NeuStream®-EOR

Supplying Field Deployable Systems for CO₂ and Power Generation for the Enhanced Oil Recovery Market

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July 09th, 2014
Outline

NeuStream®-EOR value proposition

CO₂ capture
  General considerations
  NeuStream® technology for carbon capture

NeuStream®-EOR
  Field deployable sized unit
    System performances
    Economics
  Other possible implementations: supplementing existing CO₂ supply
Value Proposition: *Liberating stranded oil reserves by providing innovative carbon dioxide (CO₂) and power solutions*

- In the U.S. 67 Billion barrels of oil are economically recoverable using 385,000 Bcf of CO₂ for Enhanced Oil Recovery (EOR)¹
  - 30-yr annual projected U.S. demand for CO₂ is 12,500 Bcf/yr
  - CO₂ market currently $3.4 B/yr & supply limited

- Several reasons limit the development of CO₂ EOR:
  - US CO₂ supply today is 1,160 Bcf per year
  - Only ~10% of the reservoirs amenable to CO₂-EOR have access to CO₂ supply
    - Pilot EOR, Huff’n’Puff, CO₂ fracking rely on expensive/limited trucked CO₂
    - Deployment of CO₂ pipeline infrastructure takes long time (and is costly)
  - Opportunities for alternative/transportable sources of CO₂

Systems generate compressed CO₂ and power for oil recovery at a competitive price at any location.

NeuStream®-EOR sized for 1.2MMscf/day (60 tonnes/day), sufficient for:

- Pilot EOR projects: 1-5 wells
- Huff’n’Puff: typ. injection 40-600 tonnes/well over few days
- Water-free fracking: typ. 100-200 tonnes/stage, ~1 stage/day, up to 30 stages/well injection 3-8 tonnes/min. : need CO₂ storage tank

Matching location specific requirements for CO₂ and power by:

- Parallel multiple systems to meet CO₂ flow rate required for EOR operation
- Capture CO₂ from exhaust gas of existing sources (e.g. natural gas engines, diesel engines, steam boilers): economical alternatives to increase CO₂ supply in existing pipelines
NeuStream®-EOR: capturing CO₂ from flue gas

- Gas powered engine
- Diesel engine
- Steam boiler (e.g. ethanol plant, oil refinery, SAGD...)

Existing Engines

Exhaust gas
Typ. [CO₂] 6-12%, 600-900F

Power

Generators

Compressor

NeuStream®
Absorber + Stripper

Exhaust gas
w/o CO₂

SC CO₂
Typ. 98% pure

CO₂

Enhanced Oil Recovery

Exhaust Gas
w/ CO₂

NeuStream®-EOR

Generators

Gas powered engine

Diesel engine

Steam boiler (e.g. ethanol plant, oil refinery, SAGD...)

Typ. 98% pure
NeuStream®-EOR Transportable System: Implementation at any CO₂ EOR field

**NeuStream®-EOR**

- **Optional gas pre-processing**
- **Generators (5MW)**
- **Exhaust Gas w/ CO₂**
- **Exhaust Gas w/o CO₂**
- **DRU**
- **Absorber + Stripper**
- **CO₂**
- **SC CO₂**
- **1.21 MMscf/day**
- **>95% pure, 1200 psi-2500 psi**
- **Electrical Power available for use**
- **37,230 MW.hr/yr**
- **Wellhead associated gas**
- **Cooling water (optional)**
- **Compressor**
- **Enhanced Oil Recovery**

On-site equipment and/or electrical grid

- **Switchgear (grid interconnect)**
- **Generators (5MW)**
- **Cooling water (optional)**
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Anthropogenic sources of CO₂: separation of CO₂ from
- Natural gas processing (typ. >60% CO₂)
- Ethanol plant (typ. >90% CO₂)
- Steam reforming and Syngas (Fertilizer, hydrogen plant, ammonia, methanol plant...)
- Fossil fuel boilers (very dilute CO₂)

Main technologies:
- Membranes
- Cryogenics
- Pressure/vacuum swing adsorption
- Solvent scrubber (generally amines, typ. with temperature swing stripper)

Choice of optimum technology depends on:
- CO₂ concentration in gas stream
- Other gas constituents (H₂S, CH₄, H₂...)
- Volume of gas (i.e. size of equipment) → CapEx
- Parasitic power (separation process + compression) → OpEx
Specific challenges for transportable CO$_2$ separation / source

