The NeuStream™ Advantage

NeuStream™ Enables Significantly Lower Cost of Ownership

Desulfurization System Comparison

- NeuStream™-C
- NeuStream™-S
- Conventional Dry Scrubber

CO₂ System Comparison

- Hitachi 800MW CO₂ System
- NeuStream™-C 800MW CO₂ System

Modular
- Reduce order to commission time
- Maximize plant availability

Compact
- Consume less plant real estate
- Minimize plant reconfiguration

Efficient
- Lower parasitic power
- Much lower water usage

Adaptable
- Site-specific conditions
- Variety of saleable by-products

Cost of Ownership
(Per Dollar Differential)

- Capital Cost
- Operating Cost

Volume per MW

Volume Comparison (cubic meters)

Hitachi
NeuStream™-C
Conventional Dry Scrubber

NeuStream™ Enables Significantly Lower Cost of Ownership
**CARE Schedule**

**Key Milestones**

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project CARE 0.5 MW Demonstrator</td>
<td>5/21/2012</td>
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<tr>
<td>Task 1.0 Project Management and Planning</td>
<td>5/21/2012</td>
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<tr>
<td>START OF BUDGET PERIOD 1</td>
<td>5/21/2012</td>
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<tr>
<td>Task 2.0 System Requirements and Design (BP I)</td>
<td>5/21/2012</td>
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<td>END OF BUDGET PERIOD 1</td>
<td>5/21/2012</td>
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<tr>
<td>Notice to Continue to Testing</td>
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<tr>
<td>START OF BUDGET PERIOD 2</td>
<td>5/21/2012</td>
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<tr>
<td>Task 3.0 System Construction (BP 2)</td>
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<tr>
<td>END of BUDGET PERIOD 2</td>
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<td>2/18/2013</td>
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<td>START OF BUDGET PERIOD 3</td>
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<tr>
<td>Task 4.0 System Test and Closeout (BP 3)</td>
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<tr>
<td>END of BUDGET PERIOD 3 (End of Project)</td>
<td>11/15/2013</td>
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**Project Start**  5/21/2012

**Kickoff Meeting: Final Requirements Review/Concept Design Review**  6/14/2012

**Preliminary Design Review**  8/20/2012

**Detailed (Critical) Design Review**  2/18/2013

**Test Readiness Review**  11/15/2013

**Final Project Briefing**  11/17/2014
CARE Project Objectives

• Design and fabricate 0.5 MW system

• Minimize parasitic power through efficient design

• Demonstrate
  – Steady 2 month state operation with 3-Stage Absorber and Multi-stage Stripper
  – 90% CO₂ capture efficiency utilizing best available solvent

• Show unit traceability to commercial scale
CARE Partners

- Energy and Environmental Research Center (EERC)
  - Techno-Economic Feasibility Study
  - EH&S risk assessment for carbon capture and storage
  - Brandon Pavlish (Lead and Consultant)
- URS – Bob Keeth
  - Consultant

- Colorado Springs Utilities
  - Host Site (Martin Drake Power Plant)
  - Significant Cost Share

- Service Partners
  - Althouse Electric
  - Vision Mechanical
  - ICM Construction
  - Palmer Holland (Chemical Provider)
Array of Jets

- Jets are 7 cm wide with a 4 PSI pressure drop across the nozzles.
- Gas is contacted with jets via cross-flow at 3-15 m/s.
- Jet velocity of 5-6 m/s.
- The jet array for the CO₂ scrubber have jets spaced at 3 mm along the Jet Tube (4 mm shown on left).
- Jet Tubes are spaced at 3.5 cm, and are interlaced resulting in a theoretical specific surface area of 900 m²/m³.
NeuStream – C Development

- De-rated our 2MW FGD scrubber for a 0.45 MW slipstream
- Capture only; using 3.2m K$_2$CO$_3$/1.6m PZ solvent
- Single stage capture with approximately 1000 SCFM Flow (~1600 ACFM - residence time of 0.4 sec)
- Capture efficiency ranged from 65% to 30% depending on solvent loading
NeuStream – C Development

- Bench scale closed system with vacuum stripping
- ~1kW flow rate (65 slpm); simulated flue gas
- 3.2m K$_2$CO$_3$/1.6m PZ
- Single Stage
- >70 % Capture Efficiency
NeuStream – C Development

Post Design Alterations:
- Reflux tank added post stripper
- Reflux tank added post absorber
- Increased pump size for rich pump

Contract is for 90% removal at 160 SCFM

Design Points:
- 3 stage absorber; 4 stage stripper
- ½ Jet box channels to increase gas velocity through jets
- ULFT Nozzles: 4 psi operating pressure, 7 cm wide jet
- 27 Nozzles/Tube, staggered with 3.5 cm Tube/Tube spacing and 3 mm Nozzle/Nozzle spacing
EERC Testing

- System transport to UND-EERC and setup completed on Sept 12, 2011
- Scheduled Test Dates:
  - Sept 26-Oct 6, 2011 (EERC training and acceptance testing)
  - Nov 7-11, 2011
  - Dec 19-23, 2011
  - Jan 9-13, 2012
  - Feb 6-12, 2012 (no alternative solvent, system modifications)
  - Feb 27-Mar 2, 2012
  - Mar 19-23, 2012 (reschedule to allow for system modifications – TBD)
EERC Test Results

