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Northwest Efforts Toward Producing Aviation Fuels Using Hybrid Approaches

Karl Albrecht, Karthi Ramasamy, Yunhua Zhu, Richard Hallen, Michael Lilga, John Holladay

Presented by Richard Hallen

Chemical and Biological Process Development Group
Bioproducts, Sciences, and Engineering Laboratory
Pacific Northwest National Laboratory, Richland, WA
richard.hallen@pnnl.gov

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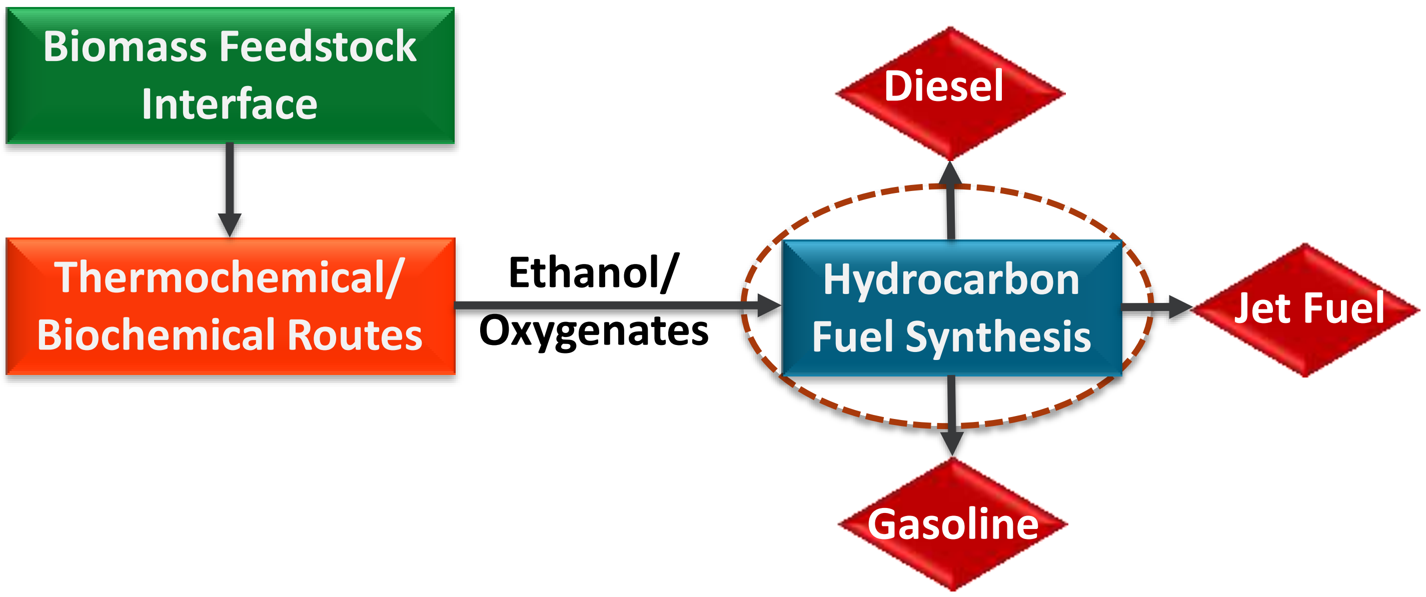
Ethanol and Other Oxygenates

- Upgrading of minimally treated, non-fuel grade ethanol, and/or
- Mixed alcohols and other oxygenates to hydrocarbon fuels



Ethanol Case Study

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- Partnership with Imperium Aviation Fuels
- Technical feasibility assessment supported by experimental data
- Demonstrated upgrading to hydrocarbon meeting jet specifications

Systems	MTG	MOGD-Base	MOGD-Jet
	Energy yield (MJ/MJ energy input)		
Jet fuel	0	0.360	0.635
LPG	0.270	0	0
Gasoline	0.574	0.399	0.087
Diesel	0.037	0.048	0.085
Fuel gas	0.046	0	0
Total	0.927	0.807	0.807

- Models assembled to assessment routes for ethanol based upon literature data for MTG and MOGD like processes
- Energy efficiency of routes estimated using model
- Experimental data from MTG like process supports the production of a fraction of hydrocarbons that have jet fuel properties

Imperium Aviation Fuels

Battelle *The Business of Innovation*

Ethanol Case Study

- Ethanol feed to a "MTG" like process (H-ZSM-5)
- Lab and bench scale experiments conducted
- Liter quantity of samples produced for further testing and evaluation

