Piperazine Advanced Stripper (PZAS™) 
Front End Engineering Design (FEED) 
DE-FE0031844

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Department of Chemical Engineering, The University of Texas at Austin

Krista Hill, NETL Project Manager

2022 Carbon Management Research Project Review Meeting 
Wed, 11:25 
August 17, 2022
PZAS FEED outline

• Project structure and Objectives
• PZAS: a superior 2G process developed with DOE support
• Mustang Station: low energy cost, abundant space, pipeline for EOR
• Design Decisions
• Project costs: capital, annual, business case
• Design Basis and Opportunities to improve and add value
• Conclusions
The Objective: Accurate installed cost of PZAS™ on NGCC at GSEC Mustang Station

Complementary Benefits:
• Develop commercial project at Mustang Station
• Qualify PZAS for use on NGCC cogen
• Provide commercial cost detail
  • Optimize PZAS & other 2G capture processes
  • Guide R&D of capture technology
Program Overview

• Funding ($5.3 MM)
  ○ 4.2 MM DOE
  ○ 1.1 MM cost sharing - ExxonMobil, Total, Chevron
  ○ [0.3 MM from Honeywell UOP outside DOE]

• Performance Period: 10/2019 – 6/2022

• Project Participants
  ○ Golden Spread Electric Cooperative (GSEC) – Host
  ○ University of Texas at Austin (UT) – Modeling/ Technology
  ○ Trimeric – Process Engineering
  ○ AECOM – EPC

○ Final Report Submitted on July 29, 2022
PZAS Process

CO₂ Product

Compressor and Coolers

Condenser

CO₂ Exchanger

Stack

Water Wash

Absorber

Flue Gas

Air cooling

Cold Rich Bypass

Warm Rich Bypass

Steam Heater

Stripper
PZAS development
comprehensive research & pilot plant demonstrations

• (2000-22) Research by 49 graduate students
  • Fundamental basis & Models

• (2006-09) UT Pilot of K$_2$CO$_3$/Piperazine (PZ), DE-FC26-02NT41440

• PZAS Pilot at 12% CO$_2$ for coal, DE- FE0005654
  • (2010-18) UT Austin
  • (2018) NCCC

• PZAS Pilot w 4% CO$_2$ For NGCC (CCP4)
  • (2016-18) UT Austin
  • (2019) NCCC
PZAS pilot at NCCC with CCP4 funding

- Heat duty 2.4 GJ/t
- Stripping at 302 F/90 psia with little degradation
- 90-95% CO$_2$ removal with 2 x 20 ft packing
- Pump-around intercooling of hot inlet gas
- Low PZ oxidation, <0.3 kg/t CO$_2$
- 304 SS up to 150$^\circ$C
- PZ emissions < 1 ppm
Host Site - Mustang Station
Golden Spread Electric Cooperative
Denver City, TX
Southwest Power Pool
Greatest wind penetration of U.S. IPO’s
460 MW NGCC
2 GT/1 ST
Changing perspective on the Mustang site

<table>
<thead>
<tr>
<th></th>
<th>Proposal, May 2019</th>
<th>FEED Report, July 2022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space</td>
<td>Excellent</td>
<td>Spread out, but still good</td>
</tr>
<tr>
<td>CO₂ Disposal</td>
<td>Existing pipeline with EOR</td>
<td>Existing pipeline to storage site</td>
</tr>
<tr>
<td>Cooling</td>
<td>Available cooling tower &amp; water</td>
<td>No water; air cooling required</td>
</tr>
<tr>
<td>Steam supply</td>
<td>Extract from existing turbine</td>
<td>Gas-fired boiler</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$2/MMBtu w pipeline access</td>
<td>$8/MMBtu</td>
</tr>
<tr>
<td>CO₂ design rate</td>
<td>126 t/hr</td>
<td>190 t/hr</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>Wholesale LMP = $20/MWh</td>
<td>Retail? = $100/MWh</td>
</tr>
<tr>
<td>Load Factor</td>
<td>&gt;52%, higher with good CO₂ value and low fuel cost</td>
<td>&lt;52%, Lower with higher fuel cost &amp; more renewables</td>
</tr>
<tr>
<td>Financing</td>
<td>&lt;5% with Non-profit</td>
<td>10% IRR with private capital</td>
</tr>
<tr>
<td>Capital cost</td>
<td>$270 million</td>
<td>$725 million</td>
</tr>
</tbody>
</table>
General Arrangement with two trains

