Next Generation Hydrocarbon Biofuels

International Sorghum for Biofuels Workshop

Houston, Texas

John R. Regalbuto
Catalysis and Biocatalysis Program
Directorate for Engineering
National Science Foundation

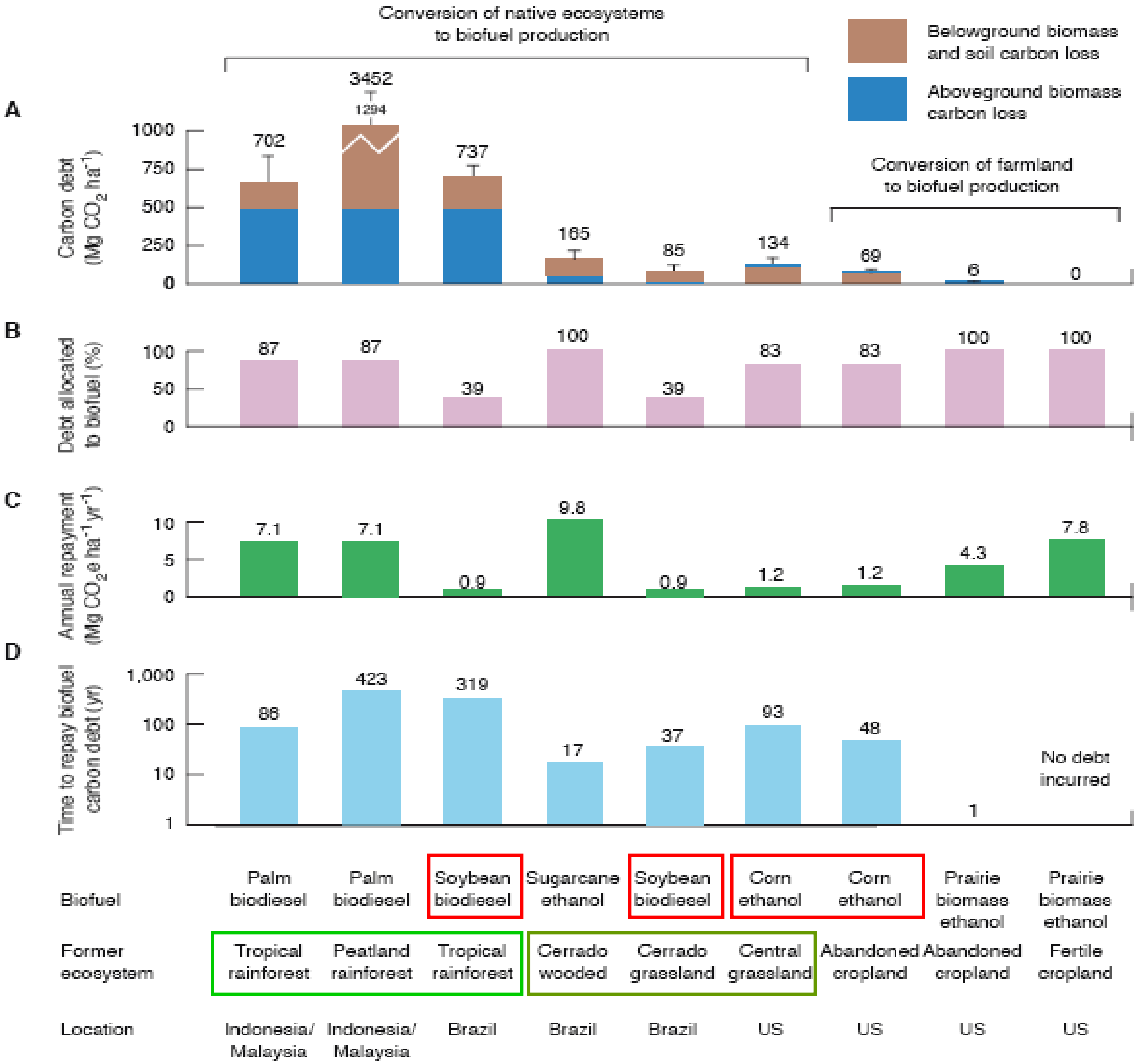
August 19th, 2008

Current Situation in Biofuels

- Energy Independence and Security Act of 2007
  - 36 billion gallons of renewable fuel by 2022
  - 15 billion cap on corn ethanol
  - Increase average gas mileage from 25 to 35 MPG
    - Flex fuel: 25 MPG $\rightarrow$ 18 MPG
    - Renewable fuels must be exempted from CAFE increase

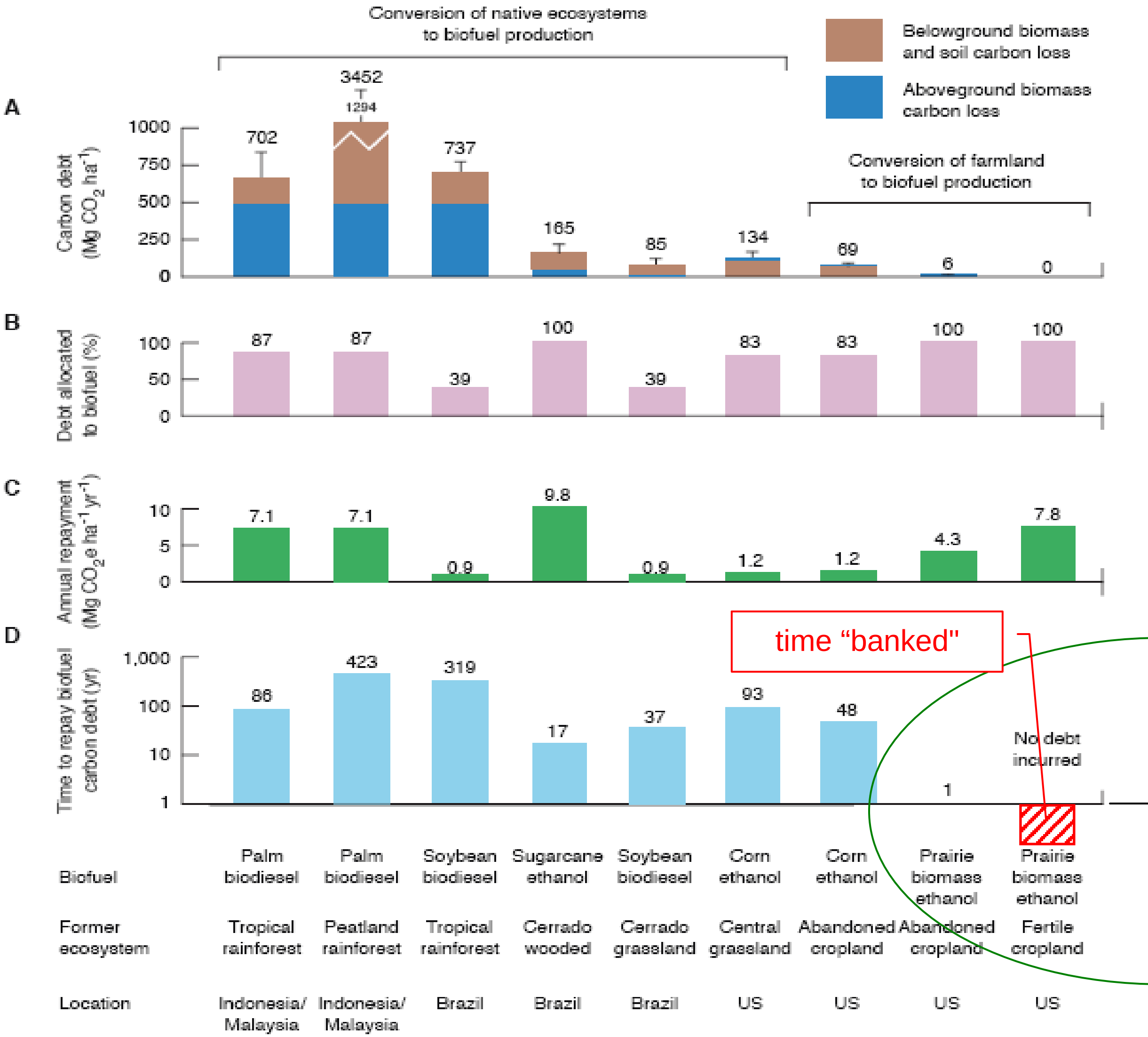
Challenge 1:
How to produce a renewable biofuel without incurring a loss in gas mileage.

