Liquid Fuels via Upgrading of Indirect Liquefaction Intermediates

WBS: 2.3.1.100/304/305

U.S. Department of Energy (DOE)
Bioenergy Technologies Office
2019 Project Peer Review

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Robert Dagle – PNNL
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Integrated and collaborative portfolio of catalytic technologies and enabling capabilities

**Catalytic Technologies**

- Catalytic Upgrading of Biochemical Intermediates (NREL, PNNL, ORNL, LANL, NREL*)
- Catalytic Upgrading of Indirect Liquefaction Intermediates (NREL, PNNL, ORNL)
- Catalytic Fast Pyrolysis (NREL, PNNL)
- Electrocatalytic and Thermocatalytic CO₂ Utilization (NREL, ORNL*)

**Enabling Capabilities**

- Advanced Catalyst Synthesis and Characterization (NREL, ANL, ORNL, SNL)
- Catalyst Cost Model Development (NREL, PNNL)
- Consortium for Computational Physics and Chemistry (ORNL, NREL, PNNL, ANL, NETL)
- Catalyst Deactivation Mitigation for Biomass Conversion (PNNL)

**Industry Partnerships (Directed Funding)**

- Gevo (NREL)
- ALD Nano/JM (NREL)
- Vertimass (ORNL)
- Opus12 (NREL)
- Visolis (PNNL)
- Lanzatech (PNNL) - Fuel
- Gevo (LANL)
- Lanzatech (PNNL) - TPA
- Sironix (LANL)

**Cross-Cutting Support**

- ChemCatBio Lead Team Support (NREL)
- ChemCatBio DataHUB (NREL)

*FY19 Seed Project
Goal Statement

Project Goal
Develop a market-responsive biorefinery concept based on indirect liquefaction (IDL) to enable control over the gasoline, diesel, jet and co-product distribution to address shifting gasoline/distillate fuel demand.

Project Outcome
- Develop new IDL processes for high-octane gasoline and distillate fuels from methanol and ethanol intermediates
- Exceed fuel product yields of benchmark Mobil Olefins to Gasoline and Distillate (MOGD) process with lower capital cost processes

Relevance
- Known drawbacks for traditional syngas-to-fuels processes at smaller production scale: High capital and process costs, limited product quality
- Advanced upgrading technologies address these shortcomings by focusing on: Mild process conditions, high yield and C efficiency, high-quality (high-value) fuel products
**Timeline**
- 10/01/2017
- 09/30/2019
- 83% Complete

### Barriers addressed & Actions

**Ct-F: Increasing the Yield from Catalytic Processes**
- Developing catalysts that enable processes with higher carbon efficiency and yield
- Understanding catalytic active sites and reaction mechanisms to minimize by-products

**Ct-E. Improving Catalyst Lifetime**
- Understanding the effects of real biomass impurities
- Exploring deactivation through characterization, and developing regeneration/mitigation strategies

### Objective
Establish the regeneration protocol for each oxygenate conversion catalyst at the bench-scale after a minimum of **200 h total time-on-stream with at least 2 total regenerations** targeting an activity goal of at least **85% of the original activity**

### End of Project Goal
Develop a market-responsive biorefinery concept based on indirect liquefaction (IDL) to **enable control** over the gasoline, diesel, jet and co-product **distribution to address shifting gasoline/distillate fuel demand**

### Quad Chart Overview

<table>
<thead>
<tr>
<th></th>
<th>Total Costs Pre FY17**</th>
<th>FY 17 Costs</th>
<th>FY 18 Costs</th>
<th>Total Planned Funding (FY 19-Project End Date)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE Funded</td>
<td>8.1 M</td>
<td>3.6 M</td>
<td>2.2 M</td>
<td>2.5 M</td>
</tr>
</tbody>
</table>

- Partners: Percentages of project funding from FY 17-18:
  - NREL (56%); PNNL (41%); ORNL (3%)
Traditional syngas to hydrocarbon fuels have known drawbacks
- Fischer Tropsch (FT): Costly catalytic upgrading to produce quality fuels
- Methanol-to-Gasoline (MTG): Capital intensive, high aromatics content
- Mobil Olefins-to-Gasoline-and-Distillate (MOGD): Capital intensive, high number of process steps

**MFSP from biomass (2016 $)**
- FT = $3.17/GGE
- MOGD = $4.23/GGE

Advanced upgrading technologies can reduce MFSP through reduced process complexity, reduced separations duty, higher quality fuel products