Field deployable sources of flue gas: large engines (generators, compressors) and/or small boilers → dilute CO$_2$ (6-12% typ.) → solvent scrubbers (amines)

Need small size scrubber:
conventional packed tower columns are very tall (~100ft)
& need structural support, foundations
→ not transportable

Minimize power requirements (steam/heat for stripper, pumps)

Cooling: water may not be available in the field
Acid gas removal determined from mass transfer analysis

\[
\eta = 1 - \frac{P_{\text{outlet}}}{P_{\text{inlet}}}
\]

\[
\eta = (1 - e^{-\frac{t}{\tau_g}})(1 - \frac{P^*}{P_{\text{inlet}}})
\]

- \( \eta \) = fractional gas absorption
- \( t \) = residence time
- \( \tau_g \) = contactor e-folding time constant
- \( P^* \) = solute equilibrium vapor pressure
- \( P_{\text{inlet}} \) = inlet solute vapor pressure
- \( \frac{1}{\frac{P^*}{P_{\text{inlet}}}} \) = fractional gas absorption
- \( a \) = specific surface area, \( \text{cm}^{-1} \)
- \( K_c \) = overall mass transfer coefficient, \( \text{cm} \text{s}^{-1} \)
NeuStream® High Surface Area Jets for Acid Gas Removal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>High specific surface area: $a_s &gt; 10 \text{ cm}^2/\text{cm}^3$; High volumetric mass transfer kinetics, $10 \times K_L a_s$ over conventional systems</td>
<td>High process efficiency; Greatly reduced column footprints</td>
</tr>
<tr>
<td>Low $\Delta P_{\text{Gas}} \sim 0.03 \text{ PSI/ft}$; Low $\Delta P_{\text{Liq}} = &lt;7 \text{ PSI}$</td>
<td>Reduced hydrodynamic/auxiliary power</td>
</tr>
<tr>
<td>Aerodynamic shaped jets</td>
<td>Reduced liquid entrainment in the gas flow</td>
</tr>
<tr>
<td>Factory fabrication of modular/serviceable units</td>
<td>Standardization/lower cost fabrication; Rapid scaling per customer needs</td>
</tr>
</tbody>
</table>

Gas flow (cross flow)
NeuStream® Modular Jet Boxes

(a) Serviceable Jet Box
   - showing 40 feed tubes each with 45 individual nozzles

(b) Jet Box being installed in the laboratory test system.

(c) Side view of Jet Box in operation
   - liquid feed pressure of ~ 5psi

(d) Nozzle Array Unit configured into 2 MW Absorber.

(e) 20 MW Absorber being operated at the Martin Drake plant
   - with 8 – 2.5 MW Scrubber Assemblies each containing 9 serviceable Nozzle Array Units.
Scaling of NeuStream® Accomplished by 2-D Stacking of Modules

- **NeuStream®-S** modular scaling
- Scales in 2 dimensions
  - Proven technology with single unit cell
  - Add additional unit cells in parallel to increase capacity
  - No efficiency loss on scale-up
- Uniform flue gas distribution
  - Rigorous CFD analysis
NeuStream®-C Absorber
Size Comparison to Boundary Dam (150MW)

SaskPower’s Boundary Dam Project
SO₂ and CO₂ Absorber Towers
~ 306,000 ft³

NeuStream® Absorbers:
CO₂, FGD, Polish and Amine Wash
~ 54,000 ft³

> 82% decrease in absorber size!

Typical absorber packed towers are 100ft tall → not field deployable

The compact, efficient flat jets absorber allows transportable CO₂ capture systems, not achievable with traditional scrubbers
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NeuStream®-EOR Transportable System: any CO₂ EOR field

1.21 MMscf/day >95% pure, 1200 psi-2500 psi

Exhaust Gas w/ CO₂

Exhaust Gas w/o CO₂

Electrical Power available for use

NeuStream®-EOR

On-site equipment and/or electrical grid

NeuStream® Absorber + Stripper

Cooling designed for no water available at site

Cooling-sized with use of site water

Cooling designed for no water available at site

Gas pre-processing

Generators (5MW)

Compressor

SC CO₂

CO₂

Generators (5MW)

Exhaust Gas w/ CO₂

Exhaust Gas w/o CO₂

Electrical Power for system needs

70%

30%

1.46 BBtu/day

Wellhead associated gas

30,660 MW.hr/yr

30,660 MW.hr/yr

1.21 MMscf/day

>95% pure, 1200 psi-2500 psi

85%

15%

85%

15%

30%

70%

30,660 MW.hr/yr

0gal/day

Enhanced Oil Recovery
NeuStream®-EOR System Layout
## NeuStream®-EOR: specifications

