



**ChemCatBio**  
Chemical Catalysis for Bioenergy

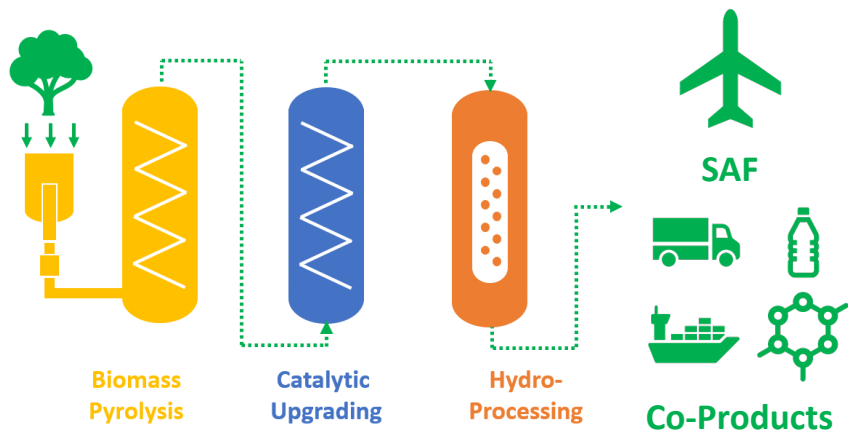
## Catalytic Upgrading of Pyrolysis Products for the Production of Sustainable Aviation Fuel

Michael Griffin  
Catalytic Upgrading Session  
BETO Peer Review  
April 3-7, 2023



# Project Overview

**Project Goal:** Develop a technology pathway to convert woody biomass into sustainable aviation fuel (SAF) and other biogenic products via catalytic fast pyrolysis (CFP) and hydrotreating



**Key Advantage:** Catalytic fast pyrolysis generates a stabilized bio-oil that de-risks down-stream hydroprocessing

**Market Trends:** Repurposing refinery hydroprocessing infrastructure for the production of renewable diesel and sustainable aviation fuel from fats, oils, and greases

*Phillips 66: Rodeo, CA*

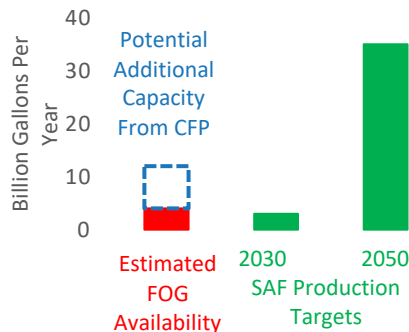


*Shell: Rotterdam, Netherlands*



*Existing approach is constrained by the availability of waste fats, oils, and greases*

*This research opens pathways for SAF production from forest resources and woody wastes*



<b>Estimated Availability of Forest Resources and Woody Wastes</b>
133 Million Dry Tons/Yr
8 BGPY Hydrocarbon Fuel Potential

DOE Billion Ton Report, 2016, ORNL/TM-2016/160



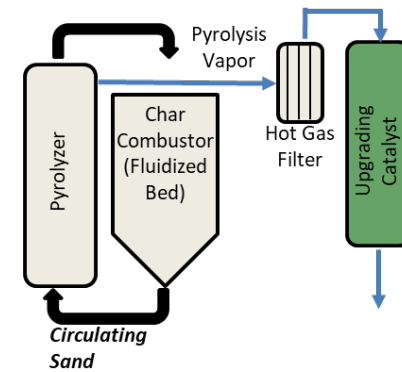
# Project Overview

## Previous Research: Fixed Bed Catalytic Fast Pyrolysis

- Demonstrated potential to achieve 78% GHG emissions reduction with a modelled minimum fuel selling price (MFSP) < \$3.00 GGE
- Evaluated durability over 100+ reaction regeneration cycles
- Identified opportunities to valorize high value co-product streams

### Challenges:

- **Requires co-fed hydrogen and utilizes noble metal catalysts**
- **Rapid deactivation necessitates multiple reactors for continuous upgrading**
- **Poor heat transfer in fixed bed**



Dutta, A., et al., J. Chem. Eng., 2023, 451, 138485  
French, R. J., et al, ACS Sustain. Chem. Eng., 2021, 9, 1235  
Griffin, M.B., et al. Ener. Environ. Sci., 2018, 11, 2904

## 2021 Pivot

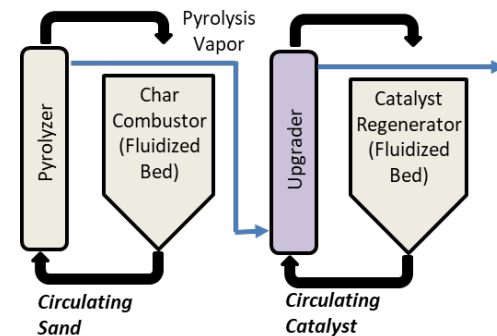
## Current Research: Fluidized Bed Catalytic Fast Pyrolysis

### Advantages:

- **Can be performed without co-fed hydrogen using zeolite catalysts**
- **Rapid deactivation can be managed through continuous regeneration**
- **Improved heat transfer in fluidized bed**

### Research Needs:

- Benchmark performance for SAF production
- Establish critical material attributes for CFP-oil
- Increase carbon efficiency and fuel yield





# Approach: Schedule

*Kickoff*  
10/1/21

## Phase 1: Current Work

*Go/No Go*  
06/30/23

## Phase 2: Future Work

*End Date*  
9/30/24

### Objectives:

Benchmark performance for SAF production and establish critical material attributes for CPF-oil

### Technical Targets:

- Demonstrate the production of **SAF that meets ASTM D4054 guidelines** for density, viscosity, boiling point, heating value, flash point, freeze point, and volatility.
- Demonstrate **≥70% GHG reduction** without requiring noble metal catalyst or co-fed hydrogen during CFP
- Establish **three critical material attributes** (CMAs) for CFP bio-oil

### Objectives:

Increase process carbon efficiency and fuel yields

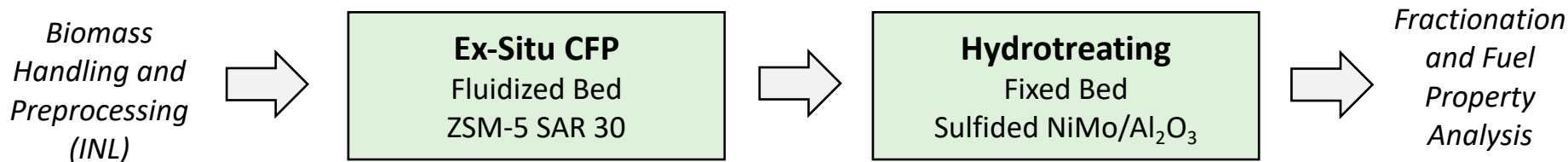
- Modification of technical CFP catalysts to reduce coking and increase bio-oil production
- Process optimization to effectively utilize byproduct streams (e.g., gasses, volatile condensables, char)

