Practical Applications and Novel EOR Methods

Jaime Almeida
Typical IOR/EOR Project Workflow

- **Project Management**
- **Screening for EOR methods.**
  - Screening based in reservoir properties
  - Predictive models
  - Dynamic simulation
- **Laboratory investigation**
  - Wettability, Relative permeability
  - Swelling test, MMP, MEC
  - SWTT (Single Well Tracer Test) Sor
  - Rock-Fluid compatibility test
- **Pilot test**
  - Pilot design
  - Pilot implementation
  - Pilot Monitoring
  - Reservoir and EOR parameter calibration.
- **Field Plan implementation**
  - Full field simulation after model calibration with pilot test.
  - Economic analysis
Project Life Cycle (Front-End Loading)

Value Identification

- Initialization (Pre-FEL)
- Visualization
- Conceptualization
- Definition
- Execution
- Operation

Value Realization

Front-End Loading (FEL)
FEL applied to an EOR project
Scenario analysis and Design Optimization, South America (National Oil Company) using DMS

**SITUATION**
1800 MMSTB oilfield under decline, Evaluate 4 potential scenarios for enhanced recovery and compare with base case. Optimize design parameters for water alternating gas scenario.

**CHALLENGE**
Identify an optimal recovery scenario based on an economic objective function (NPV). Rapidly optimize the design parameters for the WAG scenario using distributed computation (for DMS) with a combined spreadsheet model.

**VALUE ADDED BY DMS**
- Fast determination optimal recovery scenario based on NPV using distributed computation.
- Optimized WAG ratio, cycle length, injection rate, number of cycles.

**TOOLS**
- DMS (with distributed computing)
- VIP
- EXCEL (proprietary economics)
- SPOTFIRE (Data visualization package)
EOR Screening Criteria Revisited—Part 1: Introduction to Screening Criteria and Enhanced Recovery Field Projects

J.J. Taber, SPE, F.D. Martin, SPE, and R.S. Seright, SPE,
New Mexico Petroleum Recovery Research Center

EOR Screening Criteria Revisited—Part 2: Applications and Impact of Oil Prices

J.J. Taber, SPE, F.D. Martin, SPE, and R.S. Seright, SPE,
New Mexico Petroleum Recovery Research Center
### Screening criteria for EOR Methods

<table>
<thead>
<tr>
<th>Detail Table in Ref. 16</th>
<th>EOR Method</th>
<th>Oil Properties</th>
<th>Reservoir Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gravity (<em>API</em>)</td>
<td>Viscosity (cP)</td>
<td>Composition</td>
</tr>
<tr>
<td>1</td>
<td>Nitrogen and flue gas</td>
<td>&gt;35.68</td>
<td>&lt;0.4 ± 0.2</td>
</tr>
<tr>
<td>2</td>
<td>Hydrocarbon</td>
<td>&gt;23.61</td>
<td>&lt;3 ± 0.5</td>
</tr>
<tr>
<td>3</td>
<td>CO₂</td>
<td>&gt;22.36</td>
<td>&lt;10 ± 1.5</td>
</tr>
<tr>
<td>1–3</td>
<td>Immiscible gases</td>
<td>&gt;12</td>
<td>&lt;600</td>
</tr>
</tbody>
</table>

#### (Enhanced) Waterflooding

<table>
<thead>
<tr>
<th></th>
<th>Micellar Polymer, ASP, and Alkaline Flooding</th>
<th>Oil Properties</th>
<th>Reservoir Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;20.35</td>
<td>&lt;35 ± 12</td>
<td>Light, Intermediate, some organic acids for alkaline floods</td>
</tr>
<tr>
<td></td>
<td>&gt;15</td>
<td>&lt;150, &gt;10</td>
<td>NC</td>
</tr>
</tbody>
</table>

#### Thermal/Mechanical

<table>
<thead>
<tr>
<th></th>
<th>Combustion</th>
<th>Oil Properties</th>
<th>Reservoir Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;10.16</td>
<td>&lt;5,000</td>
<td>Some asphaltic components</td>
</tr>
<tr>
<td></td>
<td>Steam</td>
<td>&gt;8 to 13.5</td>
<td>&lt;2,000,000</td>
</tr>
<tr>
<td></td>
<td>Surface mining</td>
<td>7 to 11</td>
<td>Zero cold flow</td>
</tr>
</tbody>
</table>

NC = not critical. Underlined values represent the approximate mean or average for current field projects.
*See Table 3 of Ref. 16.
1 Eq. 6.55 from some carbonate reservoirs if the intent is to sweep only the fracture system.
2 Transmissivity > 20 md-ft/psi
3 Transmissivity > 50 md-ft/psi
4 See depth.
Screening for IOR/EOR methods

- Steam/Polymer/Surfactant
- Surfactant/Polymer/CO₂
- CO₂/Polymer/Hydrocarbon/Surf.
- CO₂/Hydrocarbon
- Nitrogen/Hydrocarbon
- Polymer degradation limit
- Thermal limit

Depth (m)

- Steam
- Polymer
- CO₂
- Hydrocarbon
- N₂
- Combustion
- Hot Water
- Miscellar/Polymer
- Surfactant
- Waterflooding
Screening for IOR/EOR methods

What is missing?