<table>
<thead>
<tr>
<th>CO₂ Output performances</th>
<th>Unit</th>
<th>Minimum</th>
<th>Nominal</th>
<th>Maximum</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>MMscf/d</td>
<td>—</td>
<td>95</td>
<td>1.21</td>
<td>At full load. Corresponding oil production 200bbl/d with typical CO₂ utilization</td>
</tr>
<tr>
<td>Purity</td>
<td>%</td>
<td>—</td>
<td>98</td>
<td>95</td>
<td>—</td>
</tr>
<tr>
<td>Pressure</td>
<td>psig</td>
<td>1,200</td>
<td>1,200</td>
<td>2,500</td>
<td>—</td>
</tr>
<tr>
<td>Temperature</td>
<td>F</td>
<td>—</td>
<td>140</td>
<td>140</td>
<td>—</td>
</tr>
<tr>
<td>H₂O content</td>
<td>lb/MMscf</td>
<td>—</td>
<td>30</td>
<td>30</td>
<td>Pipeline CO₂ quality</td>
</tr>
<tr>
<td>H₂S content</td>
<td>ppm weight</td>
<td>—</td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>O₂ content</td>
<td>ppm weight</td>
<td>—</td>
<td>0</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Electrical</td>
<td>Power</td>
<td>MWe</td>
<td>3.18</td>
<td>3.99</td>
<td>CO₂ output flow decreases with power</td>
</tr>
<tr>
<td>Primary voltage</td>
<td>V</td>
<td>—</td>
<td>480</td>
<td>480</td>
<td>For grid interconnection, switchgear meets safety and technical requirements from local utility</td>
</tr>
<tr>
<td>Frequency</td>
<td>Hz</td>
<td>—</td>
<td>60</td>
<td>60</td>
<td>—</td>
</tr>
<tr>
<td>Gas fuel</td>
<td>Consumption</td>
<td>MMscf/d</td>
<td>—</td>
<td>1.46</td>
<td>—</td>
</tr>
<tr>
<td>Heating value</td>
<td>BTU/scf</td>
<td>950</td>
<td>950</td>
<td>1,650</td>
<td>—</td>
</tr>
<tr>
<td>H₂O content</td>
<td>ppmv</td>
<td>—</td>
<td>no liquid water</td>
<td>no liquid water</td>
<td>—</td>
</tr>
<tr>
<td>H₂S content</td>
<td>ppmv</td>
<td>—</td>
<td>1,000</td>
<td>1,000</td>
<td>—</td>
</tr>
<tr>
<td>Water</td>
<td>Quantity</td>
<td>1000 gal/day</td>
<td>0</td>
<td>24.1</td>
<td>Zero water consumption option available</td>
</tr>
<tr>
<td></td>
<td>TDS</td>
<td>—</td>
<td>—</td>
<td>TBD</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>TSS</td>
<td>—</td>
<td>—</td>
<td>TBD</td>
<td>—</td>
</tr>
</tbody>
</table>
Economics: Cost of generating Power and CO₂ from NeuStream®-EOR

- Power required for EOR operations: current price up to $0.10/kWh
- Current price of CO₂ = $2/Mcf (where available, pipeline delivered in field, $40/tonne)
Example CO$_2$-EOR Economics

Assumes
Purchased CO$_2$ ($/Mcf) = 2.5% x Crude oil ($/bbl)
Recycled CO$_2$ ($/Mcf) = 1% x Crude oil ($/bbl)

<table>
<thead>
<tr>
<th>Economic Parameter</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Revenue</td>
<td>$85.0</td>
</tr>
<tr>
<td>Royalties</td>
<td>($14.9)</td>
</tr>
<tr>
<td>Production Taxes</td>
<td>($3.5)</td>
</tr>
<tr>
<td>CO$_2$ Purchase Costs</td>
<td>($12.2)</td>
</tr>
<tr>
<td>CO$_2$ Recycle Costs</td>
<td>($9.8)</td>
</tr>
<tr>
<td>O&amp;M/G&amp;A Costs</td>
<td>($9.0)</td>
</tr>
<tr>
<td>CAPEX</td>
<td>($6.0)</td>
</tr>
<tr>
<td>Total Costs</td>
<td>($55.4)</td>
</tr>
<tr>
<td>Net Cash Margin</td>
<td>$29.6</td>
</tr>
</tbody>
</table>

