DOE Bioenergy Technologies Office (BETO)
2023 Project Peer Review

Cellulosic-Derived Advantage Jet Fuel

April 3, 2023
Systems Development and Integration Session A

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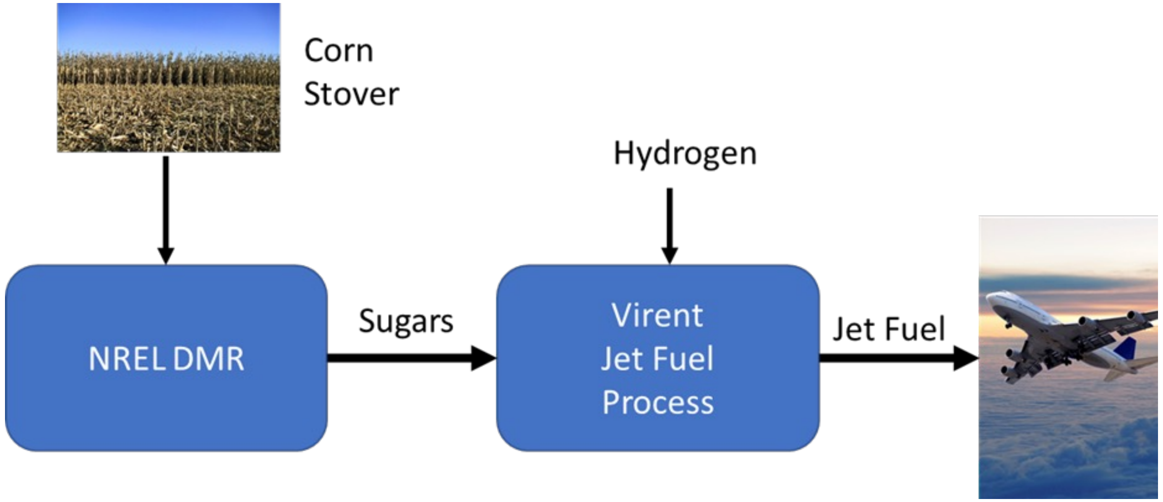
Project Overview