Challenge 2:
Fargione et al; Land Use Change Penalty



- CO_2 debt is created when land is cleared
- This CO_2 debt can be considerable:
  - rainforest
  - woods or thick grassland
- Will take a long time to repay if:
  - land is heavily wooded
  - payback is slow (soy based diesel, corn ethanol)

Avoidance of Land Use Change Penalty



- Use fallow/abandoned farmland and marginal land with high debt-paying energy crops:
  - Lignocellulose:
    - Switchgrass
    - Sorghum
- Avoid land use change altogether:
  - Forest waste
  - Agricultural residue

Fargione et al: "biofuels made from waste biomass… or grown on abandoned… lands planted with perennials incur little or no carbon debt…

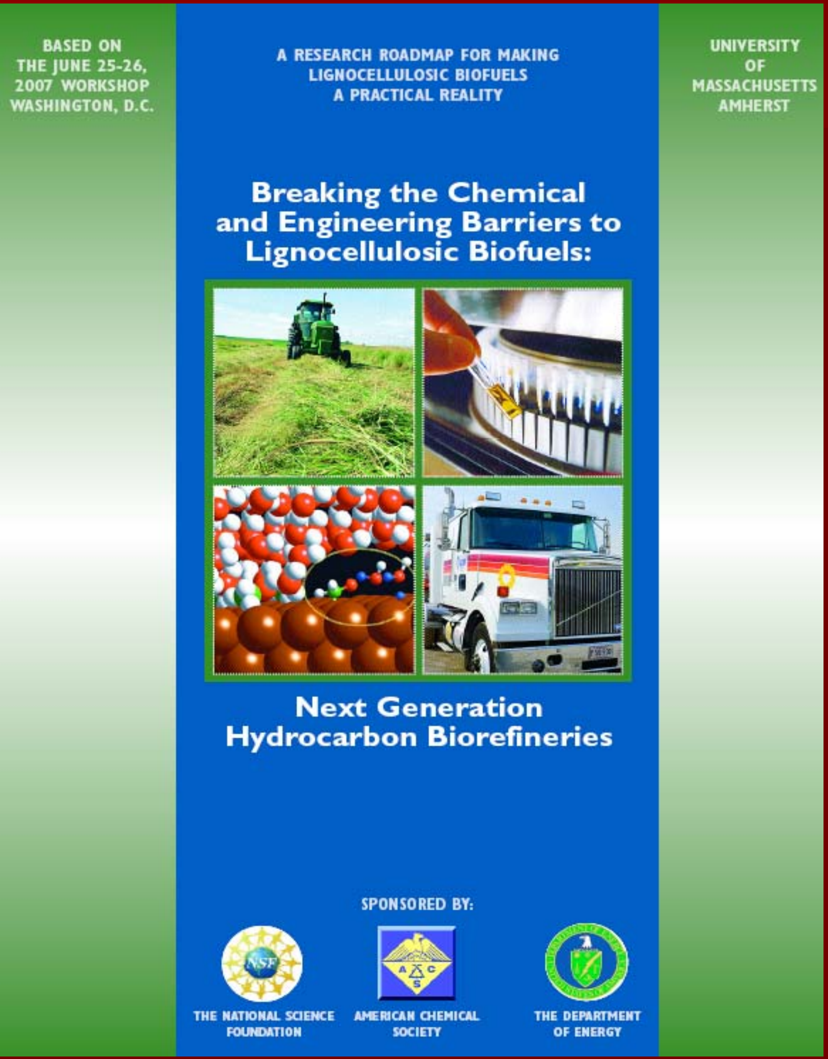
Challenge for Biofuels:

- Mass produce a renewable biofuel which incurs penalties in neither gas mileage or lifecycle greenhouse gas emissions.

The Solution:

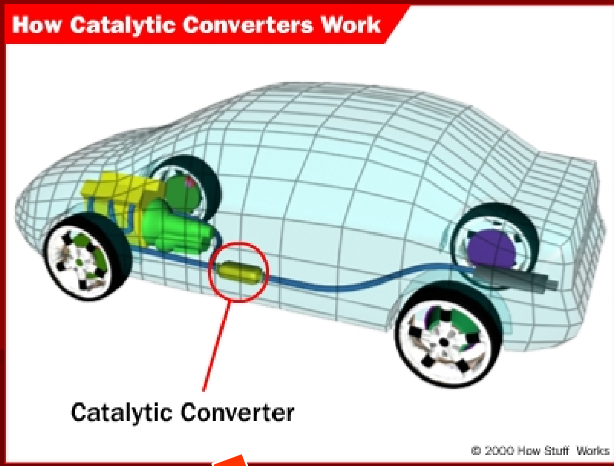
- Hydrocarbons from lignocellulose grown with minimal land use change

Roadmap for Hydrocarbon Production

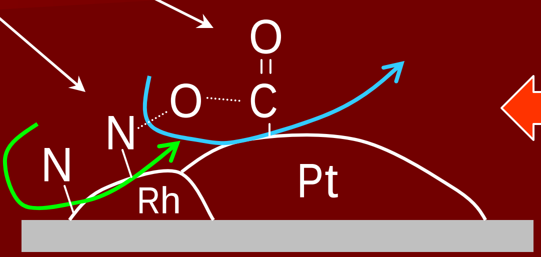


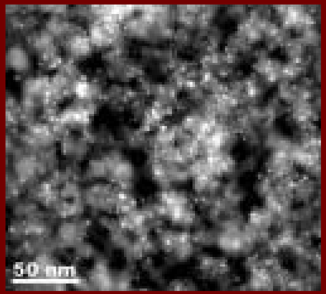
- 2007 NSF/ENG and DOE/EERE Cosponsored Workshop in June, 2007
- Workshop participants:
  - 71 invited participants
  - 27 academics from 24 universities
  - 19 companies, small and large
  - 13 representatives from 5 national labs
  - 10 program managers (NSF, DOE, USDA)
- Workshops Goals:
  - Articulate the role of chemistry and catalysis in the mass production of green gasoline, diesel and jet fuel from lignocellulose.
  - Understand the key chemical and engineering challenges.
  - Develop a roadmap for the mass production of next generation hydrocarbon biofuels.
- Final Report Released April 1, 2008
  - www.ecs.umass.edu/biofuels/roadmap.htm
- Input for Interagency Working Group on Biomass Conversion

