The Coal-Based Jet Fuel Program

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Prehistory of JP-900 program

- In the 1980s, the Air Force had a program to make a replacement JP-8 from the by-product coal tar from the Great Plains gasification plant.
- Congressman John Murtha asked PSU if there was anything we could do in the area of making jet fuel from coal.
- We already had a white paper (by HHS) on the prospect of making high volumetric energy density fuels from coal. The rest is history.

Fuel as on-board heat sink

- Advanced engine designs call for increased compression of air (ten-fold increase). The compressor outlet air becomes too hot to be cooled by external air. An on-board heat-sink is needed.
- Former Ass’t. Deputy Secretary Engle says that fuel for F-22 needs to be cooled before loading, and “we’re out of heat-sink capacity for the F-35.” The only practical solution is to use the fuel as both the propulsion energy source *and* the heat sink.
- Conventional JP-8 undergoes thermally induced cracking at 325 °F.

The JP-900 Challenge

- Development of a fuel with good heat-sink capabilities, initially for advanced military applications
- Original goals established by the Air Force:
  - Stable at 900^0 F for two hours
  - No more than 5¢ per gallon more expensive than JP-8

Plugged Fuel Lines: A Costly Maintenance Issue from Fuel Decomposition

The seminal experiment: Coal-derived JP-8 has superior thermal stability

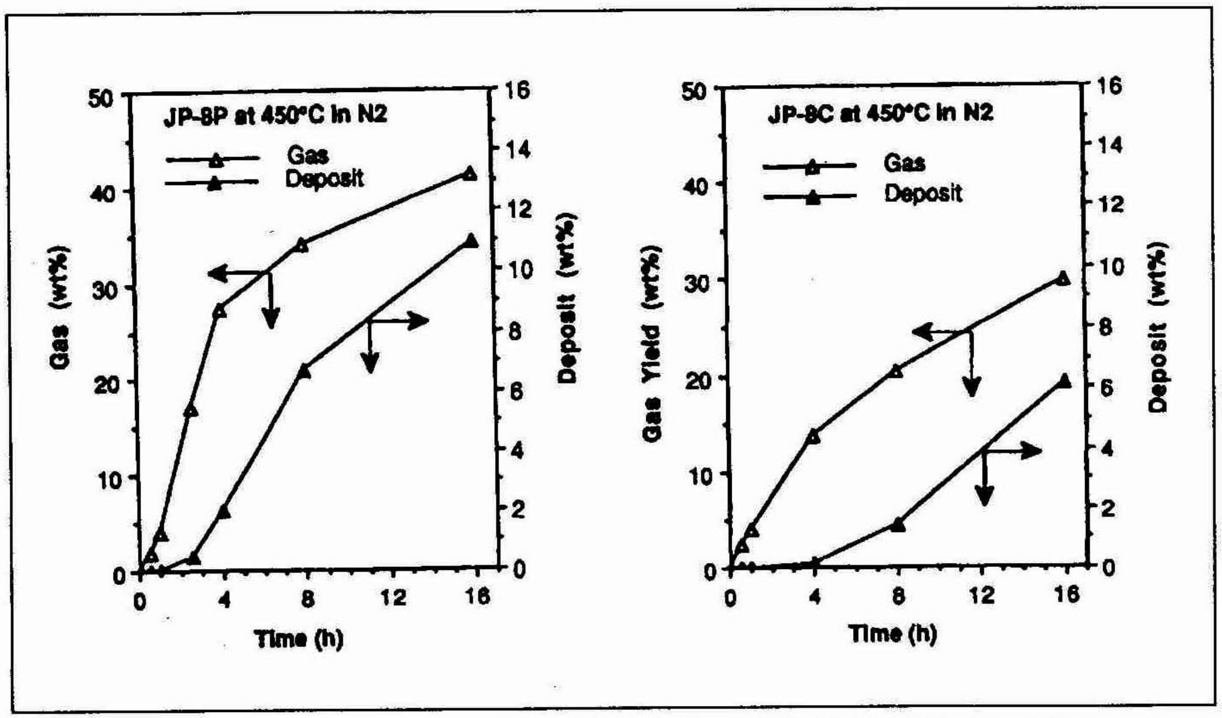


Figure 3. Formation of solid and gas from JP-8P (left) and JP-8C (right) fuels vs time.

- Both JP-8P and JP-8C meet specs.
- The difference in behavior at high temperatures must relate to differences at the molecular level.