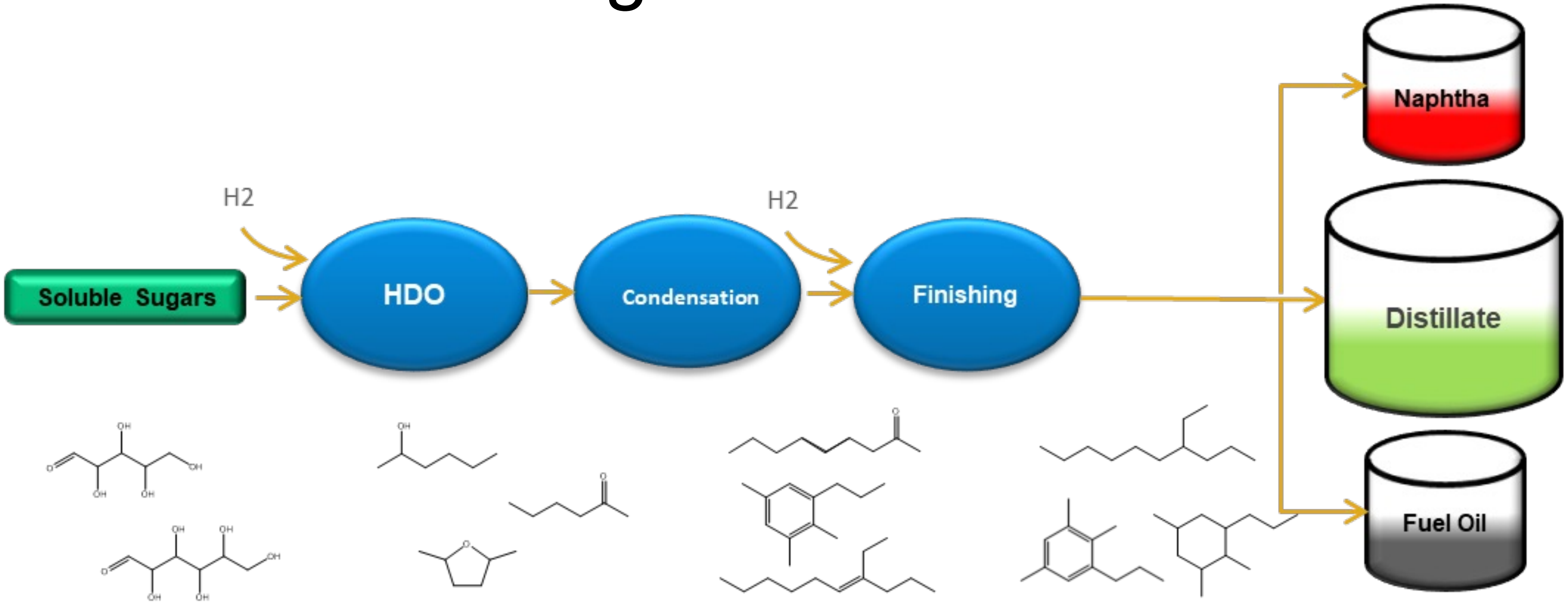
Team

University of Colorado Boulder	Project Lead Improved Condensation Catalyst
NREL	Biomass Deconstruction Integrated Processing
Shell	Jet Fuel Analysis
VIRENT	Technology Provider

Project Objectives:

- Continued development of a Novel Catalytic Conversion of Sugars to Advantage Jet Fuel
- Construction and operation of an integrated processes
- Generation of at least 2 gallons of Jet Fuel for Blending Studies
- Combined expertise from CU-Boulder, NREL, Shell, and Virent

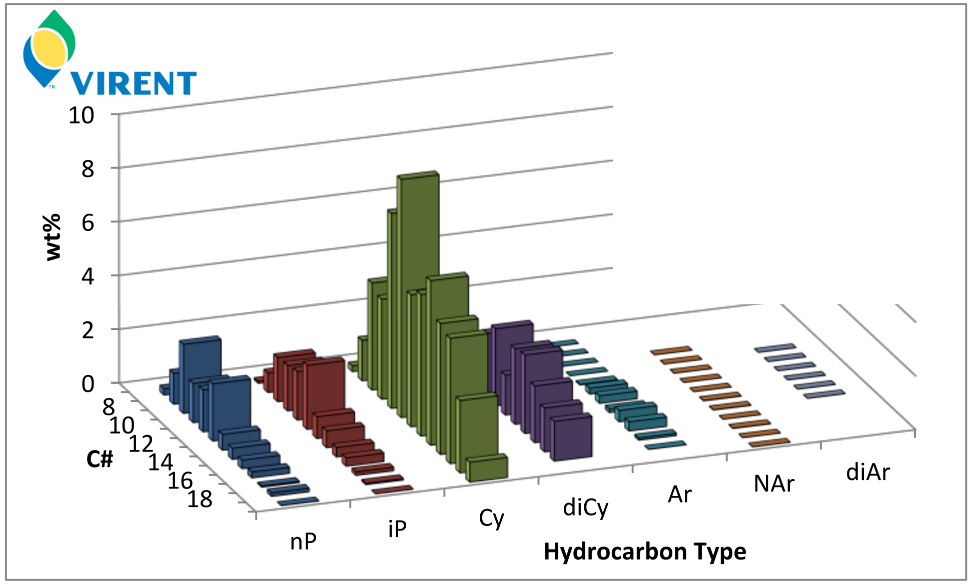
Virent's BioForming® Distillate Process Chemistry

