DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Ultra-low Sulfur Winterized Diesel

April 4, 2023
Systems Development and Integration Session B

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LanzaTech

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

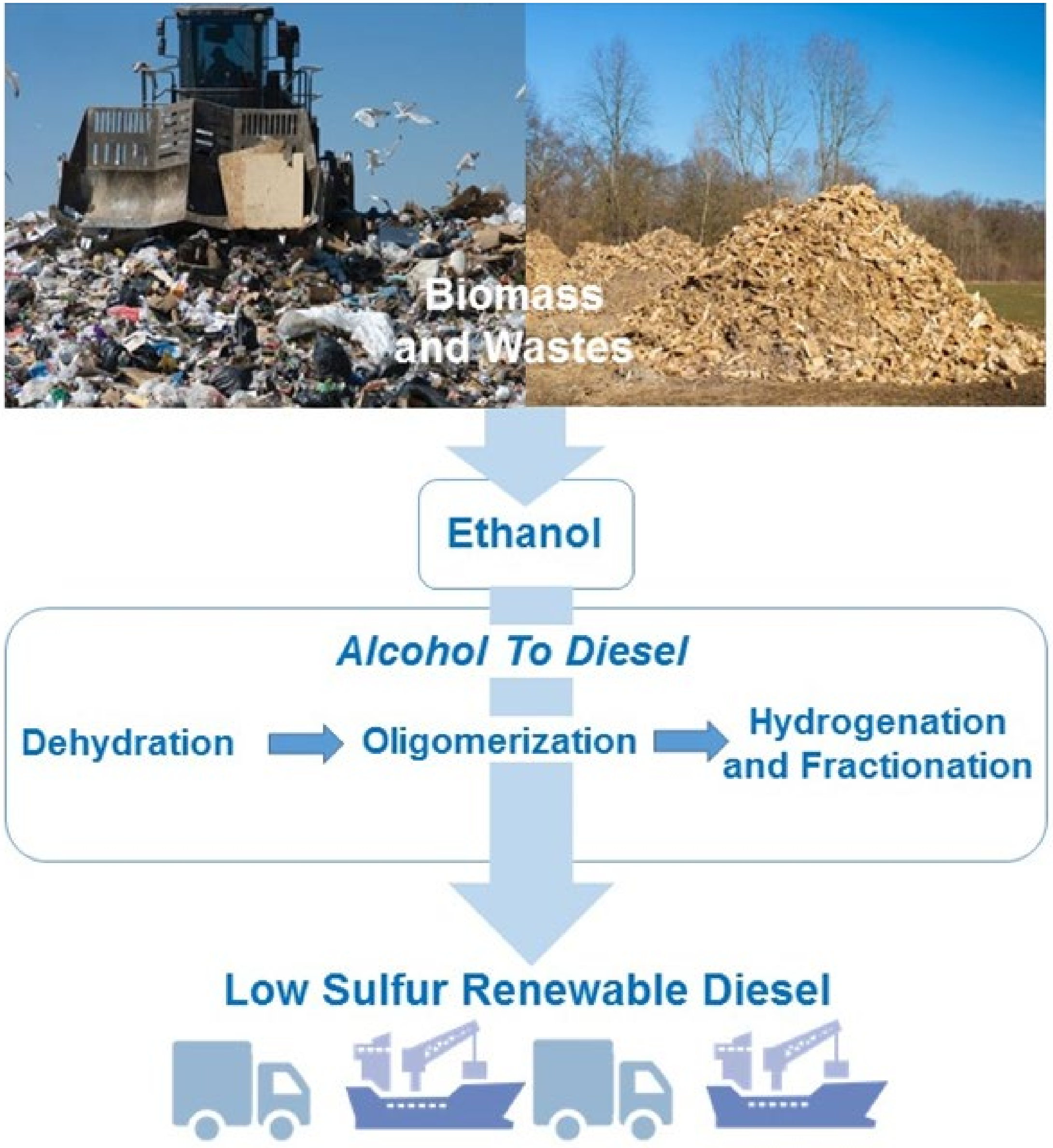
- 100 to 1,000 gallons of Renewable Diesel for testing and evaluation
- Basic Engineering Package for next-scale implementation at a minimum throughput of 1 DTPD biomass or 16,000 Mbtu/day industrial flue gas