- Reservoir heterogeneity
- Relative permeability/rock wettability
- Reservoir geometry
- Minimum Miscible Pressure (MMP)
- Minimum Miscible Enrichment (MME)
Screening for IOR/EOR methods

- Predictive models
  - DOE Predictive models
    - Steamflood, In-situ Combustion, Polymer, Chemical Flood, CO2 Miscible Flood, Infill, Single-Well Chemical Tracer
  - CO2 Prophet and other commercial software
  - EOR RATE MODEL (2008) (*)

- Correlations

- Computer methods of Screening
  - MAESTRO™
  - SelectEOR™ (ALBERTA RESEARCH COUNCIL) (2009)

(*) Source: Danish Energy Agency
What is the target oil for EOR?

Residual Oil Saturation
Sor\textsubscript{w}=100-70=30\%
Target for EOR after Waterflooding

Wettability effect in Sor

Residual Oil Saturation
Sor\textsubscript{w}=100-90=10\%
Target for EOR after Waterflooding

Strong water wet system
Conformance Control Solutions

Temperature 65 to 160 °C
Importance of capillary number in defining EOR

\[ N_c = \frac{k \frac{\Delta p}{\Delta L}}{\sigma} \]

- Wetting
- Nonwetting

Dombroski & Brownell
Foster
Taber
Du Prey
Gupta
Effect on reducing interfacial tension

Source: Bardon & Longeron SPE 7609
Effect of mobility ratio in Sweep efficiency

\[ M = \frac{\lambda_w}{\lambda_o} = \frac{k_{rw}\mu_o}{k_{ro}\mu_w} \]

Laboratory investigation

- Wettability, Relative permeability
- Swelling test, MMP, MME
- SWTT (Single Well Tracer Test) for Sor estimation
- Rock-Fluid compatibility test

- Slim tube test
- Rising Bubble method
- Vanishing interfacial tension
## MMP Correlations

### Pure CO2

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameters</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1974</td>
<td>T MWC5+</td>
<td>Holm and Josendal, Cronquist</td>
</tr>
<tr>
<td>1977</td>
<td>T MWC5+ C1</td>
<td>Yellin and Metcalfe, Johnson and Pollin</td>
</tr>
<tr>
<td>1980</td>
<td>T</td>
<td>Glaso, Alston</td>
</tr>
<tr>
<td>1981</td>
<td>T MWC7+</td>
<td>Yellin and Metcalfe, Johnson and Pollin</td>
</tr>
<tr>
<td>1985</td>
<td>T MWC7+ C2-C6</td>
<td>Alston</td>
</tr>
<tr>
<td>2004</td>
<td>T MWC7+ C2-C6</td>
<td>Yuan et al.</td>
</tr>
<tr>
<td>2007</td>
<td>T MWC5+ C1N2 C2-C4,CO2</td>
<td>Shokir</td>
</tr>
</tbody>
</table>

### CO2 with Impurities

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameters</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td>Gas composition</td>
<td>Johnson and Pollin</td>
</tr>
<tr>
<td>1985</td>
<td>Gas composition</td>
<td>Sebastian et al.</td>
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<tr>
<td>2004</td>
<td>T MWC7+ C2-C6 Gas composition</td>
<td>Yuan et al.</td>
</tr>
<tr>
<td>2007</td>
<td>T MWC7+ C2-C6 Gas composition</td>
<td>Shokir</td>
</tr>
</tbody>
</table>

### N2 and lean gas

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameters</th>
<th>Authors</th>
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<tbody>
<tr>
<td>1986</td>
<td>T MWC7+ C2-C5</td>
<td>Firoozabadi and Aziz</td>
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</table>

### Hydrocarbon gas

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameters</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>T MWC5+ Gas composition</td>
<td>Kuo</td>
</tr>
</tbody>
</table>

Estimation based on EOS calculations (T, compositions oil and gas).
Shokir method

Linear regression Methods

\[ Y = \beta_0 + \sum_{i=1}^{p} \beta_i X_i + \varepsilon \]