### Technical Targets

- Demonstrate a **≥ 20% increase in carbon efficiency to SAF** while maintaining the ability to meet the fuel property, GHG reduction, and CMA targets outlined in the project's GNG.
- Demonstrate hydroprocessing durability for **≥ 500 h time on stream**



# Approach: Integrated Experimental Campaigns



## Supporting Analysis

Pre- and Post-Reaction  
Characterization of Technical  
Catalyst Formulations

Bio-Oil Thermal  
Stability  
Assessments

Technoeconomic  
and Lifecycle  
Analysis

- Continuous CFP experiments performed **without requiring co-fed hydrogen or noble metal catalysts**
- **Realistic biomass feedstocks** including clean pine and waste forest residues
- Sufficient product volume for **fuel property assessment**
- **Technical catalyst formulations** for CFP and hydrotreating steps
- Comprehensive analytical capabilities to achieve **material balances of 100 ± 5%**



# Approach: Management Plan

## Task 1: Project Management and Industry Engagement

Lead: Mike Griffin

## Task 2: Catalytic Fast Pyrolysis of Biomass

Lead: Cody Wrasman

## Task 3: Hydroprocessing of CFP-Oil to SAF

Lead: Kristiina Iisa

## Task 4: Thermal Stability of CFP-Oil

Lead: Mark Nimlos

## Task 5: Characterization of Catalyst Properties

Lead: Susan Habas

## Task 6: Refinery Economic and Optimization Modelling

Lead: Michael Talmadge

## Diversity, Equity, and Inclusion

Lead: Anne Starace

- Dedicated funding to support DEI efforts
- DEI-position on the project management team
- Inclusion of DEI milestones as project deliverables



Partnering  
with Minority Serving  
Institutions



Supporting  
Minority Owned  
Businesses



Engaging through  
workshops and  
'DEI-minutes'



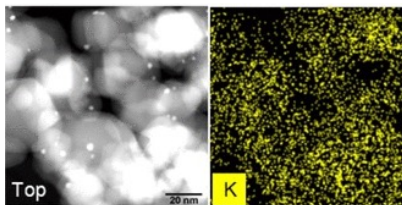
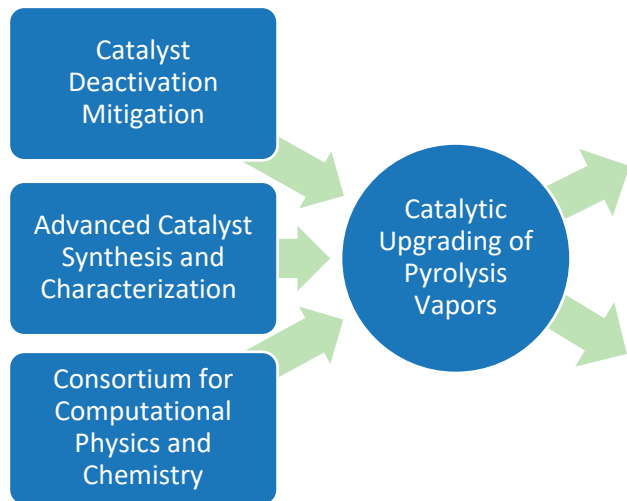
Collaborating on 'JUST-  
R' Metric  
Development\*

\*Dutta, N. S., et al., "Just-R metrics for considering energy justice in early-stage energy research", Joule, 2023, in press

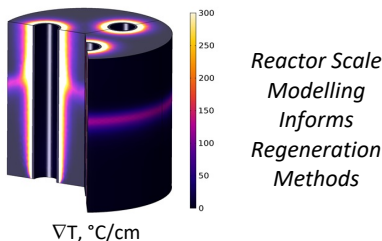


# Approach: Communication and Collaboration

## Coordination with Enabling Projects Provides Fundamental Insight into Catalyst Deactivation and Regeneration



Impact of Potassium Deposition on Catalyst Performance



### 6 Collaborative Manuscripts with Enabling Projects Since 2021

- Adkins, B., et al., *Reaction Chemistry & Engineering*, **2021**
- Unocic, K.; et al. *Microscopy and Microanalysis*, **2021**, 27, 796-798
- Unocic, K., et al. *Journal of Visualized Experiments*, **2021**, 173
- Lin, F., et al., *ACS Catalysis*, **2022**, 12, 1, 465-480
- Downes, C. A., et al., *Chemistry of Materials*, **2022**, 34, 6255
- Unocic, K. A., et al., *Microscopy and Microanalysis*, **2022**, 28, 2472

## Industry Engagement Promotes Commercially Impactful R&D Outcomes

### Johnson-Matthey

CRADA: Accelerating CFP catalyst and process development through collaborative R&D

### ExxonMobil

CRADA: Advancing biomass pyrolysis technologies through collaborative R&D

### Phillips 66

Project-level collaboration focused on hydroprocessing of biogenic oils

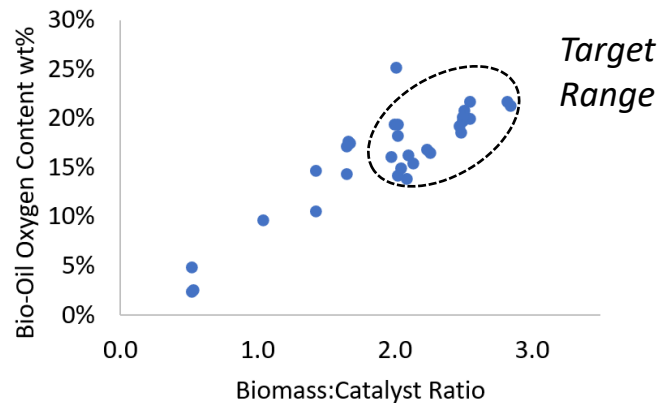
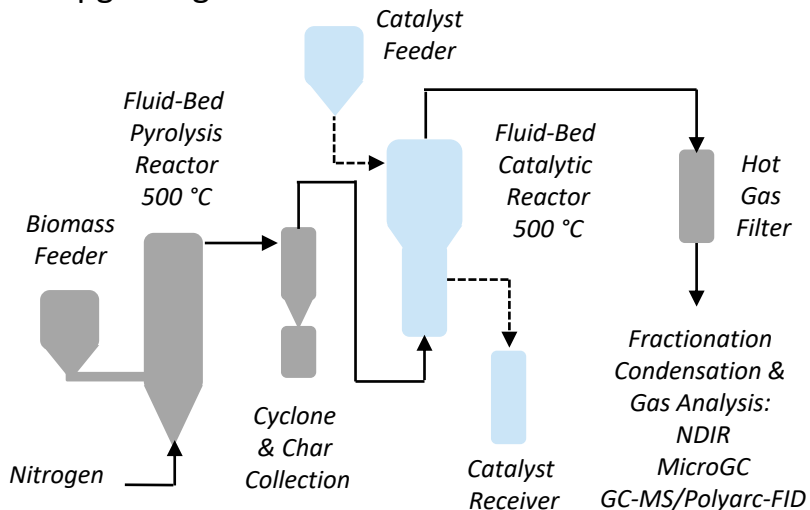
### ChemCatBio Industrial Advisory Board