The Catalytic: Heart of a Catalytic Converter

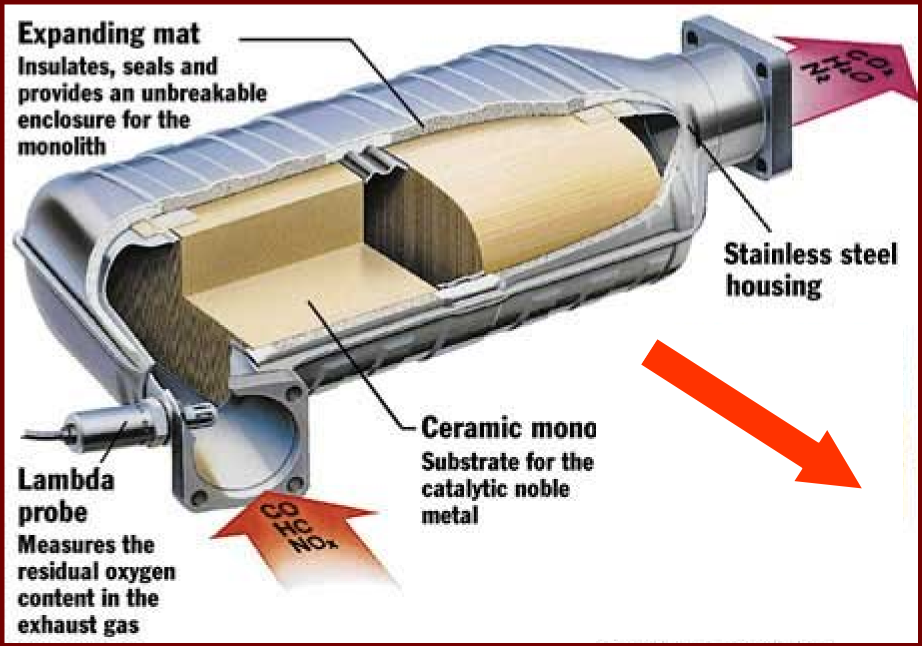


$$NO + CO \rightarrow N_2 + CO_2$$

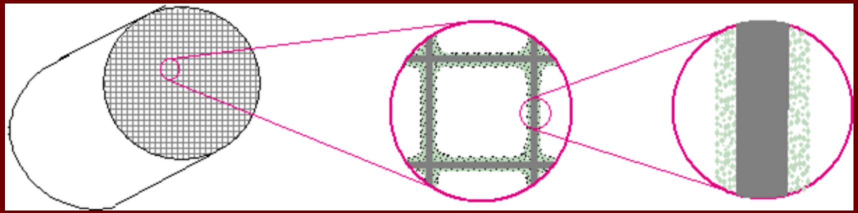




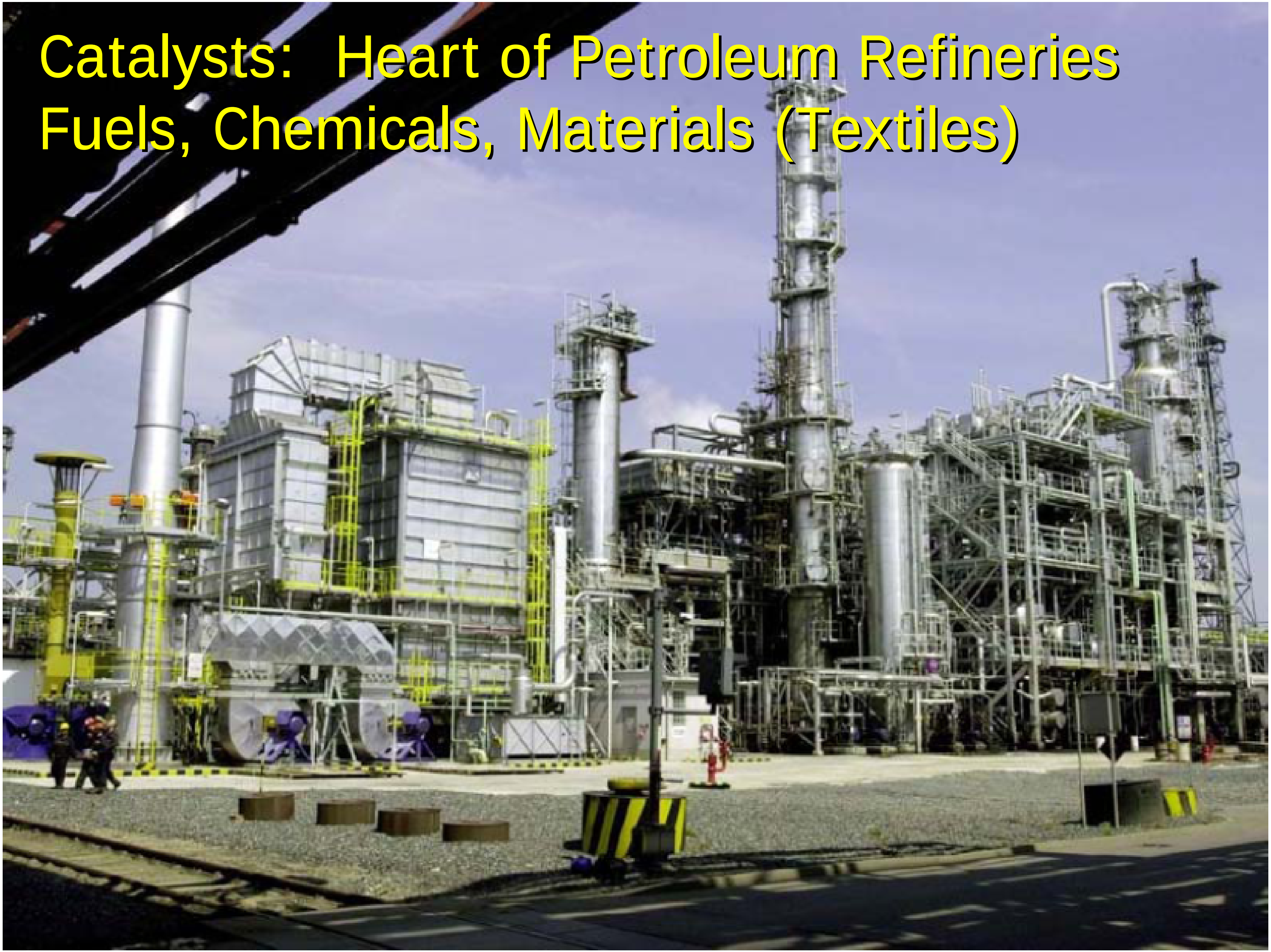
$Pt/Rh/Al_2O_3$ catalyst



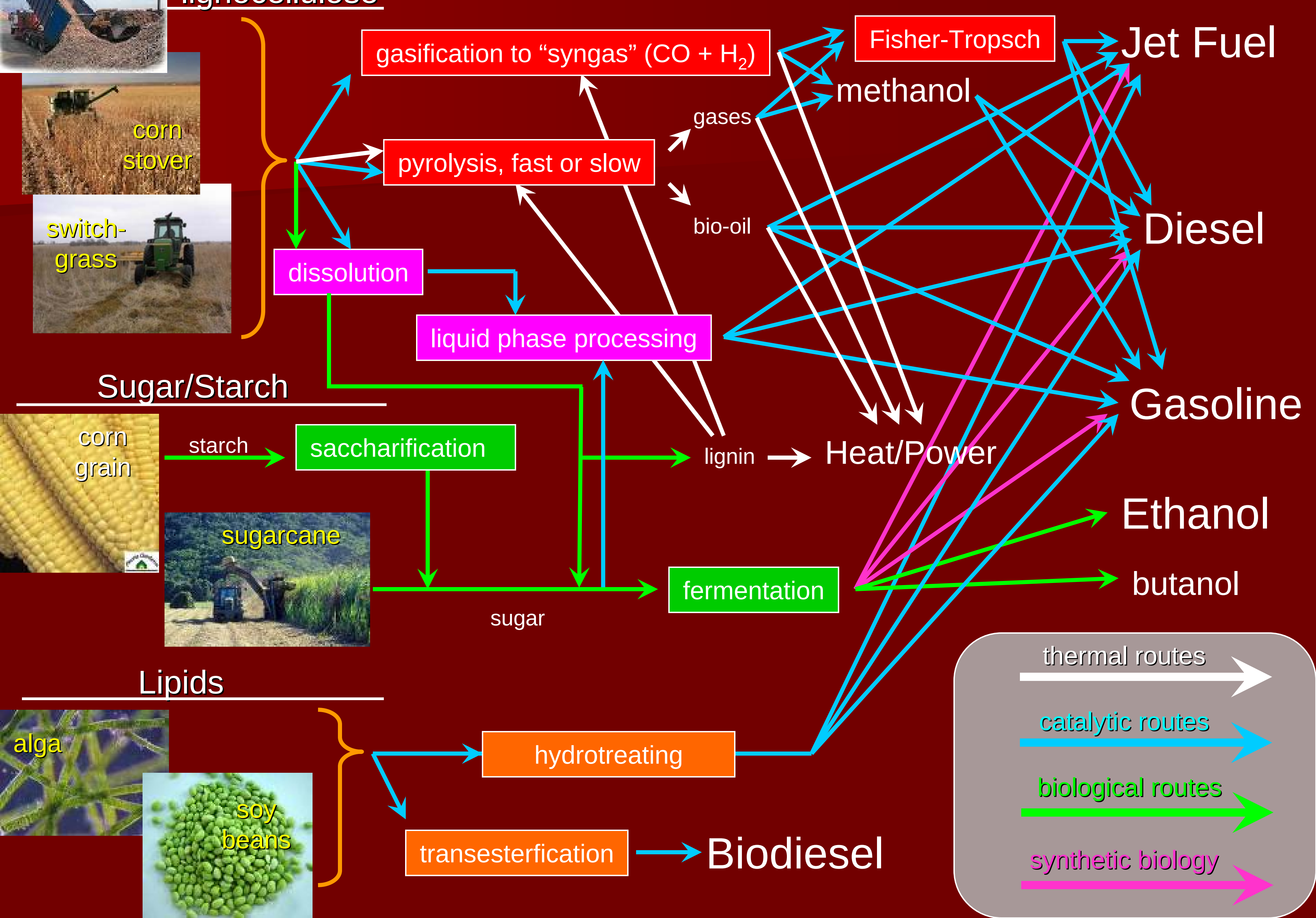
washcoat



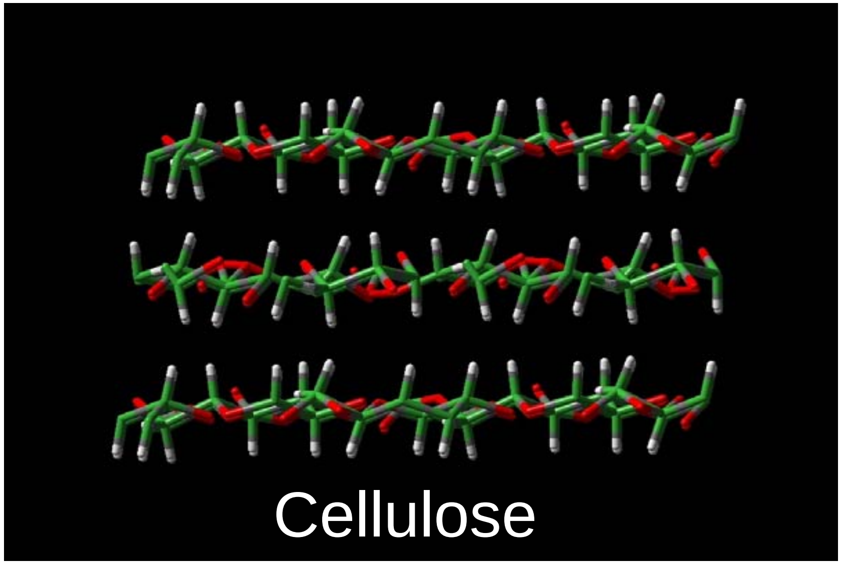
Catalysts: Heart of Petroleum Refineries
Fuels, Chemicals, Materials (Textiles)



