Tensleep TZ/ROZ Study, Bighorn Basin
A Revolutionary Concept on Oil Recovery

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Study Objective

- Characterization of EOR potential of transition zone (TZ)/residual oil zone (ROZ) in Tensleep Sandstone, Bighorn Basin.
Main Pay Zone (MPZ), Transition Zone (TZ) & Residual Oil Zone (ROZ)

OIL COLUMN
- Top of Trap
- Free-Oil Level
- Econ. o/w Contact
- Prod. o/w Contact
- 100% Water Level
- Free-Water Level

Jennings, 1987

ARI, 2006

Oil Saturation (%)

0 20 40 60 80 100
0 20 40 60 80 100

S_o (%)

MPZ
TZ
ROZ

Bighorn Basin Tensleep
Structural Contour Map of Tensleep Sandstone

Zapp, 1953
Tensleep Sandstone Potentiometric Map

Bredehoeft et al., 1992
Topics

• Tensleep TZ/ROZ in Bighorn Basin.

• Mechanisms for Thick TZ/ROZ.

• Active ROZ CO$_2$-EOR Production in Permian Basin.

• Comments and Future Study.
Tensleep TZ/ROZ in Bighorn Basin

• Below main pay zone within existing reservoirs.

• Around existing reservoirs.

• Non-productive structures (green fields).

• Oil Properties are similar in TZ/ROZ and MPZ
Below Main Pay Zone within Existing Reservoirs.

Thick permeable intervals with high $S_\phi$ not produced during primary and secondary production.
Perforation Interval in a Tensleep Reservoir

Total Tensleep thickness: 180 ft
Average perforation thickness: 47 ft
Non-commercial Wells around Existing Reservoirs

Wells with high $S_o$, but not economically viable by primary and secondary recovery techniques
Core Photos, Non-productive Well

320410
C L Zwemer 1
57N-97W-21
Bighorn Basin
Traps with Oil Saturation not High Enough for Primary and Secondary Recovery (Green Fields)
Well Located in Non-commercial Structure (Green Field)

Tectonic information from Ploeg, 1985)
Total thickness of Tensleep Sandstone: 142 ft.

3706-3750 ft, sandstone, even light brown heavy oil stain, free oil droplets in samples and within pore spaces, even dark yellow fluorescence, strong petroleum odor.

10-12% log porosity.

Perf: 3718-3728 ft (10 ft thick).

No production, plug & abandon.

Tectonic information from Ploeg, 1985)
Example Showing $S_o$, Perforation, and Water Cut

Produce 75 bbls/day with 70% water cut constant over one year

Data from Aufricht, 1965
Tensleep Reservoirs
Aufricht, 1965

• Oil-water transition zone of several hundred feet in thickness.

• Transition zone with $S_o$ of 80% still produce with extremely high water cuts.

• OOIP approaching 1000 barrels per acre foot may produce at water cuts greater than 95%.

• Intervals with $S_w$ of 15 to 30% are commercially interest for primary and secondary recovery techniques.
**ROZ CO₂-EOR Potential**

- **ARI estimated TZ/ROZ OIP in 13 Bighorn Basin Tensleep Productive reservoirs: 4.4 BBbls**

  - These 13 Tensleep reservoirs with cumulative production: from 345.4 to 6.2 MMBbls

<table>
<thead>
<tr>
<th>13 Bighorn Basin Tensleep Reservoirs</th>
<th>MPZ OOIP (BBbls)</th>
<th>MPZ Remaining OIP (BBbls)</th>
<th>TZ/ROZ OIP (BBbls)</th>
<th>Total Reserve for CO₂-EOR (BBbls)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. CO₂-miscible fields: 8</td>
<td>4.5</td>
<td>3.1</td>
<td>4.4</td>
<td>7.5</td>
</tr>
<tr>
<td>2. CO₂-immiscible fields: 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂-EOR recovery: 11%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CO₂-EOR recovery: 30%</td>
<td></td>
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</tr>
</tbody>
</table>
Oil Properties are similar in TZ/ROZ and MPZ

Reservoir Oil

From Non-productive Wells

GC Analysis
Summary

Green Field

TZ/ROZ
CO₂-EOR

Brown Field

MPZ
Primary & secondary

TZ/ROZ
CO₂-EOR
Mechanisms for Thick TZ/ROZ

• Tertiary oil migration from stratigraphic to structural traps creates rich TZ/ROZ.

• Heavy oil reservoirs favor to generate thick TZ/ROZ.

• Reservoir heterogeneity retards gravity separation of oil from water, resulting a thick TZ with uneven oil saturation.