*Assumed 0.3 tonne/bbl of purchased CO$_2$,
0.6 tonne/bbl of recycled CO$_2$
### Economics of NeuStream®-EOR: Oil Producer Perspective

#### Example CO₂-EOR Economics*

<table>
<thead>
<tr>
<th></th>
<th>Pipeline CO₂</th>
<th>NeuStream®-EOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Revenue</td>
<td>$85.00</td>
<td>$85.00</td>
</tr>
<tr>
<td>Royalties</td>
<td>($14.90)</td>
<td>($14.90)</td>
</tr>
<tr>
<td>Production Taxes</td>
<td>($3.50)</td>
<td>($3.50)</td>
</tr>
<tr>
<td>CO₂ Purchase Costs</td>
<td>($12.20)</td>
<td>($10.54)</td>
</tr>
<tr>
<td>CO₂ Recycle Costs</td>
<td>($9.80)</td>
<td>($9.80)</td>
</tr>
<tr>
<td>O&amp;M/G&amp;A Costs</td>
<td>($9.00)</td>
<td>($9.00)</td>
</tr>
<tr>
<td>CAPEX</td>
<td>($6.00)</td>
<td>($6.00)</td>
</tr>
<tr>
<td><strong>Total Costs</strong></td>
<td>($55.00)</td>
<td>($53.74)</td>
</tr>
<tr>
<td>Power production cost</td>
<td>($23.63)</td>
<td></td>
</tr>
<tr>
<td>Power sale/avoided costs</td>
<td>$31.25</td>
<td></td>
</tr>
<tr>
<td><strong>Net Cash Margin</strong></td>
<td>$29.60</td>
<td>$38.88</td>
</tr>
</tbody>
</table>

Assumed 0.3 tonne/bbl of purchased CO₂, $40/tonne for pipeline CO₂, 0.6 tonne/bbl of recycled CO₂


![Diagram showing the flow of natural gas through NeuStream®-EOR, resulting in 1 tonne CO₂ and 1610 kWh, with EOR operation leading to ~3.35 bbl oil and ~$285 revenue.](image)

Assumes crude oil 85 $/bbl

![Graph showing the relationship between natural gas cost and net cash margin](image)
Economics of NeuStream®-EOR: CO₂ Supply Perspective

NeuStream®-EOR:
- Provides additional CO₂ and secures supply for users
- Generates significant margin for a company operating systems and selling CO₂ to market

West Texas Index oil price ($/bbl, 2011 dollars) and Henry Hub Natural gas spot price ($/Mcf) projections from EIA Energy Outlook 2013
NeuStream® add-on to existing gas engines (e.g. compressors at CO₂ recycling station)

- Exhaust gas
  Typ. [CO₂] ~7%, 900F, 15MMscf/d

- Generators (< 1.5MW)
- NeuStream® Absorber + Stripper
- SC CO₂

- Exhaust Gas w/ CO₂
- CO₂

- Exhaust Gas w/o CO₂

- Enhanced Oil Recovery

- 1.2 MMscf/day (typ.)
  >95% pure, 1200 psi-2500 psi

- On-site equipment

- Neustream®-EOR

- Natural gas
- Existing Engines/generators

- Generators
- Compressor
- SC CO₂

- Enhanced Oil Recovery
A typical 50MGY ethanol plant generates 7MMscf/d (133,000 tonnes/yr) of CO₂ for EOR (Purity >97%)

- Power requirement 4.2MW (typ. purchased from grid)
- Steam boilers: typ. flue gas [CO₂]=10% → opportunity to capture 65,000 tonnes/yr CO₂

Need 1 NeuStream®-EOR system to generate site power
Need 5 systems to capture CO₂ from flue gas

Total for 6 systems ~135,000 tonnes/yr
→ Double flow of CO₂ (pipeline infrastructure already in place)
→ Offset site power
Concluding remarks

NeuStream® CO₂ capture systems:
- Based on proven proprietary flat jets technology
  (5000h continuous test of 20MW unit, commercial 227MW FGD under construction)
- Compact and efficient scrubber allows:
  - Design of transportable sources of CO₂
  - Economical capture/generation of CO₂ from existing gas streams currently untapped

NeuStream®-EOR systems:
- Provide alternative for the supply of CO₂, including generation at the site
- Allows economical use without pipeline infrastructure, well suited for applications like pilot EOR, Huff’n’Puff stimulation, CO₂ fracking...
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