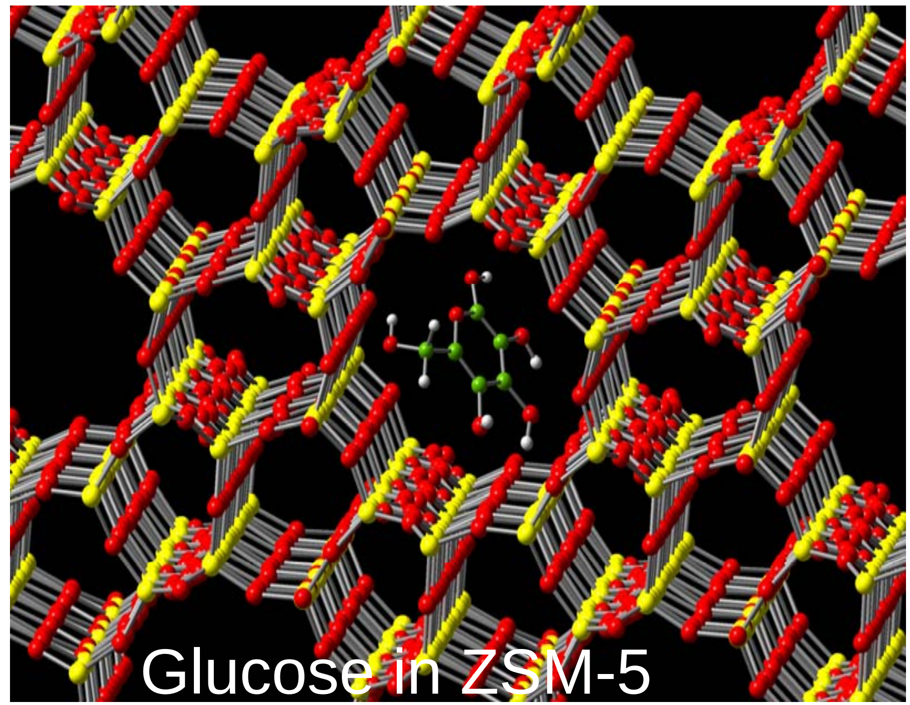
Biofuel Production Alternatives



Gasoline from Cellulose by Catalytic Fast Pyrolysis in a Single Reactor



Pyrolysis to Sugars, Adsorption into catalyst

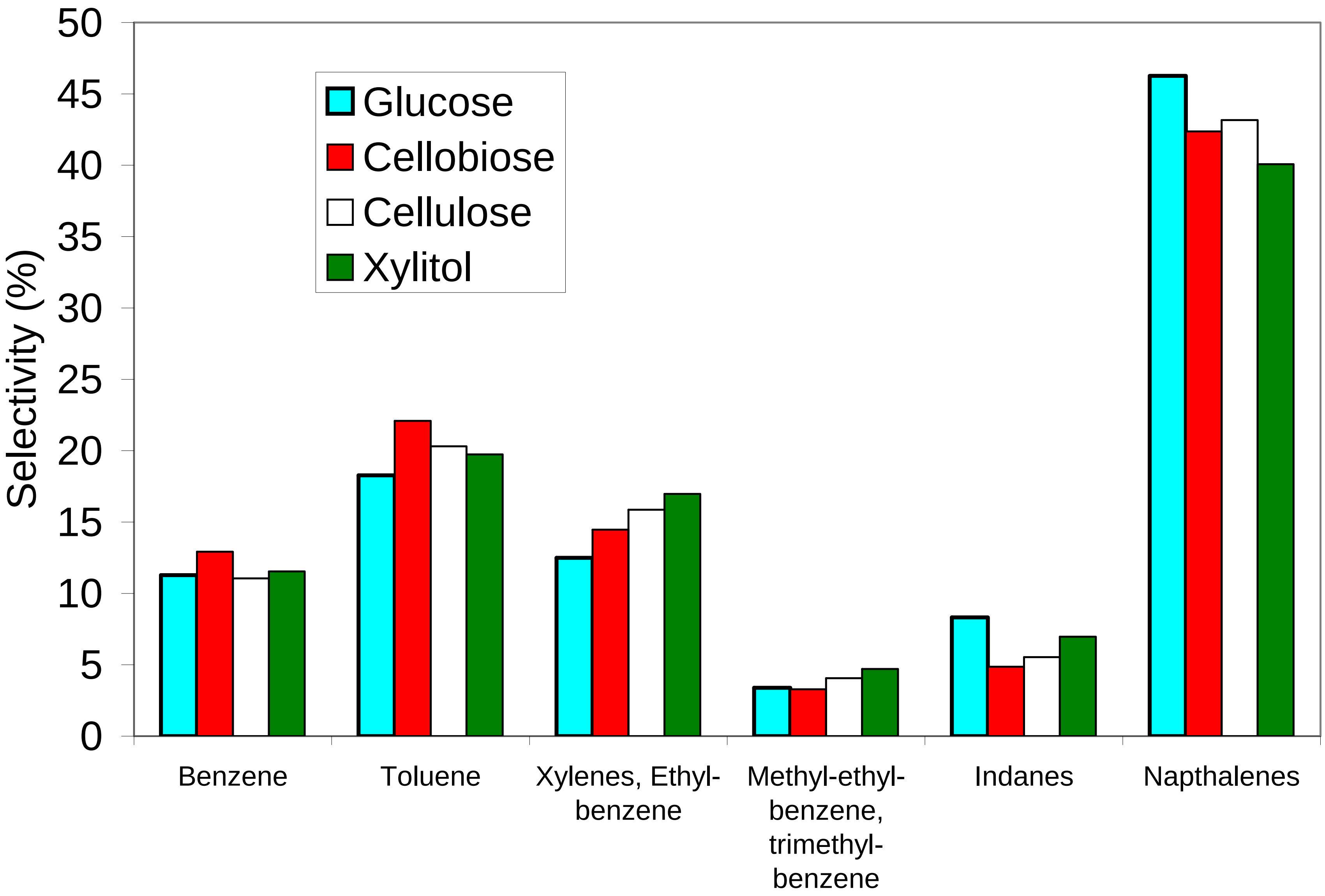


Catalytic Conversion

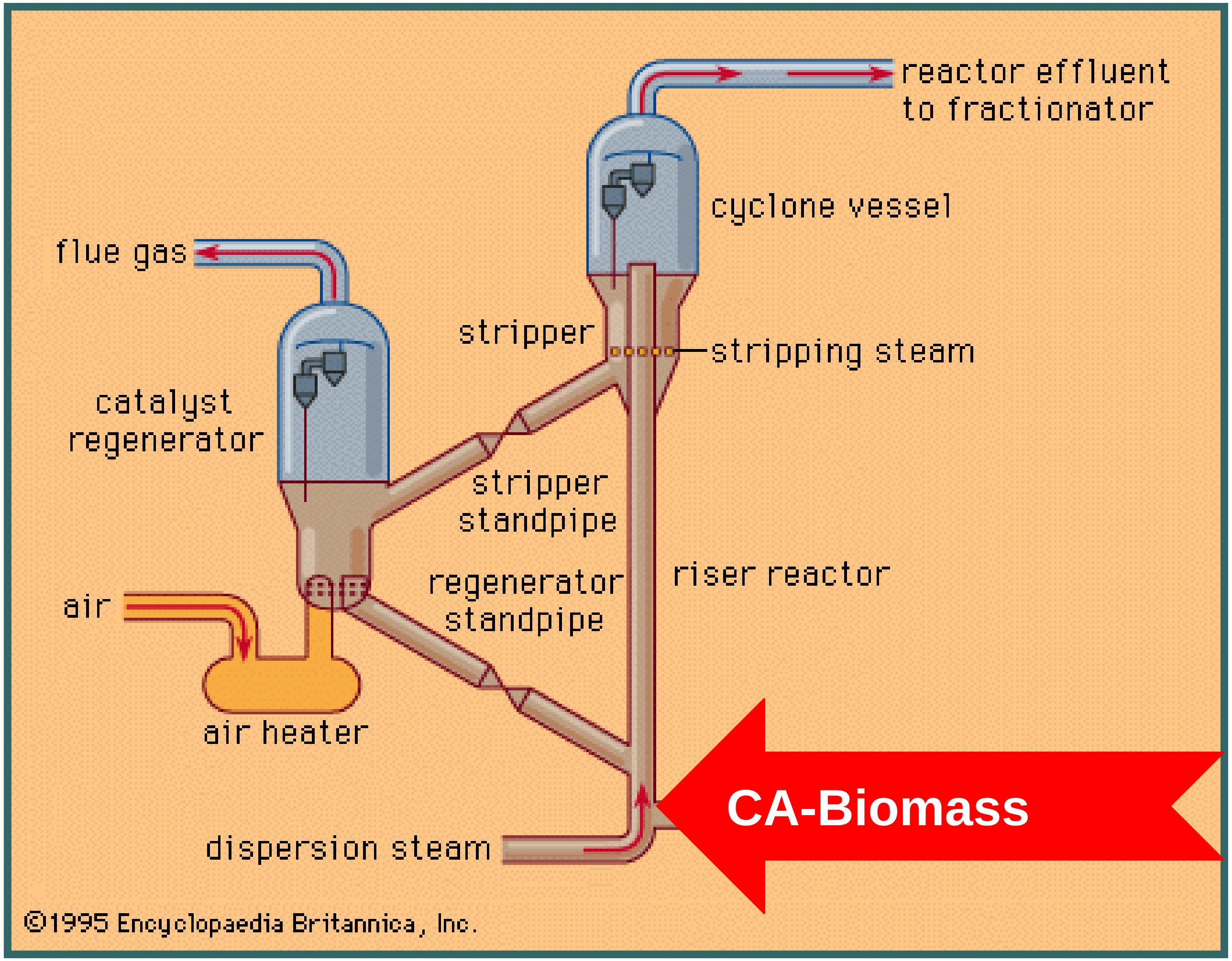
Gasoline, CO_2, Water

UMassAmherst

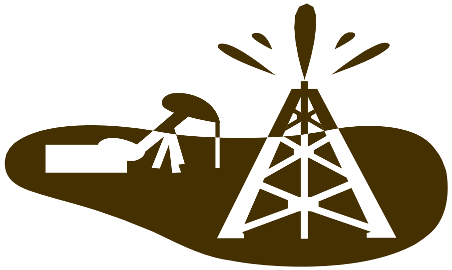
Aromatic Selectivity



BCC = Biomass Catalytic Cracking

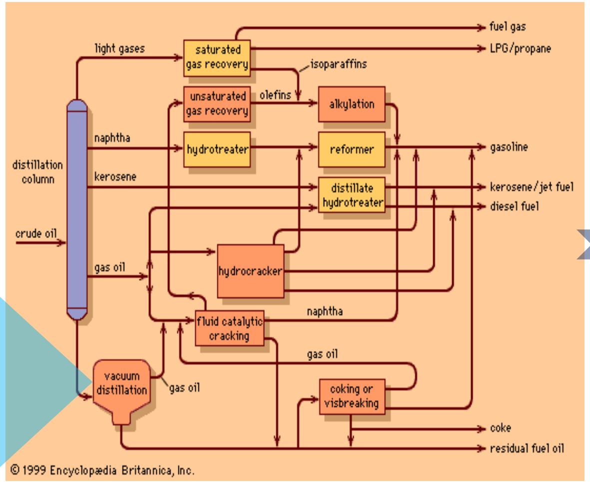


KiOR connects the Biomass and Oil Industry



Crude oil

Bio Crude



- **Bio-Crude compatible with refining streams (but no Sulfur, metals etc)**
- **Technology based on existing refining technology**
- **Compatibility with existing infra-structure → lower entry barrier**

  → fast Time-To-Market!
- **KiOR creates feedstock diversity for oil refiners !**

ConocoPhillips

2nd Generation Biofuels
Perspectives of a Global Refiner

Lisa Myers
Congressional Research & Development Caucus
Washington D.C.
October 4, 2007

2nd Generation Biofuels

- Anything other than Ethanol and Biodiesel
- Require massive low cost resource
  - Ag./forest waste, wood, grass, cane, MSW