Project Goal

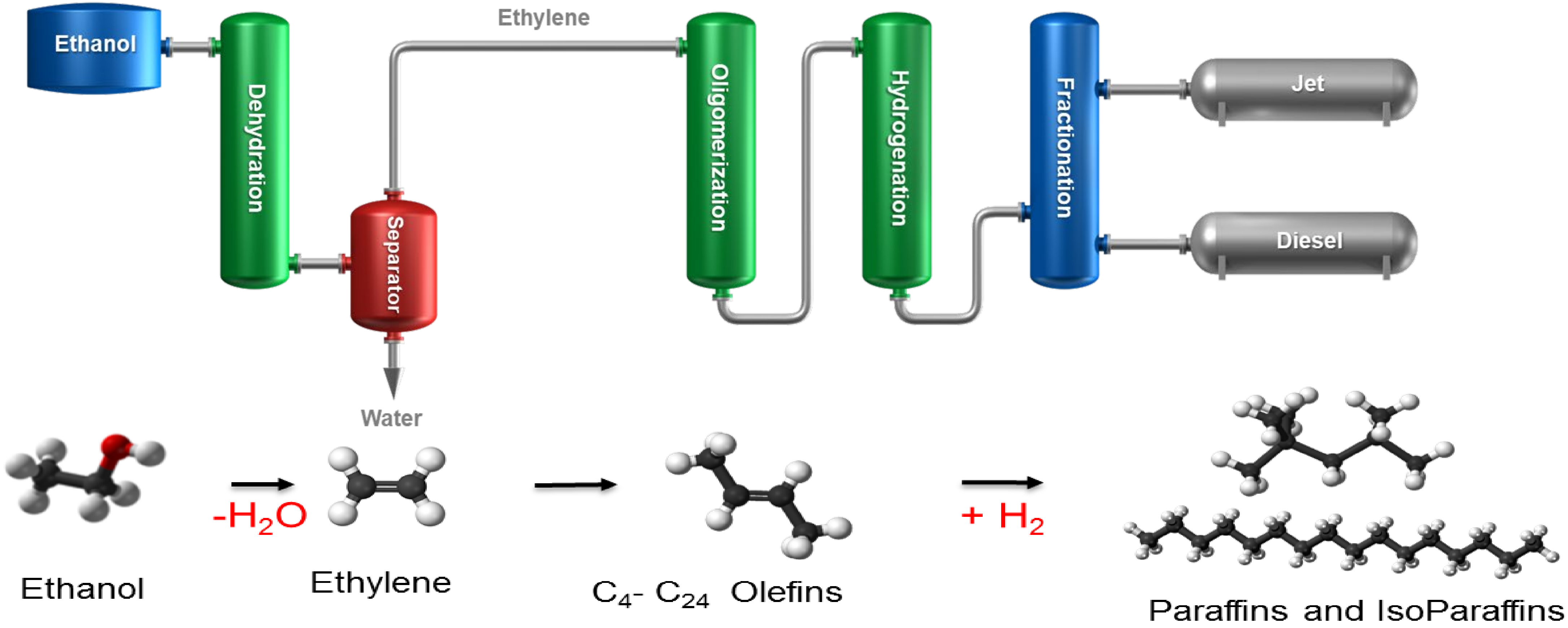
Project Goal
Develop and validate a robust, flexible Alcohol-to-Diesel (ATD) process for producing drop-in, renewable, diesel fuel blend-stocks from biomass-derived ethanol

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



Diesel:Jet Ratios

	Max Jet	Max Diesel
Alcohol-to-Jet (current)	10:90	75:25
Alcohol-to-Diesel (target)	10:90	**90:10**