Consortium level guidance related to the conversion of biomass and waste carbon

# Progress and Outcomes: Catalytic Pyrolysis

## Progress

- Commissioned a fluidized bed reactor system with continuous pyrolysis and catalytic upgrading capabilities
- Completed an experimental campaign to determine product yield and composition at varying levels of catalytic upgrading



CFP-Oil Properties			
B:C, g/g	1.7	2.5	2.8
Carbon Efficiency, %	26	30	31
Oxygen Content, wt% db	17	20	22
Carboxylic Acid Number, mg KOH/g	19	29	30
Sulfur, ppm	32	32	27

## Outcomes

- Established benchmark product yield and composition data for CFP
- Achieved carbon balance closures of  $100 \pm 5\%$  through comprehensive analysis of the feedstock and product streams
- Generated three 500+ mL samples of CFP-oil with oxygen content ranging from 17-22 wt%

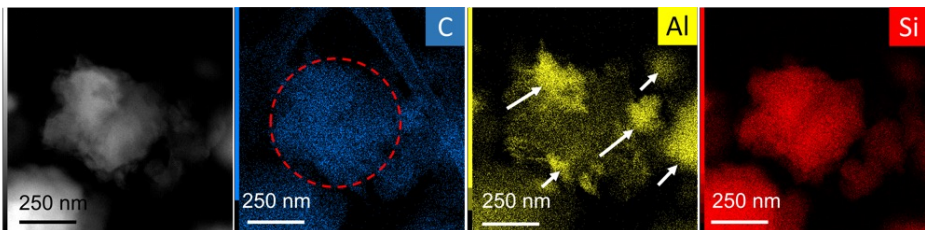
Feedstock: 50/50 Clean Pine + Forest Residues  
Catalyst: ZSM-5 SAR 30 with Alumina Binder





# Progress and Outcomes: Catalyst Characterization

**Progress:** Applied physical and chemical characterization techniques to evaluate deactivation mechanisms and inform regeneration procedures for CFP catalysts

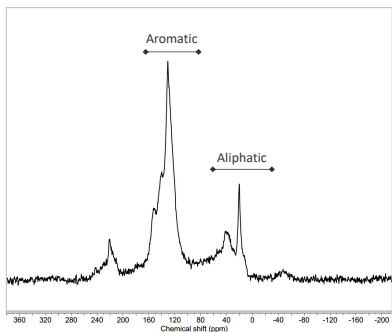


Sample	Surface Area (m <sup>2</sup> /g)	Acid Site Density (μmolNH <sub>3</sub> /g)
Fresh Catalyst	340	765
Post Reaction	51	516
Regenerated	336	722

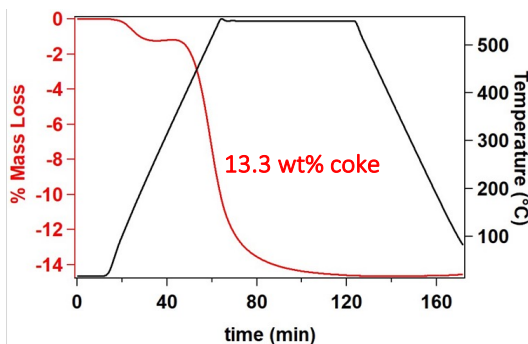
## Outcomes:

- Generated benchmark characterization data for technical zeolite catalysts with an emphasis on determining the unique composition and combustion properties of biogenic coke
- Confirmed efficacy of oxidative regeneration procedure to restore CFP catalyst active sites
- Ongoing: Pre- and post-reaction characterization of hydrotreating catalysts

<sup>13</sup>CNMR



TGA-IR

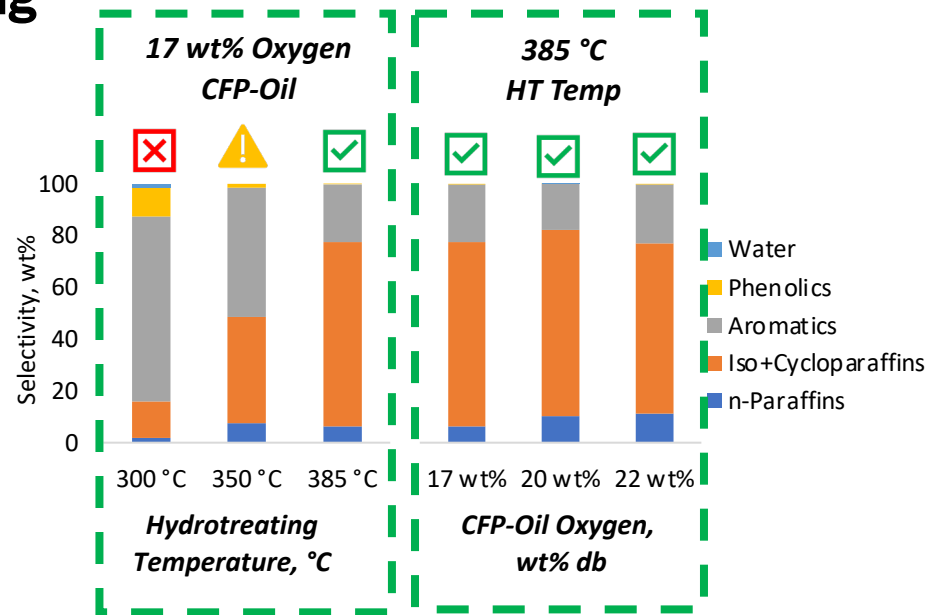
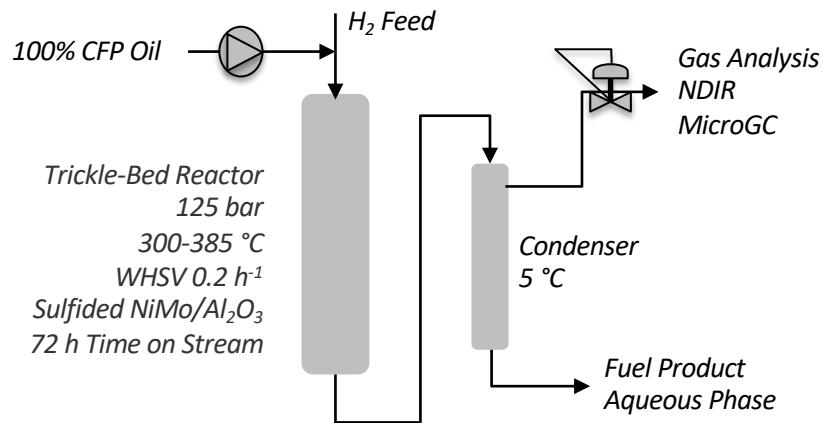