- System Performance
  - Capture Subsystem is performing on the same level as baseline testing
  - Stripper Subsystem is also consistent with baseline testing
  - Comparison of Stripper subsystem to EERC traditional packed tower stripper indicates that the NSG stripper is undersized
    - Working capacity of NSG stripper: 0.06 – 0.07 mol CO$_2$/mol Alk
    - Typical working capacity of a packed tower stripper: 0.12 – 0.15 mol CO$_2$/mol Alk
    - The under-performing stripper is reducing the performance of the system, resulting in lower than expected capture efficiencies
EERC Modifications

• **Stripper Subsystem Modification #1:**
  - Carryover flooding in gas path due to high liquid levels
  - Liquid flows limited to 12 GPM max
  - Added 12” section to vessels to allow for required liquid head to maintain higher flows.
  - Have since operated up to 18 GPM with no flooding or increased carryover
EERC Testing: Loading
(After Stripper Modification 1)

- Liquid Flow: 16 GPM
- Gas Flow: 160 SCFM (14.4% CO₂)
- Absorber (1, 2 and 3) Volumes:
  - 115, 110, 101 Gal
- Stripper Volume (Each Vessel):
  - 11 Gal
- Absorber Residence Times:
  - 7.2 min, 6.8 min, 6.3 min
- Stripper Residence Times:
  - 41.2 seconds per vessel
  - 2 min 45 sec for stripper subsystem

Working Capacity ~ 0.06 mol CO₂/mol Alk
EERC Modifications

• Stripper Subsystem Modification #2
  – Original configuration
    • Mimicked a traditional packed tower with 4 stages (trays)
    • Heat added via reboiler stage only
    • First two stages were for heat transfer (heat of condensation)
    • Last two stages primarily where stripping CO$_2$ occurred.
  – Modified Configuration
    • Heat added to rich stream to bring to target stripper temperature
    • Reboiler used to maintain heat throughout the stripper and reduce re-absorption of CO$_2$
EERC Testing: Loading (After Stripper Modification 2)

- Liquid Flow: 16 GPM
- Gas Flow: 160 SCFM (13.3 % CO₂)
- Difficult to compare results to previous testing:
  - Lower CO₂ concentration in flue gas leads to lower loadings
  - Lower loadings results in better capture efficiency
- Working capacity is about the same as previous configuration
- All stripping occurs in first vessel... no benefit from remaining vessels or reboiler.

Working Capacity ~ 0.06 mol CO₂/mol Alk
EERC Modifications

- Separate gas flow between vessels
- Single Pass through vessels 2-4
- Recirculation on vessel 1
- Vary pressures per stage (decreasing)
### EERC Solvent Testing

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Capture Efficiency - O₂ Corrected</th>
<th>Stg 3 Loading</th>
<th>Expected CE*</th>
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<tbody>
<tr>
<td>Date</td>
<td>Gas Flow Rate</td>
<td>Liquid Flow rate</td>
<td>Overall</td>
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<tr>
<td>2/28/2012</td>
<td>190.1</td>
<td>15.9</td>
<td>68.3%</td>
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<tr>
<td>2/28/2012</td>
<td>159.3</td>
<td>16.1</td>
<td>72.9%</td>
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<tr>
<td>2/29/2012</td>
<td>130.1</td>
<td>16.1</td>
<td>79.6%</td>
</tr>
<tr>
<td>3/1/2012</td>
<td>130.6</td>
<td>17.2</td>
<td>88.1%</td>
</tr>
<tr>
<td>2/29/2012</td>
<td>158.8</td>
<td>17.1</td>
<td>85.5%</td>
</tr>
<tr>
<td>3/1/2012</td>
<td>189.2</td>
<td>17.5</td>
<td>83.9%</td>
</tr>
<tr>
<td>3/1/2012</td>
<td>218.0</td>
<td>17.8</td>
<td>79.9%</td>
</tr>
</tbody>
</table>

- **MEA (4.3M) and Piperazine (4.0M) Testing**
  - Tested at 16 gpm liquid transfer rate with various gas flow rates
  - Investigated capture efficiency per stage
  - Working capacity of stripper is less than typical; indicating that we are operating at higher loadings and reduced capture efficiencies.
  - Stage 2 absorber CE data indicated a problem in the system; gasket on stage 2 absorber had slipped resulting in up to 50% gas bypassing this stage
  - “Expected CE*” column is the expected CE when stage two is fixed
  - Piperazine (Pz) solvent had drastically improved performance
NSG Absorber (Flat Jet)

- Currently achieving (experimental) $400 \text{ m}^2/\text{m}^3$ surface area at $4+ \text{ m/s}$ flow
- Results in a **2x reduction** in reaction volume of absorber compared to packed tower
- Has approximately a **15 m/s gas velocity limit**, where the absorber can be operated with any gas velocity below 15 m/s
- Measured pressure drop due to jets with a $4 \text{ m/s}$ gas velocity: **5 inH$_2$O** through 6 m of jets

