How we invented jet fuel—without knowing what we were doing

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Nottingham University, May 2011
Frank Whittle—
The Father of Jet Propulsion
The Jet Engine

Diagram showing the components of a jet engine:
- Fuel Spray
- Igniter
- Turbine
- Air Intake
- Compressor
- Combustion Chamber
- Nozzle
The Gloucester Meteor
The MIG-25 “Foxbat”

- In the mid-1980s a Soviet pilot defected with his MIG-25, flying it to the supposed limit of its operational range.
- Military analysts were surprised to find the fuel tanks nearly half full.
The key is in the fuel

- Most conventional jet fuels, made from petroleum, are rich in alkanes.
- The Soviet fuel was rich in cycloalkanes (naphthenes)—carbon atoms linked in rings.
- Cycloalkanes have higher volumetric energy density (MJ/L) than corresponding alkanes.
Naphthenic fuels from coal

- Most coals are thought to consist of contain abundant aromatic structures linked by short aliphatic or heteroatomic groups.
- If these aromatic structures could be chemically “cut” out of coal, and then hydrogenated, it should be possible to make naphthenic fuels from coals.
Thermal Management

- High-performance aircraft generate enormous amounts of excess heat:
  - Friction heating in the atmosphere
  - Waste heat from the engines
  - Compressor outlet air
- Heat needs to be controlled to protect electronics, hydraulics, and people.
- The simplest approach is to use fuel as a heat sink, before it goes to the engines.
- *But*—most hydrocarbon fuels decompose to solid carbon at relatively low temperatures, ≈325°.
- Decomposition leads to maintenance problems (and possibly worse...)

Plugged afterburner fuel lines

Carbon deposition in fuel lines represents a costly maintenance problem.
Penn State was approached by a U.S. Congressman to see if there was anything PSU could do to make jet fuel from coal.

We already had a white paper (by HHS) on the possibilities of making naphthenic, high volumetric energy density fuels from coal.

Our JP-900 project began in 1989 with a $90,000 (≈£55,000) contract from the U.S. Department of Energy.

At the time we started this program, none of us had ever even seen jet fuel.
The JP-900 Challenge

- Development of a fuel with good heat sink capabilities, especially for advanced applications.

- The challenge: develop a fuel that would resist decomposition at 900°F (480°C) for two hours.
The seminal experiment

- The difference must lie in molecular composition.
Why is coal-derived jet fuel more stable?

- We tested ≈60 pure compounds, and learned that cycloalkanes and the related hydroaromatics have higher thermal stability than do alkanes.
- Coal-derived jet fuel turned out to be rich in cycloalkanes and hydroaromatics—its composition is inherently more stable than a conventional petroleum-derived fuel.
Conventional coal-to-liquids technologies

*Indirect liquefaction*: Coal is converted to a mixture of CO and H$_2$ (synthesis gas). In a separate step, synthesis gas is converted to liquids (Fischer-Tropsch synthesis). This process destroys the molecular structure of the original coal.

*Direct liquefaction*: Coal is reacted directly with hydrogen to produce a synthetic crude oil. This product is then refined further, into clean liquid fuels. Vestiges of the coal structure are preserved in the liquid.
The temper of the times

- By the time we had figured out the “recipe” for a high thermal stability, naphthenic jet fuel, it was the early to mid-1990s.
- At that time, interest in coal liquefaction technologies in public and private sectors of the U.S. was zero.
- We knew we had to find another way.
The concept of a “coal-based” fuel

- Lack of interest in coal liquefaction in the 90s was a blessing in disguise. We had the opportunity to think of new approaches.
- A “coal-derived” fuel is one made entirely from coal. A “coal-based” fuel would have the thermally stable molecules from coal, but also components from petroleum.
- Making a coal-based fuel could rely on existing refinery infrastructure, meaning lower capital investment and quicker time to completion.
Making Coal-Based Fuel

- The primary route selected was to use a liquid commonly available in oil refineries (light cycle oil) to extract the desired molecular components from coal.
- A secondary process would add coal to refinery units called delayed cokers. (It never hurts to have a “Plan B.”)
Crushed and ground coal → Solvent Extraction → Solid/Liquid Separation → Solvent Stripping → Stage 1 Hydrotreating

Unextracted coal and ash → Solid/Liquid Separation

$H_2$ → Stage 1 Hydrotreating → $H_2S$ → Stage 2 Hydrotreating Aromatics Saturation

$H_2$ → Stage 2 Hydrotreating Aromatics Saturation

Fractionation

Gasoline → Jet fuel → Diesel fuel → Fuel oil
Parallel Pathways

- What if...we invested a lot of effort in converting coal, and it turned out that the product wasn’t any good?
- We needed a way to simulate the likely final product *simultaneously* with figuring out how to make it.
- We chose a commercially available, coal-derived material, refined chemical oil, to use as a surrogate for our eventual coal product.
The RCO:LCO Approach
Pilot-scale Production of Prototype JP-900