Project Overview and Objectives

- Explore multiple, alternative pathways (tasks) that leverage light oxygenate intermediates
  - Develop new catalysts that outperform commercial catalysts
  - Identify commercial catalysts that can be adapted to upgrading routes
  - Compare against benchmark processes (e.g., MOGD)
- Leverages lab-specific strengths in oxygenate production and conversion
- Synergize efforts for olefin coupling to distillates and fuel-property testing across the labs
2 - Technical Approach – Dual Research Cycle

- **Hypothesis-driven catalyst development** coupled with sophisticated catalyst synthesis and characterization (with Adv. Catalyst Synthesis & Characterization)
- Develop **structure-function relationships** (with Cons. Comp. Physics & Chemistry)
- **TEA-informed research targets**, experimental data informs process models and TEA

![Diagram of research cycle]

**Synthesis & Characterization**
- Cu/BEA
- Hydrotalcites

**Computation**
- Foundational Catalysis Science

**Foundational Catalysis Science**

**Catalyst Testing**
- Bench-scale reactions
- Product analysis

**Techno-economic Analysis (TEA)**

**Applied Engineering**

**Catalyst Scaling & Process Models**

**Chart showing technological advancements and projected costs**
2 - Technical Approach and Success Factors

**Research Challenges**

- Balancing *multiple reactions* under lower severity conditions
- *Selectively producing fuel-range (C\textsubscript{5+}) products*
- Maximizing catalyst *lifetime*
- Generating relevant *quantity* to confirm *high-quality fuel properties* to compete with mature, conventional fuel-synthesis processes

**Critical Success Factors**

– Maximize carbon efficiency via *multi-functional catalysts that perform cascade chemistry*
– *Recycle by-products* to higher value fuel products to maximize yield
– Collaborate with Enabling Technologies to *understand deactivation, develop regeneration/mitigation approaches* at the bench-scale
– Utilize *multiple ASTM International test methods* with fuel-testing experts
– *Advance technologies* with bioenergy industry partnerships, TCF funding
2 – Management Approach

Task management integrated with CCB enabling technologies and analysis team, other BETO projects and consortia, and technology advancement opportunities

- **“Constant contact” between PIs and Enabling Technology** points-of-contact
- **Cooperative and synergistic research areas** identified
  - Leverages lab-specific strengths in oxygenate production and conversion
  - Olefin coupling and fuel testing between NREL, PNNL, ORNL
- **TEA-informed metrified milestones and Go/No-Go** to relate catalyst improvements to costs
- Utilized the **TEA-informed FY18 Go/No-Go** to re-focus FY19 research
3 – Research Progress: Baseline in FY17

<table>
<thead>
<tr>
<th>MOGD Benchmark</th>
<th>Task 1: C\textsubscript{1} to Gasoline</th>
<th>Task 2: C\textsubscript{2+} to Dist. (Guerbet)*</th>
<th>Task 2: C\textsubscript{2+} to Dist. (C\textsubscript{4}-Olefin)*</th>
<th>Task 3: EtOH to Dist. (C\textsubscript{3}+ Olefins)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst</td>
<td>ZSM-5</td>
<td>Cu/BEA</td>
<td>Cu/MgO-Al\textsubscript{2}O\textsubscript{3}</td>
<td>ZnZrO\textsubscript{x}</td>
</tr>
<tr>
<td>Severity of Process Conditions</td>
<td>350–400 °C 20 atm Frequent regen.</td>
<td>200–220 °C 1–3 atm Stable &gt;100h</td>
<td>300-350 °C 1 atm 200 h, aq. EtOH</td>
<td>400-450 °C 1 atm Aq. EtOH</td>
</tr>
<tr>
<td>Start of FY17 Metrics</td>
<td>_</td>
<td>19% DME conv. 0.044 g/g\textsubscript{cat}/h</td>
<td>44% EtOH conv. 75% C\textsubscript{4}+ sel.</td>
<td>99% EtOH conv. 47% C\textsubscript{4} sel.</td>
</tr>
<tr>
<td>Fuel Yield* and MFSP</td>
<td>G= 34 GGE/ton D= 27 GGE/ton $$3.99$/GGE</td>
<td>G= 50 GGE/ton D= 42 GGE/ton $$4.04$/GGE</td>
<td>D= 41 GGE/ton $$5.90$/GGE</td>
<td>D= 16 GGE/ton $$5.21$/GGE</td>
</tr>
</tbody>
</table>