Imperium Aviation Fuels

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Ethanol Case Study

- PNNL prepared samples for fuel property evaluation
- Off-site specification testing conducted by AFRL
- Possible jet fuel blend stock
- Large volume samples required for fit-for-purpose testing

Specification Test	MIL-DTL-83133H Spec Requirement	PNNL-1	PNNL-2	FT-SPK	JP-8
Aromatics, vol %	≤25	1.9	2.2	0.0	18.8
Olefins, vol %		1.2	1.1	0.0	0.8
Heat of Combustion (measured), MJ/Kg	≥42.8	43.1	43.1	44.3	43.3
Distillation:					
IBP, °C		161	165	144	159
10% recovered, °C	≤205	165	171	167	182
20% recovered, °C		166	173	177	189
50% recovered, °C		171	183	206	208
90% recovered, °C		190	220	256	244
EP, °C	≤300	214	243	275	265
T90-T10, °C	*22*	25	49	89	62
Residue, % vol	≤1.5	1.1	1.1	1.5	1.3
Loss, % vol	≤1.5	1	0.8	0.9	0.8
Flash point, °C	≥38	44	48	45	51
Freeze Point, °C	≤-47	<-60	<-60	-51	-50
Density @ 15°C, kg/L	0.775 - 0.840 *(0.751 - 0.770)*	0.803	0.814	0.756	0.804

Upgrading Mixed Alcohol Product

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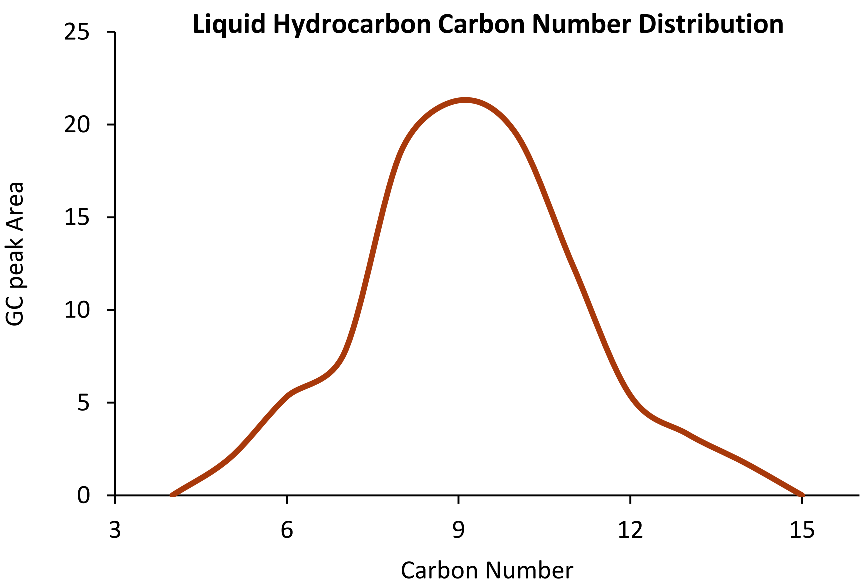
- Mixed alcohol product from PNNL Syngas to Alcohols Project
- Demonstrated feasibility of upgrading to hydrocarbon
- The product contains primarily aromatic components in the gasoline range carbon number with ~50% overlap with jet

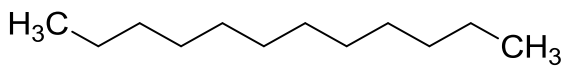
Compounds	Feed Concentration (wt%)
Methanol	0 to 2.5
Ethanol	8 to 28
C3+ Alcohols	1 to 3
Acetic Acid	4 to 14
C2+ Aldehydes	6 to 17
Ethyl Acetate	1 to 18
Water	41 to 60



