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

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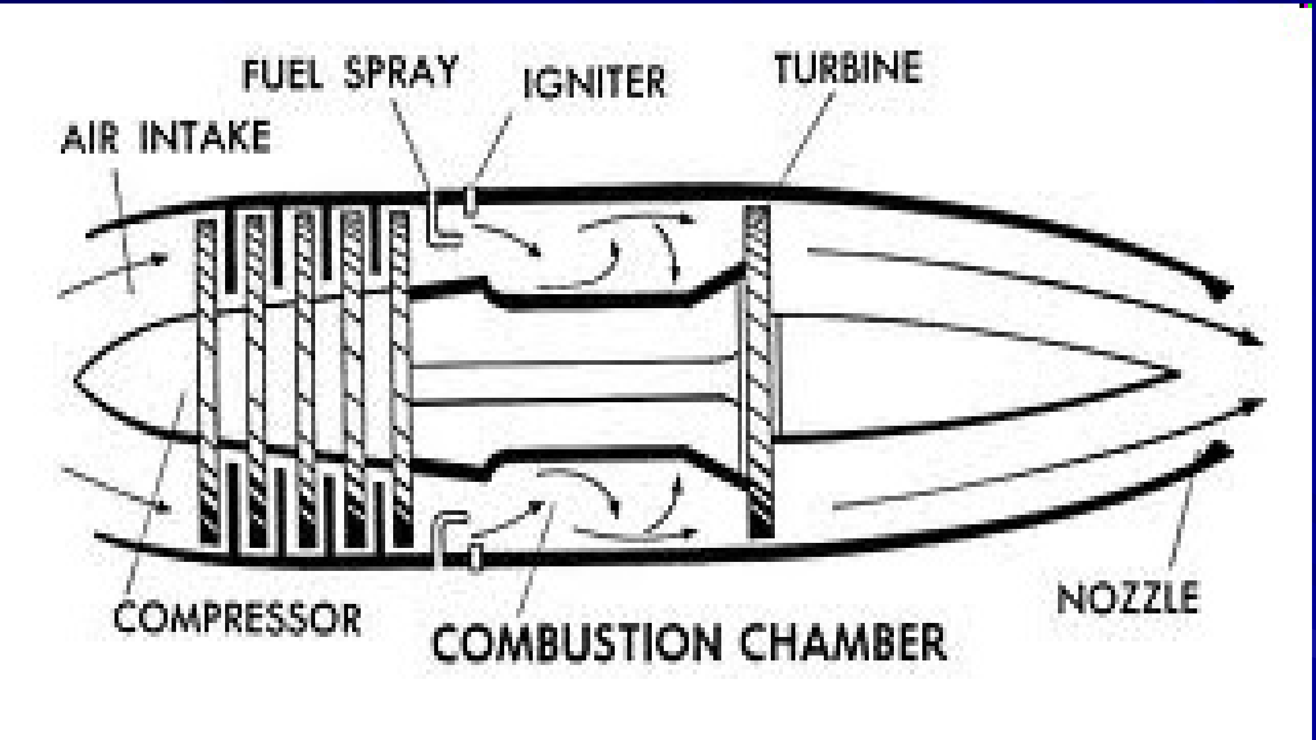
Frank Whittle—
The Father of Jet Propulsion

The Jet Engine



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.

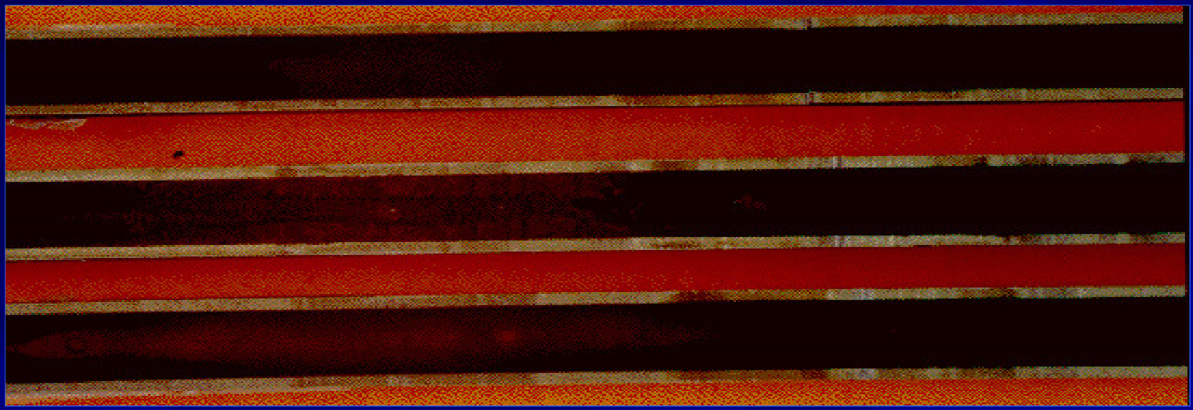
Naphthenic fuels from coal

- 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.

