CAP CO2’s focus is the use anthropogenic CO2 for enhanced oil recovery, with concurrent carbon storage.
Outline – Growing Opportunities

1. Geologic sequestration
   • A key alternative
   • Costs
   • Kansas geology suitability and capacity
   • Kansas projects

2. Interim solution: Concurrent Enhanced Oil Recovery (EOR) and Carbon Capture and Storage (CCS)
   • “Green” oil with industrial CO2
   • Technical requirements
   • Kansas opportunities and economic impact
CO₂ Basics

• 1 ton CO₂ = 17.2 mcf
• 1 metric ton = 19 mcf
• An average human exhales 6 mcf CO₂/yr
• Combustion of 1 barrel of oil yields 8 mcf CO₂
• 7 mcf CO₂ / BO (Net utilization: Sequestered)
• Ethanol (55mgy) – 8.3 mmcf/d, 0.16 million tonnes/yr (1-2 mbopd)
• Coffeyville fertilizer plant – 40 mmcf/d, 0.8 million tonnes/yr (6-8 mbopd)
• New Sunflower 895 MW plant deal – 6.7 million tons/yr

Kansas:
• Total 72.8 Million Metric Tons/Year
• Coal-fired Power 37.2 Million Metric Tons/Year

Handy CO₂ properties calculator:
http://abyss.kgs.ku.edu/pls/abyss/nat
carb.co2_calc.co2_prop

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US Stationary CO2 Sources

Kansas
73 Million Tons/Year
Power 37 Million Tons/Year

Carbon legislation
+ Carbon capture
+ Need for geologic storage
+ CO2 pipeline infrastructure
= Opportunity for CCS and CO2 EOR in Kansas

Source: NATCARB, NETL
Seven Wedges to CO2 reduction

Billion of Tons of Carbon Emitted per Year

14 GtC/y

Geologic Sequestration Wedge

Historical emissions

Currently projected path

Flat path

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Graphic: Socolow & Pacala
• Accumulated total reflection amplitude from all nine layers of the Sleipner CO2 plume.

• I am not sure how much had been injected in 2006, but as of 2008 ~10 M tons had been injected.

• Sleipner project is about the size of some Arbuckle “domes” on the CKU.
Kansas CO2 EOR and CCS studies and proposed projects

KGS and TORP (KU) - successful Russell CO2 pilot project (99-09)

Gas Oil & Gas

KGS 5-yr DOE-funded study area

KGS 5

Gas
Oil & Gas
Oil

DOE-funded study area

CAP CO2, Blue Source et al – Phase I DOE study. Two sources, multiple sinks

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Arbuckle EOR and CCS target

Geneseo-Edwards field could store >8.5 million tons CO2
Arbuckle injection rates and sequestration

**Injectivity Documented**

- 2000 SWDW in Arbuckle in Kansas
- 3-5,000 BWPD common; some >10,000 BWPD, on a vacuum.
- 100 - 350 metric tons/day, (37 - 130 k metric tons/yr)
- 50 -175 injection wells for the planned 850MW Sunflower plant
- 1-3 wells for a 55mgy ethanol plant

(CO2 properties at 110F and 1100psi – supercritical, 13.8 lbs/ft^3, and 0.22 gm/cc)

**Storage space available**

**A Single Example: Ellsworth anticline (saline aquifer)**

- 126 square miles (6X21 mi)
- 100 ft of closure
- 15% porosity
- Sw = 100%
- Store 278 million metric tons supercritical displacement
- 66 million metric tons as dissolved gas

(Assumed 100F, 1200psi, TDS = 30,000 ppm)

Carr, et al. (2005)
Volumetric estimates for storing CO2 in Arbuckle domes on CKU