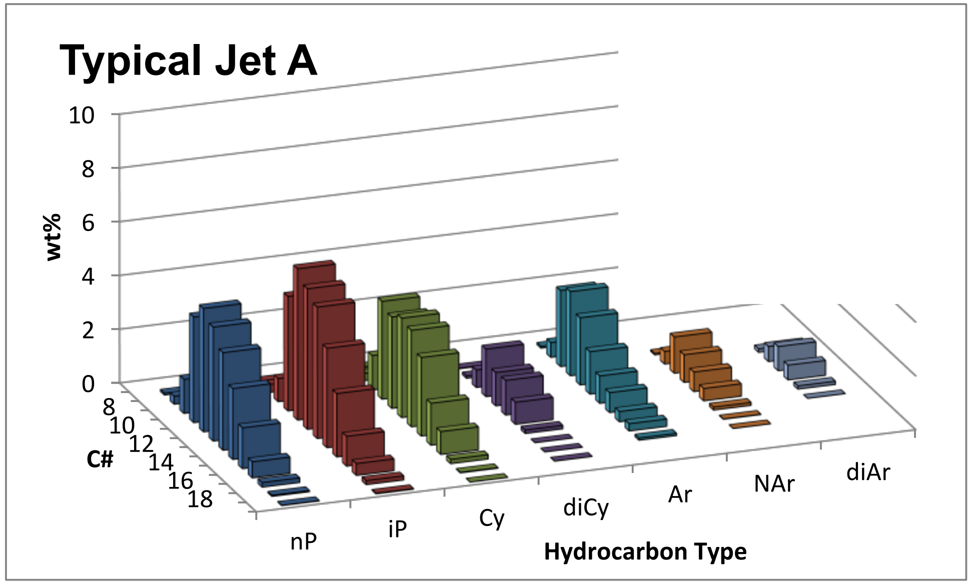


Reactive Oxygenates	Moderate Functionality Controlled Reactivity Oxygenates	Low Functionality Hydrocarbons and Residual Oxygenates	Hydrocarbons
Sugars, Oligosaccharides, Polyols, Furans	*Alcohols, Ketones, Furans, Carboxylic Acids*	*Olefins, Paraffins, Aromatics, Ketones, Esters*	*Paraffins,Cycloparaffins, Aromatics*
Carbon Chain Length ≤ 6	Carbon Chain Length ≤ 6	Carbon Chain Length 4-40	Carbon Chain Length 4-40
2-6 Oxygen/Carbon Chain	1-3 Oxygen/Carbon Chain	0-1 Oxygen/Carbon Chain	0 Oxygen/Carbon Chain

US Patents 9,944,869, 9,593,054, 9,228,134, 9,217,114, 9,206,366, 8,933,281, 8,455,705, 8,367,882, 8,362,307, 8,053,015, 8,017,818, 7,977,517

Virent's Synthetic Kerosene





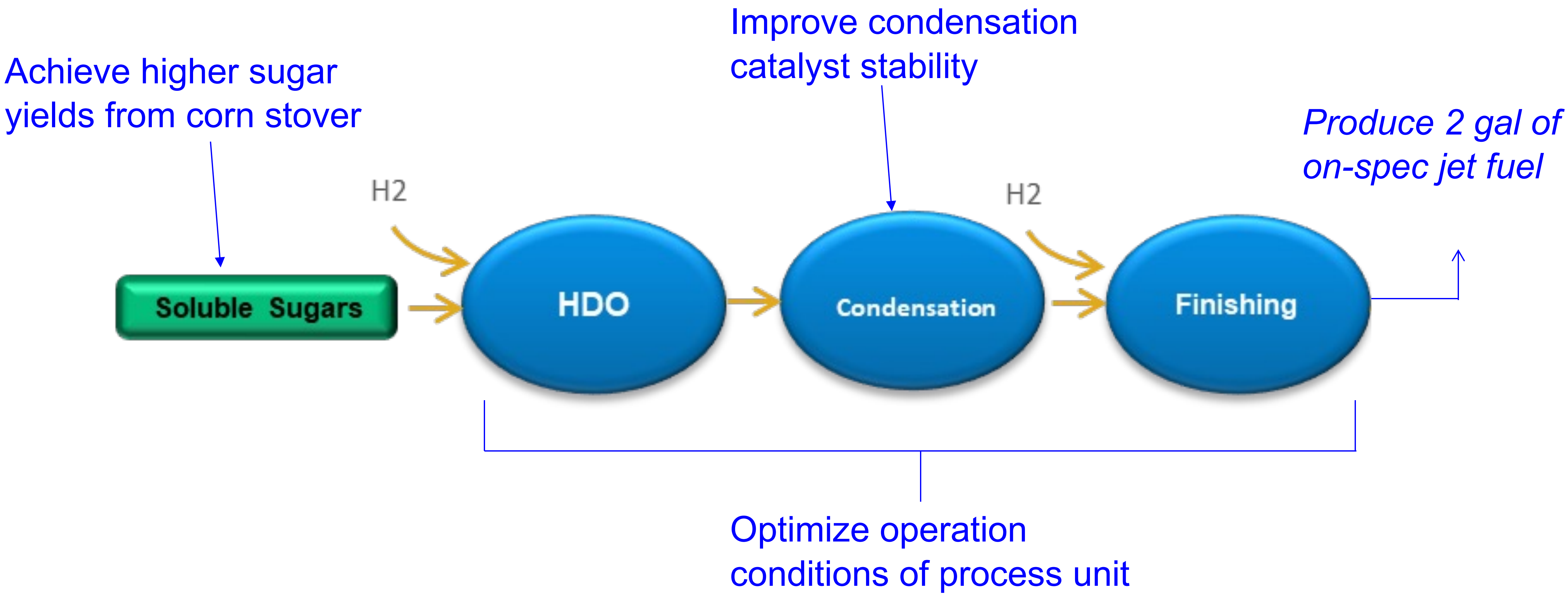
- Same hydrocarbons present in SK and Jet A
  - Broad carbon number range
  - Higher cyclo-paraffin content
  - Low aromatic content