The beginning

- 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

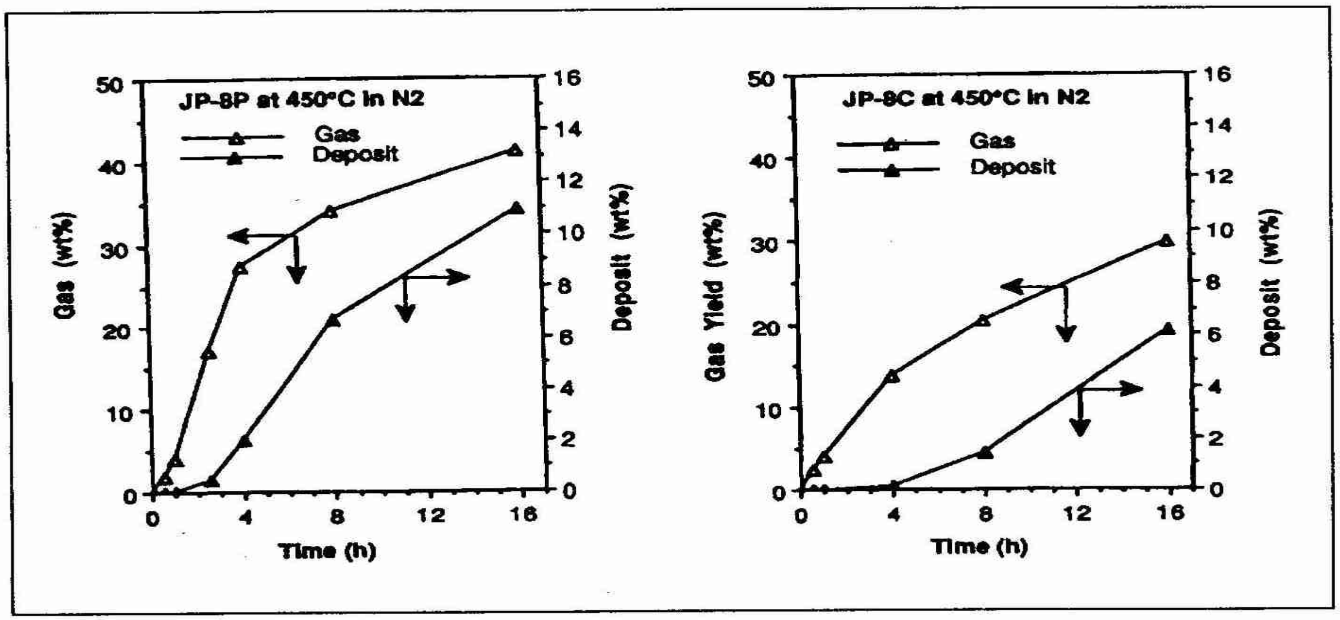


Figure 3. Formation of solid and gas from JP-8P (left) and JP-8C (right) fuels vs time.

- JP-8P and JP-8C both meet procurement specifications. Yet JP-8C has much greater thermal stability.
- 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