- Want omnivorous, efficient conversion technology
  - Makes the most of the resource
  - Should integrate with manufacturing infrastructure
  - Linked to distribution infrastructure

- Need conversion to market compatible fuel
  - Gasoline, Diesel

- Other Issues: Sustainability, Economics

ADM and COP Alliance

- Research next-generation biofuels
- Seek to commercialize technology for:
  - Conversion of biomass into biocrude
  - Refining biocrude into transportation fuels
- Target Fuels which are:
  - Sustainable economically & environmentally
  - Compatible with existing infrastructure; such as renewable gasoline or renewable diesel

Courtesy of Laurel Harmon, UOP

UOP Vision

Fuel Additives / Blends

Ethanol **Biodiesel**

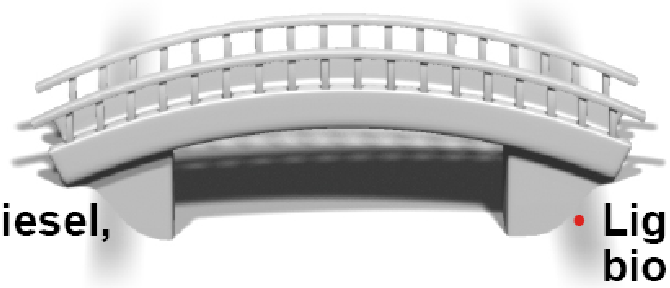
Fuels

Diesel **Gasoline**

UOP's Bio-Fuels Technology Goals

Identify and utilize processing, composition, and infrastructure synergies to lower capital investment, minimize value chain disruptions, and reduce investment risk.

Inedible Oils: Jatropha



Generation 1

- **Vegetable oils to diesel, petrol and jet fuel**

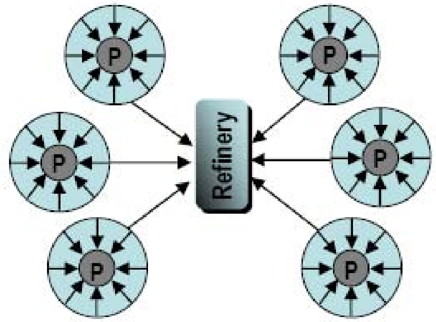
Generation 2

- **Lignocellulosic biomass to fuels**
- **Algal oils to fuels**

OPIS

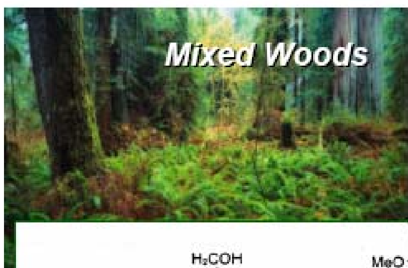
UOP 4941-10

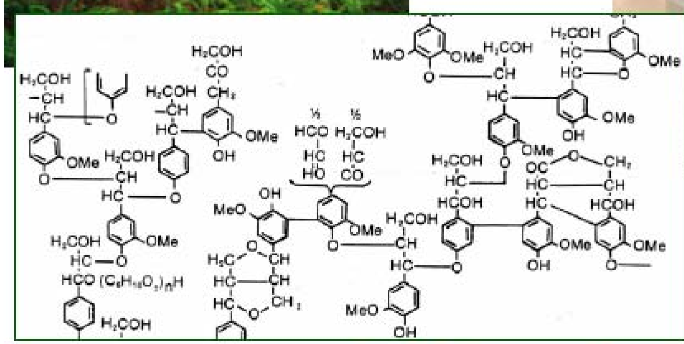
Lignocellulosic Biomass to Fuels Via Pyrolysis

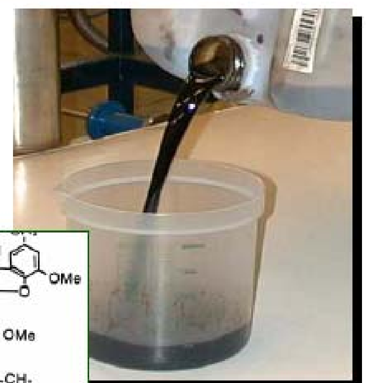


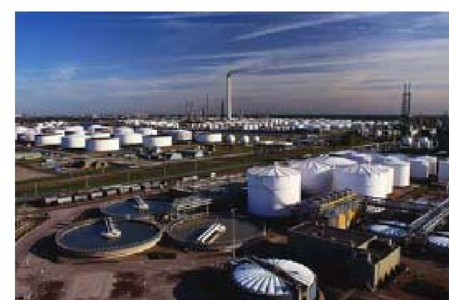
Biomass → Pyrolysis → Stabilization → Biocrude → Deoxygenate / Other Refinery Processes →

