Ultra-Low Sulfur Winterized Diesel

March 25, 2021
Systems Development and Integration

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LanzaTech, Inc.
Project Overview
**FOA Objectives**

DE-FOA-0001926: Process Development for Advanced Biofuels and Biopower (PDABB)
Topic Area 2: Drop-in Renewable Diesel Fuel Blendstocks

**Specific FOA Objectives**

- Product drop-in Renewable Diesel Fuel compatible with current infrastructure and vehicles
- Product qualifying as Advanced or Cellulosic Biofuel under Renewable Fuel Standard
- Primary product stream containing at least 50% biogenic carbon
- Modeled mature price of ≤ $3/Gallon of Gasoline Equivalent (GGE) of Advanced Biofuel

**Required Outcomes**

- 100 to 1,000 gallons of Renewable Diesel for testing and evaluation
- Basic Engineering Package for next-scale implementation at a minimum throughput of 1 DTPD biomass or 16,000 Mbtu/day industrial flue gas
**Project Goal**

Develop and validate a robust, flexible Alcohol-to-Diesel (ATD) process for producing drop-in, renewable, diesel fuel blendstocks from biomass-derived ethanol

**Project objectives:**
- Adaptation of Alcohol-to-Jet process for maximum synthetic paraffinic diesel (SPD) production
- Process protocols for producing synthetic paraffinic diesel suitable for select applications
- Optimized catalysts and commercially-relevant catalyst preparation methods
- Alcohol-to-Diesel Production Unit (ATDPU) to produce 500 gallons of ATD-SPD
- Basic Engineering Package for the next-scale implementation of the ATD process
Alcohol-to-Diesel Process

Ethanol $\xrightarrow{-\text{H}_2\text{O}}$ Ethylene

Ethylene $\rightarrow$ C$_4$-C$_{24}$ Olefins $\rightarrow$ C$_8$ to C$_{16}$ Hydrocarbons

Jet range hydrocarbons (C$_8$ to C$_{16}$) selectively built
LanzaTech Jet and Diesel Production at Freedom Pines Biorefinery

LanzaTech Produced
✓ 4000 gallons Jet
✓ 600 gallons Diesel

- Demonstrated feedstock flexibility
  - Waste Gas Ethanol (Lanzanol)
  - Grain Ethanol
- Waste gas ethanol (Lanzanol) produced in an RSB-certified demonstration facility
  - Shougang-LanzaTech 100,000 gal/yr China demonstration plant
- Site of SGLT Commercial Plant
Background

- FAME (Fatty Acid Methyl Ester) biodiesel is a staple of road transport but blending levels are constrained by properties (oxygenate).
- HEFA (Hydroprocessed Esters and Fatty Acids) processes make renewable diesel as Synthetic Paraffinic Diesel, which is a drop-in fuel meeting ASTM D975.
- FAME and HEFA processes rely on lipid feedstocks whose supplies are limited in the long run, even as demand increases.
- FAME and HEFA product yields and properties are determined largely by chemistry and feedstock.
- Maximum theoretical diesel yield from HEFA is ~75%.
- Optimization of HEFA yield for one product impacts overall yield.
Alcohol-to-Diesel

- Alcohol-to-Diesel (ATD) produces a drop-in renewable diesel fuel meeting ASTM D975
- ATD can use ethanol from any source, expanding feedstock supply and long-term production potential
- ATD product properties are controlled by processing conditions as long-chain hydrocarbons are built up from C2 starting point
- Current Alcohol-to-Jet process can achieve 75% diesel product, equivalent to HEFA maximum theoretical yield
- ATJ and ATD product slate can be varied with no loss of overall product yield

*Project will increase yield of renewable diesel from abundant, low-cost feedstocks, and provide process and protocols to serve multiple diesel applications on demand*
1 - Management
Management

Management Approach
Project builds on prior LanzaTech-PNNL collaborations combined with experience and data from developing the Alcohol-to-Jet process.

LanzaTech (prime)
- Scale up catalysts for sample production
- Adapt and augment existing process equipment to build an ATD Production Unit (ATDPU)
- Install and shake down ATDPU at LanzaTech Freedom Pines Biorefinery in Soperton, Georgia
- Produce 500+ gallons of diesel from ethanol for multiple diesel applications

PNNL (CRADA partner)
- Experimentally study effects of catalyst and process parameters on diesel properties
- Optimize catalyst and process at lab scale
- Produce gallon quantities of fuel
- Coordinate engine testing

Other Stakeholders
- Project will leverage infrastructure and O&M staff of Freedom Pines Biorefinery and Freedom Pines Fuels
## Risk Assessment and Mitigation