Project Objectives

1. Generate significant quantities (at least 2 gallons) of jet fuel with a high cyclo-paraffin and dicyclo-paraffin content using corn stover as a feedstock;
2. Show that this jet fuel has superior freeze point, stability, and energy content compared to conventional jet fuel;
3. Demonstrate that this jet fuel is compatible with the existing infrastructure
4. Show that this production pathway meets BETO requirements for MFSP cost requirements and is cost competitive with conventional jet fuel derived from fossil fuels

Overall Approach

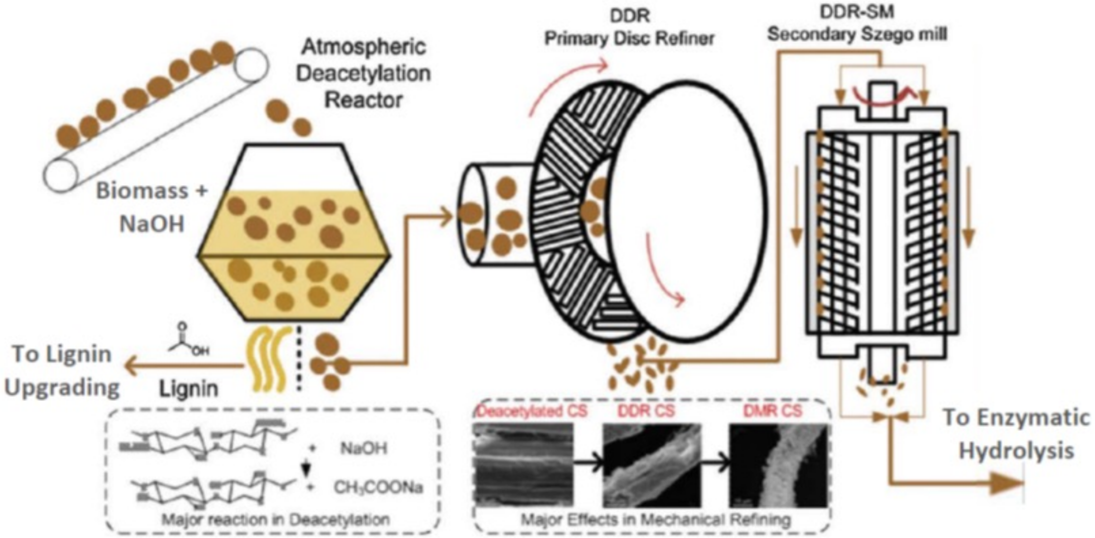
Improve economics of jet fuel production pathways by the following methods:



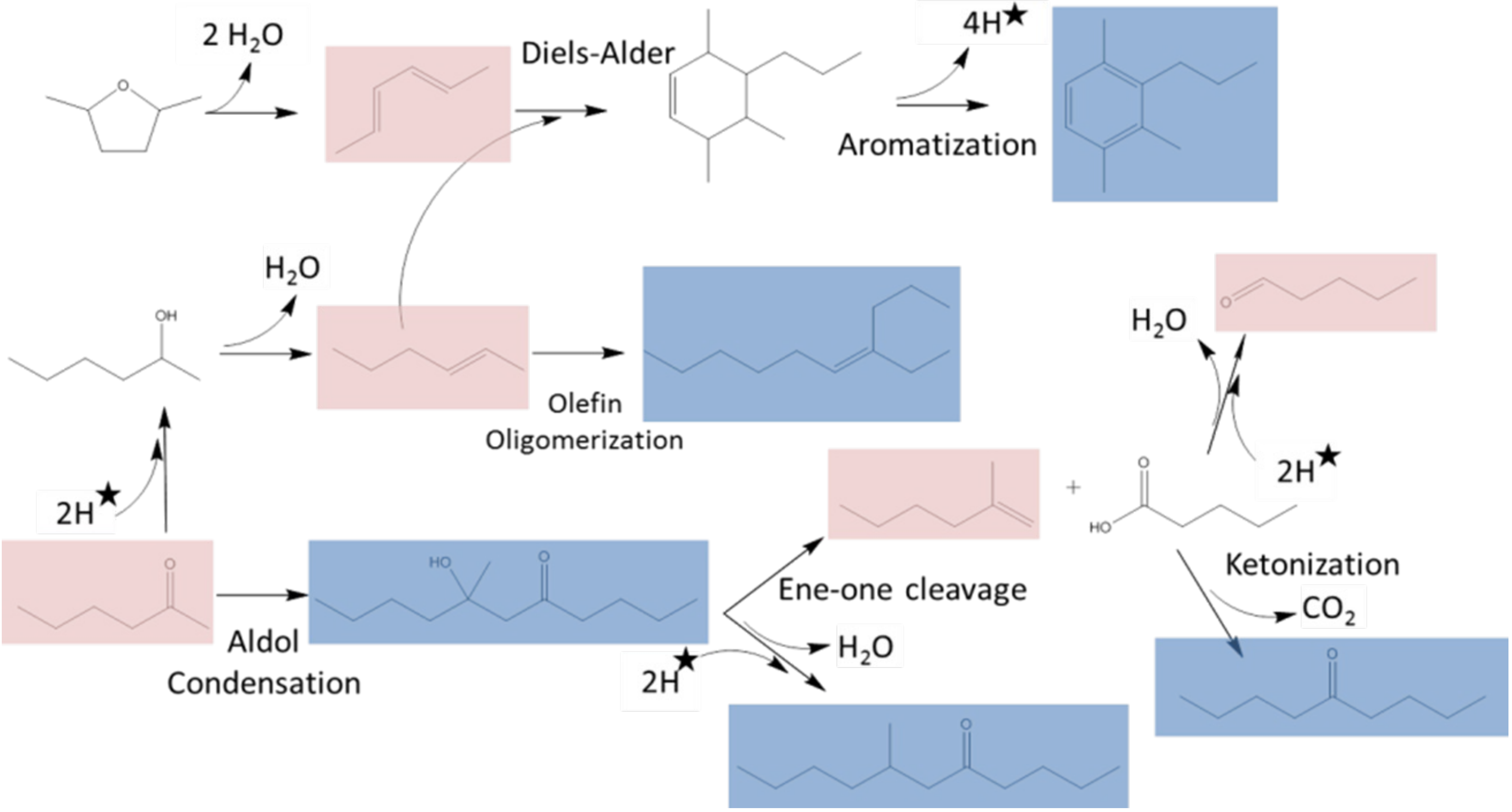
Go / No-go decision point: process unit commissioning