Thermal stability from coal-derived molecules

- Both JP-8P (conventional JP-8 from petroleum) and JP-8C (from Great Plains by-product tar) meet standard specifications for JP-8. Yet JP-8C is greatly superior at high temperatures.
- This difference must come from differences at the molecular level.
- Our testing of ≈50 pure compounds showed that cycloalkanes and hydroaromatics have superior resistance to thermal decomposition.
- In principle, these molecules could readily be made from coal.

Original PSU/Air Force Program Plan

- In 1990, PSU presented a 15-year program plan for JP-900 development:

  Phase I: Developing scientific knowledge base: $10 M (5 years if funded at $2M/yr);

  Phase II: Developing engineering know-how in pilot plant: $50 M (5 years if funded at $10M/yr);

  Phase III: Construction of commercial plant: $2 Bn (5 years if wildly optimistic).

The Concept of a "Coal-Based" Fuel

- A coal-derived fuel is one produced entirely from coal.For our purposes, this would require the so-called direct liquefaction of coal.

- A coal-based fuel is one containing a significant proportion of components produced from coal, but also contains components from other sources, such as petroleum.

- The Penn State program now focuses on development of a coal-based jet fuel.This could take advantage of existing refinery infrastructure, and not require construction of an entirely new plant.

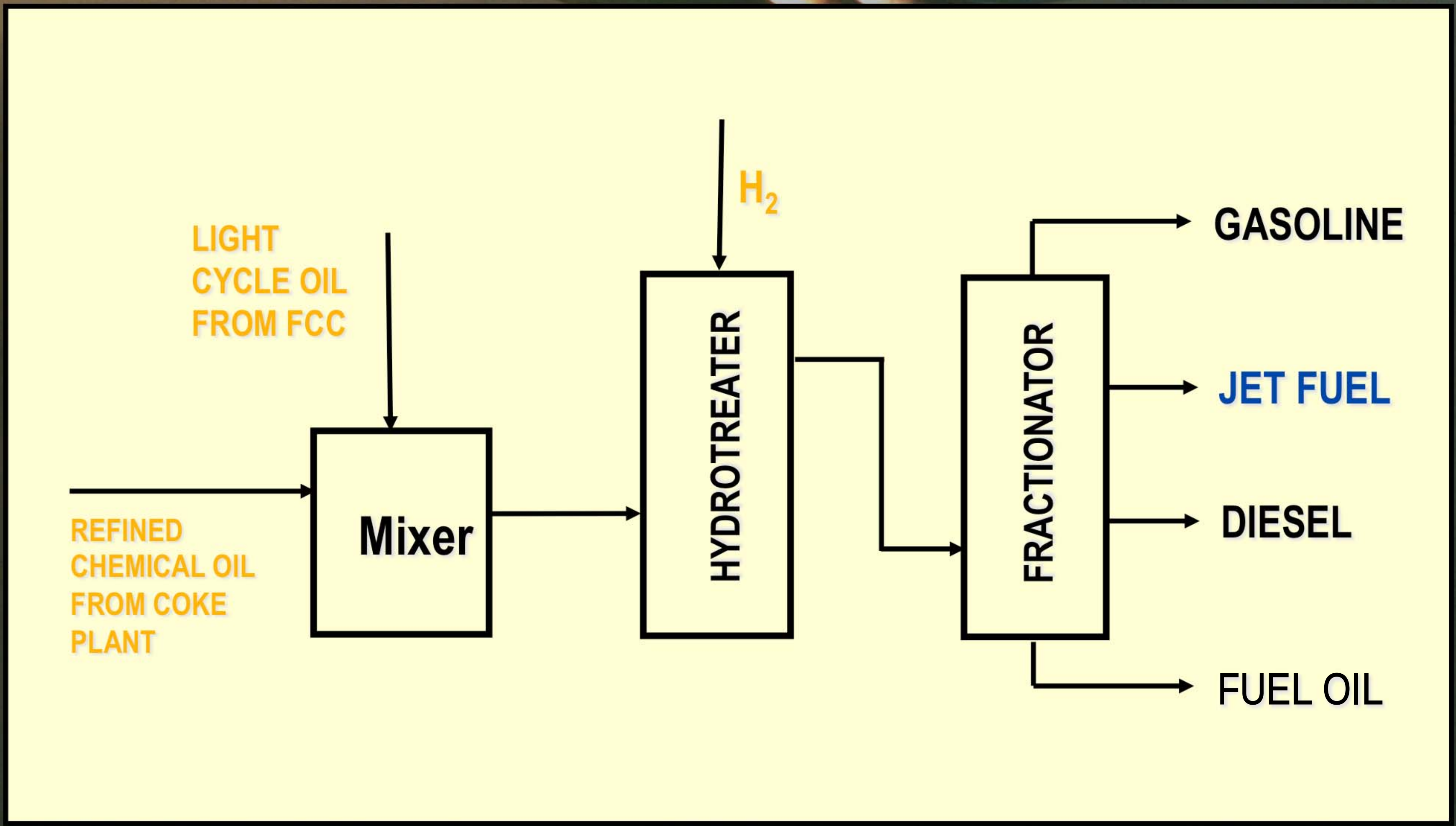
The PSU JP-900 Program Structure

- Fuel production: How do we make a coal-based JP-900 and develop its specifications?
- Fuel stability: How do we achieve the requisite high-temperature stability without compromising storage and low-temperature stability?
- Fuel combustion: How does the fuel burn in simulators or engines? What are the emissions?

The Two-fold Way: Process Routes to JP-900 Using Refinery Infrastructure

- Coal-tar blending: hydrogenation of mixtures of coal tar product (refined chemical oil) with refinery stream (light cycle oil).
- Co-coking: adding solid coal to delayed cokers with refinery stream (decant oil); downstream hydrogenation and fractionation of liquid.

Coal Tar Blending – Block Flow Diagram



Coal-tar blending: status

- Successful pilot plant operation (PARC Technical Services, Harmarville, PA) to produce prototype JP-900 in multiple 55 gallon drum quantities.
- Recent production was ten drums (8 shipped to AFRL).
- Prototype fuels meet most JP-8 specifications but have greatly superior thermal stability.

Hydrotreating Pilot Units at PARC

Partial Comparison of JP-8 and Prototype JP-900

	JP-8 spec.	JP-900 (actual)
Flash point, °C	38 (min.)	61
Viscosity, cSt	8.0 (max.)	7.5
Freezing pt, °C	–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.	25 mm (max.)	0
Calorific value, Btu/lb	18,400	18,401