**Ongoing:** Experimental/computational collaboration with CCB enabling projects to evaluate the composition, distribution, and combustion kinetics of biomass-derived coke (CFP, CDM, ACSC, CCPC)

# Progress and Outcomes: Hydrotreating

## Progress

Completed an experimental campaign to determine the impact of CFP-oil oxygen content and hydrotreating temperature on product yield and composition



## Outcomes

- Established benchmark yield and composition data for stand-alone hydrotreating
- Identified conditions suitable for the production of a high-quality hydrotreated oil with oxygen levels below detection limits

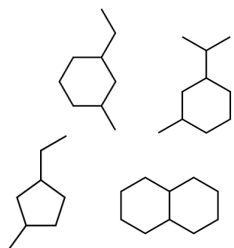
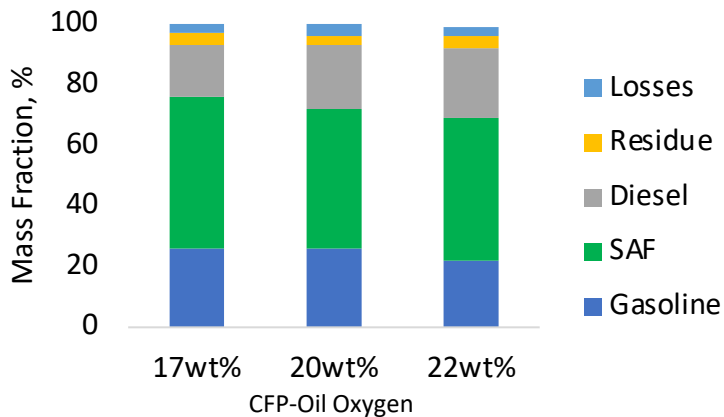
Hydrotreating Results, 385 °C			
CFP-Oil Oxygen Content	17 wt%	20 wt%	22 wt%
HT Carbon Efficiency	91%	92%	89%
Hydrogen Consumption	7%	8%	13%
HT-Oil Oxygen Content	<0.001 wt%	<0.001 wt%	<0.001 wt%
HT-Oil H:C Ratio	1.76	1.76	1.81



# Progress and Outcomes: Fractionation and Fuel Properties

## Progress

Fractionate the hydrotreated oils into gasoline, SAF, and diesel cuts using a micro-spinning band distillation system



### >75 wt% Cycloalkanes in SAF Fraction

- Primary component in Jet A
- Difficult to access via other SAF pathways (HEFA, FT, ATJ)
- Increased energy density and cleaner burning than aromatics

## SAF Properties

CFP-Oil Oxygen Content, wt% dry basis	17 wt%	20 wt%	22 wt%
Density @15°C, 0.730-0.880 g/ml	0.854	0.843	0.847
Flash Point >38 °C	41.5	41.5	39.5
Freezing Point, <-40 °C	<-80	<-80	<-80
Surface Tension 22°C, 25-29 mN/m <sup>b</sup>	28	27	28
Lower Heating Value, >42.8 MJ/kg	42.5	42.7	42.6
D86 Simdis T10 150-205 °C	162	162	161
D86 Simdis FBP <300 °C	253	250	254

## Outcomes

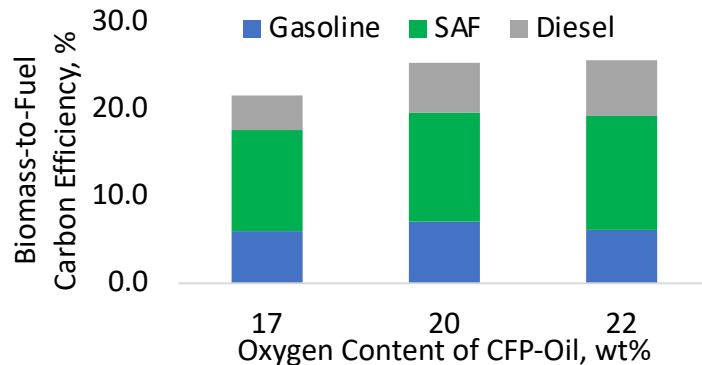
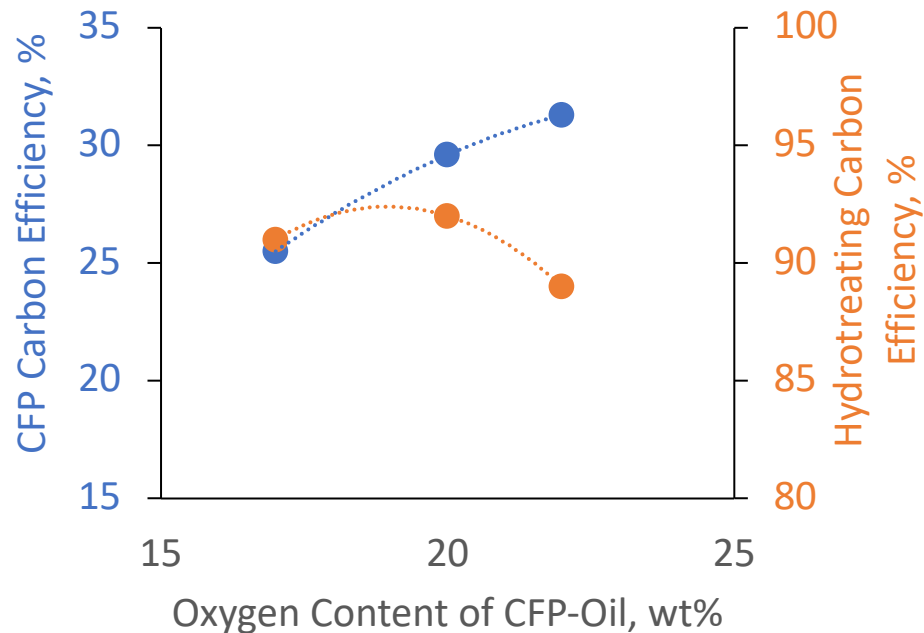
- Established benchmark yield and compositional data for gasoline, diesel, and SAF fractions
- Generated a cycloalkane-rich SAF product that meets key ASTM D4054 guidelines for fuel properties



# Progress and Outcomes: Yield Structures

## Progress

Determined carbon efficiencies and compositional data for the integrated biomass-to-fuels process



Preliminary TEA/LCA: Thermochemical Process Analysis 2.1.0.302

Oxygen in CFP Oil, wt%	17%	20%	22%
Estimated Minimum Fuel Selling Price	6.1-7.5	5.7-6.9	5.3-6.5
Estimated GHG Reduction, %	84	78	75

<sup>1</sup> Modelled *Minimum Fuel Selling Price* (MFSP) in 2016\$, with ±10% variation

<sup>2</sup> Approximate GHG reduction over petroleum gasoline (93 g CO<sub>2</sub>e/MJ) with [coproduct electricity](#) from usable excess energy not converted to liquid fuels.