- Gasoline
- Diesel
- Jet
- Chemicals





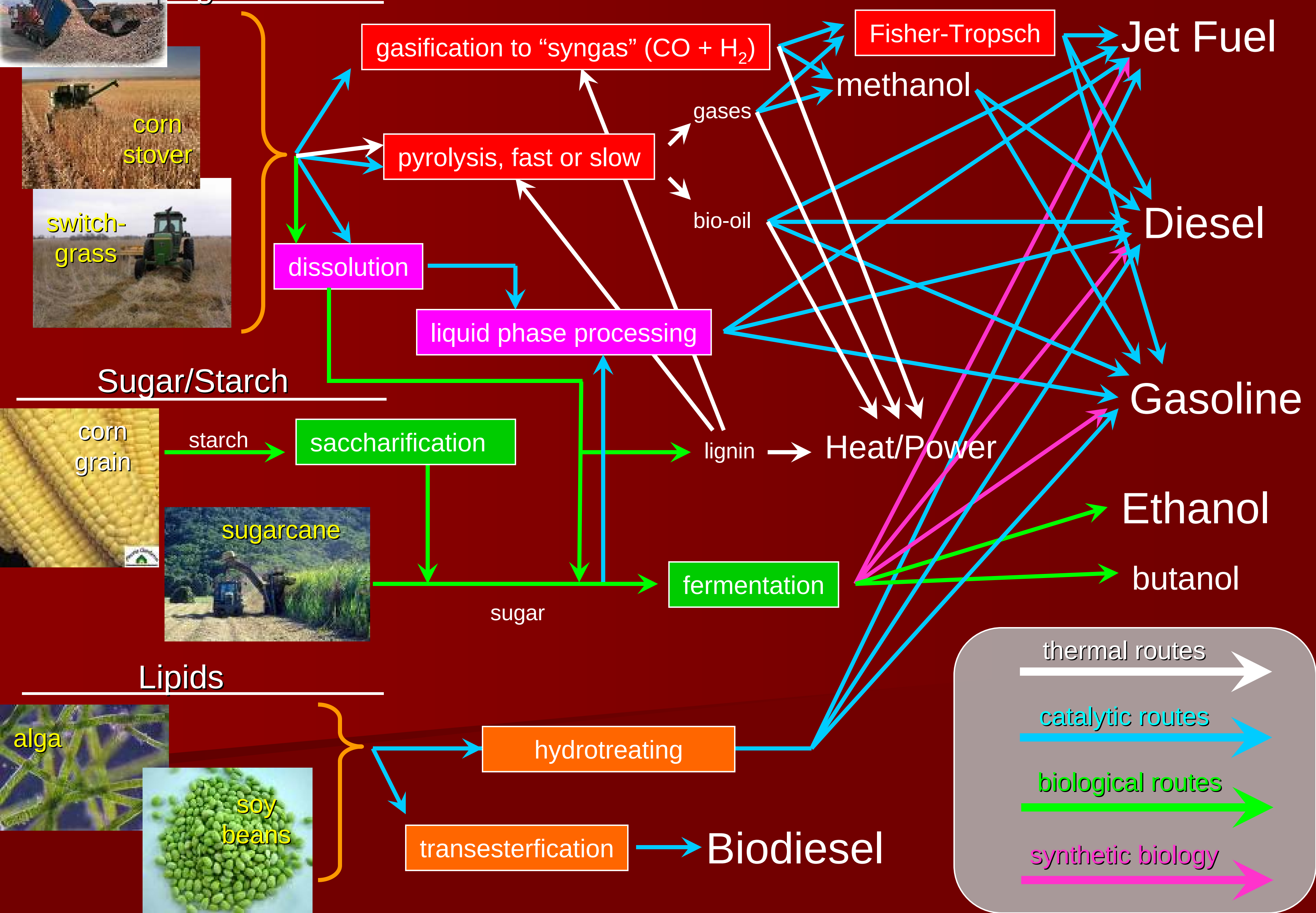




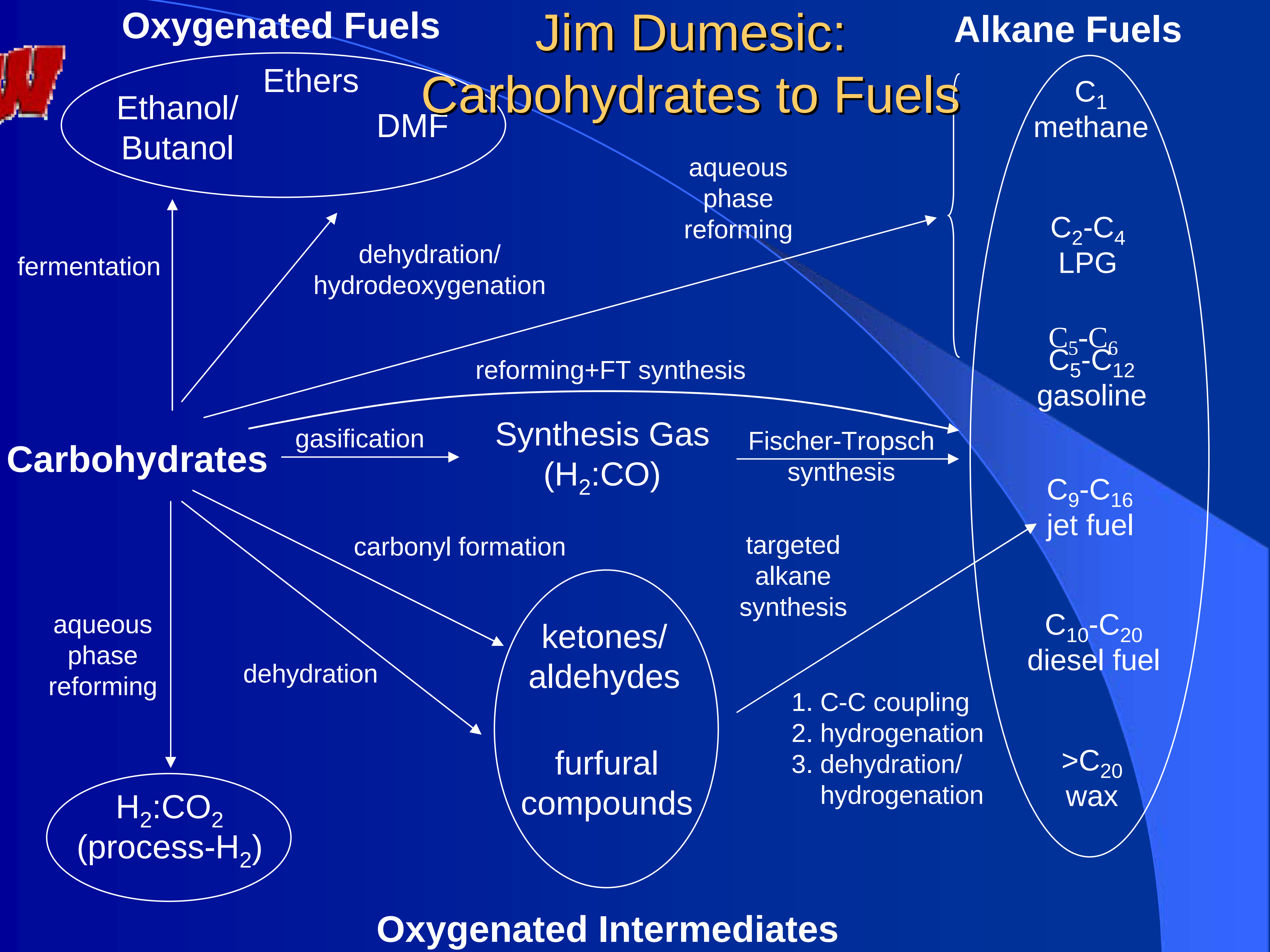
Collaboration with DOE, NREL, PNNL

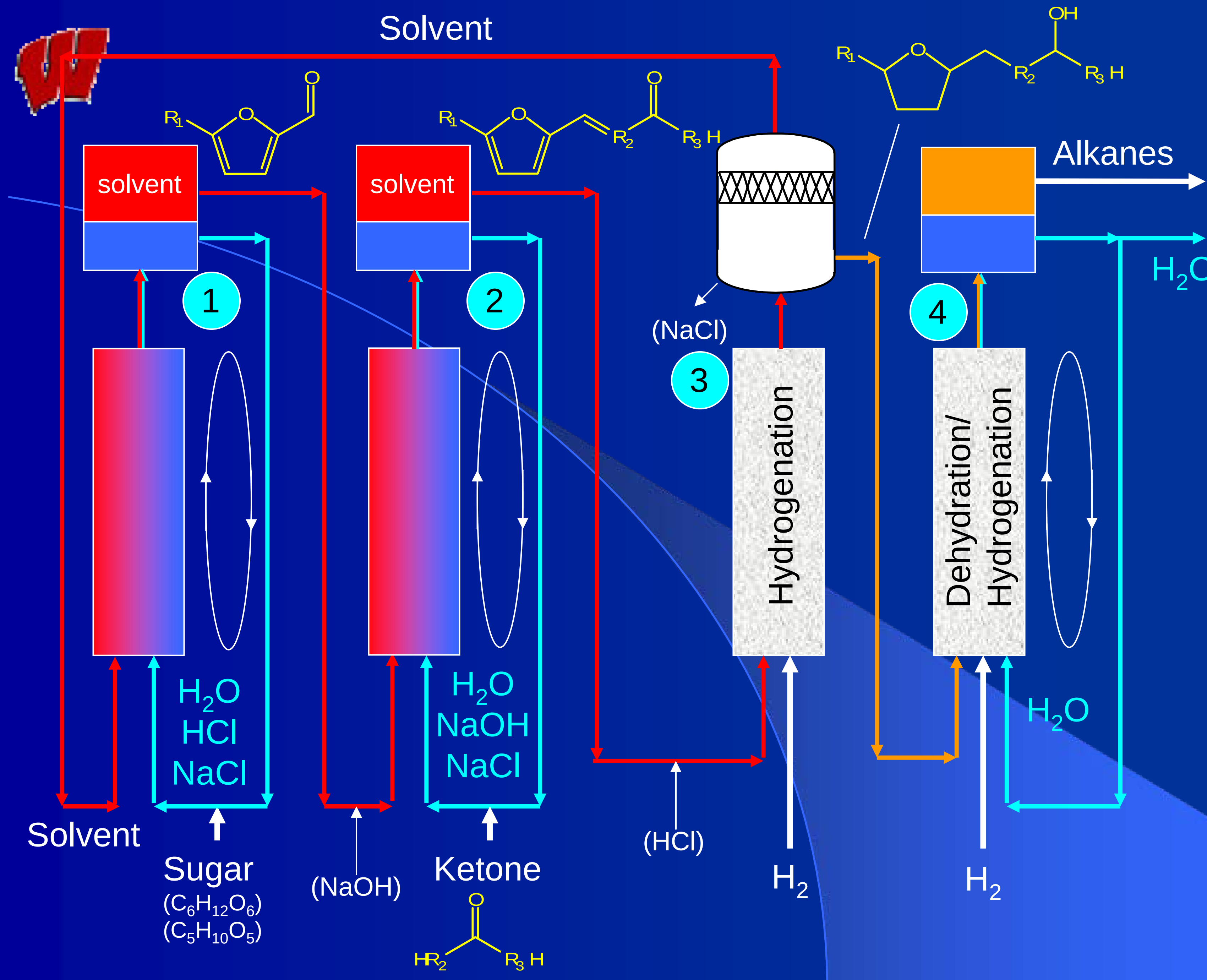
UOP 4941-22

Biofuel Production Alternatives



Jim Dumesic: Carbohydrates to Fuels





Solvent
solvent
solvent
1
2
3
4
(NaCl)
Alkanes
H_2O
Hydrogenation
Dehydration/ Hydrogenation
H_2O
HCl
NaCl
H_2O
NaOH
NaCl
H_2O
Solvent
Sugar
($C_6H_{12}O_6$)
($C_5H_{10}O_5$)
(NaOH)
Ketone
(HCl)
H_2
H_2

Virent Energy Systems Overview

VIRENT

THE UNIVERSITY of WISCONSIN MADISON

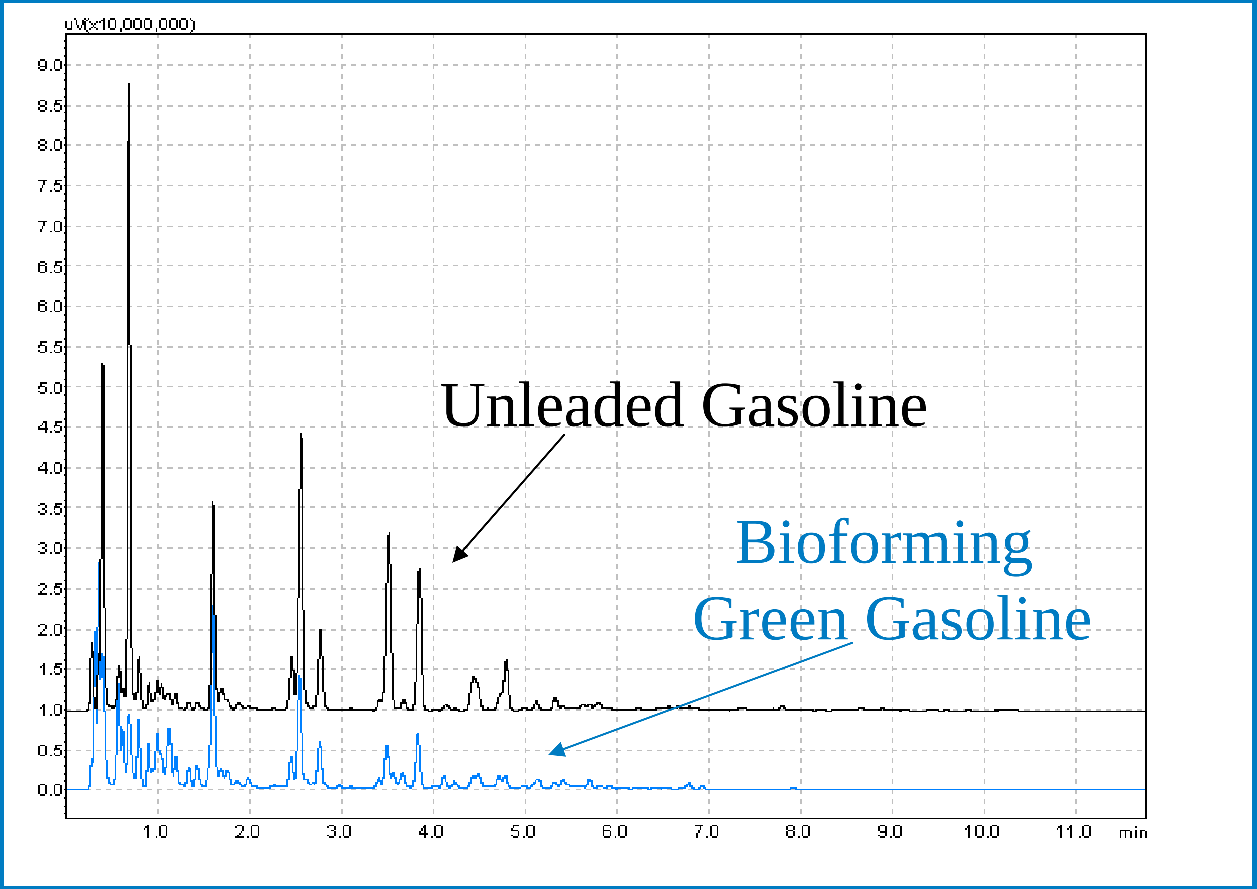
WARF
Wisconsin Alumni Research Foundation