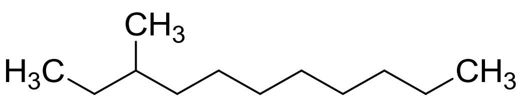
The compound classes in jet fuels

Ideal Carbon Length C8-C16

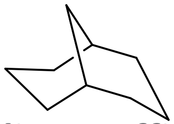
Paraffins
70 - 85%



Normal Paraffins

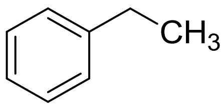


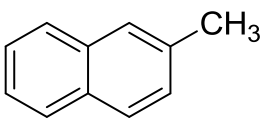
Iso-paraffins

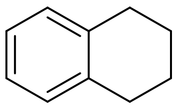


Cyclic Paraffins

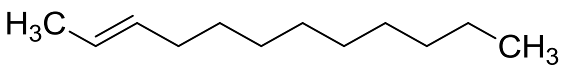
Aromatic
< 25%

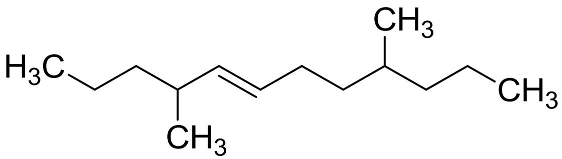




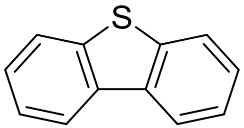


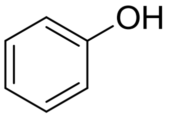
Olefins
< 5%

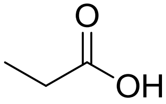




***S, N, O containing Compounds* < 5%**







We desire fuels with composition similar to above
(i.e. a replacement or "drop-in" fuel)

Contribution of Different Hydrocarbon Classes to Jet Fuel

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Potential Contribution* of Each Hydrocarbon Class to Selected Jet Fuel Properties
(For hydrocarbons in the jet fuel carbon number range)

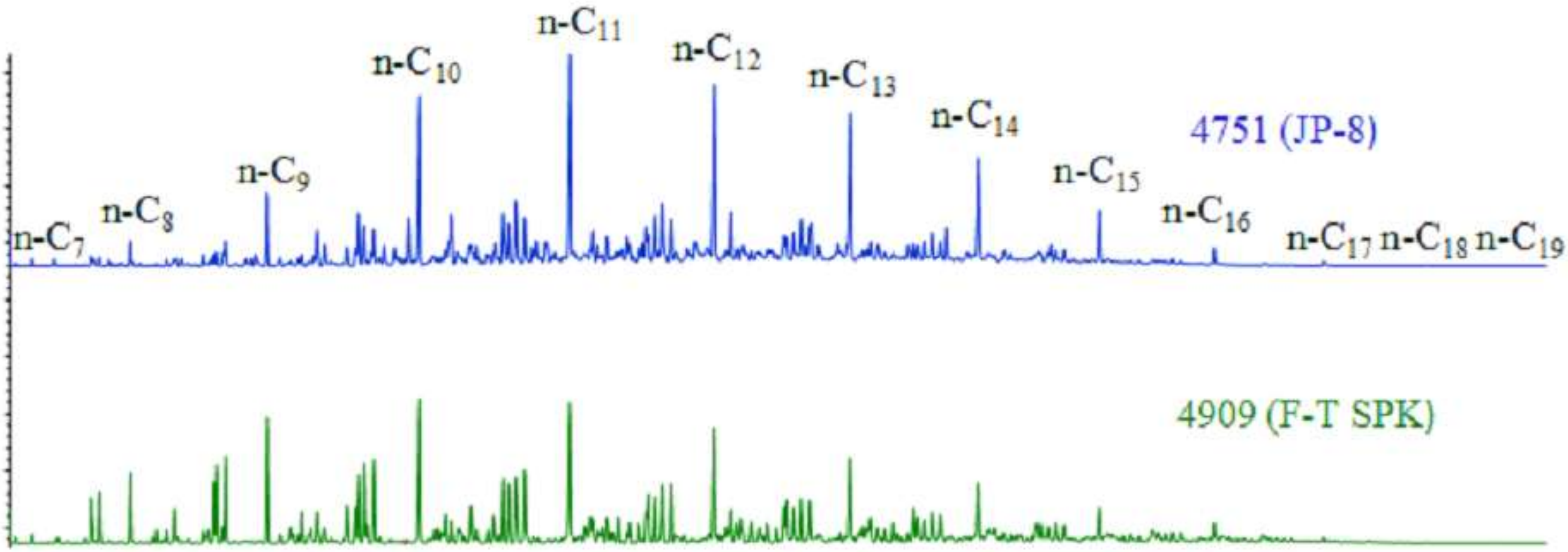
	Hydrocarbon Class			
Jet Fuel Property	**n-Paraffin**	**Isoparaffin**	**Naphthene**	**Aromatic**
Energy content:				
Gravimetric	+	+	0	–
Volumetric	–	–	0	+
Combustion quality	+	+	+	–
Low-temperature fluidity	– –	0/+	+	0/–

* "+" indicates a beneficial effect, "0" a neutral or minor effect, and "–" a detrimental effect.

