High Energy Systems for Transforming CO$_2$ to Valuable Products

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NETL CO$_2$ Capture Technology Project Review Meeting, Pittsburgh, PA, August 26-30, 2019
Outline

• Project Overview
• Technology Background
• Technical Approach Discussion
• Progress and Current Status
• Plans for Future
Introduction to GTI

- Research organization, providing energy and environmental solutions to the government and industry since 1941
- Facilities: 18 acre campus near Chicago
Project Overview
High Energy Systems for Transforming CO$_2$ to Valuable Products

- **Sponsor**

- **Funding**: Federal: $799,997, Cost-share: $206,000, Total: $1,005,997
- **Duration**: 39 months
  - BP1: 5/1/2017 – 10/31/2019
  - BP2: 11/1/2019 – 7/31/2020
- **Objective**: Develop a direct electron beam synthesis (DEBS) process to produce valuable chemicals such as acetic acid, methanol, and carbon monoxide, using carbon dioxide captured from a coal-fired power plant and natural gas.
Project Objectives

• Develop the Direct E-Beam Synthesis (DEBS) process
  Use high-energy electron beams from an accelerator to break chemical bonds

• Produce valuable chemicals, such as acetic acid, methanol, and carbon monoxide, at relatively low severity (pressure near one atmosphere and temperatures <150°C)
  Utilize near-pure CO₂ captured from a pulverized coal (PC)-fired power plant and methane, imported as natural gas
# High Energy Systems for Transforming CO2 to Valuable Products

## Team:

<table>
<thead>
<tr>
<th>Member</th>
<th>Role</th>
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<tbody>
<tr>
<td>gti®</td>
<td>• Overall project integration and management</td>
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<tr>
<td></td>
<td>• Design and construct E-Beam reactor and testing unit</td>
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<td></td>
<td>• Conceptual design for coal-fired power plants with DEBS</td>
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<tr>
<td>PCT</td>
<td>• Provide guidance in E-Beam reactor design and E-Beam accelerator for testing</td>
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<td></td>
<td>• Provide commercial size electron accelerator design and costing</td>
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<tr>
<td>ESF</td>
<td>• Develop kinetic model for the E-Beam reactor</td>
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Technology Background
DEBS Process for Post- and Pre-combustion
**Electron Beam Fundamentals**

**200keV & 20mA E-Beam:**
E-Beam power = 4000 watt (4000 J/sec)

Each electron will have:
3.2 x 10^{-14} J of energy

E-Beam will have:
1.25 x 10^{17} electrons per second

Bond dissociation energy (kJ/mol):

<p>| | |</p>
<table>
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<tr>
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<tbody>
<tr>
<td>C-H</td>
<td>337.2</td>
</tr>
<tr>
<td>C-O</td>
<td>1076.5</td>
</tr>
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</table>

Each electron has the potential to break:
~60,000 C-H
~20,000 C-O
Comparison of Plasma Conversion Technologies


**Vinokurov et al., Chemistry & Technology of Fuels and Oils, V-41, #2, 2005
Advantages Over Traditional Processes

- The DEBS process uses **high-energy electron beams** to break chemical bonds, allowing production of the desired chemicals at **near-ambient pressure and temperatures**

- Valuable chemical production by DEBS technology applied to CO$_2$ captured from coal-fired power plant will provide:
  1. Low pressure / low temperature single reactor operation
  2. More energy-efficient CO$_2$ utilization
  3. Lower capital and operating costs
Challenges

• Technology Challenge:
  • Delivering maximum e-beam dose
  • Determining which products are more probable
  • Minimizing power use by E-Beam Accelerator
Experimental Design & Key Experimental Parameters

- E-Beam dose, (kJ/gm)
- Gas residence time (ms)
- E-Beam energy : 80-200 (keV), 20 (ma)
- Use of a promoter
- Use of catalyst(s) to promote desired reactions
# Milestone Schedule