- Founded in 2002 by Dr. Randy Cortright and Professor Jim Dumesic from the Department of Chemical Engineering of the University of Wisconsin

Cane Sugar to Green Gasoline

Green Gasoline Composition

Same Components as Standard Unleaded Gasoline



Unleaded Gasoline
115,000 BTUs/Gal

Bioforming
Green Gasoline
115,000 BTUs/Gal

Ethanol
76,000 BTUs/Gal

NEWS RELEASE

SHELL AND VIRENT ANNOUNCE COLLABORATION TO DEVELOP BIOGASOLINE

Shell and Virent Energy Systems, Inc., (Virent™) of Madison, Wisconsin USA, today announced a joint research and development effort to convert plant sugars directly into gasoline and gasoline blend components, rather than ethanol.

The collaboration could herald the availability of new biofuels that can be used at high blend rates in standard gasoline engines. This could potentially eliminate the need for specialized infrastructure, new engine designs and blending equipment.

Virent's BioForming™ platform technology uses catalysts to convert plant sugars into hydrocarbon molecules like those produced at a petroleum refinery. Traditionally, sugars have been fermented into ethanol and distilled. These new 'biogasoline' molecules have higher energy content than ethanol (or butanol) and deliver better fuel efficiency. They can be blended seamlessly to make conventional gasoline or combined with gasoline containing ethanol.

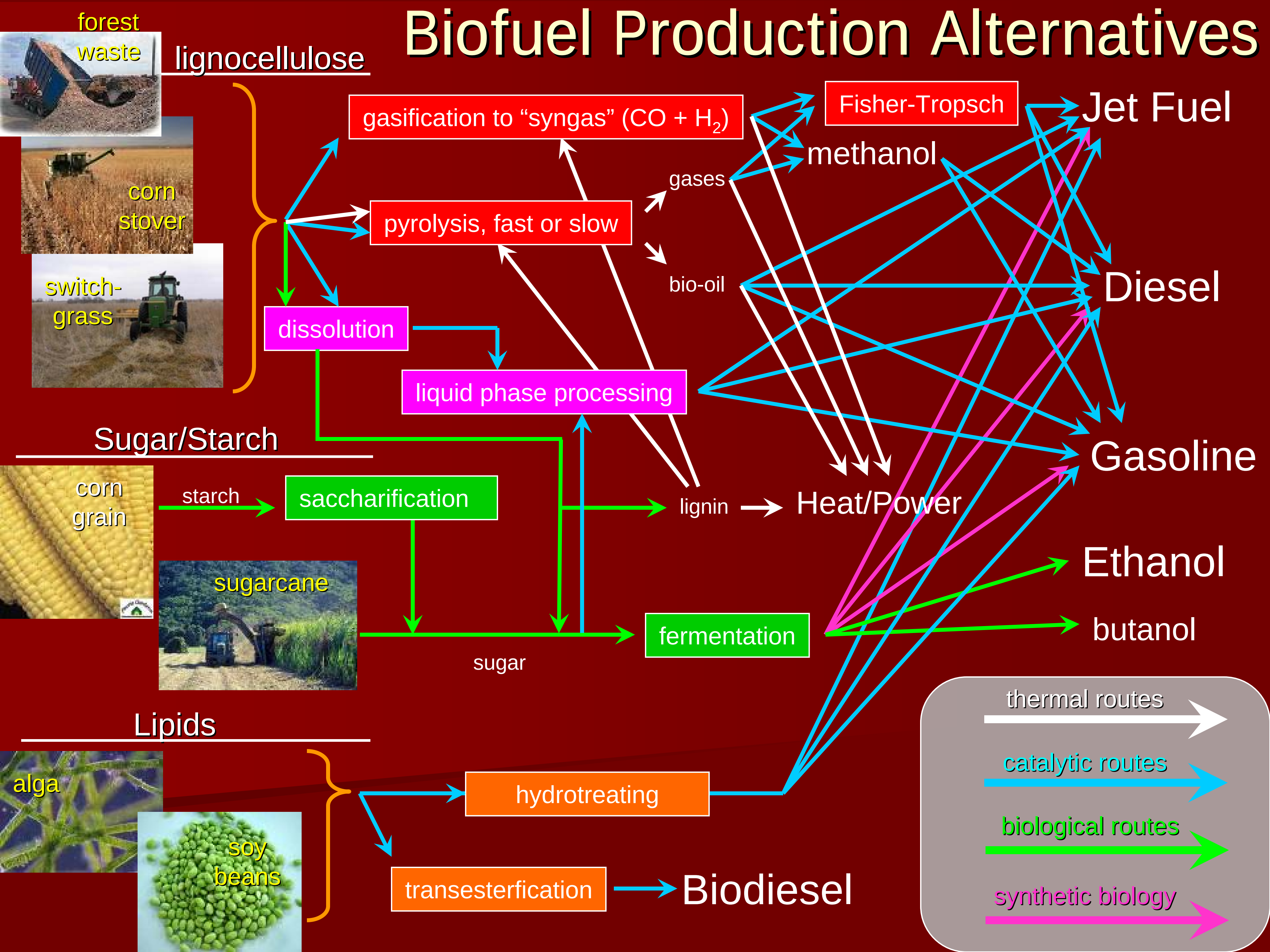
The sugars can be sourced from non-food sources like corn stover, switch grass, wheat straw and sugarcane pulp, in addition to conventional biofuel feedstock like wheat, corn and sugarcane.

The companies have so far collaborated for one year on the research. The BioForming™ technology has advanced rapidly, exceeding milestones for yield, product composition, and cost. Future efforts will focus on further improving the technology and scaling it up for larger volume commercial production.

"The technical properties of today's biofuels pose some challenges to widespread adoption," Dr. Graeme Sweeney, Shell Executive Vice President Future Fuels and C02 said. "Fuel distribution infrastructure and vehicle engines are being modified to cope but new fuels on the horizon, such as Virent's, with characteristics similar or even superior to gasoline and diesel, are very exciting."

Dr. Randy Cortright, Virent CTO, Co-Founder and Executive Vice President said, "Virent has proven that sugars can be converted into the same hydrocarbon mixtures of today's gasoline blends. Our products match petroleum gasoline in functionality and performance. Virent's unique catalytic process uses a variety of biomass-derived feedstocks to generate biogasoline at competitive costs. Our results to date fully justify accelerating commercialization of this technology."

Biofuel Production Alternatives



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THE BEST REPLACEMENT FOR PETROLEUM **IS** PETROLEUM

RENEWABLE.

OUR FOUNDERS ASKED:

"If you removed all constraints, what would the ideal biofuel be?"

THEIR ANSWER: petroleum.

A biological, fermentation-based process starting from renewable sugars offers the most compelling economics. However, petroleum products could not be made in this way. Until now.

LS9 Renewable Petroleum™ technology enables the rapid and widespread adoption of renewable transportation fuels. Patent-pending DesignerBiofuels™ products are custom engineered to have higher energetic content than ethanol or butanol; to have fuel properties that are essentially indistinguishable from those of gasoline, diesel, and jet fuel; and to be distributed in existing pipeline infrastructure and run in any vehicle. Learn more about LS9

What is Renewable Petroleum™ Technology?

Learn about our DesignerBiofuels™ Products

Join Our Team!

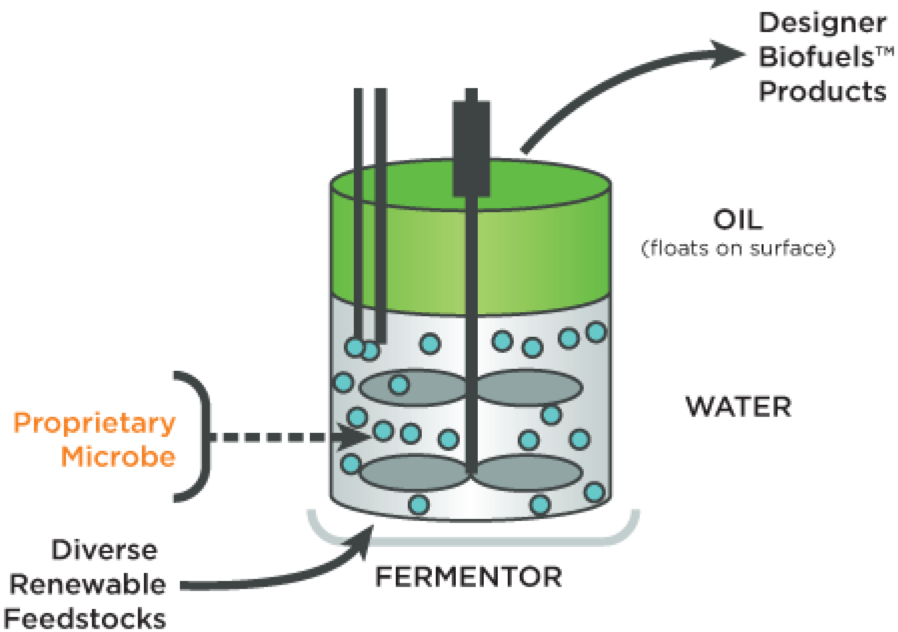
Renewable Petroleum™ Technology

> LS9's patent-pending technologies will transform the transportation fuel market. These breakthroughs will offer a commercially attractive path to sustainability.
>
> — Noubar Afeyan
> Managing Partner and CEO
> Flagship Ventures

Petroleum, on which modern day society was built and is now dependent, is a diminishing resource with increasing environmental, political, and economic disadvantages.

