As the oil supply declines, there is a greater need for cleaner alternative fuels. There will undoubtedly be a shift from crude oil to non-petroleum sources as a feedstock for aviation (and other transportation) fuels. The Fischer-Tropsch process uses a gas mixture of carbon monoxide and hydrogen which is converted into various liquid hydrocarbons; this versatile gas-to-liquid technology produces a complex product stream of paraffins, olefins, and oxygenated compounds such as alcohols and aldehydes. The Fischer-Tropsch process can produce a cleaner diesel oil fraction with a high cetane number (typically above 70) without any sulfur and aromatic compounds. It is most commonly catalyzed by cobalt supported on alumina, silica, or titania or unsupported alloyed iron powders. Cobalt is typically used more often than iron, in that cobalt is a longer-active catalyst, has lower water-gas shift activity, and lower yield of modified products. Promoters are valuable in improving Fischer-Tropsch catalyst as they can increase cobalt oxide dispersion, enhance the reduction of cobalt oxide to the active metal phase, stabilize a high metal surface area, and improve mechanical properties. Our goal is to build up the specificity of the Fischer-Tropsch catalyst while adding less-costly transition metals as promoters; the more common promoters used in Fischer-Tropsch synthesis are rhenium, platinum, and ruthenium. In this report we will describe our preliminary efforts to design and produce catalyst materials to achieve our goal of preferentially producing C₈ to C₁₈ paraffin compounds in the NASA Glenn Research Center Gas-To-Liquid processing plant. Efforts at NASA Glenn Research Center for producing green fuels using non-petroleum feedstocks support both the Sub-sonic Fixed Wing program of Fundamental Aeronautics and the In Situ Resource Utilization program of the Exploration Technology Development and Demonstration program.
Fischer-Tropsch Catalyst for Aviation Fuel Production

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Cleveland, OH, 44135

Lauren M. Best and Aloysius F. Hepp
NASA Glenn Research Center, Cleveland, OH, 44135
Fischer-Tropsch Process Overview

CO/H₂

Synthesis Gas Production:
Coal, Natural Gas, Biomass

F-T Synthesis in Reactor

Product Recovery

H₂O

Oil

Wax

Product Upgrade:
Hydrocracking Isomerization

GC Analysis

Transportation Fuels

(2n+1) H₂ + n CO => CₙH_(2n+2) + n H₂O

ΔH = - 49 kcal/mol
FTS Research Objectives at NASA GRC

- Synthesize Cobalt Catalysts (supported on alumina) for Longer-chain Hydrocarbon Production
  - Increase dispersion of Co on Alumina

- Examine the Promoter Effects on Catalytic Activity
  - Ag, Pt, Cu, etc.

- Compare the Catalyst Morphology and Function
  - SEM/EDS

- Look for Opportunities to Develop Processes for ISRU
  - Use other gas feedstocks relevant to atmospheres
  - Catalysts related to other feedstocks/products (CH₄)
Projects

❖ Synthesis of Catalyst
  ❖ Cobalt on Alumina
  ❖ Noble metal promoted catalyst

❖ Catalyst Characterization
  ❖ Brunauer Emmett Teller (BET) Surface Area Measurements
  ❖ Temperature Programmed Reduction (TPR)
  ❖ Scanning Tunneling Microscopy
  ❖ Energy Dispersive Spectroscopy
  ❖ Inductively Coupled Plasma – Atomic Emission Spectroscopy

❖ Use of Catalyst for Fuel Production
  ❖ Fischer-Tropsch Synthesis
Cobalt on Alumina

- Co(NO₃)₂ * 6H₂O
- Al₂O₃
- Slurry impregnation
  - Multiple additions increase the loading of the cobalt nitrate onto the alumina
- Promoters Added:
  - Platinum
  - Silver
  - Manganese
  - Nickel
  - Ruthenium
  - Palladium
## Characterization

### Catalyst Synthesized

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Co Loading %</th>
<th>Promoter%</th>
<th>ICP-AES Elemental Analysis</th>
<th>Surface Area (m²/g)</th>
<th>Reduction Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>No Promoter</td>
<td></td>
<td>127.135</td>
<td>350</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>Ag 0.5</td>
<td>23.6 / 0.278</td>
<td>109.35</td>
<td>369</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>Mn 0.5</td>
<td>25.7 / 0.592</td>
<td>103.17</td>
<td>366</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>Ni 0.5</td>
<td>23.8 / 0.891</td>
<td>128.66</td>
<td>348</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>Ru 0.5</td>
<td>25.5 / 1.26</td>
<td>78.57</td>
<td>322</td>
</tr>
<tr>
<td>7</td>
<td>25</td>
<td>Pt 0.5</td>
<td>24.8 / 0.459</td>
<td>115.93</td>
<td>265</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>Ru 1.0</td>
<td>23.0 / 2.20</td>
<td>123.85</td>
<td>264</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
<td>Mn 0.5</td>
<td>13.8 / 0.572</td>
<td>101.01</td>
<td>354</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>Pd 0.5</td>
<td>14.1 / 0.429</td>
<td>111.37</td>
<td>229</td>
</tr>
</tbody>
</table>
Characterization