Jet range hydrocarbons (C_8 to C_{16}) selectively built

LanzaTech Jet and Diesel Production using Freedom Pines Biorefinery

Increased Run Time and Production Rate → Improved Product Yield → Reduced Operating Cost → Lower Cost Commercial Product

LanzaTech Produced

✓4000 gallons Jet

✓<u>**600 gallons Diesel**</u>

- **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**

Industry 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

LanzaTech 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 run in a maximum diesel mode can achieve 75% diesel product, equivalent to HEFA maximum theoretical yield
- ATJ and ATD product slate can be varied from maximum jet to maximum diesel mode 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

LanzaTech-PNNL ATJ-SPD

High-Quality Diesel Product Meets or Exceeds World Diesel Standards More Stringent than ASTM D975

Property, unit	Limit	Stage IV	Stage IV proposed	LT Diesel Demo	Meets or Exceeds Spec
Ash, %mass	Max	0.01	0.01	<0.001	>10X Lower
Carbon Residue, %mass	Max	0.3	0.3	<0.01	>30X Lower
Cetane Number	Min	51	51	53	Meets
Flash Point, °C	Min	35	35	75	Exceeds
Kinematic Viscosity, 40°C cst	Range	2.0-4.5	2.0-4.5	2.4	Meets
Total Sulfur, mg/kg	Max	50	10	<0.1	>100X Lower
Water Content, mg/kg	Max	200	200	11	Exceeds
Cold Filter Plug Point, °C	Max	6	6	-25	Exceeds
Total Contaminants, mg/kg	Max	24	24	<12	>2X Lower
Polycyclic Aromatics, %mass	Max	11	11	<0.1	>100X Lower

1 -Approach

Overview

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

LanzaTech (prime)

- Prepare catalysts for sample production; optimize HMB and process design based on lab scale performance
- 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 with Colorado State Univ (CSU)

Other Stakeholders

- Project will leverage existing ATJ personnel and infrastructure as well as O&M staff of Freedom Pines Biorefinery

Overview of Approach

- Use existing Alcohol-to-Jet process as baseline, originally designed to maximize jet range hydrocarbons (synthetic paraffinic kerosene or SPK) but capable of producing 75% diesel
- 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 and process optimization studies to maximize yield
- Determine minimum hydrogen requirements for hydrogenation of olefins
- Scale up catalyst and process developing 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
- Optimize HMB and PFD design based on process updates
- 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

Risk Assessment and Mitigation

Risk Area	Mitigation
Ethanol feedstock quality	• LanzaTech , PNNL and Technip have demonstrated successfully produc ethylene from multiple sources of ethanol. • Ethanol clean-up is part of numerous commercial ethanol dehydration technologies
Catalyst performance and robustness	• Performed parametric evaluations of several variables on diesel production, identified key variables to optimize performance
Engine performance	• Prior product samples generated using the ATD process have shown excellent properties
Process performance	• Incorporated select optimization activities into project plan • All process steps have been operated successfully at prior scale
Process scale up	• Project leveraged the results of ongoing projects using related process technology • All process steps have been operated successfully for the jet application
Catalyst scale up	• LanzaTech has relationships with commercial-scale catalyst producers who have experience producing similar types of catalysts
Execution risk	• LanzaTech and PNNL have a history of successful collaborations
Market risk	• Regulations continue to push for low-sulfur, low-carbon fuels

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

2- Progress and Outcomes

BP1 Baseline Verification

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 Tasks – BP1 and BP2

Budget Period	Task	Title	Status	Summary
BP1	1	Initial Verification	Completed	Develop test plan for approval by IE. Reproduce baseline performance of unit operations in the laboratory and deliver data package to IE.
BP2	2	Process Improvement	Completed	Maximize yield of diesel range product. Conduct parametric study of process variables and product properties. Optimize catalysts. Establish minimum hydrogen requirements. Leverage results from literature and prior operations.
	3	Preparation and Testing of Diesel Samples	Completed/ Additive testing in progress	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.
	4	Intermediate Verification	Pending	IE verification in laboratory that process and catalyst from Task 2 produce 85% SPD product with target properties.
	5	Alcohol-to-Diesel Production Unit	In progress	Develop ATDPU engineering package including equipment specifications evaluation, procurement and integration with existing assets. HAZOP review to include IE.
	6	Technoeconomic and Life Cycle Analyses	In progress	Interim TEA and LCA using data from interim verification.
	7	BP2 Project Management	In progress	On-going project management and reporting.