<table>
<thead>
<tr>
<th>FIELD</th>
<th>DISC YR</th>
<th>CUM. OIL (mmbo)</th>
<th>CO2 REPLACE OIL</th>
<th>CO2 TO SPILL (~2.5X*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRAPP</td>
<td>1929</td>
<td>308</td>
<td>11.9</td>
<td>29.8</td>
</tr>
<tr>
<td>CHASE-SILICA</td>
<td>1929</td>
<td>280</td>
<td>10.8</td>
<td>27.0</td>
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<tr>
<td>BEMIS-SHUTTS</td>
<td>1928</td>
<td>261</td>
<td>10.1</td>
<td>25.3</td>
</tr>
<tr>
<td>HALL-GURNEY</td>
<td>1931</td>
<td>160</td>
<td>6.2</td>
<td>15.5</td>
</tr>
<tr>
<td>KRAFT-PRUSA</td>
<td>1937</td>
<td>137</td>
<td>5.3</td>
<td>13.3</td>
</tr>
<tr>
<td>GORHAM</td>
<td>1926</td>
<td>98</td>
<td>3.8</td>
<td>9.5</td>
</tr>
<tr>
<td>GENESEO-EDWARDS</td>
<td>1934</td>
<td>89</td>
<td>3.4</td>
<td>8.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,333</strong></td>
<td><strong>51.5</strong></td>
<td><strong>128.8</strong></td>
<td></td>
</tr>
</tbody>
</table>

Kansas:
- **Total 72.8 Million** Metric Tons/Year
- **Electric Power 37.2 Million** Metric Tons/Year
- New **Sunflower** 895 MW plant deal – 6.7 million tons/yr (metric tons?)

* Assumptions: Cumulative oil is ~40% OOIP and 28% of pore volume, FVF = 1.1, Swi = 30%, final Sco2 = 70% and reservoir is filled to spill point. CO2 properties at 110F and 1100psi – supercritical, 13.8 lbs/ft^3, and 0.22 gm/cc.
Theoretical CO\textsubscript{2} storage volume in “depleted” Kansas oil and gas reservoirs

*Filling only the space vacated by the hydrocarbon*

### OIL

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Production</td>
<td>6.3 Billion BO</td>
</tr>
<tr>
<td>Reservoir Volume</td>
<td>6.93 Billion bbls ((FVF=1.1))</td>
</tr>
<tr>
<td>Reservoir Volume</td>
<td>38.9 BCF</td>
</tr>
<tr>
<td>Tonnes CO\textsubscript{2}</td>
<td>243 million tonnes</td>
</tr>
</tbody>
</table>

### GAS

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumulative Production</td>
<td>38.4 TCF</td>
</tr>
<tr>
<td>Reservoir Volume</td>
<td>1.12 TCF ((Bg = 34.3))</td>
</tr>
<tr>
<td>Tonnes CO\textsubscript{2}</td>
<td>2,232 million tonnes</td>
</tr>
</tbody>
</table>

* Assumes 110\textdegree F and 1100 psi for average oil reservoir - CKU

13.8 lbs CO\textsubscript{2} / ft\textsuperscript{3}

** Assumes 100\textdegree F and 500 psi for average gas reservoir - Hugoton

4.4 lbs CO\textsubscript{2} / ft\textsuperscript{3}

Kansas:

- Total 72.8 Million Metric Tons/Year
- Electric Power 37.2 Million Metric Tons/Year
- New Sunflower 895 MW plant deal – 6.7 million tons/yr (metric tons?)

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Arbuckle as saline aquifer storage

**Positives**
+ Proven seal
+ Proven injection zone
+ Vast storage capacity
+ Fluid gradients working in our favor (Carr, et al., 2005)
+ Fluid velocities in aquifer are very slow (Jorgensen et al., 1993)

**Negatives**
- Much is below supercritical
- Existing wellbores may be problematic
- Best structures are still oil productive *

* But….what about concurrent EOR and CCS?
# Reality of costs

<table>
<thead>
<tr>
<th>Activity</th>
<th>Cost per Ton CO2 ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture</td>
<td>0 - 50 (pure vs. coal-power)</td>
</tr>
<tr>
<td>Compression</td>
<td>15 - 20</td>
</tr>
<tr>
<td>Transportation</td>
<td>0 - 20 (on site vs. distant)</td>
</tr>
<tr>
<td>Injection &amp; monitor</td>
<td>5 - 10</td>
</tr>
</tbody>
</table>

$20 - $100 per ton

Present financial incentive to capture and store: $0 - $20*/ton

* $20 tax credit for sequestration for large CO2 sources

**Interim solution: “Green Oil”**

- 2.8 Barrels of oil recovered ($200 gross value)
- One ton CO2 permanently stored
- Combust 2.8 Barrels of oil yields 1.1 tons CO2
CO2 Retention in EOR