## Outcomes

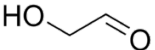
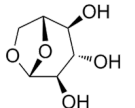
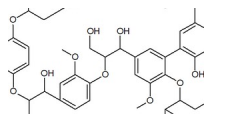
- Revealed correlations between process yield and bio-oil oxygen content for CFP and hydrotreating steps
- Provided experimental data to support techno-economic and lifecycle analysis



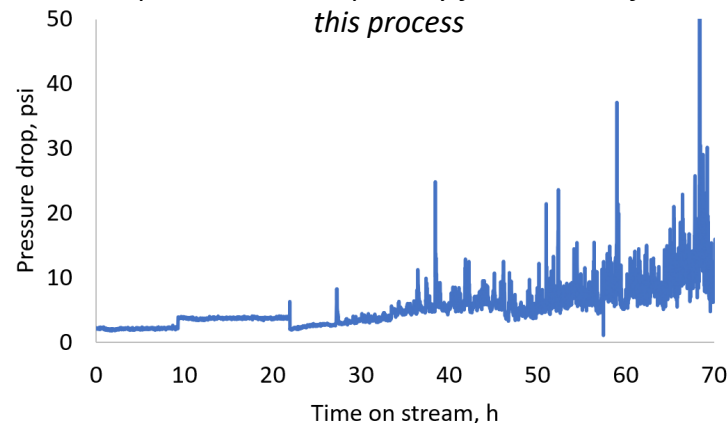
# Progress and Outcomes: Critical Material Attributes

## Progress

Identified CFP-oil compound classes with potential links to system plugging during hydrotreating

Compound Class	Proposed Plugging Mechanisms	Critical Material Attribute (CMA)	Detection Methods
Reactive Carbonyls	Condensation Reactions	 Hydroxyacetaldehyde	GCMS
Anhydrosugars	Cross-Linking & Gelation	 Levoglucosan	GCMS
High Molecular Weight Oligomers	Viscosity & Nucleation	 > 500 Dalton Heavies	GPC

*Plugging of the hydrotreater represents an important risk and primary failure mode for this process*



*Data were collected during experiments performed under a collaborating project: 3.2.1.005 "Advancing the Development of Biofuels for the Maritime Sector"*

## Outcome

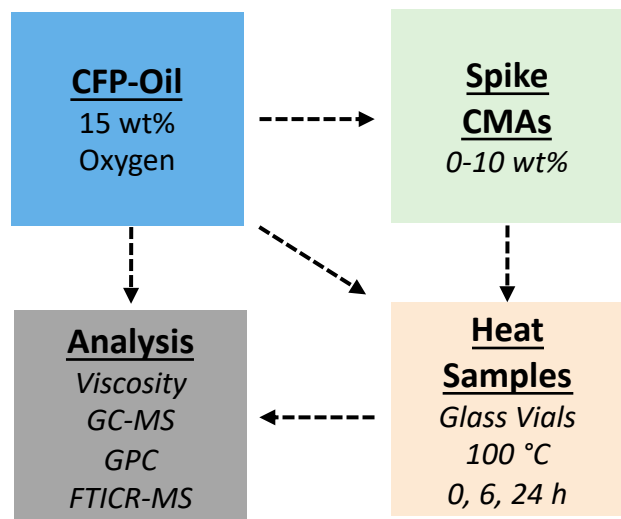
Down-selected three critical material attributes (CMAs) for further analysis via chemical spiking and thermal stability experiments



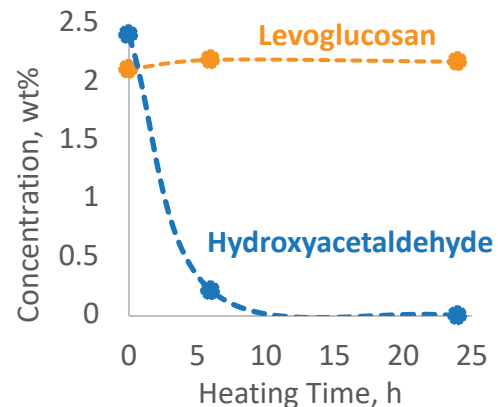
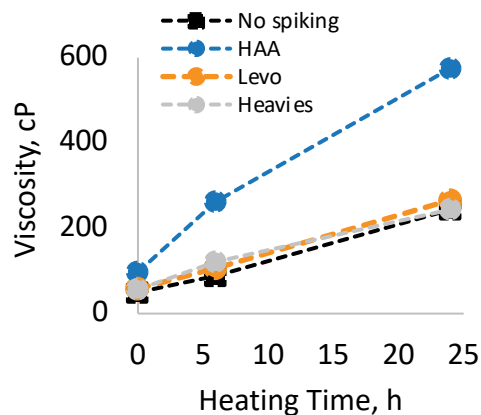
# Progress and Outcomes: Critical Material Attributes

## Progress

Completed a series of chemical spiking experiments to evaluate the impact of CMA concentration on thermally-driven increases in viscosity and molecular weight



**High Throughput; < 10 mL Material Requirements**



## Outcomes

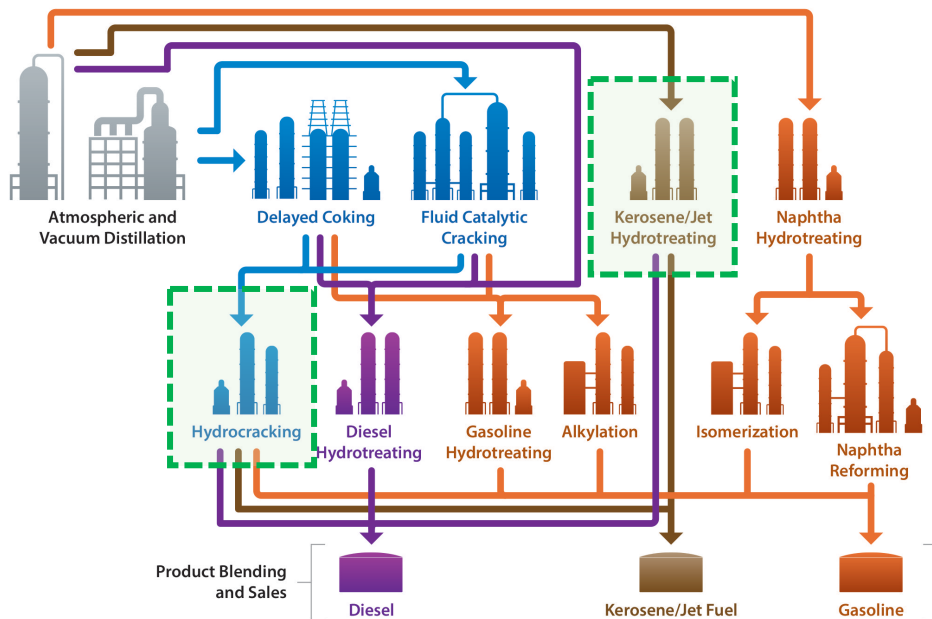
- Identified correlations between hydroxyacetaldehyde (HAA) concentration, viscosity, and molecular weight growth
- Identified reactive carbonyls as a primary species of concern