Engine testing results with CSU

- Blend made with lab prepared ATD were basically indistinguishable from the baseline fossil diesel regarding general performance, combustion phasing/duration, and resulting emissions
- PM 2 5 gravimetric measurements reveal no statistically significant difference in particulate emissions
- Fuel blends containing lab prepared can be used in compression ignition engines with no adverse effects on engine efficiency or emissions

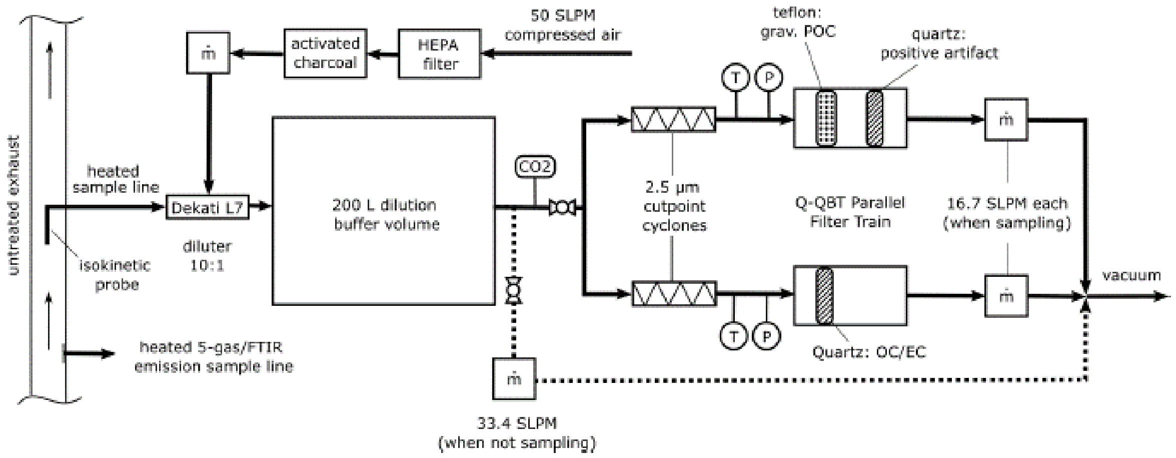
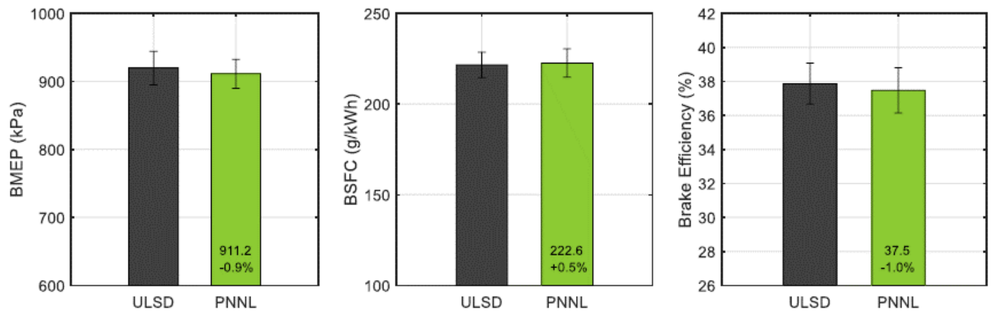