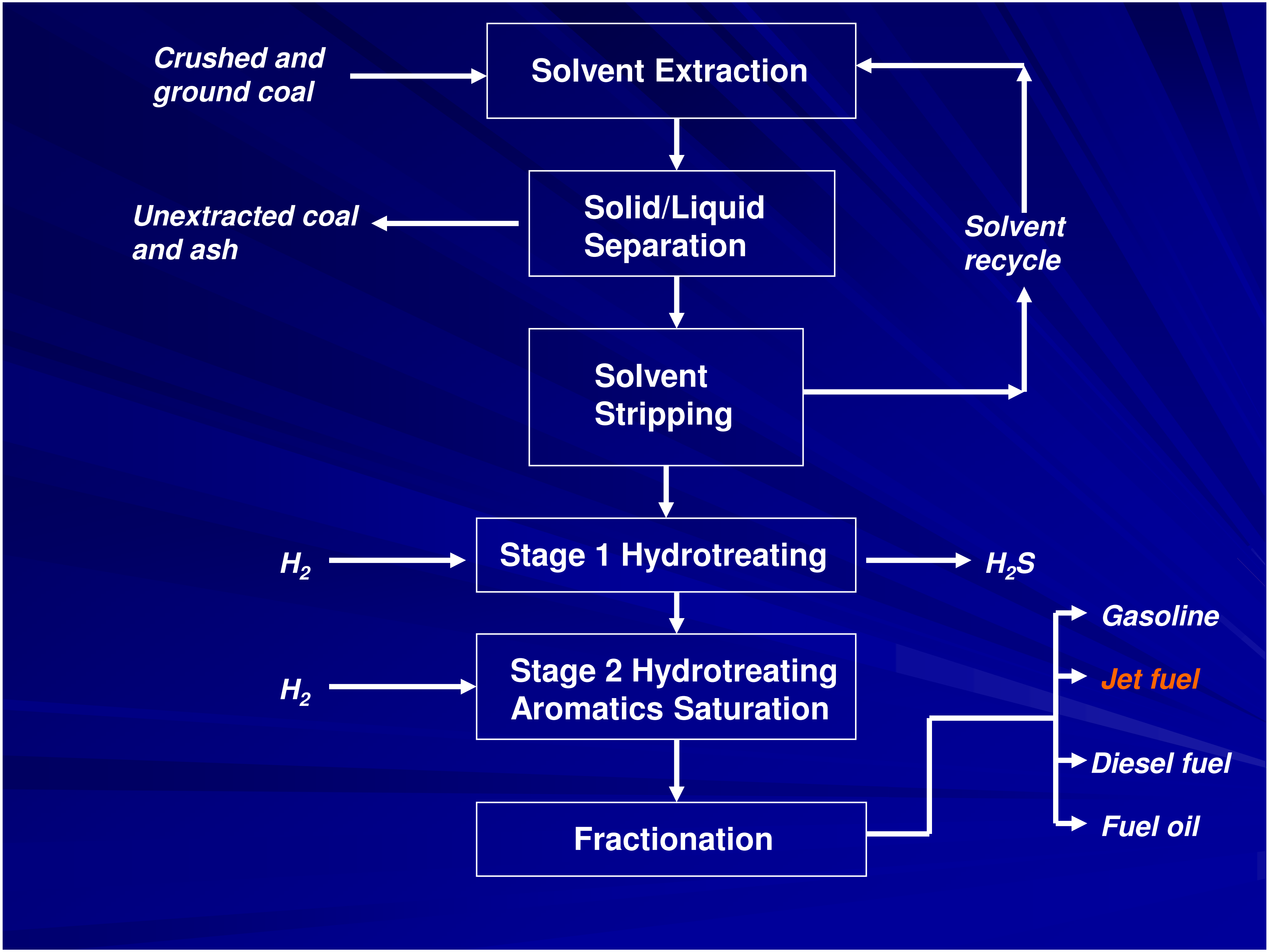
- By the time we had figured out the “recipe” for a high thermal stability, naphthenic jet fuel, it was the early to mid-1990s.
- At that time, interest in coal liquefaction technologies in public and private sectors of the U.S. was zero.
- We knew we had to find another way.