**Ongoing:** Follow-on thermal stability experiments and statistical analysis to further probe correlations between concentration, viscosity, and molecular weight for reactive carbonyls



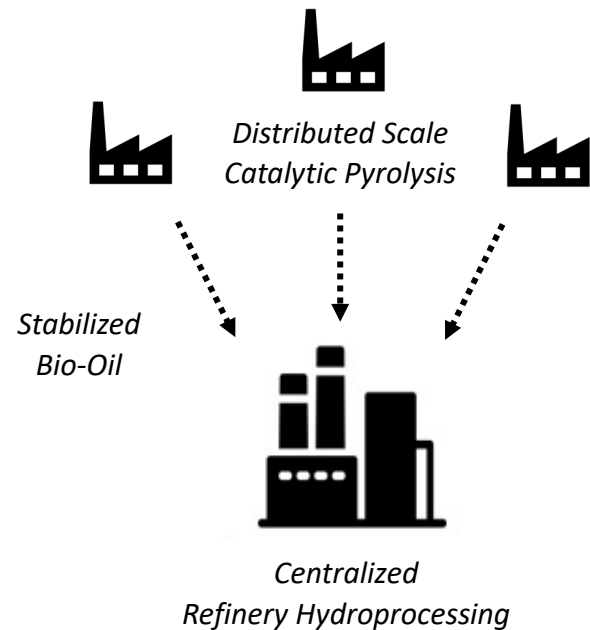
# Impact: Pathway to Market

## Refinery Hydroprocessing



- Refinery integration points with direct pathway to SAF
- 100+ BGPY current US hydrotreating/hydrocracking capacity
- Leverages existing workforces and institutional knowledge
- Potential for blending multiple biogenic and fossil streams

## Hub and Spoke Production Model



### US 2022 Refinery Capacity Summary

<b>US 2022 Refinery Capacity Summary</b>	
<b>Diesel Hydrotreater</b>	<b>70 BGPY</b>
<b>Hydrocracker</b>	<b>37 BGPY</b>

<https://www.eia.gov/petroleum/refinerycapacity/>



# Impact: Scientific Knowledge



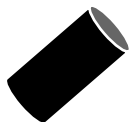
**12 Peer Reviewed Publications**  
Since 2021  
*See Supporting Slides*



**12 External Presentations**  
Since 2021  
*See Supporting Slides*



**2 Issued Patents**  
**6 Pending Applications**  
*Novel catalysts, processes,  
and co-products*



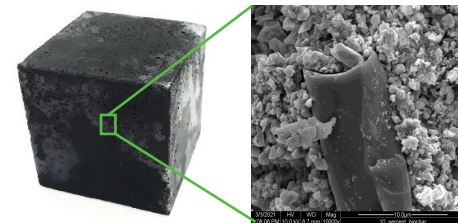
**Synthesis and  
Characterization of  
Technical Catalysts**  
*CCB Focus Area*

## Spin-Off Projects Since 2021

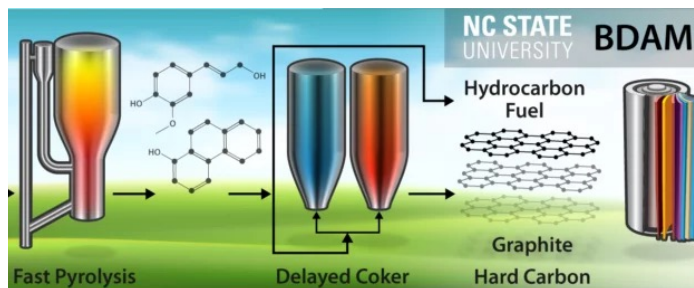
**High-Performing Carbon-Negative Concrete Using Low-Value  
Byproducts From Biofuels Production**



*Carbon Upcycling*  
*Colorado School of Mines*  
*University of Colorado Boulder*



## Biocrude Derived Anode Materials for Lithium-Ion Batteries



*NC State University*  
*Birla Carbon*  
*Yale University*  
*Battery Innovation Center*  
*Ensyn Corporation*





# Summary

---

## Approach

- **Supports BETO SAF production goals** through integrated pathway development that reduces technical risk, addresses feedstock constraints, and informs process scale-up
- Active project management **with integrated risk identification and mitigation efforts** as well as a **dedicated DEI effort**
- Established avenues for coordination with **multi-lab collaborators** and **industrial partners**

## Progress and Outcomes

- Established **benchmark yield structures and compositional data** for three levels of CFP upgrading
- Provided first-of-its kind **evaluation of SAF fuel properties** and identified opportunities to produce a cycloalkane-rich product stream
- Generated benchmark **characterization data for technical zeolite catalysts** with an emphasis on determining the unique composition and combustion properties of biogenic coke
- Established **bio-oil critical material attributes** to mitigate the risk of plugging during down-stream hydroprocessing

## Impact

- Informed the development of **TEA/LCA process models** through the generation of high-quality data sets
- Generated **broadly enabling scientific knowledge and multiple spin-off projects** to advance the state of technology
- Aligned with a **promising pathway to market** that addresses an emerging demand for biogenic oils



# Acknowledgements

---



**Kristiina Iisa**



**Cody Wrasman**



**Mark Nimlos**



**Susan Habas**



**Michael Talmadge**



**Anne Starace**

Trevor Smith (BETO)  
Steven Rowland (NREL)  
Calvin Mukarakate (NREL)  
Nolan Wilson (NREL)  
Abhijit Dutta (NREL)  
Joshua Schaidle (NREL)  
Fred Baddour (NREL)  
Brittney Petel (NREL)  
Nicole LiBretto (NREL)  
Matt Yung (NREL)  
Kellene Orton (NREL)  
Tyler Cary (NREL)  
Rianna Martinez (NREL)