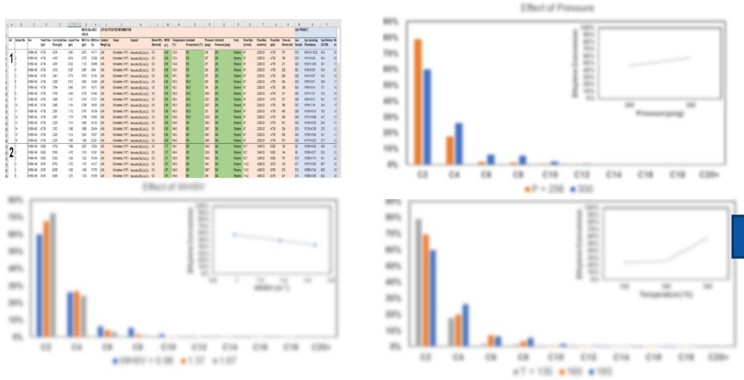
Diagram of the exhaust sample dilution and particulate measurement equipment used in this study.



Brake mean effective pressure (BMEP) - used as an indicator of engine load. Output shaft torque and speed (325 Nm; 1700 RPM) were maintained within 1% across all reported data.
Brake specific fuel consumption (BSFC) - excellent agreement with baseline, indicating that the test fuel's liquid and energy densities are similar to those of diesel.
Brake efficiency within 1.0% of the baseline.

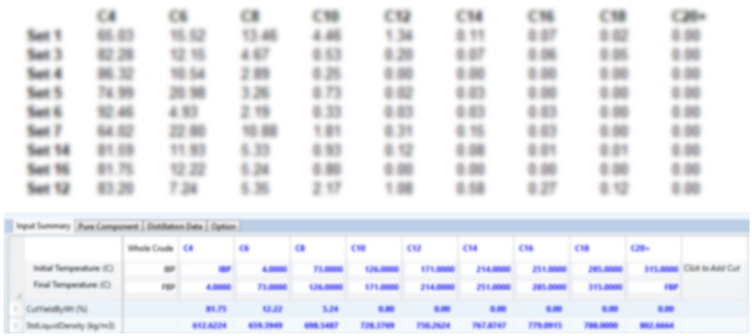
Heat and Mass Balance Generation → Process Design, PID, Equipment Lists