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

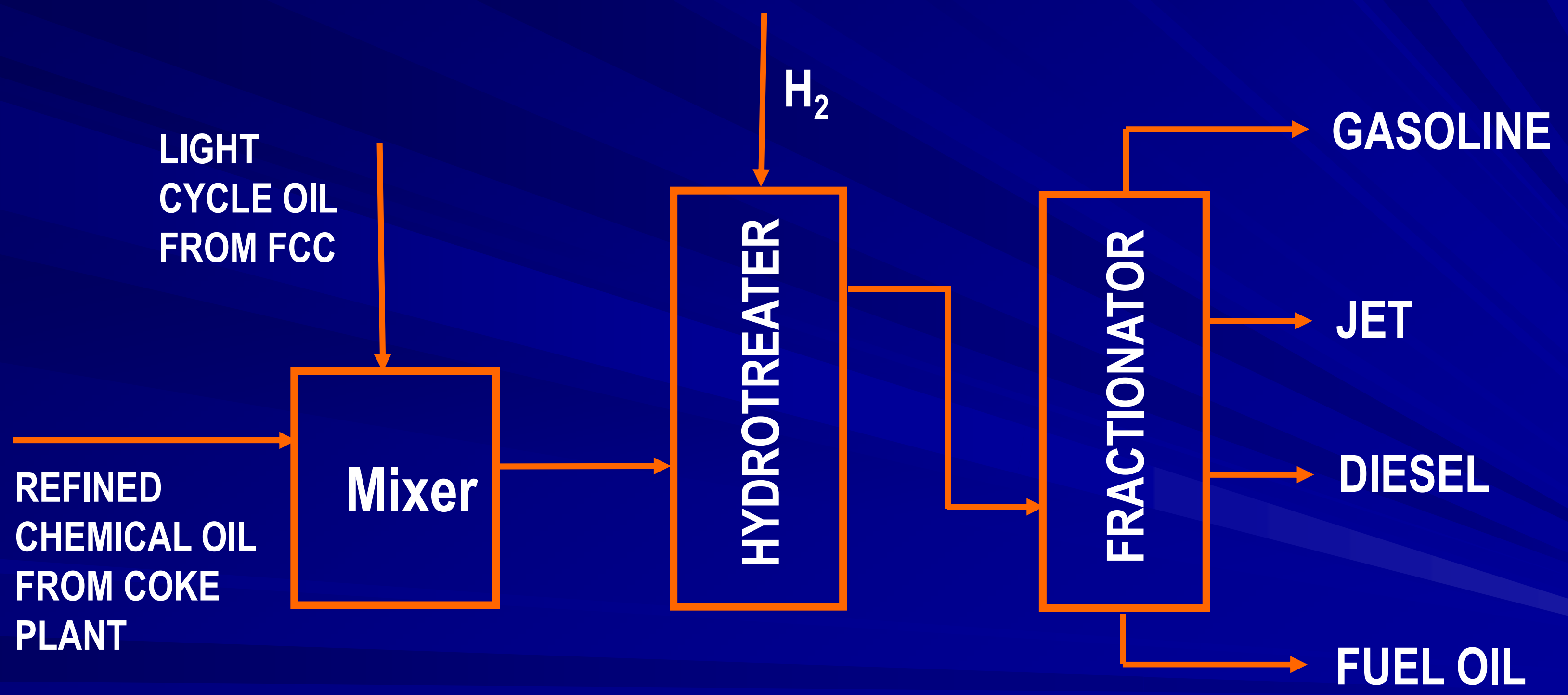
- The primary route selected was to use a liquid commonly available in oil refineries (light cycle oil) to extract the desired molecular components from coal.
- A secondary process would add coal to refinery units called delayed cokers. (It never hurts to have a "Plan B.")


Crushed and ground coal
Solvent Extraction
Solid/Liquid Separation
Unextracted coal and ash
Solvent recycle
Solvent Stripping
H_2
Stage 1 Hydrotreating
H_2S
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

	JP-8 spec.	JP-900 (actual)
Flash point, ℃	38 (min.)	61
Viscosity, cSt, –20℃	8.0 (max.)	7.5
Freezing pt, ℃	–47 (max.)	–65
Smoke pt., mm	19 (min.)	22

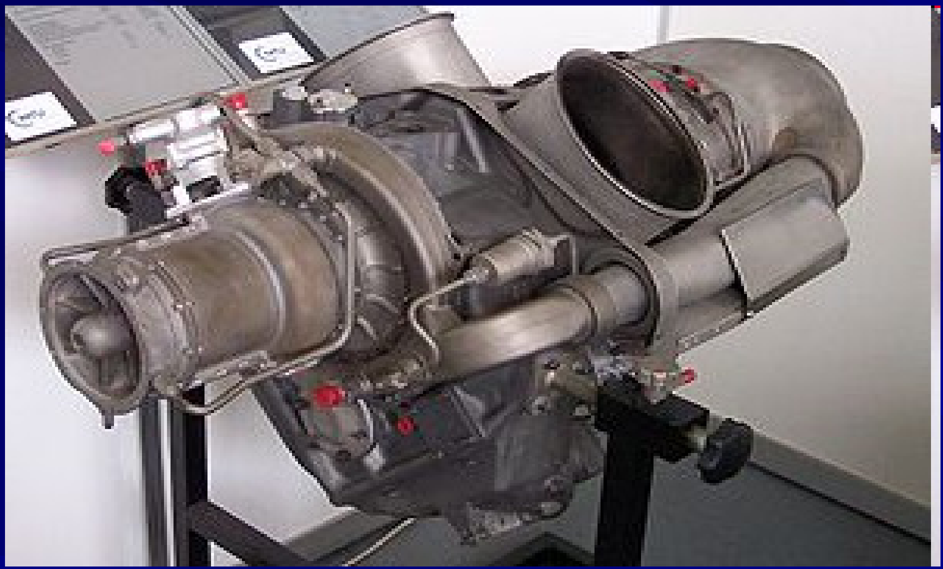
Partial Comparison of JP-8 and Prototype JP-900