Scott Palmer (NREL)  
Carson Pierce (NREL)  
Renee Happs (NREL)  
Earl Christensen (NREL)  
Robert McCormick (NREL)  
Alexander Rein (NREL)  
Andy Young (NREL)  
Xiaolin Chen (NREL)  
Cheyenne Paeper (NREL)  
Huamin Wang (PNNL)  
Fan Lin (PNNL)  
Kinga Unocic (ORNL)  
Biva Talukdar (ORNL)





# Questions

---

[chemcatbio.org](http://chemcatbio.org)

*This work was performed in collaboration with the Chemical Catalysis for Bioenergy Consortium (ChemCatBio, CCB), a member of the Energy Materials Network (EMN)*

This research was supported by the DOE Bioenergy Technology Office under Contract no. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

# Additional Slides



# Quad Chart

## Timeline

10/1/21- 9/30/24

	FY22 Costed	Total Award
<b>DOE Funding</b>	<i>1.7 MM + 300 k Carryover</i>	<i>2.0 MM</i>

TRL at Project Start: 3

TRL at Project End: 4

## Project Goal

The objective of this project is to produce sustainable aviation fuel (SAF) from lignocellulosic biomass through catalytic fast pyrolysis (CFP) and hydrotreating

## End of Project Milestone

Perform a series of integrated CFP and hydrotreating experiments to achieve a  $\geq 20\%$  relative increase in carbon efficiency to jet-range products compared to the baseline established in FY22. The CFP-oil will meet the CMAs and tolerance ranges identified previously, and the SAF fraction will meet ASTM4054 specifications for density, viscosity, boiling point, heating value, flash point, freeze point, and volatility. Hydroprocessing durability will be demonstrated via experiments performed in a realistic environment for a minimum of 500 h time on stream. Technoeconomic and lifecycle analysis will be performed to determine the minimum jet selling price and demonstrate a  $\geq 70\%$  reduction in GHG emissions compared to fossil-based pathways.

## Funding Mechanism

*FY22 Lab Call*

## Project Partners

- ExxonMobil (CRADA)
- Johnson Matthey (CRADA)
- Phillips 66 (Hydrotreating Advisors)

# TEA/LCA– Additional Preliminary Information

## Financial assumptions consistent with FY20-21 State of Technology report\*

Description of Assumption	Assumed Value
Cost year	2016
Internal rate of return on equity	10%
Plant financing by equity/debt	40%/60% of total capital investment
Plant life	30 years
Income tax rate	21%
Interest rate for debt financing	8.0% annually
Term for debt financing	10 years
Working capital cost	5.0% of fixed capital investment (FCI) (excluding land purchase cost)
Depreciation schedule	7-year MACRS <sup>a</sup> schedule [9]
Steam plant depreciation	20-year MACRS schedule [9]
Construction period (spending schedule)	3 years (8% Y1, 60% Y2, 32% Y3)
Plant salvage value	No value
Startup time	6 months
Revenue and costs during startup	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
Onstream percentage after startup	90% (7,884 operating hours per year)

<sup>a</sup> Modified accelerated cost recovery system

\*Reference: <https://www.nrel.gov/docs/fy21osti/80291.pdf>; GGE: gallon gasoline equivalent

CFP Oil Oxygen Contents →	17%	20%	22%
Feedstock cost* (\$/dry US ton)	67	67	67
Capital investment total (million \$) <sup>1</sup>	707	728	740
Chemical coproducts	No	No	No
Electricity credit (cents/GGE)	78	57	45
MFSP <sup>2,3</sup> (\$/GGE)	6.1-7.5	5.7-6.9	5.3-6.5
GHG Reduction over gasoline (%)	84	78	75

<sup>1</sup> Capital and operating costs based on the *ex situ* case in the 2015 design report (<https://www.nrel.gov/docs/fy15osti/62455.pdf>). Current model at lower pressure than 2015 report, leading to larger equipment sizes and higher capital costs for CFP equipment.

<sup>2</sup> Model yields considered hydrotreated products heavier than diesel and other losses during product distillation as fuel products because the heavy ends from distillation are hydrogenated and stabilized, and can likely be used as marine fuel

<sup>3</sup> CFP catalyst replenishment is based on values in the 2015 design report (based on typical FCC values). The reactor heat balance is used to determine the flow rate. With a less active catalyst (reflected by different biomass to catalyst ratios in our experiments), cheaper catalyst diluents can allow CFP catalyst cost reduction.

## Publications Since 2021 (2/2)

Wrasman, C. J.; Wilson, A. N.; Mante, O.; lisa, K.; Dutta, A.; Talmadge, M. S.; Dayton, D. C.; Uppili, S.; Watson, M. J.; Xu, X.; Griffin, M. B.; Mukarakate, C.; Schaidle, J. A.; Nimlos, M. R., Catalytic Pyrolysis As A Platform Technology for Supporting the Circular Carbon Economy, *Nature Catalysis*, **2023**, In Press.

Lin, F.; Lu, Y.; Unocic, K.; Habas, S.; Griffin, M.; Schaidle, J.; Meyer, H.; Wang, Y.; Wang, H. "Deactivation by Potassium Accumulation on a Pt/TiO<sub>2</sub> Bifunctional Catalyst for Biomass Catalytic Fast Pyrolysis" *ACS Catalysis*, **2022**, 12, 1, 465-480.

Mukarakate, Calvin; lisa, Kristiina; Habas, Susan E.; Orton, Kellene A.; Xu, Mengze; Nash, Connor; Wu, Qiyuan; Happs, Renee M.; French, Richard J.; Kumar, Anurag; Miller, Elisa M.; Nimlos, Mark R.; Schaidle, Joshua A. "Accelerating Catalyst Development for Biofuel Production through Multiscale Catalytic Fast Pyrolysis of Biomass over Mo<sub>2</sub>C" *Chem Catalysis*, **2022**, 2, 7, 1819-1831.

C. A. Downes, K. M. Van Allsburg, S. A. Tacey, K. A. Unocic, F. G. Baddour, D. A. Ruddy, N. J. LiBretto, M. M. O'Connor, C. A. Farberow, J. A. Schaidle, S. E. Habas, "Controlled Synthesis of Transition Metal Phosphide Nanoparticles to Establish Composition-Dependent Trends in Electrocatalytic Activity", *Chemistry of Materials*, **2022**, 34, 6255.

L. R. Karadaghi, M. S. Madani, E. M. Williamson, A. T. To, S. E. Habas, F. G. Baddour, J. A. Schaidle, D. A. Ruddy, R. L. Brutchey\*, N. Malmstadt, Throughput Optimization of Molybdenum Carbide Nanoparticle Catalysts in a Continuous Flow Reactor Using Design of Experiments, *ACS Applied Nano Materials*, **2022**, 5, 2, 1966-1975.

