effect could be positive (increase in oil rate), or negative (increase in GOR)
Effect of Pay Thickness

- All other conditions being equal, stimulation ratio increases with pay thickness.
- Stimulation ratio is defined as the monthly oil production rate after CO$_2$ injection divided by monthly oil production rate prior to CO$_2$ injection.
Effect of Swelled Oil Volume

- The higher the swelling factor ($\text{Bo}$), the higher the incremental oil production.
- The Swelling factor depends mainly on the oil composition. The heavier the oil the lower the swelling.
Effect of Reservoir Pressure

Suggested boundaries
Monger, 1988

Immiscible
Near Miscible
Miscible

INC OIL/PAY INTERVAL (STB/FT)

1000

100

10

1

CO2 DENSITY (G/CC)

0.01

0.1

Monger, 1988

Suggested boundaries

Graph showing the effect of reservoir pressure on oil production.
Effect of Soak Period
Simplified Predictive Method

- Based on a study by Haskin & Alston Texaco Inc. (SPE 15502)
- Oil swelling and viscosity reduction are the key recovery mechanisms in cyclic CO₂
- Texas 23-30 API crude Oil, strong water drive reservoirs

\[
(S_{or})_{CO2} = (S_{or})_{w} \times \left( \frac{(\mu_o)_{CO2}}{\mu_o} \right)
\]

- \((S_{or})_{CO2}\) Residual CO₂-saturated oil saturation
- \((S_{or})_{w}\) Residual oil saturation to water flooding
- \((\mu_o)_{CO2}\) CO₂-saturated oil viscosity
- \(\mu_o\) Oil viscosity @ reservoir conditions
Estimation of Viscosity Reduction
MODIFIED HASKIN AND ALSTON'S METHOD

South Louisiana Wells

CALCULATED INCREMENTAL OIL (STB)

OBSERVED INCREMENTAL OIL (STB)
Numerical Simulation

- Reservoir numerical simulation can be used to predict the performance of huff’n’puff.
- The success of huff’n’puff is not that sensitive to reservoir heterogeneity, less detailed reservoir description suffices.
- Time and effort might not be warranted because of the relatively small investment, and data may not be available in economically marginal reservoirs.
Performance of a 2-cycle huff’n’puff
Paradis Field, Louisiana (Texaco)
Performance of a Multi-cycle huff’n’puff Paradis Field, Louisiana (Texaco)
### Classification of Gas Reservoirs

<table>
<thead>
<tr>
<th>Depletion Drive</th>
<th>Water Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td>❖ Recovery factor as high as 90%</td>
<td>❖ Recovery factor ranges from 35-75%</td>
</tr>
<tr>
<td>❖ Recovery limited by attainable minimum reservoir pressure</td>
<td>❖ Recovery factor controlled by reservoir:</td>
</tr>
<tr>
<td></td>
<td>- properties</td>
</tr>
<tr>
<td></td>
<td>- geometry</td>
</tr>
<tr>
<td></td>
<td>- Heterogeneity</td>
</tr>
</tbody>
</table>
Microscopic bypassing of gas
Macroscopic bypassing of gas
Macroscopic bypassing of gas
Co-Production Technique
Eugene Island Block 305

Pressure Predictions

Reservoir pressure, psia

- B-2 Shut In
- B-3 Shut In
- B-1 Shut In

Conventional Performance

Co-Production Performance

Time, Years

Eugene Island Block 305
Cumulative Gas Production Predictions

124 BCF Produced prior to 1984
+47 BCF Incremental Recovery
RF 62%

+102 BCF Incremental Recovery
RF 83%

Co-Production 55 BCF Reserves
Present Value Cash Flow
Before tax, 15% Discount rate

@$5/mcf

>$100 million

GAS PRICE, $/MCF

PRESENT VALUE CASH FLOW (BFF), 10%$
Water-flooding of Low-Pressure Gas Reservoirs

SPE 12041 /SPE 69651
Waterflooding Implemented above Pa

Waterflooding history

Depletion history

Abandonment conditions

Depletion reserves

Waterflooding reserves

\( P/z \)

\( P/z_a \)

\( G_p \)

\( G_{pd} \)

\( G_{pwf} \)
Compression vs. Waterflooding

Primary stage $Q_g$

Waterflooding $Q_g$

Compression $Q_g$

Primary stage ends

$Q_g$ (MCFPD)

$Q_g^a$

Time

WATERFLOOD
COMPRESS.
Case History

- First and only known implementation in early 1970’s – Duck Lake D–1 reservoir, Louisiana
- Additional recovery of 3.6% of OGIP, or 25 BCF
- High water requirements
Water Requirement

Reservoir temperature = 250 °F
Gas Gravity = 0.6

\[ W_{\text{inj}} = B_g G_p \]
Economic Sources of Water

1) Water Disposal
2) Underlying aquifer, (Dumpflood)
Case Study – Godchaux Reservoir A

- 4 producers, 7 injectors in a line drive
Case Study – Godchaux Reservoir A
## Case Study – Godchaux Reservoir A

### Economics

<table>
<thead>
<tr>
<th></th>
<th>Comp.</th>
<th>Press. Main.</th>
<th>Press. support</th>
<th>WF/Blow-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPV ((10^6 $))</td>
<td>91</td>
<td>98</td>
<td>91</td>
<td>110</td>
</tr>
<tr>
<td>Water Disposal</td>
<td>198</td>
<td>156</td>
<td>175</td>
<td></td>
</tr>
</tbody>
</table>
Conclusion

- The DDP using air injection, co-production technique, and water flooding of low pressure gas reservoirs are technically viable IOR methods.
- Economic viability will vary from reservoir to another.
- These methods should be added to the list of reservoir management tools.
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