*Task 2: thermochemically derived C\textsubscript{2+} alcohols; Task 3: fermentation derived ethanol  

FY17 TEA data sets the stage for catalyst development
- TEA-directed research goals to target most impactful metrics
- Comparison against benchmark MOGD process
- Discontinued ZnZrO\textsubscript{x} catalyst research due to high MFSP, low C-efficiency
  - Developing new catalysts for this pathway
Overview of the pathway

C₁ OXY’s

DME

\[ \text{Cu/BEA} \]

200-220 °C
1-3 atm

\[ \text{C₄-C₇ high-octane gasoline} \]
(low aromatics)

Differentiators versus MTG

- **Catalyst** – BEA vs MFI
- **Product composition** – Alkylate vs regular-gasoline
- **Higher product RON** – ≥95 vs 92
- **Lower coking rate**
- **Higher yield from biomass** – +18%


NREL-developed Cu/BEA catalyst reduces MFSP versus commercial BEA by 20%
- Increases gasoline fuel product yield by 38% vs BEA
- Reincorporates non-fuel C₄ alkanes into C₅+ fuel products at Cu(I) active sites
**Goal:** Increase C₄ recycle conversion to increase yield, reduce MFSP

- **Computationally predicted ionic Ni, Zn, and Ga** to outperform Cu(I) for alkane dehydrogenation
  - Lower activation energy
  - Motivated bimetallic catalyst development to increase alkane re-activation
  - **Experimentally** Ni(2+), Zn(2+), Ga(3+) outperform Cu(+)

**Simulated C₄H₁₀ Recycle with DME + H₂**

<table>
<thead>
<tr>
<th>Catalyst</th>
<th>C₄H₁₀ Recycle Conversion (%) 1 atm</th>
<th>C₄H₁₀ Recycle Conversion (%) 3 atm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu/BEA</td>
<td>12</td>
<td>22</td>
</tr>
<tr>
<td>Zn-Cu/BEA</td>
<td>20</td>
<td>28</td>
</tr>
</tbody>
</table>

- Developed a 2-step method to prepare bimetallic catalysts with targeted structures (with ACSC)
  - Zn-Cu/BEA increased C₄ recycle conversion (27-33% relative) vs Cu/BEA
  - Direct impact to reduce MFSP

**Bimetallic catalysts with predicted and synthetically-controlled active sites enable increased C₄ recycle conversion**
3 - Task 1: DME to High-Octane Gasoline Research Progress

**Goal:** Control paraffin:olefin (P:O) product ratio to control fuel properties

<table>
<thead>
<tr>
<th>Paraffin Products</th>
<th>Olefin Products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compounds</td>
<td>RON/MON</td>
</tr>
<tr>
<td>Branched-C₆</td>
<td>99/94</td>
</tr>
<tr>
<td>Branched-C₇</td>
<td>94/90</td>
</tr>
<tr>
<td>Triptane</td>
<td>112/101</td>
</tr>
</tbody>
</table>

- **Sensitivity** \( S = \text{RON} - \text{MON} \) is a key metric for gasoline applications
  - Automotive fuel – high S
  - Aviation gasoline – low S
- Co-optima Merit Function favors greater S
- +1 S increases efficiency more than +1 RON

Controlling olefin content enables control of S, directs fuel application

**Paraffin:Olefin Product Ratio from DME + H₂**

- Bimetallic catalysts change the product P:O ratio and resulting estimated S

**Bimetallic catalysts with predicted and synthetically-controlled active sites enable fuel property tuning**

3 - Task 2: Ethanol to Distillates Research Progress

Overview of the pathway

- **Metal-acid bifunctionality** produces **crotonaldehyde intermediate**
  
  - **Branch-point** to give butanol, butadiene, or butenes
  
  - Catalyst design and process conditions can **direct crotonaldehyde to desired intermediate**

\[
\begin{align*}
2 \text{OH} & \rightarrow \text{Crotonaldehyde} \\
\text{Crotonaldehyde} & \rightarrow \text{Butanol} \quad \text{OH} \\
\text{Crotonaldehyde} & \rightarrow \text{Butadiene} \\
\text{Crotonaldehyde} & \rightarrow \text{Butenes}
\end{align*}
\]

**Differentiators versus ATJ**
- Multifunctional catalyst
- Eliminates dehydration step
  - 3 vs 4 unit ops
- Aqueous ethanol compatible
- Decreased CapEx