Approach (1): Utilize NREL’s DMR technology that delivers higher sugar yields

- This unit will be operated with corn stover-derived hydrolysate generated using NREL’s Deacetylation and Mechanical Refining (DMR) deconstruction technology
- Decreases the cost and carbon losses of the purification step due to lower ash content of the hydrolysate from the DMR process

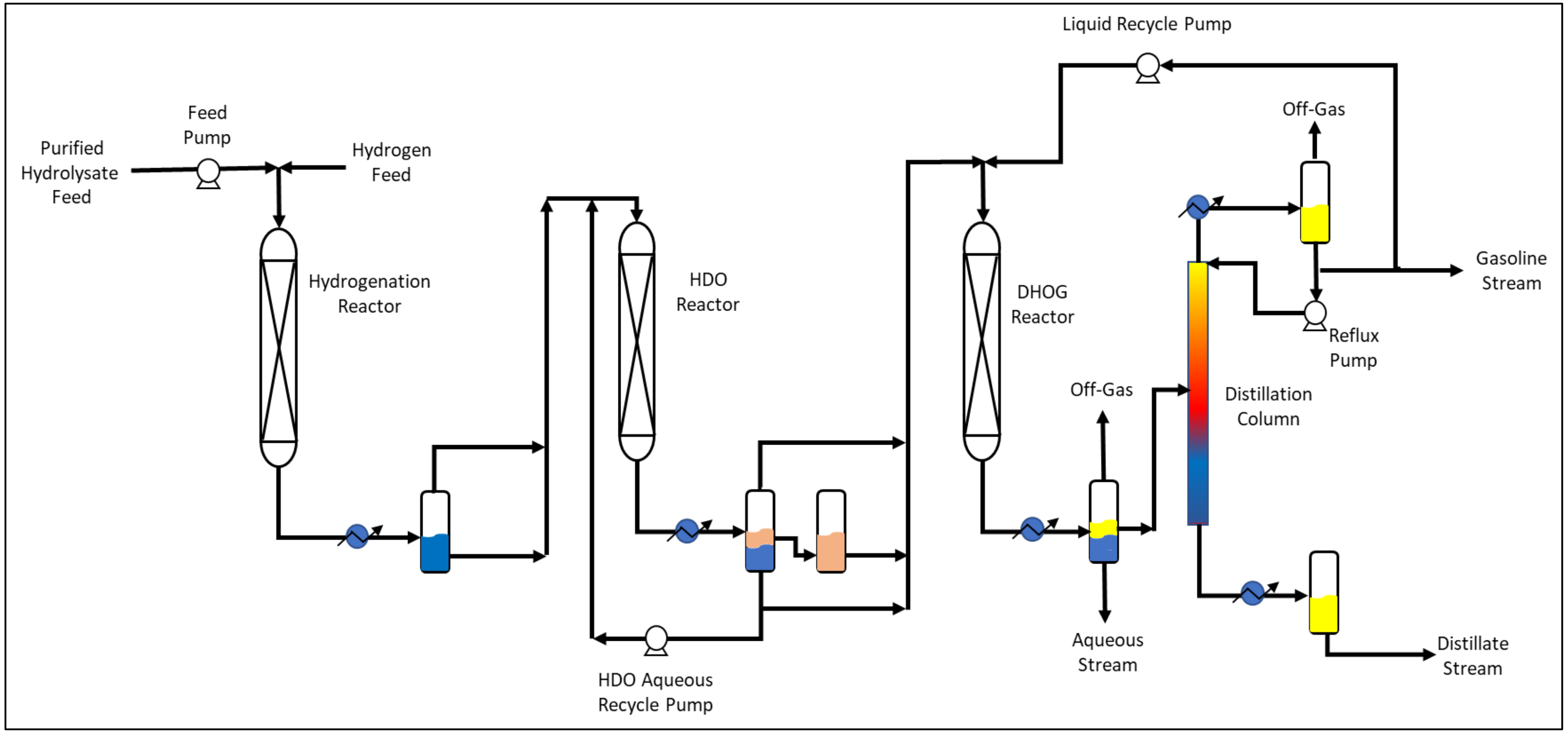


Approach (2): Condensation catalyst development



Approach (3): Process Integration
Build an Integrated System at NREL for Jet Fuel Production

PFD of Integrated Process System



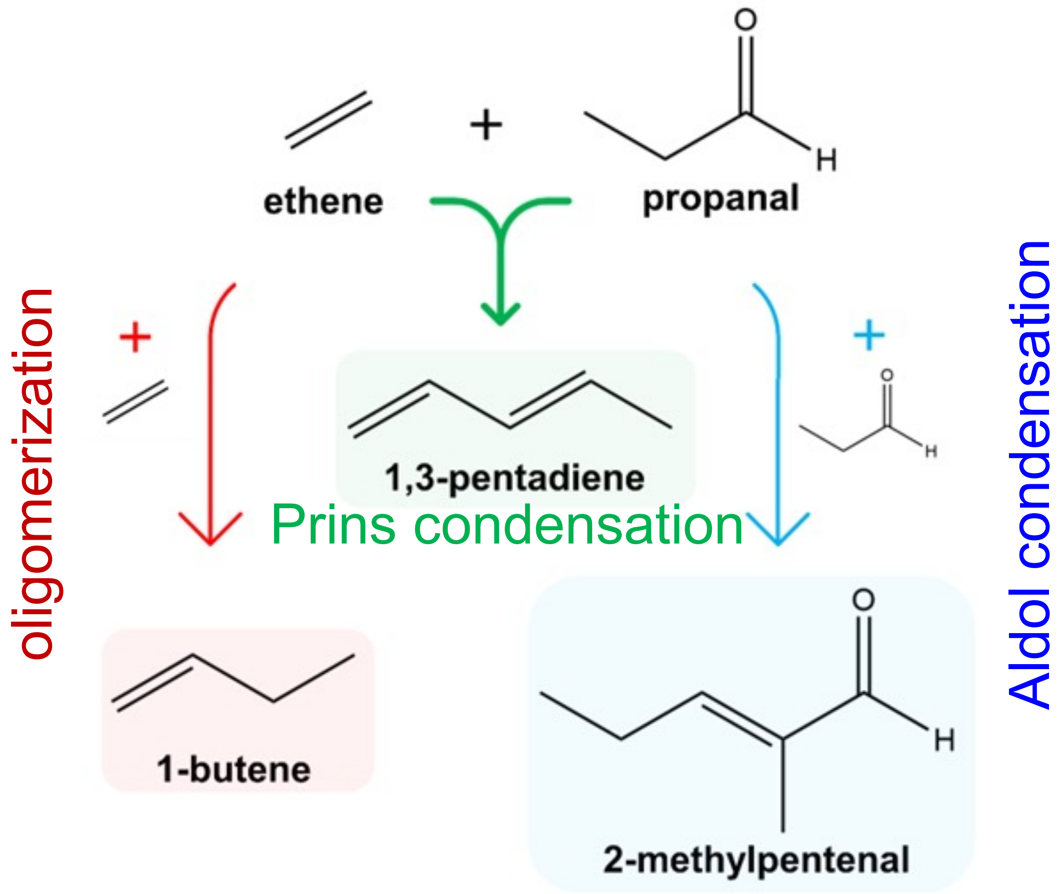
Approach: Challenges, Risks, and Mitigation Strategies