	JP-8 spec.	JP-900 (actual)
Sulfur, wt. %	0.3 (max.)	0.0003
Aromatics, %	25 (max.)	1.9
Thermal stab.@ 260°C	25 mm (max.)	0
Calorific value, Btu/lb	18,400	18,401

The light dawns….

- Prototype JP-900 meets or exceeds almost all specifications for conventional Jet-A and JP-8.
- 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

- 8400 L of “second-generation” JP-900 burned in >100 engine cycles.
- Totally comparable with Jet-A.

The JP-900 Challenge—Part 2

- 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!*

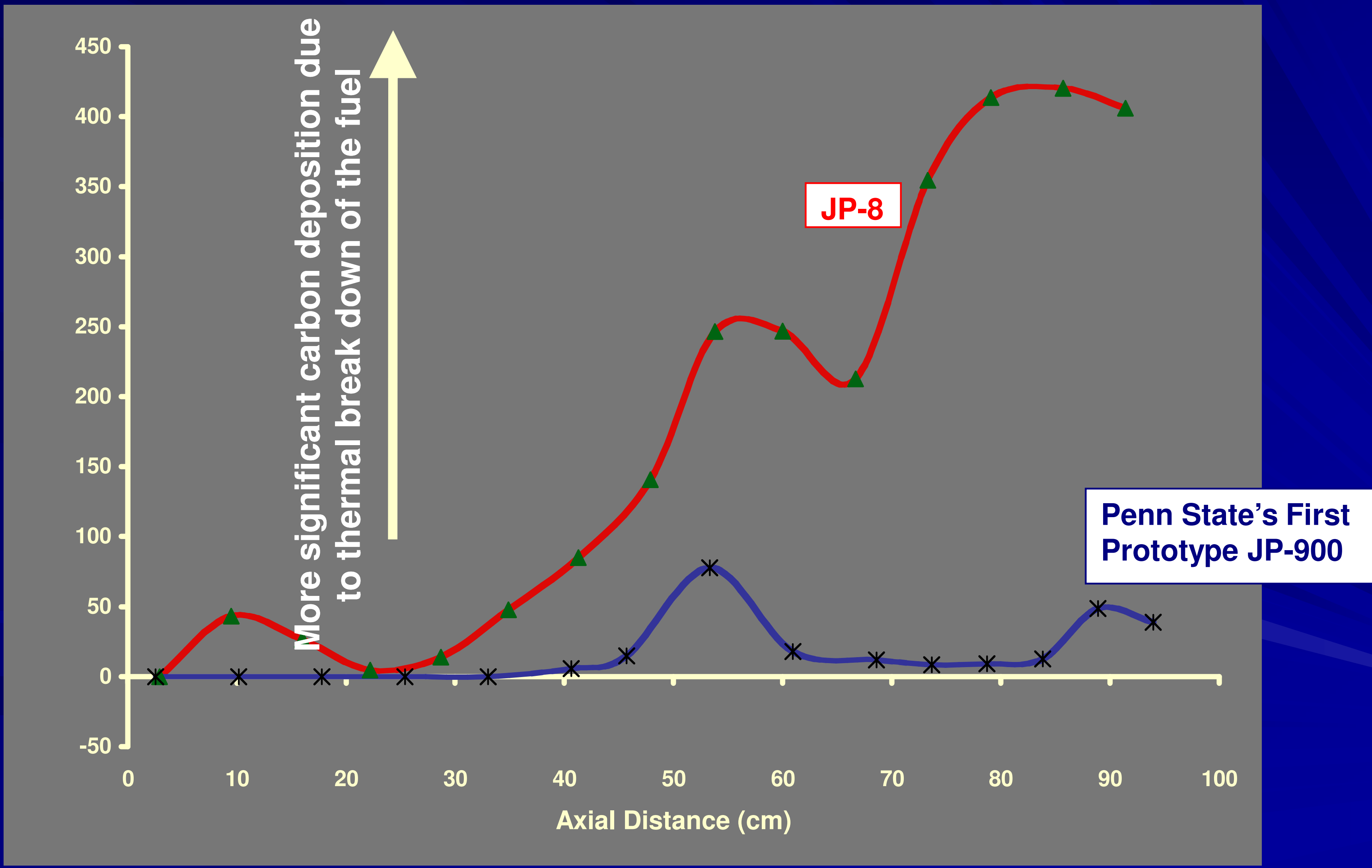
Batch Reactor Stability of JP-900

Comparison of stressed jet fuels