General arrangement with two trains
• Each train treats all flue gas from 1 GT and one new gas boiler
• Turndown to match Mustang Station operation
• Sequenced, isolated maintenance
• Off-site fabrication of some large equipment (strippers)
• Sequenced construction
• Reasonable absorber size
Other Design Decisions

– 90% CO$_2$ removal at median ambient T

– Air cooling
  • Absorber intercooling
  • Water wash with 24-hour water balance in summer

– One package boiler for each train to provide steam for stripping
  • Boiler flue gas treated in absorber

– Moderate energy requirement by design (3.0 GJ/t CO$_2$)
  • 5 plate-and-frame exchangers per train
  • (2.5 GJ/t could be obtained with 10 exchangers/train)

– One 3-stage reciprocating compressor for each train
  • Air intercooling
Project Costs and Business Case
<table>
<thead>
<tr>
<th>Cost Category</th>
<th>Cost, $Million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Direct Cost</td>
<td>384</td>
</tr>
<tr>
<td>Total Indirect Cost</td>
<td>93</td>
</tr>
<tr>
<td>Engineering</td>
<td>37</td>
</tr>
<tr>
<td>Insurance, Taxes, Bonds &amp; Permits</td>
<td>19</td>
</tr>
<tr>
<td>Contingency</td>
<td>105</td>
</tr>
<tr>
<td>Contractor Overhead &amp; Profit</td>
<td>60</td>
</tr>
<tr>
<td><strong>Project Total Cost</strong></td>
<td><strong>698</strong></td>
</tr>
<tr>
<td>Owner’s Cost</td>
<td>27</td>
</tr>
<tr>
<td><strong>Total Overnight Cost</strong></td>
<td><strong>725</strong></td>
</tr>
</tbody>
</table>
# Direct costs (total DC = $384 million)

<table>
<thead>
<tr>
<th></th>
<th>Cost, $M</th>
<th>% of total</th>
<th>Potential Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Cooling Systems</td>
<td>90.0</td>
<td>23</td>
<td>Use water</td>
</tr>
<tr>
<td>Absorber</td>
<td>37.0</td>
<td>10</td>
<td>Use Carbon Steel</td>
</tr>
<tr>
<td>CO₂ Compression</td>
<td>24.2</td>
<td>6</td>
<td>Shorten ductwork</td>
</tr>
<tr>
<td>Ductwork, Dampers, Fans</td>
<td>21.6</td>
<td>5.6</td>
<td>Revisit</td>
</tr>
<tr>
<td>Solvent Reclaiming</td>
<td>19.6</td>
<td>5.1</td>
<td>Use steam extraction</td>
</tr>
<tr>
<td>Stripper, CO₂ Conditioning</td>
<td>17.4</td>
<td>4.5</td>
<td>Use more exchangers</td>
</tr>
<tr>
<td>Steam Generation</td>
<td>14.1</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Solvent Heat Exchangers</td>
<td>9.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Solvent Storage</td>
<td>6.5</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>Cost (MM $)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Annual Variable Operating Costs @ 52% LF</strong></td>
<td><strong>$21.5 MM</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas (417 MMBtu/hr) @$3/MMBtu</td>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 % increase in total NGCC fuel rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Use more exchangers to reduce heat duty]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Extract Steam from existing turbine]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Tariff for transport and storage ($5/t)</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity (33 MW) @$25/MWh</td>
<td>3.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 % decrease in net power from NGCC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[Replace Air Cooling with Cooling Water]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piperazine solvent</td>
<td>2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (Caustic, Water, TEG, N2, waste)</td>
<td>1.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Annual Fixed Operating Costs

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property Taxes and Insurance (Year 1) @ 2.5%</td>
<td>18.2</td>
</tr>
<tr>
<td>Maintenance Labor &amp; Material</td>
<td>9.9</td>
</tr>
<tr>
<td>Operating Labor</td>
<td>3.3</td>
</tr>
<tr>
<td>Admin &amp; Support Labor</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Total Annual Fixed Operating Costs: **$32.6 MM**

*Note: Property Taxes and Insurance (Year 1) @ 2.5% can be negotiated for a local tax break.*
Net Cash Flow at base case conditions
52% Load Factor, $3/MMBtu, $25/MWh

<table>
<thead>
<tr>
<th>Table Title</th>
<th>$million</th>
</tr>
</thead>
<tbody>
<tr>
<td>Income from 45Q @ $85/t</td>
<td>64</td>
</tr>
<tr>
<td>Fixed annual costs</td>
<td>-32.6</td>
</tr>
<tr>
<td>Variable annual costs</td>
<td>-21.5</td>
</tr>
<tr>
<td>Net Cash Flow</td>
<td>+9.9</td>
</tr>
</tbody>
</table>
Economic Performance of the Mustang Project