Key Technical Risk Area	Mitigation Strategy
Clean, low-cost, monomeric biomass sugar streams are difficult to process	Improved DMR process expected to generate hydrolysate with lower cost oligomers and significantly less ash
Traditional purification methods are too costly	1) Use of proven ion exclusion technology utilizing a simulated moving bed is expected to decrease purification cost compared to traditional ion exchange technology 2) Lower ash content of DMR generated hydrolysate will decrease severity and cost of purification
Catalyst performance decreases due to sulfur, neutralizing agents, or reactive intermediates	1) DMR will not use sulfuric acid 2) Improve purification to remove contaminants 3) Use hydrogenation to stabilize hydrolysate and mitigate undesirable intermediate formation
Low carbon utilization / yields	1) Improved carbon yields from DMR 2) Lower ash content increases yields 3) Improved operations of condensation will decrease carbon losses 4) Improved separations decreases losses of carbon in aqueous phase

Progress and Outcomes Summary

- Initial verification (Budget Period 1) completed in 2022
- Conditions on Budget Period 2 lifted December 2022
- Initial progress: establishing capabilities
  - Catalyst evaluation for condensation reactions
  - Initial design for catalytic process unit
- Go / No-go decision point: Commissioning of process unit (June 2024)

Progress and Outcomes: Bench-scale catalyst testing



Progress and Outcomes: Initial Catalyst Testing

- Condensation products observed under conditions ranging from near-complete conversion (key for applications) to differential yield (important for kinetic studies).
- Aldol condensation studies of mixtures on conventional catalyst (TiO_2) show strong preference toward consumption of lighter oxygenates, which is beneficial for the process.
- Prins condensation reveals optimal ratio of olefin : oxygenate concentrations.

Progress and Outcomes: Catalytic process unit design

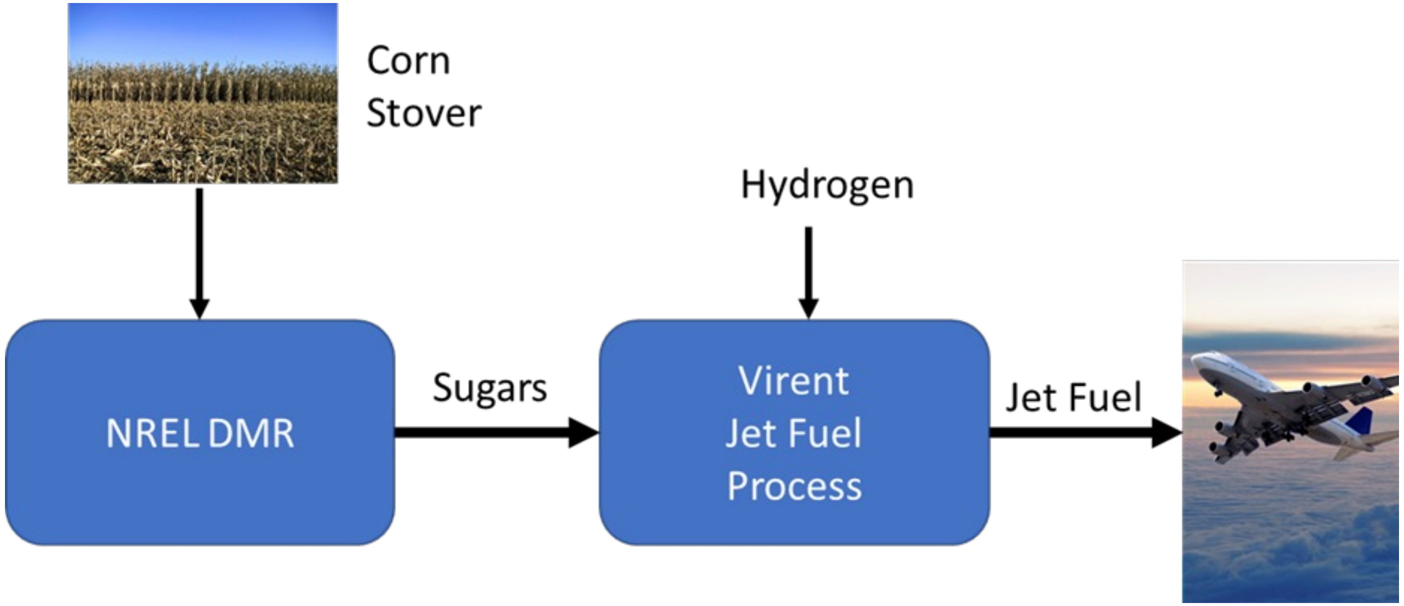
- Plan to construct and operated integrated systems at NREL
- Virent is providing detailed P&ID, control logic, equipment drawings, and potentially critical equipment (e.g. reactors, separators, and distillation equipment)
- Virent will assist in PHA reviews with NREL to provide background on operations of equipment.