Compilation of Experimental Data

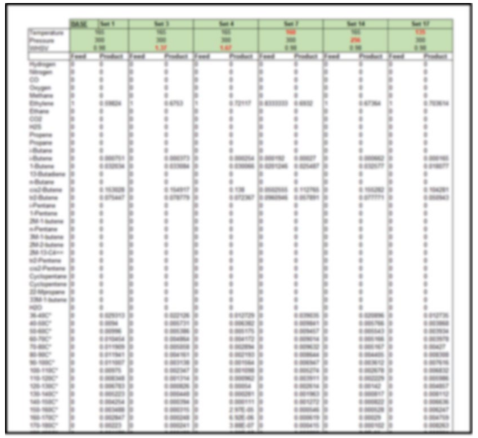


Reactor Modeling

Reactor Inlet and Outlet Compositions

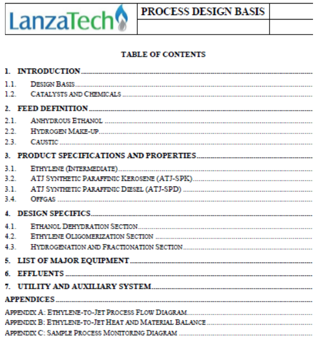


Heat and Mass Balance

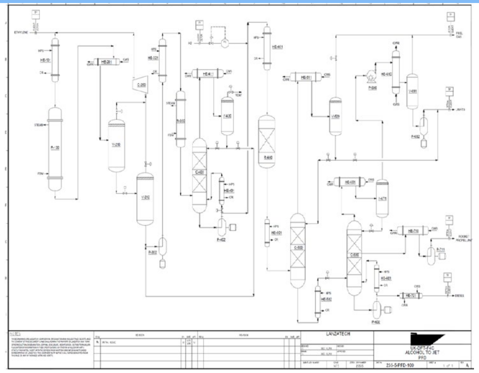


Equipment Lists

Process Design



Piping and Instrument Diagram



Summary of Tasks – BP3

Budget Period	Task	Title	Status	Summary
BP3	8	Mobilization of ATDPU Equipment	Not Started	Procure, install, and integrate ATDPU equipment. Commission ATDPU
	9	Catalyst Optimization and Scale Up	Not Started	Scale up catalyst from Task 2 and procure quantities needed for ATDPU operation. Establish robust catalyst production protocols for future commercial production.
	10	Synthetic Paraffinic Diesel Production and Testing	Not Started	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.
	11	Basic Engineering Package	Not started	Develop Basic Engineering Package for next-scale unit, as basis for future detail design and construction by EPC firm.
	12	Final Verification	Not started	IE observation of ATDPU operation to verify SPD yield and suitability for different diesel applications, based on properties of samples prepared under different conditions.
	13	Technoeconomic and Life Cycle Analyses	Not started	Final TEA and LCA using data from final verification.
	14	BP3 Project Management	Not started	On-going project management and reporting.

Summary of Completed and Planned Activities

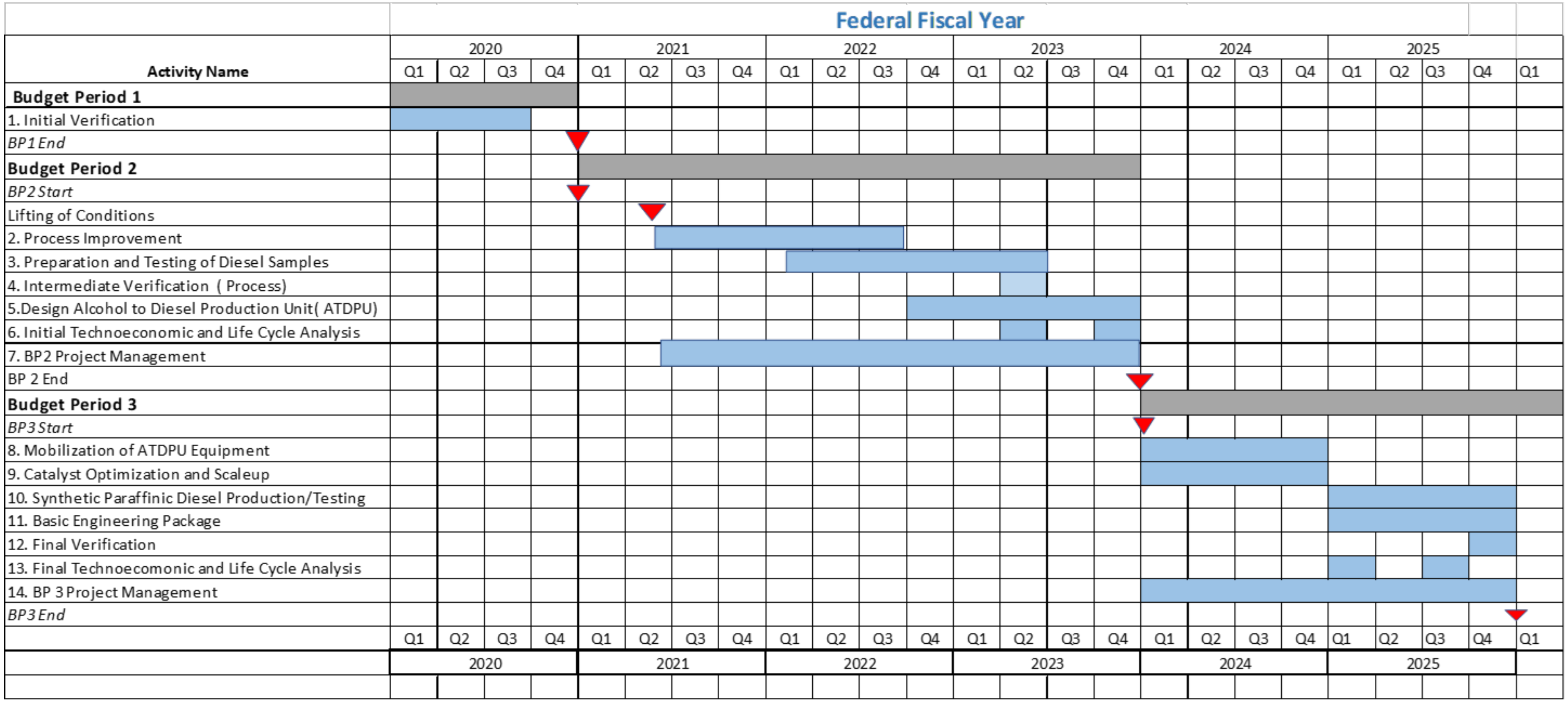
Budget Period 1
- ✓ Conduct initial verification
- ✓ Lift conditions to proceed into Budget Period 2