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Milestone Number</th>
<th>Title or Brief Task Description</th>
<th>Original Planned</th>
<th>Revised Planned</th>
<th>Actual</th>
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<tbody>
<tr>
<td>1A</td>
<td>1.1</td>
<td>Update Project Management Plan</td>
<td>4/30/17</td>
<td>6/1/17</td>
<td>6/27/17</td>
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<tr>
<td>1A</td>
<td>1.2</td>
<td>Kickoff Meeting</td>
<td>4/30/17</td>
<td>6/13/17</td>
<td>7/13/17</td>
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<tr>
<td>1B</td>
<td>2.1</td>
<td>Complete Final Design</td>
<td>5/1/17</td>
<td>8/1/19</td>
<td>8/1/19</td>
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<tr>
<td>1B</td>
<td>1.3</td>
<td>Submit Continuation Application</td>
<td>1/1/18</td>
<td>8/1/19</td>
<td>8/21/19</td>
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<tr>
<td>1B</td>
<td>7.1</td>
<td>Develop Preliminary Kinetic Model</td>
<td>12/31/17</td>
<td>10/31/19</td>
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<tr>
<td>2</td>
<td>5.1</td>
<td>Start Parametric Testing</td>
<td>2/1/18</td>
<td>11/15/19</td>
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<tr>
<td>2</td>
<td>5.2</td>
<td>Determine key operating parameters that would Maximize per pass CO₂ Conversion</td>
<td>3/31/18</td>
<td>12/31/19</td>
<td></td>
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<tr>
<td>2</td>
<td>6.1</td>
<td>Identify Operating Conditions and Catalyst Combinations for Chemical Production</td>
<td>7/31/18</td>
<td>12/31/19</td>
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<tr>
<td>2</td>
<td>7.2</td>
<td>Develop Kinetic Model</td>
<td>2/28/19</td>
<td>7/31/20</td>
<td></td>
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<tr>
<td>2</td>
<td>8.1</td>
<td>Report Analysis of Experimental Data</td>
<td>2/28/19</td>
<td>7/31/20</td>
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<tr>
<td>2</td>
<td>8.2</td>
<td>Complete Economic Analysis</td>
<td>2/28/19</td>
<td>7/31/20</td>
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<tr>
<td>2</td>
<td>1.4</td>
<td>Submit Final Technical Report</td>
<td>4/1/19</td>
<td>8/31/20</td>
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# Success Criteria

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<tr>
<th>Decision Point</th>
<th>Date</th>
<th>Success Criteria</th>
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| Go / No-Go              | 10/31/2019 | • Complete design and manufacture of testing skid with E-Beam reactor.  
                          |            | • Successful commissioning of a viable reactor system and testing unit:  
                          |            |   Verify gas flow meter control by measuring the vent using a dry test meter  
                          |            |   Operate chiller for condenser to achieve less than -20°C in the condenser  
                          |            |   Verify detection limit of acetic acid and methane using RGA at 100ppmv  
                          |            | • Identify at least two catalysts to control the recombination and increase the yields for more valuable products  
                          |            | • Complete design and cost estimate for the modification to a commercial electron accelerator shield housing |
| Completion of the project | 7/31/2020 | • 85% acetic acid, 15% methanol and CO selectivity  
                          |            | • Higher than 25% CO₂ conversion per pass  
                          |            | • Development of kinetic model  
                          |            | • Reduce the COE by at least 50% compared to DOE Case 12-B  
                          |            | • Achieve no net GHG emissions in production of products |
Risk Status

Initial Risks:
1. Reactor size too small for practical use in testing unit
   1a. Reduce E-Beam power and increase reactor size
2. Recombination reactions occur too quickly
   2a. Decrease residence time in reactor
   2b. Include a “recombination chamber”
   2c. Change location of catalyst
3. Reactions produce unidentified products
   3a. Increase analytical diagnostic capability
   3b. Change catalyst

Resource Risk:
4. Accelerator provider not able to perform project
   4a. Reserved “beam time” for GTI’s experiments
   4b. Collaborate with other accelerator facilities
   4c. Operate accelerator at GTI

Resource Issue:
5. Accelerator provider not able to perform experiments
   5a. Identify other facilities with similar capability
   5b. Collaborate with other accelerator facilities
   5c. Working with PCT-Ebeam Integration
Progress and Current Status of Project
Electron Accelerator

- Electron accelerator provided by PCT E-Beam Integration
- Uses a seal lamp unit from COMET
- Custom made accelerator and reactor housing
COMET Sealed Lamp Accelerator

- 200 keV, 20 ma electron beam
- Beam window is 40mm x 400mm
Completed Accelerator Housing

- Construction and completed accelerator housing during Factory Acceptance Test at PCT E-Beam Integration.
GTI Facility Modification

• Remodeled a section of existing laboratory to accept electron accelerator.

• Upgraded ventilation to allow for high volume of combustible gas use.
Electron Accelerator Delivered to GTI
Plans for Future Testing
Plans for future testing/development

• Finish reactor and testing skid fabrication
• Begin testing at GTI with new reactor and accelerator
• Kinetic model verification
• Techno-economic analysis

• Scaling up accelerator and reactor is not expected to be an issue:
  1. Available beam coverage from existing equipment is large
  2. Multiple accelerators can be connected to increase beam coverage if necessary
Summary

• Objective is to develop a commercially viable non-equilibrium process that breaks bonds directly unlike conventional chemistry that requires heating the entire molecule

• Irradiation of CH₄ and CO₂ mixture has been modeled for over 200 compounds with over 1600 reactions

• E-Beam reactor designed and constructed

• Electron accelerator is delivered to GTI and being commissioned for parametric testing
Acknowledgements

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