**Down-select of Ethanol-to-1-Butanol (Guerbet) at FY18 Go/No-Go**

- **50% yield** to higher alcohols (single pass)
- Stable lifetime >500 h in plug flow reactor.
- Cu(I) limits undesired side products
- De-emphasized at FY18 Go/No-Go, moved to Co-optima Project evaluating branched alcohols as gasoline blendstocks
Goal: Control cascade chemistry to increase yield of C\textsubscript{4}-olefins

\[
2 \text{OH} \rightarrow \text{Crotonaldehyde} \rightarrow \text{Butadiene} \rightarrow \text{Butenes}
\]

**PNNL developed a Ag/ZrO\textsubscript{2}-SiO\textsubscript{2} catalyst for high-yield of butadiene**
- Achieved 90% conversion, 70% butadiene selectivity
  - Highest butadiene production rate reported (0.40 g\textsubscript{BD}/g\textsubscript{cat}/h vs 0.11 g\textsubscript{BD}/g\textsubscript{cat}/h)
  - Tailored Lewis acidity with highly dispersed Ag nanoclusters (< 3 nm)


- Butadiene vs butenes selectivity can be controlled with co-fed N\textsubscript{2} vs H\textsubscript{2}
- Co-fed H\textsubscript{2} directs crotonaldehyde to butenes product
- No Butadiene observed

**Ag/ZrO\textsubscript{2}-SiO\textsubscript{2} catalyst offers product tunability from butadiene to butenes**
3 - Task 2: Ethanol to Distillates Research Progress

Structure-function relationships explored via in-situ XPS with ACSC

Ag/ZrO$_2$-SiO$_2$ catalyst explored under inert versus reducing conditions with flowing ethanol
- **Butadiene** formed over oxidized Ag species (N$_2$ co-feed)
- **Butenes** formed over reduced Ag species (H$_2$ co-feed), mild hydrogenation activity

Lifetime is significantly increased with co-fed H$_2$ versus N$_2$

- Activity steadily decreases with co-fed N$_2$
- Initial decrease in activity with H$_2$, then stable for 80 h, and after regenerations

Co-fed H$_2$ has multiple impacts: reduces Ag, shifts products to butenes, and improves catalyst lifetime
3 - Task 3: Ethanol to Distillates Research Progress

Overview of the pathway

C₂ OXY’s → C₃-₆ olefins → Diesel and Jet Fuels

Differentiators versus ATJ
- Multifunctional catalyst
- Eliminates dehydration step – 3 vs 4 unit ops
- Aqueous ethanol compatible
- Decreased CapEx

Goal: Control cascade chemistry to mixed olefins from ethanol

Selectivity shift from C₂H₄ to C₃⁺ olefins

Zeolite provides a scaffold to introduce well-defined active sites
- No H⁺ sites required
- Achieved 99% conversion and 87% selectivity of C₃-C₆ olefins

Cu-Zn-Y/BEA catalyst enables a step-change in selectivity
Sets the state-of-the-technology for further development
Project Technological Achievements (FY17–18)

- Significant increases in critical performance metrics and reductions in MFSP
- *Lifetime and regeneration* studies are on-going, including with known biomass impurities
High-octane Gasoline technology awarded a Technology Commercialization Fund - $740k investment by DOE + $750k cost-share from Enerkem

- Demonstrated high-octane gasoline production at the pilot scale (20-kg$_{\text{cat}}$) with MSW-derived methanol for 500 h time-on-stream
- Produced 20 L of high-octane gasoline, sent to refinery industry partners

High Octane Product

73.9% Triptane
RON = 108
MON = 97

HOG product targets growing premium gasoline fuel demand

– Unlike ethanol, gasoline product has no blend limit.
– Control over fuel properties (S = RON – MON) enables automotive and aviation gasoline target markets
  – Automotive – synthetic alkylate blendstock
  – Aviation – high-MON blendstock

Increasing market share of premium, high-octane gasoline
Jet-range hydrocarbon from ethanol-derived C₄ olefins met 4 key ASTM standards for jet fuel

<table>
<thead>
<tr>
<th>Property</th>
<th>Jet-Range Hydrocarbons</th>
<th>Blendstock Requirements (ASTM D7566)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>86.9</td>
<td>–40 max (D5972)</td>
</tr>
<tr>
<td>(b.p. 150 to 300 °C, wt. %)</td>
<td>(75 single pass)</td>
<td></td>
</tr>
<tr>
<td>Freezing point (°C)</td>
<td>–74</td>
<td>–40 max (D5972)</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>51.5</td>
<td>38 min (D445)</td>
</tr>
<tr>
<td>Viscosity (mm²/s)</td>
<td>2.0</td>
<td>8 max (D93)</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>780</td>
<td>775 to 840 (D4052)</td>
</tr>
</tbody>
</table>

Properties for C₄-olefin derived oligomerization products after distillation and hydrotreatment.