<table>
<thead>
<tr>
<th>Risk Area</th>
<th>Level</th>
<th>Mitigation</th>
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</table>
| Ethanol feedstock quality          | Low   | • LanzaTech and PNNL have both produced ethylene from multiple sources of ethanol.  
                                      |       | • Ethanol clean-up is part of commercial ethanol dehydration technology                                                               |
| Catalyst performance and robustness| Low   | • Will perform parametric evaluations of a number of variables on diesel production, identifying key variables to optimize performance  |
| Engine performance                 | Low   | • Product samples generated using the ATD process have shown excellent properties                                                         |
| Process performance                | Low   | • Incorporated select optimization activities into project plan  
                                      |       | • All process steps have been operated successfully at prior scale                                                                    |
| Process scale up                   | Low   | • Project will leverage the results of ongoing projects using related process technology  
                                      |       | • All process steps have been operated successfully for the jet application                                                           |
| Catalyst scale up                  | Low   | • LanzaTech has relationships with commercial-scale catalyst producers who have experience producing similar types of catalysts       |
| Execution risk                     | Low   | • LanzaTech and PNNL have a history of successful collaborations                                                                            |
| Market risk                        | Low   | • Regulations continue to push for low-sulfur, low-carbon fuels                                                                             |
2 - Approach
Overview of Approach

- Use existing Alcohol-to-Jet process as baseline, originally designed to maximize jet range hydrocarbons (synthetic paraffinic kerosene or SPK)
- Develop Alcohol-to-Diesel process capable of 90% yield of diesel range hydrocarbons
- Develop protocols to produce ATD-SPD meeting requirements of different diesel applications
- Validate Alcohol-to-Diesel process at 5,000 gallon per year scale (ATDPU)
- Develop Basic Engineering Package for next scale Alcohol-to-Diesel unit
- Verify progress toward BETO’s $3/gge target using TEA and LCA
Technical Approach – Process and Catalyst

- Analyze literature data and prior results from operation from lab to field pilot scale
- Determine optimum conditions to increase degree of oligomerization
- Systematically vary process conditions to develop correlations between process and product properties such as cloud point and cold filter plugging point
- Perform catalyst optimization studies
- Determine minimum hydrogen requirements for hydrogenation of olefins
- Scale up catalyst and develop protocol for future commercial production
Technical Approach – ATD Production and Testing

- Produce and characterize lab-scale samples to verify ATD yield
- Develop diesel application-specific protocols for operating ATD process and verify at lab scale
- Implement ATD at bench-scale and produce 1 gallon SPD sample
- Characterize SPD fuel and perform engine testing in third-party laboratory
- Implement ATD in ATD Production Unit (ATDPU) at LanzaTech Freedom Pines
- Operate ATDPU to produce a total of 500 gallons of SPD, with portions tailored to different applications
- Provide SPD from the ATDPU for detailed engine and emissions testing in third-party laboratory
## Summary of Tasks – BP1 and BP2

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Task</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP1</td>
<td>1</td>
<td>Initial Verification</td>
<td>Develop test plan for approval by IE. Reproduce baseline performance of unit operations in the laboratory and deliver data package to IE.</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Preparation and Testing of Diesel Samples</td>
<td>Produce SPD samples for testing at bench scale under conditions established at lab scale. Produce over 1 gallon SPD and supply to external testing laboratory for detailed characterization and engine testing.</td>
</tr>
<tr>
<td>BP2</td>
<td>4</td>
<td>Intermediate Verification</td>
<td>IE verification in laboratory that process and catalyst from Task 2 produce 85% SPD product with target properties.</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Alcohol-to-Diesel Production Unit</td>
<td>Develop ATDPU engineering package including equipment specifications and integration with existing assets. HAZOP review to include IE.</td>
</tr>
<tr>
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<td>6</td>
<td>Technoeconomic and Life Cycle Analyses</td>
<td>Interim TEA and LCA using data from interim verification.</td>
</tr>
<tr>
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<td>7</td>
<td>BP2 Project Management</td>
<td>On-going project management and reporting.</td>
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### Summary of Tasks – BP3

<table>
<thead>
<tr>
<th>Budget Period</th>
<th>Task</th>
<th>Title</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP3</td>
<td>8</td>
<td>Mobilization of ATDPU Equipment</td>
<td>Procure, install, and integrate ATDPU equipment. Commission ATDPU</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Catalyst Optimization and Scale Up</td>
<td>Scale up catalyst from Task 2 and procure quantities needed for ATDPU operation. Establish robust catalyst production protocols for future commercial production.</td>
</tr>
<tr>
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<td>10</td>
<td>Synthetic Paraffinic Diesel Production and Testing</td>
<td>Produce at least 500 gallons of SPD in ATDPU, demonstrating 90% SPD in products. Supply SPD to external testing laboratory for characterization and combustion studies of neat SPD and blends, including emission reports.</td>
</tr>
<tr>
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<td>11</td>
<td>Basic Engineering Package</td>
<td>Develop Basic Engineering Package for next-scale unit, as basis for future detail design and construction by EPC firm.</td>
</tr>
<tr>
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<td>12</td>
<td>Final Verification</td>
<td>IE observation of ATDPU operation to verify SPD yield and suitability for different diesel applications, based on properties of samples prepared under different conditions.</td>
</tr>
<tr>
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<td>13</td>
<td>Technoeconomic and Life Cycle Analyses</td>
<td>Final TEA and LCA using data from final verification.</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>BP3 Project Management</td>
<td>On-going project management and reporting.</td>
</tr>
</tbody>
</table>
Schedule extended to reflect contracting timeline and slowdown due to impacts of pandemic.
Primary Challenges