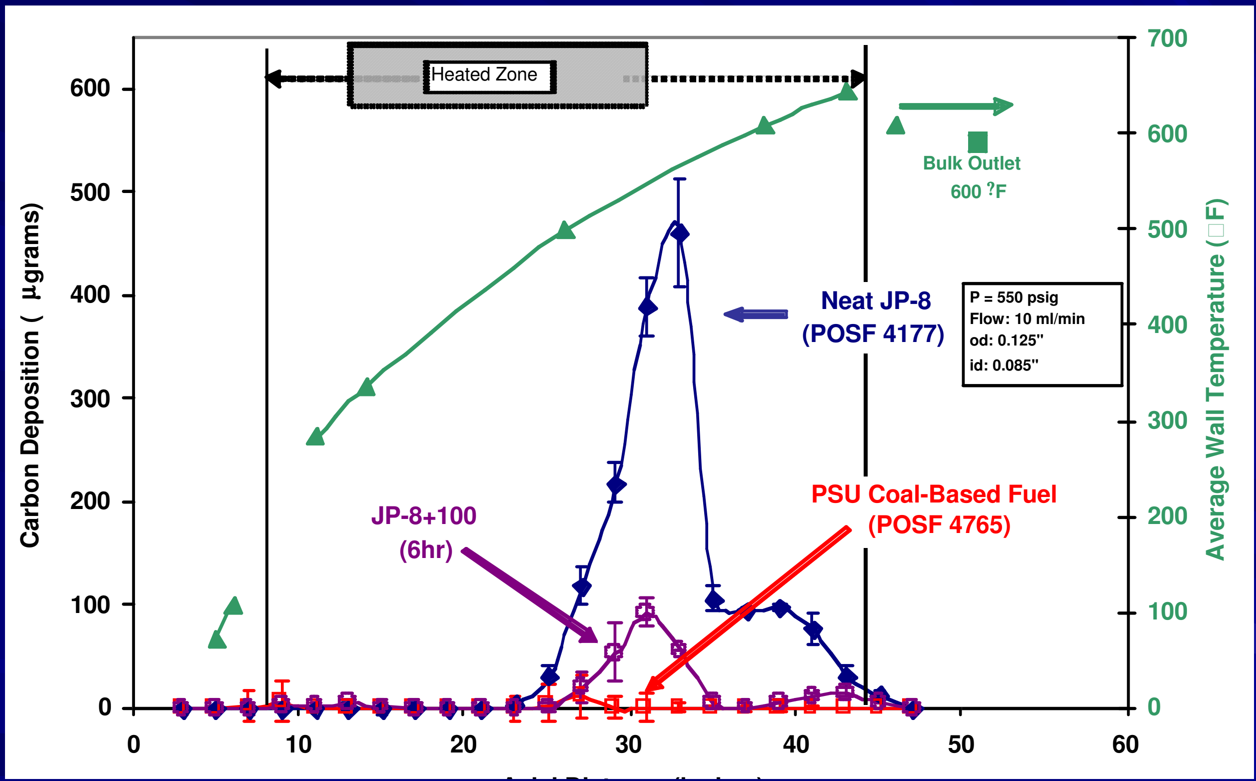
JP8		JP8+100		JP900	
Before	After	Before	After	Before	After

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



Flow Reactor Stability of Second-Generation JP-900



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

- JP-900 consists of the best combination of thermal stability, smoke point and combustion performance for operation in gas turbine 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/cm^2, JP-900 produces 0.40 V *vs*. 0.48 for JP-8.
- Under same conditions, H_2 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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