- Aromatics in jet fuel also helps elastomers in the fuel system to swell and seal properly at low temperature

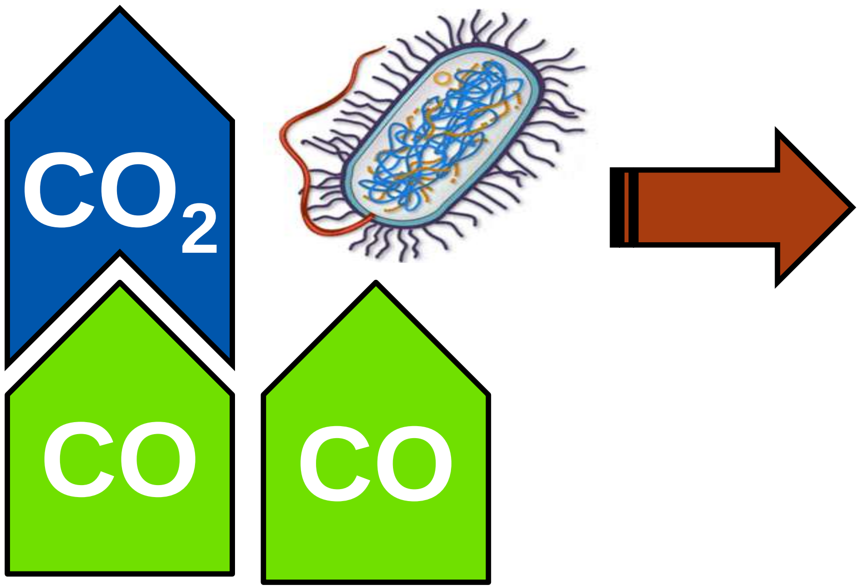
Source: Aviation Fuels Technical Review (FTR-3) prepared by Chevron

Type of molecules



Ethanol-to-Jet Requires Low Cost Ethanol

CO-rich gasses can be captured from syn gas or from industrial processes. Industrial-rich CO is **always** converted to CO_2 either before or after release into the atmosphere



Fuels

***Intercept CO_2** formation by using CO for alcohol production*

LanzaTech

Gas flexibility opens up new options for waste resources

LanzaTech

Industrial flue gas
e.g. from Steel Mill

Syngas
Municipal Solid Waste (MSW)

Steam Reformed Methane
e.g. Biogas

Coke Ovens Gas

- ✓ **Available**
- ✓ **High volume**
- ✓ **Point Sourced**
- ✓ **Low value**
- ✓ **Non food**

Focus of PNNL-Imperium-LanzaTech CRADA is on use of Biomass-Derived Synthesis Gas

Building from Pilot Plant Operations from Steel Mill waste gasses

- Gas & services connection with Mill
- Gas management and buffering module
- 1000 liter capacity fermentation module
- Media storage, process cleaning and sterilization module
- Data and control linkage to all modules
- Process control module

LanzaTech

Initial demonstration using biomass shows promise…

- Process used with biomass syngas
- Syngas from two biomass gasification technologies successfully tested
- Real biomass syngas used in all process demonstrations
- Initial results show ability to reach commercial production rates