• Strong hydrodynamic flow aids to generate rich TZ/ROZ.
Late Permian Paleogeographic Map
(Phosphoria Period)

Miller et al., 1991
Oil Migrated into Tensleep Through Unconformity

Bighorn Basin

Modified from Stone, 1967

Oil Accumulated in Stratigraphic Traps before Laramide Orogeny
Folds and Thrust Faults Generated during Laramide Orogeny

Zapp, 1953
Re-Migration of Oil Creating Rich TZ/ROZ

Bighorn Basin

Post-Tensleep Strata 9500’ thick

After Laramide (Paleocene-Eocene)

Oil migrated and accumulated in structure top

Meteoric water Flushing

Tensleep outcropped

Oil flushed downdip or escaped updip

9500’ thick

Post-Tensleep Strata

Bighorn Mountain

A

B

Tensleep

Tensleep

Oil

TOZ/ROZ

Oil

TOZ/ROZ

Oil

TOZ/ROZ

Oil

TOZ/ROZ
East Flank of Bighorn Basin
An Example of Present Hydrocarbon Distribution
Perforation Bottom Deepening from NE to SW
Recent multiple oil migration
OWC modification
Heavy oil
Reservoir heterogeneity

Summary

- Left oil in previous traps
- Thick TZ/ROZ
- Changes of oil column
- Less oil degradation
Mechanism of Secondary Hydrocarbon Migration and Entrapment

- **Driving force**: buoyancy caused by difference of density between hydrocarbon and water.
- **Resistant force**: capillary pressure.
  - Radius of pore throats.
  - Hydrocarbon-water interfacial tension.
  - Wettability of reservoir rocks.

\[
R: \text{Radius of pore throat.} \\
\theta: \text{contact angle of oil and water against the solid.}
\]

From Schowalter, 1979
Heavy Oil Reservoirs with Thick TZ/ROZ

Thickness Difference Due to Oil Density

$$P_c = h(\rho_w g - \rho_o g)$$

From Aufricht, 1965
Water Cut as Functions of Relative Permeability and Oil Viscosity

Water cut, % = 100 × f_w = \frac{100}{1 + \frac{\mu_w}{\mu_o} \left(\frac{k_o}{k_w}\right)}

Reservoir A
- 14 API
- 500 cp

Reservoir B
- 23 API
- 10 cp

Reservoir C
- 34 API
- 1 cp

From Aufricht, 1965
Hydrodynamic Traps Contributed by Bed Thinning, Faulting, or Bending

Levorson, 1966

Pedry, 1975
56 fields in five major Permian Basin oil plays that have potential for significant TZ/ROZ resources were identified by Advanced Resources Intl. TZ/ROZ OOIP in these 56 fields is estimated to be 30.7 Billion Barrels.

<table>
<thead>
<tr>
<th>Field/Unit</th>
<th>MPZ OOIP (BB)</th>
<th>TZ/ROZ OOIP (BB)</th>
<th>No. of Fields</th>
<th>No. of MPZ Fields with CO2-EOR Projects</th>
<th>No. of Fields with TZ/ROZ CO2-EOR Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Northern Shelf Permian Basin (San Andres)</td>
<td>13.0</td>
<td>13.2</td>
<td>13</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>2. North Central Basin Platform (San Andres/Grayburg)</td>
<td>2.9</td>
<td>2.6</td>
<td>6</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3. South Central Basin Platform (San Andres/Grayburg)</td>
<td>9.9</td>
<td>7.9</td>
<td>16</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>4. Horseshoe Atoll (Canyon)</td>
<td>5.4</td>
<td>2.9</td>
<td>10</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5. East New Mexico (San Andres)</td>
<td>2.3</td>
<td>4.1</td>
<td>11</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>33.5</strong></td>
<td><strong>30.7</strong></td>
<td><strong>56</strong></td>
<td><strong>18</strong></td>
<td><strong>4</strong></td>
</tr>
</tbody>
</table>

Koperna et al., 2006
Oil Production Increase by Including ROZ CO$_2$-EOR

Goldsmith San Andres Unit

Seminole San Andres Unit

Thurmond, 2010

2010 CO$_2$ Flooding Conference
ROZ & MPZ Have Consistent Properties in Permian Basin

Concluded by Thurmond for Goldsmith San Andres Unit, 2010

• Core oil saturation is consistent.

• Reservoir quality is consistent.

• Bulk oil composition is consistent.

• Chemical process behavior is consistent.
Ideas and Future Study

• Recognition of thick Tensleep TZ/ROZ in Bighorn Basin.
  – TZ/ROZ below main pay zone.
  – TZ/ROZ around current reservoirs.
  – TZ/ROZ in non-commercial structures.

• New discovery of CO$_2$-EOR resources in Bighorn basin.
  • EOR resources not counted by traditional main pay zones.

• There will be high potential for CO$_2$-EOR, and even a new wave of exploration for EOR targets.

• Development of TZ/ROZ simultaneously with MPZ.

• Further integrate the TZ/ROZ concept in Tensleep reservoirs.
• Evaluation of all non-productive structures (green fields).
• Search for rich TZ/ROZ fairways.
• Estimation of CO$_2$-EOR potential in TZ/ROZ.
• Communication and cooperative with oil companies.
Conclusions

• There is tremendous oil reserve for CO$_2$-EOR in Tensleep Sandstone, Bighorn Basin.

• CO$_2$-supply will be available in 3-5 years.

• It is advantageous to develop TZ/ROZ at the same time with MPZ.

• TZ/ROZ must be comprehensively understood before start of CO$_2$-EOR in Bighorn Basin.