- Historically 50% of CO2 is retained in the reservoir
- The other 50% is captured, recycled and re-injected
- Eventually nearly all is stored, permanently (<5% loss over time)

Anthro-CO2 oil is nearly carbon neutral*
  ✓ 7 mcf CO2 sequestered
  ✓ 8 mcf /barrel oil oxidized

* Excludes, refining, transportation CO2 costs

Long-lived CO2 EOR projects, mainly Permian basin

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CO2 storage capacity and mode

Amount of CO2 sequestered depends on temperature, pressure, brine chemistry, hydrocarbon properties, rock chemistry, and pore throat diameters (capillary pressures)

Modes of storage
1. Displacement – \( f(\text{density}) = f(P, T) \)
2. Residual saturation – \( f(\text{pores}) \)
3. Solubility trapping* – \( f(\text{salinity, P, T}) \)
4. Mineralization – \( f(\text{mineralogy, T, brine}) \)

*Noteworthy: Solubility of CO2 in oil is > than in Sw

State of CO2 stored is function of time

Hermanrud, et al. (2009)
**CO2 Processing Styles**

**Horizontal (piston) flood**
- Application: Follow waterfloods
- KS targets: L-KC, Bartlesville, Morrow, Chester
- Well documented

**Gravity-stable flood**
- Application: bottom-water drive reservoirs
- KS targets: Arbuckle, Simpson, Viola
- Fewer analogues
Technical Requirements

Miscible – piston displacement

1. Inject pressure > CO2 in supercritical state (>1073)
2. Inject pressure < frac pressure
3. Reservoir operating pressure > MMP (1200-2000 psi)
4. Adequate working pressure range (Frac pressure – MMP)
5. Adequate Remaining OIP
6. Reservoir conditions allowing contact throughout the reservoir (good waterflood)

Miscible or near-miscible gravity-stable displacement

Same constraints………

• Reservoir BHP above MMP for miscible (for bottom-water drive reservoirs)
• Reservoir conditions & wellbore configuration to build uniformly expanding CO2 gas cap

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Minimum Miscibility Pressure

MMP = system pressure at which 90% of lease crude oil in sand-packed slim tube is recovered

MMP’s performed by TORP, KU

API = 37.5°-38.4°

Lansing-KC
Hall-Gurney

Other KS Crudes
Recent Arbuckle
~1350 psi

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Miscible floods operate at:
- > supercritical (1073 psi)
- above MMP (MMP > 1200 psi)

Kansas reservoir properties range:
- 400 psi, 85°F at 1000 ft
- 1600 psi, 125°F at 6000 ft
**CO2’s operating requirements and reservoir constraints**

**Target screen dimensions determined by pressure constraints (miscible)**
- CO2 supercritical at >1073 psi
- MMP variable, >1200 psi and increases with BHT (depth)
- Frac pressure is upper limit to injection pressure
- High absolute maximum operating pressure range is desirable (Delta P = frac P – MMP)

**Density and viscosity varies significantly**
from light liquid to heavy super-critical within the range of P & T for surface to BH

*Properties from SPE Monograph 22*

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Relative volume for CO2 under “normal” pressure and temperature conditions. Kansas is under-pressured
Defining Kansas Resource Targets

**Pressure constraints** (Miscible, Delta P could vary, but generally >300 psi)
- Shallowest ~2000 ft (BHP 800 psi)
  - Can work at shallow depths: low BHT lowers MMP and improved frac P with pressered reservoir.
- Ideal miscible >4000 ft (BHP 1300 psi)

**Process rate and uniformity**
- Higher Delta P for higher process rate
- Low vertical heterogeneity and good later communication (good sweep efficiency demonstrated by good waterflood)

**Large remaining oil in place**
- “Critical mass” is required to justify non-oil field capital requirements
- High ROIP per-acre required to justify oil-field capital requirements
- Maximize return on capital

**Gravity-stable targets**
- High BHP preferred
- High gravity, lower MMP preferred
- Vertical permeability, layering, coning are complicating factors
CO\textsubscript{2} EOR impact in Kansas will be significant…. just how significant will be determined by future events.

- Carbon management legislation and laws (Cap & Trade)
- Geologic storage regulations (Federal and State)
- Kansas oil industry response

*Plus the usual underlying fundamentals*
- EOR resource base
- Oil price
- Favorable / unfavorable tax environment
Convergence

The CO2 landscape has changed dramatically over the past seven years at the state, regional, and federal level.

