We will begin momentarily at 2pm ET

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Industrial Technology Advisor,
Industrial Research Assistance Program,
National Research Council of Canada

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2016 Material Science Series

Ever since the Model-T first rolled off the production line in 1908, the world of transportation has never been the same. Join us as we examine the science behind innovations that will drive the world for the next 100 years.

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“The Chemistry of Go:
Innovations in Alternative Fuels”
Jennifer Holmgren, CEO, LanzaTech

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Easter Parade New York City 1900

Easter Parade New York City 1913

Source: George Grantham Bain Collection.
What do we need to “Go”?

Movement requires energy.
Fuels carry energy.

What makes a good fuel?
Energy-dense
Inexpensive
Easy to handle

Audience Survey Question

Answer the question on blue screen in one moment

What percentage of cars in 1900 were electric?

• Less than a quarter
• About a quarter
• Between a quarter and a half
• More than half
• About three-fourths
Audience Survey Question

What percentage of cars in 1900 were electric?

• Less than a quarter
• About a quarter
• Between a quarter and a half (37%)
• More than half
• About three-fourths

Evolution of Go...Steam, Electricity and Coal
And then came Petroleum…

- Reliable
- Practical
- Cheap
- Efficient
- Easier to Control
- Less likely to explode

**Refinery Output**

**Refinery Products**

- Gasoline/Cars
- Jet Fuel/Airplanes
- Diesel Trucks/Construction Equipment
- Lube Oils
- Asphalt
- Bunker Fuel (Ships)
Refinery Overview

• Crude oil is a complex mixture of various lengths and shapes of carbon and hydrogen molecules, with different chemical properties. In addition, crude oil contains significant levels of heteroatoms such as S, N which must be removed before burning fuels.

• A typical US refinery processes 100,000 – 250,000 barrels (~ 4 – 10 million gallons) of crude oil per day.

• Processing unit operations vary by refinery and depend on crude oil used as input as well as desired product slate.

Crude Oil

• Crude oil varies in both density and sulfur content depending on its origin around the world.

• This results in differences in cost for purchasing the oil and required technology to refine it into products.
Chemical Conversion: Adding Value

• **Cracking**
  – Converts heavy gas oils and residual to higher value gasoline and diesel components
  – Cracking can be thermal (Coker) or catalytic (Fluidized Catalytic Cracker)

• **Alkylation**
  – Converts shorter-chain molecules to longer-chain molecules
  – Typically C₃/C₄ molecules upgraded to gasoline components

• **Upgrading**
  – Improvement of low-octane fuels to high-octane fuels (Reformer)
  – Dehydrogenation reactions, converting linear hydrocarbons to branched and cyclic hydrocarbons

---

Boiling Point Separation

• Smaller hydrocarbons are gaseous with low boiling points

• Longer chains are liquids, then waxes and finally solids

---

Temperatures in °F

- Gasoline (C₅–C₁₀): 32-100 °F
- Naphtha (C₅–C₁₅): 100-200 °F
- Kerosene and jet fuels (C₁₆–C₉): 200-400 °F
- Diesel and fuel oils (C₁₀–C₁₇): 400-600 °F
- Heavy fuel oils (C₁₈–C₉₂): 600-1000 °F
- Lubricating oils (C₉₃–C₁₅₀): 1000+ °F

---

23/24
Generic Refining Flowscheme

How are the hydrocarbons produced at the top of the column, different from those produced lower down?

- They have longer chains and lower boiling points
- They have shorter chains and lower boiling points
- They have longer chains and higher boiling points
- They have shorter chains and higher boiling points
Audience Survey Question
ANSWER THE QUESTION ON BLUE SCREEN IN ONE MOMENT

How are the hydrocarbons produced at the top of the column, different from those produced lower down?

• They have longer chains and lower boiling points
• They have shorter chains and lower boiling points
• They have longer chains and higher boiling points
• They have shorter chains and higher boiling points

* The longer the chain the higher the boiling temperature.

Evolution of “Go”

Vehicles have changed a lot. Their fuel? Not so much

Cars have been tied to gasoline for most of their history, but fuel tech keeps evolving...