Budget Period 2
- ✓ Design and execute laboratory experiments to optimize process parameters and catalyst
- ✓ Prepare lab- and bench-scale samples for analysis and testing
- ✓ Produce 1 gal of 85% Yield ATD product
- ✓ Engine and property testing successful
- ➢ Design, HAZOP ATD Production Unit
- ➢ Conduct intermediate verification of lab experiments

Budget Period 3
- Integrate and Build 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

Schedule

Schedule extended to reflect contracting timeline slowdown due to impacts of pandemic, supply chain



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

Go/No-Go	Description
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

Quad Chart

Timeline

- *Project start date: 1/2020*
- *Project end date: 10/2025**

	FY22 Costed	Total Award
DOE Funding	183,666.39 *(excludes PNNL)*	$3,118,737 *(Includes $995,000 direct to PNNL)*
Project Cost Share	31.2%	31.2%

TRL at Project Start: 5
TRL at Project End: 6

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

- PNNL(+ engine testing facility)**

**Revised dates due to contracting, pandemic, supply chain 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 was positioned for success based on prior collaboration in development and scale up of baseline ATJ process
- Project has completed initial verification, key higher yield diesel samples, successful property and engine testing and initial design of ATDPDU
- BP2 Schedule has been extended to accommodated coronavirus-related restrictions on R&D and ongoing supply chain issues

Thank you!

Additional Slides

Responses to Reviewers Comments

LanzaTech response to reviewer comments

Weakness from 2021 DOE Review	LanzaTech Response
Concerns about project performance	• **Fuel standards**: fuel meets and exceeds ASTM D975 standards . The fuel offers value, with a high cetane, +50, and low CFPP (−25°C). • **Delays**: BP1 delays were contractual. PNNL completed initial IE verification, demonstrating 75% diesel selectivity, movied project to BP2.
Business case/economics,	**Business case for bioethylene to fuels**: • Using ethanol overcomes feedstock limitations for current commercial Renewable Diesel production because it is abundant and can be produced sustainably without fraud concerns associated with lipid feedstocks. • Process economics for ATD benefit from mild conditions, with no special metallurgy. • DOE's objective for the project is reducing GHG emissions from transportation; ethylene to chemicals is outside of project scope. LanzaTech has extensive experience supplying ethylene supply chains for many commercial customers, including L'Oreal, Mibelle, On Running, Lululemon, Zara, etc. Please see www.lanzaech.com.
Risk assessment	**Why not address risks associated with FOAK plant**? • Project is R&D and relevant risks center on the performance: selectivity (control of carbon length and branching), rate, and life. Optimization of the design is key. • PNNL demonstrated higher selectivity with carbon length control and cetane exceeding 50 (control over branching). Analytical and Engine testing looked excellent. In earlier work, PNNL demonstrated catalyst life and rate. Therefore, we believe the risk is manageable. . To be clear, we do firmly believe that risks must be regularly assessed in a realistic manner. • We note that LanzaTech's Waste Gas to SAF project is for a FOAK plant for the related ATJ technology.