- BET – Brunauer Emmett Teller Results

**Surface Area**

<table>
<thead>
<tr>
<th>Promoter Concentration, %</th>
<th>Surface Area, m²/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni 0.5</td>
<td>140</td>
</tr>
<tr>
<td>No</td>
<td>120</td>
</tr>
<tr>
<td>Ru 1.0</td>
<td>100</td>
</tr>
<tr>
<td>Pt 0.5</td>
<td>80</td>
</tr>
<tr>
<td>Ag 0.5</td>
<td>60</td>
</tr>
<tr>
<td>Mn 0.5</td>
<td>40</td>
</tr>
<tr>
<td>Ru 0.5</td>
<td>20</td>
</tr>
</tbody>
</table>

9th IECEC | San Diego, CA | August 2011
Characterization

- Scanning Electron Microscopy
- Energy Dispersive Spectroscopy

SEM image of 1.0% Ru and 25% Co on Alumina. 100X magnification, catalyst made by slurry impregnation.

<table>
<thead>
<tr>
<th>Element</th>
<th>Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>43.14</td>
</tr>
<tr>
<td>Al</td>
<td>28.29</td>
</tr>
<tr>
<td>Ru</td>
<td>1.15</td>
</tr>
<tr>
<td>Co</td>
<td>26.91</td>
</tr>
</tbody>
</table>
Characterization

- Temperature Programmed Reduction

TPR 25% Co on Al₂O₃

Co₃O₄ → CoO → Co°
Characterization

- Temperature Programmed Reduction

Reducibility of 25% Cobalt Catalyst with Promoters

Noble Metal Promoter Concentration, %

Reduction Temperature, °C

- No Promoter
- Ag 0.5
- Mn 0.5
- Ni 0.5
- Ru 0.5
- Pt 0.5
- Ru 1.0
Fuel Production

- Fischer-Tropsch Synthesis
  - Three 1-Liter continuous Stirred Tank Reactors (CSTR)
  - Converts synthesis gas (CO/H₂) to fuel by running at high pressures and temperatures

[Diagram showing the process flow from SynGas to GC analysis with intermediates such as H₂O, Oil, and Wax]
Research Objectives of F-T Fuels

- Improve reactor yield, reduce energy input, and reduce CO$_2$ by-product by conducting bench scale Fischer-Tropsch reactor screening experiments with innovative catalysts
  - Investigate FT product distributions
  - Identify the effects of critical parameters (T, P, H$_2$:CO Ratio, catalyst) on F-T reactor product distribution with respect to aviation fuel yields, compositions and physical properties
Fischer-Tropsch Reaction
Overview Chemistry & Testing

\[(2n+1) \text{H}_2 + n \text{CO} \Rightarrow \text{C}_n\text{H}_{(2n+2)} + n \text{H}_2\text{O}\]

Catalysts
- Cobalt: 180 – 450 psig, 180 – 270 °C
- Iron: 180 – 450 psig, 330 – 350 °C

Pressure
- Cobalt: 180 – 450 psig
- Iron: 180 – 450 psig

Temperature
- Cobalt: 180 – 270 °C
- Iron: 330 – 350 °C

Feed conditions / test variables (typical)
- H$_2$:CO ratio: 0.6 – 2.5
- H$_2$ / CO flow rates: 20 – 100 SLPH (Max design 120 SLPH – H$_2$/CO/Ar)
- Argon mol %: 10 – 50 (inert carrier gas)
- Space velocity: 1,000 to 10,000 hr$^{-1}$ at STP
- Catalyst Type: Co or Fe; promoted/unpromoted; supports Al$_2$O$_3$, SiO$_2$, TiO$_2$
Fischer-Tropsch Autoclave Reactor – 1 liter

- **Reactor capacity**
  - 1 liter (internal volume)
  - 6000 psig @ 650 °F (ASME rated)
  - 316 SS
  - Agitator – Dynamag mixer
  - Jacket heater (electric – 2.4 kW)

- **Operating Conditions**
  - Max Operating Pressure: 500 psig
  - Max Operating Temperature: 842 °F (450 °C)
  - Reactors have safety relief valves set to 750 psig
  - Normal test conditions range from 180-450 psig and 356-518 °F (210-270 °C)
Catalyst Performance:
Catalyst 0.5% Pt, 15% Co on Alumina Support