- Mixing, hydrotreating, and fractionation of JP-900 prototypes was done by Intertek-PARC, Harmarville, PA, USA.
- Two campaigns were run: 10 barrels, then 100 barrels.
Partial Comparison of JP-8 and Prototype JP-900

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<tr>
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<th>JP-8 spec.</th>
<th>JP-900 (actual)</th>
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<tbody>
<tr>
<td>Flash point, °C</td>
<td>38 (min.)</td>
<td>61</td>
</tr>
<tr>
<td>Viscosity, cSt, –20°C</td>
<td>8.0 (max.)</td>
<td>7.5</td>
</tr>
<tr>
<td>Freezing pt, °C</td>
<td>–47 (max.)</td>
<td>–65</td>
</tr>
<tr>
<td>Smoke pt., mm</td>
<td>19 (min.)</td>
<td>22</td>
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# Partial Comparison of JP-8 and Prototype JP-900

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<tr>
<td><strong>Sulfur, wt. %</strong></td>
<td>0.3 (max.)</td>
<td>0.0003</td>
</tr>
<tr>
<td><strong>Aromatics, %</strong></td>
<td>25 (max.)</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Thermal stab.@ 260°C</strong></td>
<td>25 mm (max.)</td>
<td>0</td>
</tr>
<tr>
<td><strong>Calorific value, Btu/lb</strong></td>
<td>18,400</td>
<td>18,401</td>
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The light dawns….

- But… *it has to!* Regardless of thermal management issues, JP-900 still has to be jet fuel!
- What we had created was a fuel made largely from coal that could be a replacement for petroleum fuels.
The T-63 Engine Test

- Overall emissions similar to, or only slightly greater than, JP-8.
- Lower volumetric fuel flow rates, but slightly higher mass flow rates.
- Comparable with JP-8 in most respects.
The Williams International Test

- Totally comparable with Jet-A.
We found that JP-900 could be a potential coal-based “drop-in” replacement for jet fuels from petroleum.

Repeated requests were made to learn the engineering basis for the 900°F/2 hours specification. Finally the secret was revealed…

The Air Force had made the numbers up!
Batch Reactor Stability of JP-900

Comparison of stressed jet fuels

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<tbody>
<tr>
<td>JP8</td>
<td>Before</td>
<td>After</td>
<td>JP8+100</td>
<td>Before</td>
<td>After</td>
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Fuels were stressed under nitrogen for 2 hours at 900°F. Solid deposition is 7–8% in JP-8 and JP-8+100; 0.0% in JP-900.
Flow Reactor Stability of JP-900

More significant carbon deposition due to thermal break down of the fuel.

Penn State's First Prototype JP-900

JP-8

- Neat JP-8 (POSF 4177)
- PSU Coal-Based Fuel (POSF 4765)
- JP-8+100 (6hr)

Parameters:
- Pressure (P) = 550 psig
- Flow: 10 ml/min
- OD: 0.125”
- ID: 0.085”

Graph showing carbon deposition and average wall temperature over axial distance.
What Did We Accomplish?

- Development of a coal-based “universal” jet fuel that
  - meets or exceeds specifications for JP-8 (Air Force) and Jet-A (civilian),
  - has the high flash point of JP-5 (Navy),
  - has the high thermal stability of JP-7 (for the SR-71 Blackbird) and
  - has the high volumetric energy density of JP-10 or RJ-5 (missile fuel).
- And…
JP-900 as fuel for CI engines


- It should be adequate diesel fuel, but may require some change in injection timing or addition of a cetane improver.

- Prototype JP-900 was successfully tested in a diesel-engine truck for 550 km, and another 550 km in a 1:3 blend with petro-diesel. No observable differences in performance compared to operation on petro-diesel.
JP-900 as Fuel for SOFCs

- Preliminary tests show comparable behavior for JP-900 and JP-8 fed “straight” to solid-oxide fuel cell.
- At 973 K, current density 0.2 A/cm², JP-900 produces 0.40 V vs. 0.48 for JP-8.
- Under same conditions, H₂ produces 0.89 V, but—running on JP-900 eliminates the need for reforming and gas separation.
Where Are We Going?

“Prediction is very difficult, especially about the future”

—— Niels Bohr
Lessons Learned

✓ Read widely.
✓ Record your ideas, no matter how wild or crazy they might seem at first.
✓ **DO NOT !!!!** be afraid of tackling the unknown.
✓ Have a “plan B” (C, D….)
✓ Leapfrog along parallel paths
✓ And, listen to the experts…. (once in a while)
Acknowledgments

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