**Tasks 2 and 3 target **_growing distillate fuel demand_

– Utilize **ethanol beyond the “blend wall”**
– Ethanol is now an approved feedstock and the **blend ratio limit for ATJ-SPK fuels has been raised to 50%**
– Oligomerization of C₄ olefins can be tailored to **jet and/or diesel target markets**

_Catalysis Science & Technology 2019, DOI: 10.1039/C8CY02297F._
4 - Relevance to BETO

Research goals directly address BETO **conversion barriers to increase yield in catalytic processes and to improve catalyst lifetimes**

- Enabled by cross-cutting foundational science and applied engineering approach
- Include **impurities** associated with **real feeds and non-ideal conditions**
- Investigate **catalyst performance and regeneration** at longer times on stream

FY17 Demonstration: biomass gasification and DME-to-HOG with scaled-up Cu/BEA catalyst

- Feedstock flexibility and blend linearity with 5 feeds
  - Collaborative with Feedstock-Conv. Interface Con.
  - **Multiple conditions and regenerations**, and **TOS >250 h**
- Identified the key challenges and **supported pilot-scale TCF project** with Enerkem
- **Lessons learned** informed new-start ADO Engineering of Catalyst Scale-Up Project

**Cost reductions across each conversion pathway**

![Graph showing cost reductions](image)

- **2017** vs. **Current** (MOGD, $C_1$ to HOG, $C_2$ to dist., $C_3$ to dist.)

5 - Future Work

Tasks 1 and 4: DME to High-Octane Gasoline

- Increase carbon yield
  - Q1 - Explore process model and TEA to direct \( \text{CO}_2 \) to high-octane gasoline
  - Q4 - Improve *C4 recycle conversion* by balancing relative dehydrogenation vs hydrogenation rates with highly-defined active site structures (with ACSC and CCPC)
- Control fuel properties/quality
  - Q4 - Develop catalyst formulations to maximize and minimize S value of fuel product

Utilize \( \text{CO}_2 \)-rich syngas for DME: *Increase fuel yield 50% with 10% MFSP reduction* (large \( \text{H}_2 \) import)

Catalyst development and process intensification for *direct syngas-to-high-octane gasoline*: *Increase fuel yield 3% with 3% MFSP reduction* (low \( \text{H}_2 \) import)

*modest catalyst performance metrics used in model*
5 - Future Work

**Tasks 1 and 4: DME to High-Octane Gasoline**

- **Increase carbon yield**
  - Q1 - Explore process model and TEA to direct CO₂ to high-octane gasoline
  - Q4 - Improve *C₄ recycle conversion* by balancing relative dehydrogenation vs hydrogenation rates with highly-defined active site structures (with ACSC and CCPC)

- **Control fuel properties/quality**
  - Q4 - Develop catalyst formulations to maximize and minimize S value of fuel product

---

**Structure-function relationships for C₄ activation directly link to process cost reductions and fuel quality metrics**
5 - Future Work

Task 2: $C_{2+}$ Oxygenates to Distillates via $C_4$-olefins

- Increase carbon yield and stability
  - Q3 - Understand the role of ZrO$_2$ and Ag to favor butenes and limit byproducts
  - Q4 - Identify and quantify the surface species that lead to deactivation

- Understand evolution of catalyst structure and surface properties
  - with ACSC
- Enhance butene selectivity and mitigate temporal changes:
  - process conditions ($H_2/H_2O$ ratio)
  - Ag particle size, dopants to stabilize Ag oxidation state

Modifying Ag catalyst structure and properties to increase $C_4$-olefin selectivity and limit byproduct formation
**Task 3: EtOH to Distillates via Mixed-Olefins**

- Understand catalyst active sites
  - Q2 - Establish the initial **structure-function relationships** for Cu-Zn-Y/BEA (with ACSC)

- Dispersed metals **without Cu, Zn, or Y metal clusters/particles** (XAS and STEM)
- Distinct **Lewis acid sites from Y** to perform the C-C coupling