- $5/t Storage
- $3/MMBtu natural gas
- $25/MWh electricity

IRR (%) vs. Cost of Capture ($/t CO₂)

- 52% load factor
- 85% load factor
Takeaways

– Completed FEED
  • Defines a technically feasible design for Mustang
  • Capital cost of $725 million
  • Cost of capture for 10% IRR is $105/t CO₂ (w $3/MMBtu, 85% LF)

– Major opportunities for enhanced performance and reduced cost
  • Steam extraction from the existing steam turbine
  • Additional absorber packing to get > 97% CO₂ removal, approaching C neutral
  • Additional exchanger area to reduce natural gas consumption

– Detailed, public FEED provides basis for an NGCC or Cogen demo
  • Ideal site: cooling water, steam extraction, low renewables, high load factor
Future work

– Further development at Mustang is not expected
– Honeywell UOP design/marketing to all applications & sites with proprietary knowhow
– Honeywell actively developing opportunities for a potential FOA for demonstration
– UT Modeling to make public use of FEED results – funded by CCSI2, TxCMP, et al.

• Optimize operations at GSEC with the existing design
• Optimize design at GSEC with estimates for improvements
• Develop & optimize design for NGCC at other sites, including stakeholder sites
  o NGCC at ideal conditions - cooling water, steam extraction, low renewables, high load factor
  o CoGen
• Develop and optimize designs of PZAS for other applications
Acknowledgements

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Other Contributors

UT Austin: Fred Closmann, Miguel Abreu, Benjamin Drewry, Tianyu Gao, Jorge Martorell, Athreya Suresh Babu
AECOM: William A. (Bill) Steen, Karen Farmer, Scott Bryan, Matt Bernau
TRIMERIC Corp Andrew Sexton, Katherine Dombrowski, Duane Myers, Michael Marsh, Brad Piggott, Rosalind Jones
Kronos Management, LLC: Jeff Lee
High Removal with PZAS at Mustang

97.2% removal at constant ldg

Lean loading: 0.2
Gas T: 116 °C
PA T: 30 °C

Design

Rich loading

Penetration = 1 - removal

25 ft, 1 PA

40 ft, 1 PA
Chronology of PZAS FEED

- August 19, 2019 – Proposal accepted for contract negotiation
- January 22, 2020 – Meeting with GSEC in Amarillo
- November 3 – Process Design Package
- March 14, 2021 – Draft Equipment List
- October 28 – Model Review
- November 18 – Completion of Capital Cost Estimate
- March 31, 2022 – Draft FEED Report
Organizational Chart

DOE-NETL Contracting Officer
Krista Hill

Host Site
Mustang Station

Project Manager
Gary Rochelle - UT

Cost Share
Exxon/Chevron/Total

Task 1 Management
Gary Rochelle - UT
Bill Steen - AECOM

Task 2 Process Design
Andrew Sexton - Trimeric

Task 3 Process Modeling
Fred Closmann - UT

Task 4 Env. Permitting
Steve Jelinek - AECOM

Task 5 Discipline Engineering
Bill Steen - AECOM

Task 6 Constructability
Bill Steen - AECOM

Task 7 Cost Estimate
Bill Steen - AECOM

Task 8 Economic Analysis
Andrew Sexton - Trimeric

Task 5 Engineering
Scott Bryan - AECOM

Task 5.1 Process
Andrew Sexton & Katherine Dombrowski - Trimeric
Fred Closmann - UT
Karen Farmer - AECOM

Task 5.2 Mechanical
Sarah Douglass - AECOM

Task 5.3 Electrical
Mike Hachem - AECOM

Task 5.4 Int. and Controls
Jim Surber - AECOM

Task 5.5 Civil/Structure
Julie Joyo - AECOM

Task 5.6 Fire Engineering
TBD - AECOM

Task 5.7 Pipeline/Compressor
Brad Piggott - Trimeric
Jeff Stephens - AECOM
Opportunities and Constraints at Mustang Station

- Ideal ample space at the site
- Competitively priced natural gas
- CO$_2$ Pipeline & EOR + potential storage
- Summer Ambient T (cool nights, hot days)
- Cooling water not available for capture system
- Competitive power grid (SPP) with renewables
  Greatest wind penetration of U.S. IPO’s