1. CO2 emissions is publicly accepted as a significant issue to be dealt with

2. Looming carbon management legislation and laws (Cap & Trade) would be a game-changer

3. Geologic storage regulations are moving forward (Federal and State)

4. Pure CO2 sources increased 4X in Kansas (3 ethanol plants, 1 ammonia plant and 30 mmcf to 10 ethanol plants, 2 ammonia plants 120 mmcf)

5. Technical advancements in CO2 EOR expand targets (gravity-stable, shallower depths, drilling and completion)
Potential CO2 EOR in Kansas

Kansas Cumulative to date: 6.3 Billion Barrels
20% of P&S: 1.2 Billion
KGS upper end technically feasible: 600 Million
Technically feasible (*ARI): 570 Million
More conservative view: 200 Million
Half of that: 100 Million (2.5x annual)

* Kusskraa (ARI), 2006

Costs for 100 million barrels CO2 EOR oil
Capital costs in field $1 Billion
CO2 costs** $1 Billion
Operating costs $1 Billion
Cost of Capital $x Billion

** $1.5/mcf + $0.50/mcf recycle. N/G = 5/10.

Costs could vary significantly. Numbers are intended only for illustrating that significant investment is required.
Impact of Technology on Kansas Oil Production

- Technology
- Demand (wars)
- Oil Price

- WW I
- WW II
- Surface Mapping
- Rotary Bits
- Single-Point Seismic
- Waterfloods
- 3D Seismic
- OPEC Price Spike
- Other CO2
- KS CO2

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Why not Kansas?

Mississippi Annual Oil Production

Total Cumulative Oil: 2.387 Billion Barrels (through 2008)

Denbury buys Jackson Dome

Denbury Resources Inc.
Why not Kansas?

- 86 projects
- 237 mbo/d

Laws of physics also apply in Kansas

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## Current CO2 Used for EOR

<table>
<thead>
<tr>
<th>State/Province (storage location)</th>
<th>Source Type (location)</th>
<th>CO2 Supply MMcfd**</th>
<th>Natural</th>
<th>Anthropogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Texas-Utah-New Mexico-Oklahoma</td>
<td>Geologic (Colorado-New Mexico) Gas Processing (Texas)</td>
<td>1,700</td>
<td>110</td>
<td>-</td>
</tr>
<tr>
<td>Colorado-Wyoming</td>
<td>Gas Processing (Wyoming)</td>
<td>-</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>Mississippi</td>
<td>Geologic (Mississippi)</td>
<td>400</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Michigan</td>
<td>Ammonia Plant (Michigan)</td>
<td>-</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Fertilizer Plant (Oklahoma)</td>
<td>-</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>Coal Gasification (North Dakota)</td>
<td>-</td>
<td>145</td>
<td></td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>2,100</strong></td>
<td><strong>645</strong></td>
<td></td>
</tr>
</tbody>
</table>

** MMcfd of CO2 can be converted to million metric tons per year by first multiplying by 365 (days per year) and then dividing by 18.9 * 10^3 (Mcf per metric ton).

Kuuskraa, ARI - 2008

Kansas currently vents **120 mmcfd** of high purity CO2 from Ethanol and Fertilizer plants *(EOR potential12-25 mbo/d)*
Kansas Strengths and Challenges for CO2 EOR CCS Development

**Kansas strengths**

- Significant oil resource base
- Well-defined, large sequestration targets
- CO2 sources: Local and regional
- Head start on regulatory framework
- Favorable relationships with research groups (TORP and KGS)
- Strong industry and professional groups (KIOGA, KGS (all of them), SPE)
- Long-standing intercompany relationships
- Skilled workforce

**Challenges - Kansas**

- Resource base – needs to be validated
- High % of wells are plugged and many pose a risk to containment
- Resources are unconsolidated
- Missing CO2 EOR skill sets
- Capital
- Tendency to be late adopters

**Challenges - Federal and State**

- Philosophical and Regulatory hurdles (CCS vs. EOR)
- Regulatory framework still in developmental stage

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Kansas Oil’s next generation?

1. Recognize opportunity
2. Understand the challenges
3. Proactive in molding public acceptance and regulatory framework
4. Take the long view, *but* be early adopters
5. Willingness to collaborate and cooperate

*END*