Now more than ever, we need to look at alternative solutions and technologies to make us “GO”
The Status Quo is not an Option

14% of Global CO₂ Emissions come from transportation fuels

A Carbon Smart World

65% of 2°C carbon budget: USED

52% of natural gas reserves
35% of oil reserves
88% of coal reserves

Must stay in the ground

2% 8% 27%
2015 2055 2050
Advanced Biofuels Taking Off

First commercial-scale cellulosic ethanol plant in the U.S. opens for business
POST-Dispatch, October 17, 2014

DuPont, Europe’s leading bioenergy company, opens new biofuel plant in Bulgaria
Biofuels Digest, October 16, 2014

Biofuels Digest
October 6, 2014

Beta Renewables and Novo Nordisk open world’s first advanced biofuels factory in Italy
Business Standard, October 9, 2013

Getting a New Process to Scale

Ease of funding
Discovery
Continuous improvement at scale
Adapt and adopt from others
Diffusion
First Commercial
Evolution
Applied R&D
Engineering Development
Pilot and Demonstration
RTP™ History

1984:
Foundation

1989-1998
Commercialization & Scale-up US - $20+M sale for Chemicals

1998-2005
Petroleum Business Development & sale for US$100 MM

2006-Present
Renewable Liquid Fuels: Key alliances & Project execution

* Since 1996, Ensyn has returned to shareholders 2x the amount it has raised in equity funding

ENSYN

Commercial Isobutanol/Ethanol Plant in Luverne, MN

**Agri-Energy**
- First commercial scale renewable isobutanol plant in the world
- Purchased in 2010 & 100% owned by Gevo
- World scale chemicals plant

**Commissioning timeline**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 2010</td>
<td>Purchased Luverne plant</td>
</tr>
<tr>
<td>May-Sep. 2012</td>
<td>Encountered unexpected levels of contamination</td>
</tr>
<tr>
<td>Sep.-May 2013</td>
<td>Revamped plant and procedures to address contamination issues</td>
</tr>
<tr>
<td>May-Sep. 2013</td>
<td>Tested new systems and procedures</td>
</tr>
<tr>
<td></td>
<td>Made minor system and hardware-upgrades</td>
</tr>
<tr>
<td>Oct.-April 2014</td>
<td>Encountered operability issues related to water recycling and solids handling</td>
</tr>
<tr>
<td>May 2014 – Present</td>
<td>Running in side-by-side mode to better handle water and solids. Improves operability of plant, and simplifies IBA production. WORKS WELL</td>
</tr>
</tbody>
</table>

**Statistics**

- 100 MM lbs per year of Isobutanol/Ethanol
- 100 MM lbs per year of animal feed

**gevo Luverne Facility**

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Typical Specialty Chemical Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates-based</td>
<td>Petroleum-based</td>
</tr>
</tbody>
</table>

(1) Derived from a sample of 10 operating specialty chemical plants producing chemicals such as Methyl Amines, Dimethyl Formamide, EPO, Phenol Aromatics, Formaldehyde, Polyamines and Methanol
Source: International Process Plants, EIA

© 2014 Gevo, Inc. | 34

© 2014 Gevo, Inc.
Natural oils contain oxygen, have high molecular weight.

First reaction removes oxygen – product is diesel range waxy paraffins.

Second reaction “cracks” diesel paraffins to smaller, highly branched molecules.

**Feedstock flexible, but with consistent product properties**

Source: Dr. James Kinder, Boeing

---

**Global green diesel & HEFA production**

Supply available to address significant aviation markets

Source: Dr. James Kinder, Boeing
Great Progress on Certification for Flight

**Certification**

“Less than a decade ago, the prospect of flying commercial aircraft on sustainable aviation fuels (SAF) seemed unrealistic due to the associated technical and safety challenges, the developments have been impressive!” IATA Roadmap

<table>
<thead>
<tr>
<th>Type</th>
<th>ASTM approval</th>
<th>When</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fischer Tropsch (FT) (or BtL)</td>
<td>Max 50% blend</td>
<td>2009</td>
</tr>
<tr>
<td>Hydrotreated Esters and Fatty Acids (HEFA)</td>
<td>Max 50% blend</td>
<td>2011</td>
</tr>
<tr>
<td>Renewable Synthesized Iso-Paraffinic (SIP)</td>
<td>Max 10% blend</td>
<td>2014</td>
</tr>
<tr>
<td>Butanol to Jet Fuel (ATJ)</td>
<td>Max 30% blend</td>
<td>2016</td>
</tr>
</tbody>
</table>

**Pipeline:** Green Diesel, Ethanol to Jet (EtJ), pyrolysis and catalytic cracking (Hydroprocessed Depolymerized Cellulosic Jet), catalytic hydrothermolysis and catalytic conversion of sugars.
Carbon Recycling: The LanzaTech Process

Gas fermentation technology converts C-rich gases to fuels and chemicals

Performance milestones achieved and exceeded for >1000 hours

ArcelorMittal, Gent

Ground Works Started
October 2015

Gas Testing Station Produces Ethanol
January 2016

Connection to Steel Mill Gas Lines
March 2016
Embrace the Circular Economy: Recycle Everything

All Solutions Must Succeed… Even Those We Don’t Yet Know.

“IF I HAD ASKED PEOPLE WHAT THEY WANTED, THEY WOULD HAVE SAID: FASTER HORSES…”

Henry Ford
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