The promise and challenge of CO2-EOR, Residual Oil Zone production, and CO2 storage

Dr. S. Julio Friedmann
Susan Carroll, Chen Mingjie, Walt McNab, and Abelardo Ramirez
Lawrence Livermore National Laboratory

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LLNL applies its expertise and capabilities to helping carbon management needs

Only group involved in R&D at all five large commercial projects (Sleipner, Snohvit, Weyburn, Cranfield, In Salah)

Other large projects in US & China

Active in 4 DOE regional partnerships

Partnered with power generators, oil & gas companies, NGOs

Advise government on regulation, legal issues, R&D investments

We focus on S&T that help enable deployment
CCUS as a bridging technology to an energy-rich, low-carbon economy

Global CO2 emissions and GHG emissions reductions

EOR as a bridging technology CCUS deployment

IEA, 2011
How wide, how long, how stable is that bridge?

- Wider than expected
- Longer than expected
- Advanced technologies help
CO2-EOR: Combines storage with production

Physics of miscible CO2-EOR
- CO2 dissolves in oil; oil dissolves in CO2
- Oil volume swells (increase volume)
- Decrease viscosity
- Reduce wettability angle

Production increases
(improves total recovery 10-15%)

EOR began in US in 1972
 Longer than expected: Large EOR volumes in US and China

- Many 10’s of billions producible (just US)
- 100’s of billions worldwide
- Chief rate limiting step (lack of CO2) likely to persist for years

**Domestic Oil Resources**

<table>
<thead>
<tr>
<th>Recoverable Type</th>
<th>Billion Barrels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technically Recoverable</td>
<td>88.1</td>
</tr>
<tr>
<td>Economically Recoverable*</td>
<td>47.4</td>
</tr>
<tr>
<td>Already Produced/Proven</td>
<td>2.3</td>
</tr>
</tbody>
</table>

**Market CO2 demand**

<table>
<thead>
<tr>
<th>Category</th>
<th>Million Metric Tons</th>
</tr>
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<tbody>
<tr>
<td>Total U.S. CO2 Demand</td>
<td>12,500</td>
</tr>
<tr>
<td>New Lower-48 CO2 Demand</td>
<td>9,700</td>
</tr>
<tr>
<td>Net Lower-48 From Captured CO2 Emissions</td>
<td>7,500</td>
</tr>
</tbody>
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ARI, 2008

[ARI, 2008 diagram showing original oil in-place, stranded oil in-place, future challenge, cumulative production, and proved reserves with CO2-EOR technology]
Wider than expected: Residual Oil Zone (ROZ) volumes

Zones of low oil saturation (80-20%) beneath and next to conventional oil fields

2x-3x recovery potential
- Six producing ROZ fields in US Permian Basin
- 12-18 Billion bbl in ROZ
- 6.4 Billion bbls in main pay zones

2x-5x storage potential
- Large areas; complex reservoirs
- Needs more CO2/barrel!
- Negative carbon oil?

<table>
<thead>
<tr>
<th></th>
<th>&quot;State of the Art&quot;</th>
<th>&quot;Next Generation&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Storage</td>
<td>19</td>
<td>109</td>
</tr>
<tr>
<td>Storage Capacity</td>
<td>13%</td>
<td>76%</td>
</tr>
<tr>
<td>Oil Recovery</td>
<td>64</td>
<td>180</td>
</tr>
<tr>
<td>% Carbon Neutral</td>
<td>80%</td>
<td>160%</td>
</tr>
</tbody>
</table>

Sources: MIT, 2010; ARI 2007 and 2010; NETL 2008

ARI, 2008
Two kinds of ROZ zones

• Beneath main pay zones in regular oil fields

• Ancient migration fairways: NOT conventional closures
Critical technology enables superior CO2-EOR and ROZ production

• Advanced reservoir characterization
• Advanced simulation
• Enhanced monitoring

Enabled by high-performance computing
Characterization: detailed core/lithology analysis plus advanced supercomputing techniques

Result: Better sweep efficiency
Better reservoir storage efficiency
For Weyburn: Modeled and validated rapid changes in porosity and permeability of vuggy reservoir

Advanced simulation tools
- NUFT2 (FD and FE methods; structured and unstructured meshes)
- GEMBOCHS (library – 128 mineral EOS)
- EQ3/6 (alt. to Geochemist’s Workbench)
- PHREEC-CD, etc.

Combine simulation with experiments for validation
- Batch and flow-through experiments
- “1-D” experimental designs
- Advanced light source (LBNL) and neutron-source images
- High pressure and temperature

Result: High confidence in models
Avoid production problems
At Weyburn: Successful integration of seismic and geochemical signals; direct permeability mapping

Result: High confidence in models
Avoid production problems
Cranfield ERT: Direct imaging of CO₂ saturation

Electrical Resistance Tomography = ERT

Deepest ever ERT array
- 10,000 feet (3000 m)
- Cross-well
- Daily measurements

Key successes
- Detected CO₂
- Good calibration to log tools
- Detected changes in saturation

Result: Fast, cheap, accurate tool
Will improve operations
CCUS a major opportunity for energy production and emissions reduction in China and US

Chu and Thornton, 2009

“...both countries will need not only bold leadership and a new set of national policies, but also a path-breaking cooperative agenda that can be sustained over the long run [over the next 5-10 years].”
LLNL has many direct partnerships and MOUs with leading Chinese companies, including state-owned enterprises:

US-China CERC (technical director)
Tsinghua-WRI CCUS Guidelines
Asia Society US-China CCS Roadmap

Huaneng-CERI
Shenhua
CNOOC
XinAo/ENN
Tsinghua Univ.
Chinese Univ. of Mining Technology
CO2-EOR/ROZ bridge is wide, long, and strong

• Larger oil production than first thought
• Much more CO2 storage potential (negative C oil)
• Advanced technologies help

Please visit San Francisco and visit Lawrence Livermore National Lab