The ideal alternative would be chemically identical to petroleum, allowing broad and rapid adoption, derived from renewable resources, scalable to support current and future demands, domestically derived, and cost competitive without subsidies.

LS9 has developed Renewable Petroleum™ technologies to meet this need.



Pushing the frontiers of synthetic biology and industrial biotechnology, LS9 has created industrial microbes that efficiently convert renewable feedstocks to a portfolio of "drop in compatible" hydrocarbon-based fuels and chemicals. LS9's unique technology provides a means to genetically control the structure and function of its fuels, enabling a product portfolio that meets the diverse demands of the petroleum economy.

LS9 has developed a new means of efficiently converting fatty acid intermediates into petroleum replacement products via fermentation of renewable sugars. LS9 has also discovered and engineered a new class of enzymes and their associated genes to efficiently convert fatty acids into hydrocarbons. LS9 believes this pathway is the most cost, resource, and energy-efficient way to produce hydrocarbon biofuels and petroleum-replacement products. This translates into efficient land and feedstock use and directly addresses tensions between food versus fuel production.

News

PDF Version
PDF Version - Portuguese

April 23, 2008

Amyris and Crystalsev Join to Launch Innovative Renewable Diesel from Sugarcane by 2010

New Fuel Works in Today's Engines, Reduces Emissions by 80 Percent

SAO PAULO, Brazil, and Emeryville, California, USA - Amyris, the leading innovator of next-generation renewable fuels, and Crystalsev, one of Brazil's largest ethanol distributors and marketers, today announced plans to commercialize advanced renewable fuels made from sugarcane including a diesel, jet fuel and gasoline. The first product, a renewable diesel that works in today's engines, is targeted for commercialization in 2010. Scale-up and testing work to date indicate that this fuel scales more quickly and economically than currently available biofuels, and reduces emissions by 80 percent over petroleum diesel.

Using Amyris' breakthrough technology platform, the new joint venture, Amyris-Crystalsev Pesquisa e Desenvolvimento de Biocombustiveis Ltda, will work with Brazilian sugarcane mills and fuel producers to quickly scale production of the Amyris renewable diesel fuel. Amyris will hold the majority stake in the Amyris-Crystalsev venture, and Crystalsev will hold the remaining stake and contribute commercialization expertise.

Santelisa Vale, the second largest ethanol and sugar producer in Brazil and majority owner of Crystalsev, has contracted to provide two million tons of sugarcane crushing capacity and plans to adopt the new technology beginning at its flagship mill - Santelisa. Santelisa Vale will also provide technical and engineering expertise to accelerate development and scale-up of the Amyris fuel. The Amyris-Crystalsev venture plans to bring other sugar producers into the fold as it launches its diesel fuel and progresses on new products.

"This partnership represents a historic first for the global transportation fuels industry. By securing a significant supply of the most sustainable feedstock and collaborating with our world renowned partners Crystalsev and Santelisa, we now have the ability to take our pioneering technology out of the lab and rapidly scale production toward supplying the needs of the worldwide renewable fuels market," said John Melo, CEO Amyris.

Unlike current biofuels, Amyris renewable fuels are designed to meet or exceed the quality of existing petroleum fuels and be fully compatible with existing fuels infrastructure and engines. They are formulated biologically through sugar fermentation to create hydrocarbons, the same molecular structure found in traditional petroleum fuels. The result is a new kind of renewable fuel that is expected to work in today's automotive and jet engines with no performance trade-offs, to blend at high-levels with other petroleum fuels, and to be fully compatible with existing distribution infrastructure, while offering advantages of significantly reduced emissions.

Conclusions

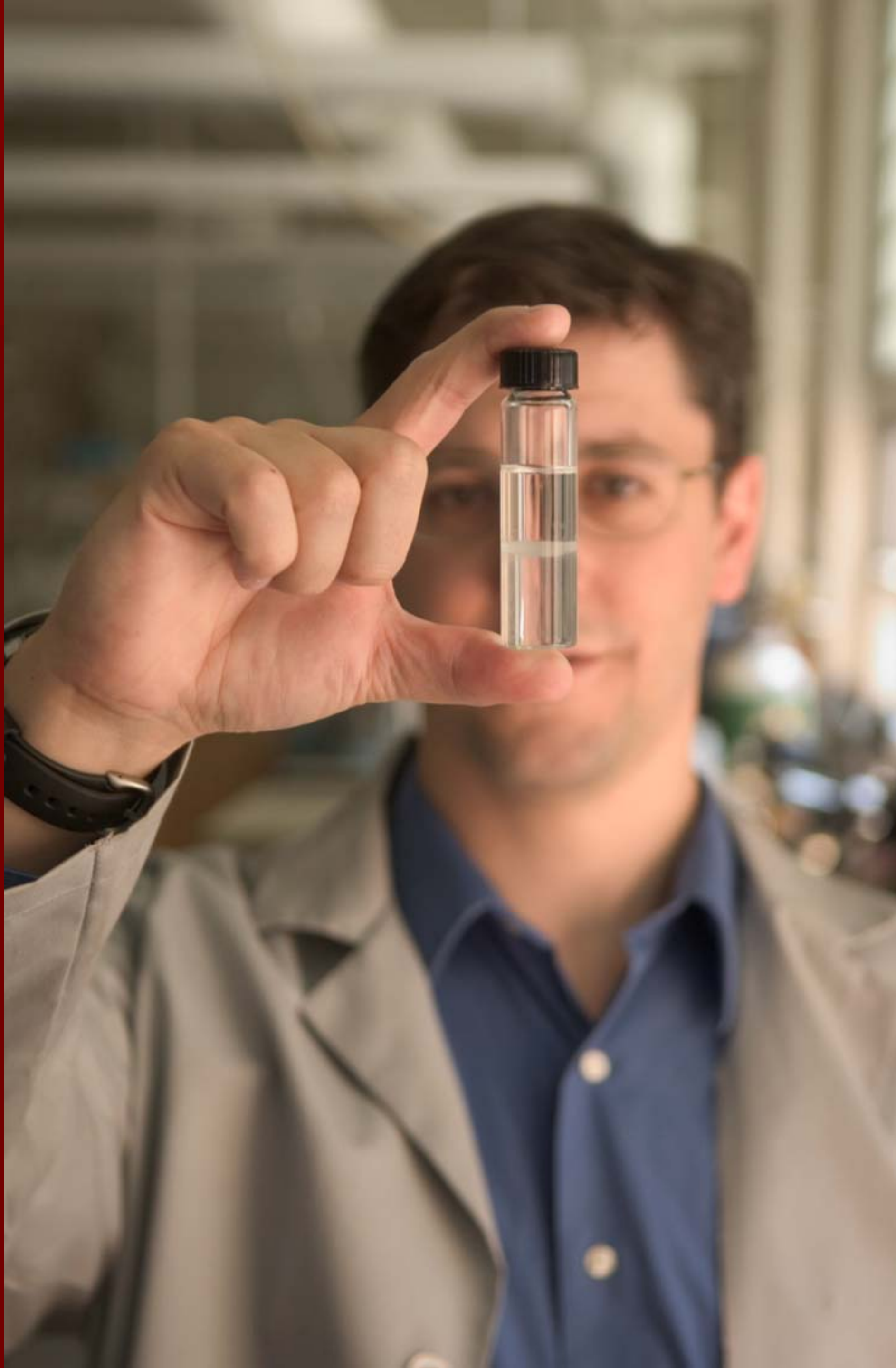
- Think “cellulosic gasoline” (and diesel and jet fuel)
  - no distillation; cheaper to produce and lower C footprint
  - no loss of gas mileage
  - fits into existing infrastructure
- Catalytic and biocatalytic routes
- New “green gasoline” paradigm is gaining momentum

Federal Agency Update

- NSF:
  - Hydrocarbons from Biomass (HyBi) selected as FY ‘09 topic for EFRI (Emerging Frontiers in Research and Innovation) program in ENG directorate
    - 5-7 projects, $10 – 14 million
    - $2 million total, 4 years
- DOE/Office of Science:
  - $100 million FY ’09 budget request for Energy Frontier Research Centers
- DOE/EERE/Office of Biofuels Program:
  - $25 million markup of FY ’10 budget for advanced biofuels
- “Next Generation Hydrocarbon Biofuels” have been written into the National Action Plan of the Biomass R&D Board

Potential advantages of hydrocarbons

- Self-separation from water - no distillation required. Less energy input:
  - lowers processing cost
  - improves the C balance
- ~30% higher energy density; won’t suffer a commensurate loss of gas mileage
- Reduction of water use
- Green gasoline/diesel/jet fuel fit into current infrastructure; no need for engine modifications or new distribution systems



Liquid Biofuels CapEx Drivers

100 million Gallon/year facility

	BioForm to Gasoline	Ethanol (Starch feedstock)
Residence time; drives vessel size	60 minutes	3,000 minutes
Distillation	Minimal; gasoline doesn't mix with H_2O	Extensive; must boil off > 88% H_2O
Catalyst/enzymes /yeast OpEx	~ $0.04/gallon Leased Catalyst	~$0.04/gallon Enzyme & yeast
Estimated CapEx per gallon of Capacity	~ $1.80 per gallon	~ $2.0 per gallon