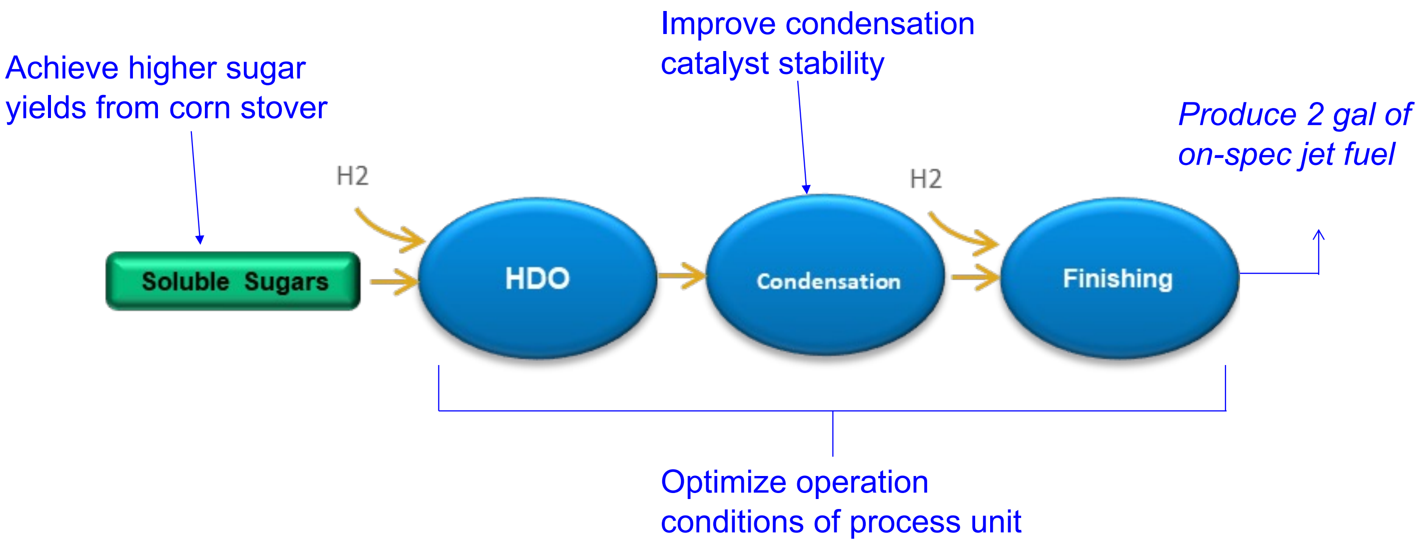
- Randy Cortright who is the NREL PI for this project, the Founder of Virent and co-inventor of the technology investigated in this project, will provide in conjunction with Virent the necessary know-how and background knowledge necessary to construct and operate the necessary equipment at NREL.

3 – Impact

- Lower profited cost for biomass-derived jet fuel while still meeting required standards by:
  - Improved yields from DMR will lower carbon losses in hydrolysis step
  - Decreased rates of catalyst deactivation in condensation will improve operability, limit downtime
  - Optimized operating conditions for catalytic processes will improve overall efficiency

Summary





Team

University of Colorado Boulder — Project Lead; Improved Condensation Catalyst

NREL — Biomass Deconstruction; Integrated Processing

Shell — Jet Fuel Analysis

VIRENT — Technology Provider

Quad Chart Overview

Timeline

- *January 1, 2022 start*
- *Dec 31, 2024 scheduled completion*

	FY22 Costed	Total Award
DOE Funding	*$34,000*	*$1,791,048*
Project Cost Share *	$332,900	$914,000

TRL at Project Start: 3
TRL at Project End: 6

Project Goal

Design and implement a process to convert biomass to jet fuel by a pathway that involves production of soluble sugars followed by catalytic hydrogenation, hydrodeoxygenation, and condensation processes.

End of Project Milestone

Generation of at least 2 gallons of jet fuel product that meets performance targets: 70 gal/tonne process yield, 75 wt% cycloparaffins and dicycloparaffins, profited cost of $3.00 per gallon of gasoline equivalent.

Funding Mechanism

DE-FOA-0002029

Project Partners*

CU-Boulder, NREL, Virent, Shell

*Only fill out if applicable.