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GRC Run CoC-001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Temp (deg C)</td>
<td>220</td>
</tr>
<tr>
<td>Reactor Press (psig)</td>
<td>268</td>
</tr>
<tr>
<td>Space Velocity (SLPH/g-Cat *)</td>
<td>5.1</td>
</tr>
<tr>
<td>Feed H₂: CO molar</td>
<td>2.02</td>
</tr>
<tr>
<td>CO conversion (mol%)</td>
<td>37.7 to 26.7</td>
</tr>
<tr>
<td>H₂ conversion (mol%)</td>
<td>55.7 to 39.7</td>
</tr>
<tr>
<td>Total time on stream (hr)</td>
<td>381 (~16 days)</td>
</tr>
<tr>
<td>Product Gas (SLPH)</td>
<td>59.2 to 71.8, avg. 66.3</td>
</tr>
<tr>
<td>Product Water (g/day)</td>
<td>246.7 to 170.7, avg. 200.5</td>
</tr>
<tr>
<td>Product Liq Oil (g/day **)</td>
<td>76.3 to 62.9, avg. 70.2</td>
</tr>
<tr>
<td>Product ReWax (g/day ***)</td>
<td>239.1 to 153.6, avg 190.6</td>
</tr>
</tbody>
</table>
CO and H₂ Conversion
GRC Run CoC-001

CO Conversion vs. TOS
RunID COC001

H₂ Conversion vs. TOS
RunID: COC001

Time on Stream (Hrs)

% Feed Converted

Time On Stream (Hrs)

% Feed Converted
Results

- Hydrocarbon production from catalyst
- Cobalt on Alumina provides

F-T Product Distribution
Jet Fuel Types, Alternatives & Details

Jet fuels classified as kerosene-, naphtha-type, or other

  - Carbon range from C\textsubscript{8} - C\textsubscript{16} (Kerosene is C\textsubscript{12} - C\textsubscript{15})
  - Standard fuel used for civilian or military aircraft
  - Conventional Jet-A:
    - Petroleum based distillate
    - Rely on foreign oil and refined fuels
    - Limited supply worldwide
- **Alternative Jet Fuels:**
  - Fischer Tropsch Fuel from coal, natural gas, non-petroleum sources
  - Biofuels from renewable sources

- **Naphtha-type ("wide-cut") jet fuels: Jet B and JP-4**
  - Carbon range from C\textsubscript{5} - C\textsubscript{15} (Petroleum Ether is C\textsubscript{7} - C\textsubscript{11})
  - Enhanced volatility generally used for cold-weather climates
Sources of SynGas

- Pure Gas Feed System
  - Initially used to test variables and find optimal settings
  - Introduce impurities to simulate real systems
- Biomass
- Waste Processing
# Alternative Feedstock Impurity Issues

## Sources of Impurity Species from Polymer Feedstocks

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Monomer</th>
<th>Impurity Element</th>
<th>Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polytetrafluoroethylene</td>
<td>$C_2F_4$</td>
<td>Fluorine ($F_2$, $HF$)</td>
<td>75.98</td>
</tr>
<tr>
<td>Polybrominatedbiphenyl</td>
<td>$C_{12}H_{10}Br_2$</td>
<td>Bromine ($Br_2$)</td>
<td>50.91</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>$C_2H_4Cl$</td>
<td>Chlorine ($Cl_2$, $HCl$)</td>
<td>55.86</td>
</tr>
<tr>
<td>Polyurethane</td>
<td>$C_{17}H_{16}N_2O_4$</td>
<td>Nitrogen ($N$)</td>
<td>8.97</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>$C_{27}H_{22}O_4S$</td>
<td>Sulfur ($S$, $SO_2$, $H_2S$, $CS_2$)</td>
<td>7.25</td>
</tr>
<tr>
<td>Polydimethylsiloxane</td>
<td>$C_6H_6OSi$</td>
<td>Silicone ($Si$)</td>
<td>37.91</td>
</tr>
</tbody>
</table>
Conclusions

- Successfully Synthesized Catalyst for FTS
- Surface area was reduced by addition of promoters
- SEM/EDS confirmed uniform particles and composition of catalyst
- Promoters Pt and Ru reduced activation temperature
- CO conversion is comparable to published results

Future Goals:

- Cobalt/Promoter dispersion studies
- Non-Petroleum or Green Feedstocks
  - Biomass (non-edible plants, bio-oils, human waste)
  - Plastic Waste (discarded or non-recyclable)
Acknowledgements

- UNCFSP and the NSTI program
- Subsonic Fixed Wing program of Fundamental Aeronautics
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  - Dr. Burton H. Davis
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- Daniel Gonzales (Angelo State University, NSTI Summer Scholar, ‘11)