- Potential catalyst performance challenges
  - Addressed by parametric studies that identify critical variables to optimize diesel yield

- Process scale up challenges
  - Mitigated by experience scaling up related ATJ technology

- Possible market challenges from uncertainty in renewable fuel mandates
  - Mitigated by increasingly stringent regulations on sulfur and growth in carbon-based regulations like the California Low Carbon Fuel Standard
**Metrics for Success**

**Critical Success Factors**

- Demonstrate diesel yield increase to 90% with economic benefits verified by TEA
- Demonstrate ability to tune diesel properties for target applications

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<tr>
<th>Go/No-Go</th>
<th>Description</th>
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</table>
| G1       | **Baseline Verification.**  
Independent Engineer verification of baseline ATD process in PNNL laboratory  
Verification report accepted by DOE |
| G2       | **Intermediate Verification**  
Independent Engineer verification of improved ATD process in PNNL laboratory  
Independent Engineer verification of ATDPU design package  
Verification reports accepted by DOE |
| Final    | Production of 500 gallons SPD meeting specifications  
TEA demonstrates support for BETO $3/gge goal  
**Final Verification**  
Independent Engineer verification of ATDPU operation |
3 - Impact
Relevance to BETO objectives

- Low sulfur, low temperature drop-in renewable diesel fuel with > 60% GHG reductions, using low-cost feedstocks
- Fully compatible with existing fueling infrastructure and engines at any blend level
- Flexible tuning of diesel properties to meet specifications for any diesel application
- Addresses limitations in lipid feedstocks for FAME, HEFA and expands renewable diesel supply potential by extending to any ethanol feedstock or ethanol production technology
- Optimizes economics via feedstock flexibility that allows a commercial ATD refinery to use the lowest-cost feedstock acceptable for each market or customer
- 66 B gallon per year production potential from domestic biomass sources
4 – Progress and Outcomes
Scope of Verification
• Ethylene through final diesel product
• Ethylene feed supplied from commercial cylinders because of prior E2E validation
• Each unit operation observed running in PNNL laboratory
• Key performance metrics compared against baseline from Application and proposed Design Basis

Results
• Performance met or exceeded baseline and proposed Design Basis
Summary of Planned Activities

**Budget Period 1**
- ✓ Conduct initial verification
- ✓ Lift conditions to proceed into Budget Period 2

**Budget Period 2**
- • Design and execute laboratory experiments to optimize process parameters and catalyst
- • Prepare lab- and bench-scale samples for analysis and testing
- • Design ATD Production Unit
- • Conduct intermediate verification

**Budget Period 3**
- • Procure equipment and integrate ATD Production Unit
- • Optimize and scale up catalyst for production
- • Produce at least 500 gallons of SPD for analysis and engine testing
- • Diesel engine testing
- • Develop Basic Engineering Package for next-scale implementation of SPD process
Quad Chart Overview

Timeline*
- Budget Period 1: 10/01/2019 to 09/30/2020
- Budget Period 2: 10/01/2020 to 09/30/2022
- Budget Period 3: 10/01/2022 to 07/31/2025

<table>
<thead>
<tr>
<th></th>
<th>FY20 Costed</th>
<th>Total Award</th>
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</thead>
<tbody>
<tr>
<td>DOE Funding</td>
<td>$75,000 (BP1)</td>
<td>$2,500,000</td>
</tr>
<tr>
<td>Project Cost Share</td>
<td>$18,750 (BP1)</td>
<td>$630,327</td>
</tr>
</tbody>
</table>

Project Goal
Develop and validate a robust, flexible Alcohol-to-Diesel (ATD) process for producing drop-in, renewable, diesel fuel blend-stocks from biomass-derived ethanol

End of Project Milestone
500 gallons of Synthetic Paraffinic Diesel produced, demonstrating 90% of product in diesel range; Basic Engineering package for next-scale implementation complete.

Funding Mechanism
DE-FOA-0001926: Process Development for Advanced Biofuels and Biopower (PDABB)
Topic Area 2: Drop-in Renewable Diesel Fuel Blendstocks

Project Partners
- Zeton
- PNNL (+ engine testing facility)**

*Revised dates due to contracting and pandemic delays.
**Contracted to PNNL
Summary
Summary

- ATD offers a unique opportunity for producing renewable diesel from abundant feedstocks to meet long-term diesel demand in medium and heavy-duty market.
- ATD offers a unique ability to tune diesel properties for different applications, including cold-weather uses.
- Experienced team is positioned for success based on prior collaboration in development and scale up of baseline ATJ process.
- Project has completed initial verification and is now starting Budget Period 2.
- Schedule has been extended to accommodate coronavirus-related restrictions on laboratory R&D.
- No other constraints or concerns are anticipated in project execution.
Additional Slides (N/A)