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Project CARE Modular Design (Conceptual)
Implementation to Plant

• Advantages:
  – **90% capture**: greater than 2-4x reduction in absorber volume, resulting in less capital cost and footprint
  – Variable gas velocity (up to 15 m/s) through jets due to low pressure drop and no flooding, where increased gas flow moves to a more efficient capture regime and increases the total carbon capture (EOR)
  – Solvent agnostic
    • tested with: 7m MEA (CO$_2$), 7m PZ (CO$_2$), FGD dual alkali solvent, BHP (chemical laser); scheduled to test with a Huntsman Solvent (CO$_2$) and a potassium carbonate with CA enzyme (CO$_2$)

• Challenges:
  – No data on a full scale system (perceived risk)
Task 2.0 – System Requirements and Design (BP 1)

- 2.1 – System Requirements (FOA, EERC results, ASPEN, DVT)
- 2.2 – Preliminary Design
- 2.3 – Detailed Design
- 2.4 – Absorber Modeling and Analysis (EERC results, ASPEN, DVT and COMSOL)
- 2.5 – Stripper Modeling and Analysis (EERC results and ASPEN)
- 2.6 – Process Modeling and Analysis (ASPEN)
- 2.7 – Absorber Verification Testing (Feeds design efforts)
- 2.8 – Process Verification Testing (Reclaimer and Amine Wash)
- 2.9 – Preliminary Assessment of EH&S Risks (HCCL)
- 2.10 – Preliminary Technical and Economic Assessment (EERC)
Tasks Required to Meet CARE Objectives

- Develop Systems Requirements
- Develop Preliminary then Detailed Design
  - Design Verification Testing (Task 2.7; Feeds Tasks 2.1-2.4)
    - Build stand with stainless sump and piping for CO2 capture
    - Modify existing test stand for FGD/DCC use
    - Build transition ducting between FGD and CO2 absorber
    - Test Stand will need “simple” stripping subsystem so that steady state can be reached
  - Develop Performance Optimization Plan:
    » Vary packing densities
    » Vary jet lengths
    » Vary gas flows
  - Results feed directly to 0.5MW demonstrator design
Absorber Verification Stand

CO₂ Absorber
Mist Eliminator
FGD/DCC

HEXs, Condenser and Stripper Flash not shown
Tasks Required to Meet CARE Objectives (cont)

– Develop Preliminary then Detailed Design (cont)

  • Design “sumpless” pump
    – Communicate with pump manufacturer to drive design
    – Fabricate prototypes:
      » Develop Stand to utilize prototype pumps
      » Metrics for test stand:
        » Flow Requirements
        » Plenum pressure
        » **Pump Efficiency** comparable to traditional centrifugal pumps

  • Flow Modeling – Gas and Liquid Flow
    – Modeling Liquid Flow through drain – pump – plenum
    – Modeling Gas Flow through jets and transition pieces

  • Process Modeling
    – ASPEN modeling of System components and interactions
    – Sizing of HEXs, Amine Wash, etc.
Tasks Required to Meet CARE Objectives (cont)

- **Process Verification Testing**
  - Reclaimer and Amine Wash – bench scale testing

- **Develop Assessment of Environmental, Health and Safety (EH&S) Risks**
  - To be completed by EERC
  - Preliminary EH&S assessment to be completed in Budget Period 1
  - Final EH&S assessment to be completed at project closeout

- **Develop Technical and Economic Assessment (TEA)**
  - To be completed by EERC (Brandon Pavlish)
  - Preliminary TEA to be completed within 8-weeks of contract start
  - Final TEA to be completed at project closeout
Conceptual Design

Design results in a 5 m/s gas velocity under nominal testing conditions.
Linear assembly for the 0.5 MW Demonstrator

Design has counter-flow gradient built in, which will increase removal efficiency by pairing rich CO$_2$ gas with rich liquid.
Conceptual Design

Wrapped assembly for the 0.5 MW Demonstrator

- More compact packaging
- Flow concerns introduced by turns
- Design still has counter-flow gradient built in

-Dimensions:
  Width = 1.8 m
  Length = 3.2 m
  Height = 1.1 m
Conceptual Design

Pump Design

- Working with pump manufacturer to develop

- 5x impellers

- Design will maintain separate channels

- Metric for pump is operating efficiency

- Expected efficiency about 70% (resulting in parasitic power of 0.5% per stage – 3 stages has 1.5%
Conceptual Design

Traceability to a Commercial Scale Reactor

Dimensions:
- Length: 2.5 m
- Width: 5.6 m
- Height: 2.5 m
- Depth: 1.1 m
- Width of individual sections: 0.5 m
- Height of individual sections: 1.1 m
Conceptual Design

3-stage, 45-MW CO$_2$ Module to achieve 90% capture

System Dimensions
(W x H x L):
17.1m x 10.7m x 10.4m
Scale up potential

- Modular approach to the Flat Jet Absorber
  - Reduces risk for scaling up scope of absorber
  - Rapid deployment of modular parts due to in-house fabrication

- Commercial design will utilize same configuration
End