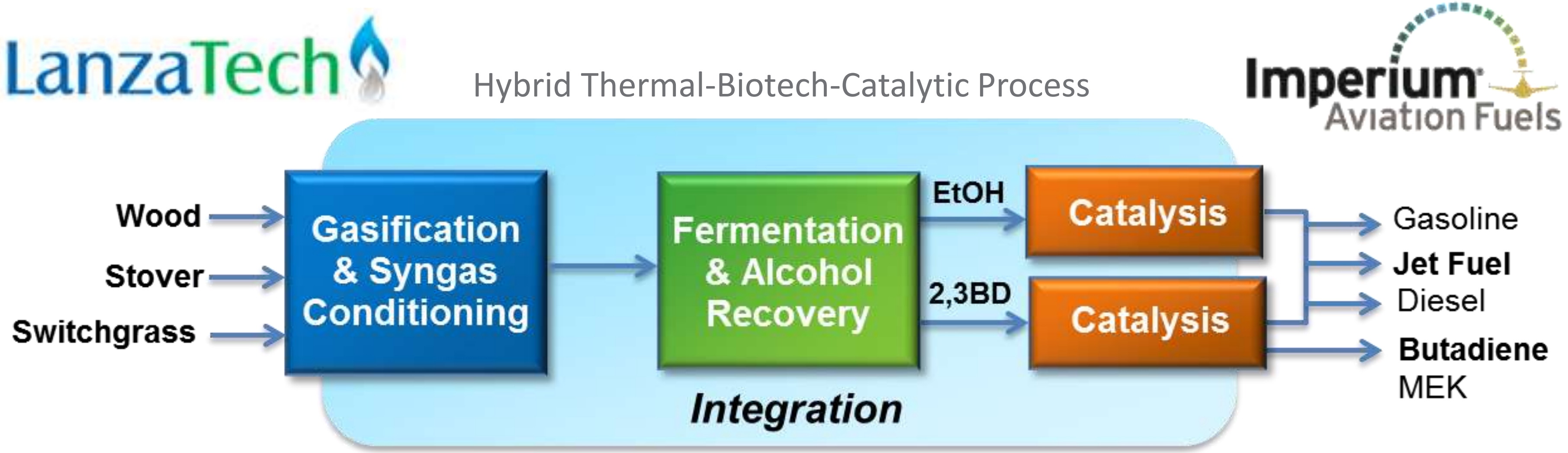
✓ **Set up pilot unit at NREL**

✓ **Focus in CRADA effort will be to determine minimum processing needs of the syn gas and to demonstrate that commercial production rates can be achieved**

LanzaTech

NREL

Alcohol to Jet Technologies



- Minimally processed alcohols produced by LanzaTech, at NREL, are being sent to PNNL
- PNNL, partnering with Imperium, is integrating the catalytic steps to produce the final fuels for the purpose of
  - Demonstrating the integration of catalytic unit operations
  - Demonstrating fuel quality (producing material for fuel qualification testing and for fit for purpose testing)
  - Develop catalyst process to produce higher value chemical compounds in the process in addition to the jet fuel

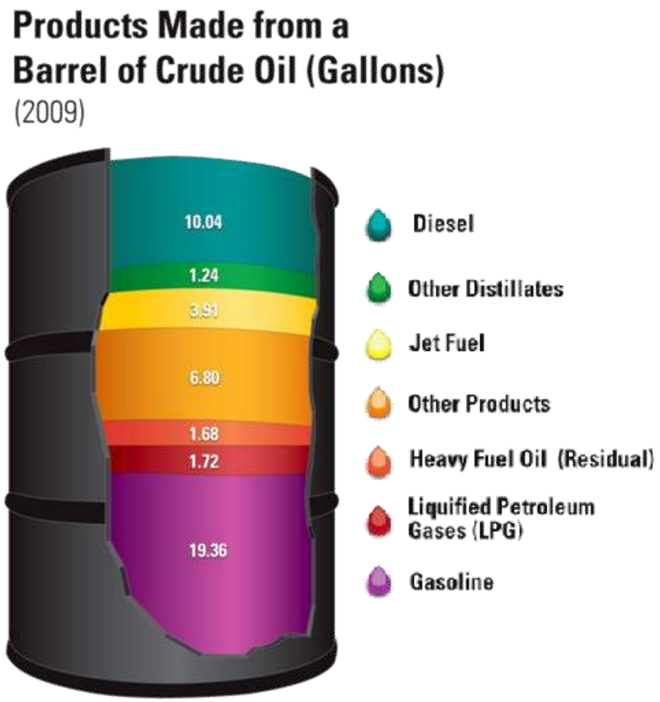
Parting Thoughts

Drop-In and Renewable Fuels can provide:

- Increased US Security (Economic/Energy)
- Reduced environmental impact relative to fossil energy sources

Looking forward:

- Examine routes that maximize existing infrastructure and capital investments, and
- Seek to replace any of the carbon in the barrel of oil with equality and commitment to long term environmental considerations.



Source: Energy Information Administration, "Oil: Crude Oil and Petroleum Products Explained" and AEO2009, Updated February 2010, Reference Case.

Acknowledgment

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LanzaTech

Imperium Aviation Fuels

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