B. Talukdar, H. M. Meyer III, C. Mukarakate, K. lisa, M. B. Griffin, S. E. Habas, K. A. Unocic\*, Deactivation study on zeolite materials using XPS and STEM characterization, *Microscopy and Microanalysis*, **2022**, 28, 2472.

## Publications Since 2021 (1/2)

Unocic, K.; Hensley, D.; Walden, F.; Bigelow, W.; Griffin, M.; Habas, S.; Unocic, R.; Allard, L., “Performing In Situ Closed-Cell Gas Reactions in the Transmission Electron Microscope”, *Journal of Visualized Experiments*, **2021**, 173.

Unocic, K.; Griffin, M.; Schaidle, J.; Habas, S.; Walden, F.; Unocic, R.; Allard, L. “Practical Aspects of Performing Quantitative EELS Measurements of Gas Compositions in Closed-Cell Gas Reactions S/TEM”, *Microscopy and Microanalysis*, **2021**, 27, 796-798.

Wilson, N. A.; Grieshop, M.; Roback, J.; Dell’Orco, S.; Huang, J.; Albert, J.; Nicholson, S.; Chiaramonti, D.; Nimlos, M.; Christensen, E.; Lisa, K.; Dutta, A.; Harris, K.; Dorgan, J.; Schaidle, “Efficacy, Economics, and Sustainability of Bioinsecticides from Thermochemical Biorefineries” *Green Chemistry*, **2021**, 23, 10145-10156.

Coan, P. C.; Farberow, C. A.; Griffin, M. B.; and Medlin, J. W., Organic Modifiers Promote Furfuryl Alcohol Ring Hydrogenation via Surface Hydrogen-Bonding Interactions. *ACS Catalysis*, **2021**, 11, 6, 3730-3739.

French, R. J.; Lisa, K.; Orton, K. A.; Griffin, M. B.; Christensen, E.; Black, S.; Brown, K.; Palmer, S. E.; Schaidle, J. A.; Mukarakate, C.; Foust, T. D., Optimizing Process Conditions during Catalytic Fast Pyrolysis of Pine with Pt/TiO<sub>2</sub>—Improving the Viability of a Multiple-Fixed-Bed Configuration. *ACS Sustainable Chemistry & Engineering* **2021**, 9, 3, 1235-1245.

Bruce D. Adkins, Zach Mills, James Parks. M. Brennan Pecha, Peter N. Ciesielski, Kristiina Lisa, Calvin Mukarakate, David J. Robichaud, Kristin Smith, Katherine Gaston, Michael B. Griffin and Joshua A. Schaidle, Predicting thermal excursions during in situ oxidative regeneration of packed bed catalytic fast pyrolysis catalyst. *Reaction Chemistry & Engineering* **2021**, 6, 888-904.



## Presentations Since 2021 (1/2)

Michael Griffin, Susan Habas, Huamin Wang, Kinga A. Unocic, Matthew Yung, Fan Lin, Joshua Schaidle, “Improving Process Durability by Addressing Catalyst Deactivation During Upgrading of Biomass Pyrolysis Vapors”, TCBiomass2022, Denver, 2022.

Michael Griffin, Kristiina Iisa, Calvin Mukarakate, Huamin Wang, Daniel Santosa, Susan Habas, Kinga A. Unocic, Bruce Adkins, Nolan Wilson, Mark Nimlos, Abhijit Dutta, Joshua A. Schaidle, “Low Carbon Transportation Fuel from Lignocellulosic Biomass via Catalytic Fast Pyrolysis and Hydrotreating”, North American Catalysis Society, New York City, 2022.

Michael Griffin, Abhijit Dutta, Calvin Mukarakate, Susan Habas, Matthew Yung, Nolan Wilson, Mark Nimlos, Josh Schaidle, “Sustainable Aviation Fuel from Lignocellulosic Biomass via Catalytic Fast Pyrolysis and Hydrotreating”, ACS Green Chemistry and Engineering, Reston, VA, 2022 (virtual).

Kristiina Iisa, Kellene Orton, Calvin Mukarakate, Abhijit Dutta, Joshua Schaidle, Michael Griffin, Luke Tuxworth, Mike Watson, “Co-Hydrotreating of Catalytic Fast Pyrolysis Oils with Straight-Run Diesel,” TCBiomass2022, Denver, 2022.

Kristiina Iisa, Earl Christensen, Kellene Orton, Calvin Mukarakate, Michael Griffin, Kristen Smith, Katie Gaston, Luke Tuxworth, Mike Watson, “Sustainable Aviation Fuel via Hydroprocessing of Catalytic Fast Pyrolysis Oil,” TCBiomass2022, Denver, 2022.

Matthew Yung, Qiyuan Wu, Susan Habas, Joshua Schaidle, Michael Griffin, “Probing deactivation of Mo<sub>2</sub>C used for HDO of biomass fast pyrolysis vapors”, North American Catalysis Society, New York City, 2022.

## Presentations Since 2021 (2/2)

Talmadge, Michael, Avantika Singh, Nicholas Carlson, Abhijit Dutta, Helena Chum, Christopher Kinchin, and Jacob Dempsey. 2022. "Techno-economic analysis for co-processing fast pyrolysis liquid in fossil refineries." BIOFIT Final Policy Conference, 2022.

Abhijit Dutta, Susan Habas, Calvin Mukarakate, Kristiina Iisa, Matthew Yung, Huamin Wang, Daniel Santosa, Kinga A. Unocic, Hao Cai, Longwen Ou, Damon Hartley, Nolan Wilson, Mark Nimlos, Joshua Schaidle, Michael Griffin, "Low Carbon Transportation Fuel from Lignocellulosic Biomass via Catalytic Fast Pyrolysis and Hydrotreating" ACS Spring Conference, 2022 (virtual).

Michael Griffin, Brennan Pecha, and Bruce Adkins, Advancing Catalytic Fast Pyrolysis through Integrated Experimentation and Multi-Scale Computational Modeling", ChemCatBio Webinar Series, 2021 (virtual).

Joshua Schaidle, "Recent Advancements in Catalytic Fast Pyrolysis for the Production of Fuels and Chemicals from Biomass" ePYRO 2021 (virtual).

Reinhard Seiser, Jessica Olstad, Kimberly Magrini, Rebecca Jackson, Braden Peterson, Earl Christensen, Mike Talmadge, Abhijit Dutta, "Co-Processing Catalytic Fast Pyrolysis Oil in an FCC Reactor", 29<sup>th</sup> European Biomass Conference and Exposition, Marseille, France, 2021.

Kimberly Magrini, Jessica Olstad, Braden Peterson, Rebecca Jackson, Earl Christensen, Reinhard Seiser, Michael Talmadge, "Feedstock and Catalyst Impact on Bio-Oil Production and FCC Co-Processing to Fuels", 29th European Biomass Conference and Exposition, Marseille, France, 2021.