**Direct next-generation catalyst development to maximize olefin selectivity**

- All Tasks 1-4: FY19 Q4 Annual Milestone (9/30/2019)
  - Understand **deactivation and develop regeneration/mitigation protocols** to restore \( \geq 85\% \) of original activity after at least 200 h time-on-stream
Summary

**Project Goal**

_Leveraging syngas-derived light oxygenates to develop new, low-severity catalytic upgrading technologies to high-value fuels that address the shifting gasoline/distillate demand_

**Approach**

- Developing **multifunctional catalysts** to perform selective, cascade reactions, leading to low operating costs and high C efficiency
- Interdisciplinary, **collaborative approach** within ChemCatBio leveraging enabling technologies

**Research progress**

- Bimetallic M-Cu/BEA catalysts for DME to high-octane gasoline _increase C_4 _recycle conversion_ and enable _product fuel property control_
- _Setting the state of the art in ethanol coupling_ with high-yield, high C efficiency processes for distillate fuel production
- Significant _increases in yield and reductions in MFSP_ demonstrated at FY18 Go/No-Go

**Relevance**

- Demonstration in FY17 (high-octane gasoline) _reduced the risk toward commercialization_ for processes developed in this project
- Demonstrated _technology transfer with the bioenergy industry_ (e.g., TCF with Enerkem)
- Patented intellectual property, and published results in top-tier peer-reviewed journals
## Acknowledgements

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- Carlos Alvarez-Vasco

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- Lesley Snowden-Swan (PNNL)
- Sue Jones (PNNL)

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- Jeffrey Miller (ANL)
- Earl Christensen (NREL)
- Yong Wang (WSU)
- Dongxia Liu (UMD)
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Responses to Previous Reviewers’ Comments

1. **Comment:** Team results are impressive and commendable. The team has well-planned approaches and excellent organizational structure to maximize results, from modeling to catalyst development to improvements since last review. One question I may have not seen an answer to is carbon efficiency for the various processes. I did see gge cost clearly identified and highlighted for Task 1. Is this in progress for Task 2?

**Response:** We appreciate the reviewers’ positive remarks about the project results, approach to target high-value fuels, organizational structure, and incorporation of enabling technologies and researchers with fuel property expertise. We did not highlight carbon efficiency for the processes during the presentation, but rather, focused on the technical accomplishments that feed into that calculation and the resulting MFSP versus mature industry comparisons (e.g., Fischer-Tropsch, Mobil olefin-to-gasoline/distillate). Techno-economics using recent data are being fed into models for determining overall performance and cost assessments, including for Task 2.

2. **Comment:** It may be difficult to select between the alternative processes in the time available.
   - Catalyst life, regenerability, and process complexity should be factors in the selection process.
   - It is important for the project team to stay focused and not get distracted by the multiple options for fuel flexibility and co-products. Co-products in a biorefinery may add value, but they also add complexity, as well as uncertainties for the future profitability if the co-product value decreases.

**Response:** FY18 Go/No-Go has been updated to reflect comments around staying focused and not getting distracted by multiple options. G/NG compares research progress against MOGD benchmark, and can be re-focused to stay on-track towards project goals.
   - Catalyst life, regenerability, and complexity are part of the decision. Cu/BEA and Cu/MgO-Al₂O₃ catalysts already evaluated for lifetime >300 h, and regenerability.

3. **Comment:** The Ni-Co catalysts are being developed by a number of groups as the next wave of Fischer-Tropsch catalysts. Showing that this type of catalyst and process conditions can be adjusted to produce olefins from real biomass would be a major leap forward.

**Response:** Our techno-economic analysis of this pathway identified it as high-risk-high-reward. Reduced project funding resulted in discontinuation of this pathway. Catalyst development from the project has been reported in manuscripts.

4. **Comment:** Fewer separations, less H₂ utilization, and close work with the fuel/engine teams is a recipe for success that will support commercial relevance.

**Response:** Continued interaction with fuel property teams, and more in-depth discussions with co-optima team are underway (e.g., efficiency merit function for HOG product).
Publications


Patents

• Zhenglong Li, “ZEOLITIC CATALYTIC CONVERSION OF ALCOHOLS TO OLEFINS” Filed August, 2018.
Selected Presentations


• S.Cheah, C.A. Farberow, S. Kim, J. Hensley, J. Schaidle, J.T. Miller, D.A. Ruddy, "Exploring Low-Temperature Dehydrogenation at Ionic Cu Sites in Beta Zeolite To Enable Alkane Recycle in Dimethyl Ether Homologation" Presented at NAM25, June 4-9, 2017, Denver, CO.