Alternating Conditional Expectation (ACE) Algorithms

\[ \theta(Y) = \alpha + \sum_{i=1}^{p} \phi_i(X_i) + \varepsilon \]

Resulting coefficients for all the input parameters

<table>
<thead>
<tr>
<th>n</th>
<th>x</th>
<th>A3</th>
<th>A2</th>
<th>A1</th>
<th>A0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oil components</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Vol., %</td>
<td>-1.3721E-05</td>
<td>1.3644E-03</td>
<td>-7.9169E-03</td>
<td>-3.1227E-01</td>
</tr>
<tr>
<td>3</td>
<td>Interm., %</td>
<td>3.5551E-05</td>
<td>-2.7853E-03</td>
<td>4.2165E-02</td>
<td>-4.9485E-02</td>
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<tr>
<td>4</td>
<td>MW_{CS+}</td>
<td>-3.1604E-06</td>
<td>1.9860E-03</td>
<td>-3.9750E-01</td>
<td>2.5430E+01</td>
</tr>
<tr>
<td>5</td>
<td>Non-CO₂ components</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C₁, %</td>
<td>1.0753E-04</td>
<td>-2.4733E-03</td>
<td>7.0948E-02</td>
<td>-2.9651E-01</td>
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<tr>
<td>7</td>
<td>C₂–C₄, %</td>
<td>6.9446E-06</td>
<td>-7.9188E-05</td>
<td>-4.4917E-02</td>
<td>7.8383E-02</td>
</tr>
<tr>
<td>8</td>
<td>N₂, %</td>
<td>0</td>
<td>3.7206E-03</td>
<td>1.9785E-01</td>
<td>-2.5014E-02</td>
</tr>
<tr>
<td>9</td>
<td>H₂S, %</td>
<td>3.9068E-06</td>
<td>-2.7719E-04</td>
<td>-8.9009E-03</td>
<td>1.2344E-01</td>
</tr>
</tbody>
</table>

JPSE, 58 (2007) 173-185
Pilot project design

Reservoir parameters
- Depth: 4421 m
- Thickness: 213 m
- Porosity: 8 - 12 %
- Permeability: 10-150 mD
- Oil Gravity: 26 API
- Temperature: 146 C
- Initial pressure: 791 BAR
- Bubble point pressure: 267 BAR
- MMP: 499 BAR
- Res. Pressure: 506 BAR
Cross section study results

- Waterflood
- Gas Injection
- 1:1 WAG

- 5-spot-ows
- 5-spt if wag
- 9-spt if wag
- gas inj
- 5-spt if
- 9-spt if
- 5-spt ows wag
- 5-spt if wf
- 9-spt if wf
- 5-spt ows wt
- 5-spt ows
- 5-spot-ows original well spacing
- 5pt with infill
- 9-spot with infill

Oil Recovery (fraction OOIP with API > 8°)

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WAG Pilot Project Design

Pilot test monitoring
Injector
- Production Profile Log (PLT)
- Down Hole P and T measurements
- Water chemical tracer
- Gas Chemical tracer

Observation well
- Production Profile Log (PLT)
- Down Hole P and T measurements
- Saturation logs

Tracers
- Fluorbenzoic acid (Water)
- Perfluorcarbon Hydrocarbon (Gas)
Monitoring

The Weyburn Monitoring Project
3D-3 component and 3D-9 component geophysical survey
• Vertical Seismic Profiling (VSP) from surface to horizontal well
• Cross-well seismic between parallel
• Horizontal wells
• Single horizontal well seismic

Source: K. Brown et al, Role of Enhanced Oil Recovery in carbon Dioxide Sequestration the Weyburn Monitoring Project, a case Study
Novel EOR Technology

*Integration of CO2 storage and EOR*

*Toe to heel air injection THAI™ (CAPRI)*

*Solvent Vapour Extraction (SVX)*
Integration of CO2 storage and EOR

Integration of CO2 storage and EOR

Source: DOE/NETL Feb 2008
THAI™ is a new combustion process

Toe to heel air injection (THAI) is a new method of extracting oil from heavy oil deposits which may have significant advantages over existing methods. The method was developed by Malcolm Greaves of the University of Bath and has been patented by Petrobank.
Solvent Vapour Extraction (SVX)

JIVE said: For every billion barrels of oil produced by SVX instead of SAGD:

- 85 millions tones of CO2 prevented from entering the atmosphere
- 400 millions barrels of fresh water saved
- 1.65 trillion cubit feet of natural gas not burned

Source: Petroleum Technology Research Centre (PTRC) JIVE Program