Long-term Supply Issues for Refined Chemical Oil

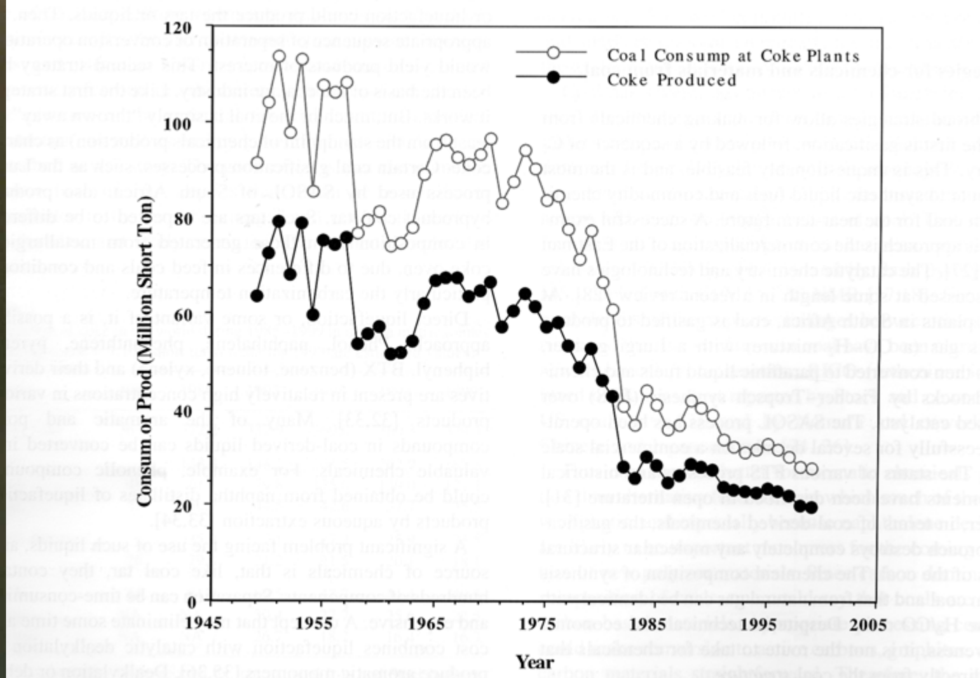
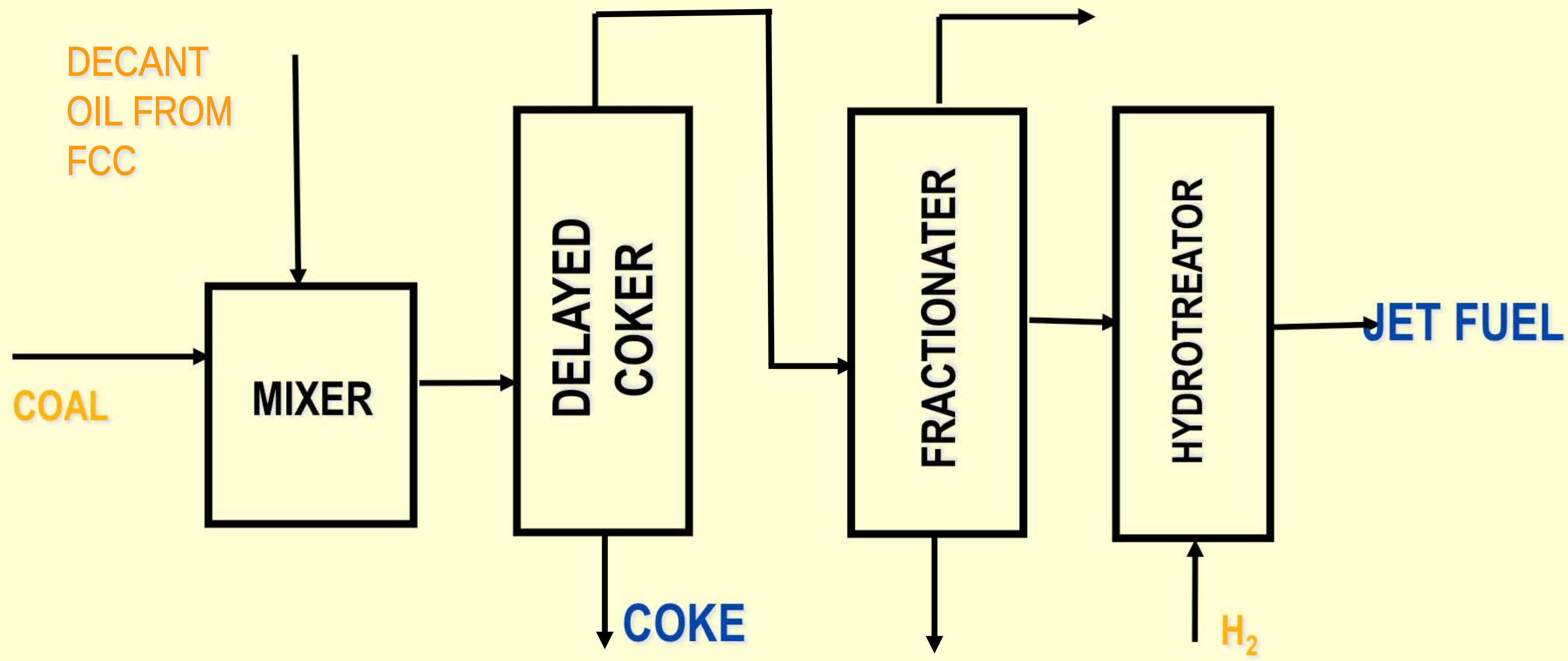


Fig. 6. US coal consumption at coke plants and metallurgical coke production during 1945–1999 (1 short ton = 0.907 metric tonne).

- Consider a "non-coke-oven" route to RCO. The current focus of our research is on solvent extraction of coal.
- Consider an alternative route to coal-based JP-900 that does not use RCO. This is the co-coking option.

Co-coking: Block Flow Diagram



Co-coking: status

- We have completed a first scale-up of the coker from the original bench-scale unit.
- We can make long-duration runs which simulate delayed coker operations, and produce quantities of liquid and solid products for further testing.
- Next goal is further scale-up to pilot-plant operation.

Premium carbon products from co-coking

- In addition to coal-based JP-900 and other distillate fuels, we also aim to produce a premium coke product.
- The value of the by-product coke could be a sufficient economic benefit to help meet our cost target for JP-900.
- Coke applications being evaluated at present are for aluminum-smelting anodes and for synthetic graphite.

Fuel Stability Studies

- Batch reactors are used for scouting studies, and in flow reactors to simulate fuel-line conditions.
- Fuel additives have been studied to achieve additional stability.
- Effects of materials (alloys) for fuel systems have been studied.

Batch Reactor Stability of JP-900

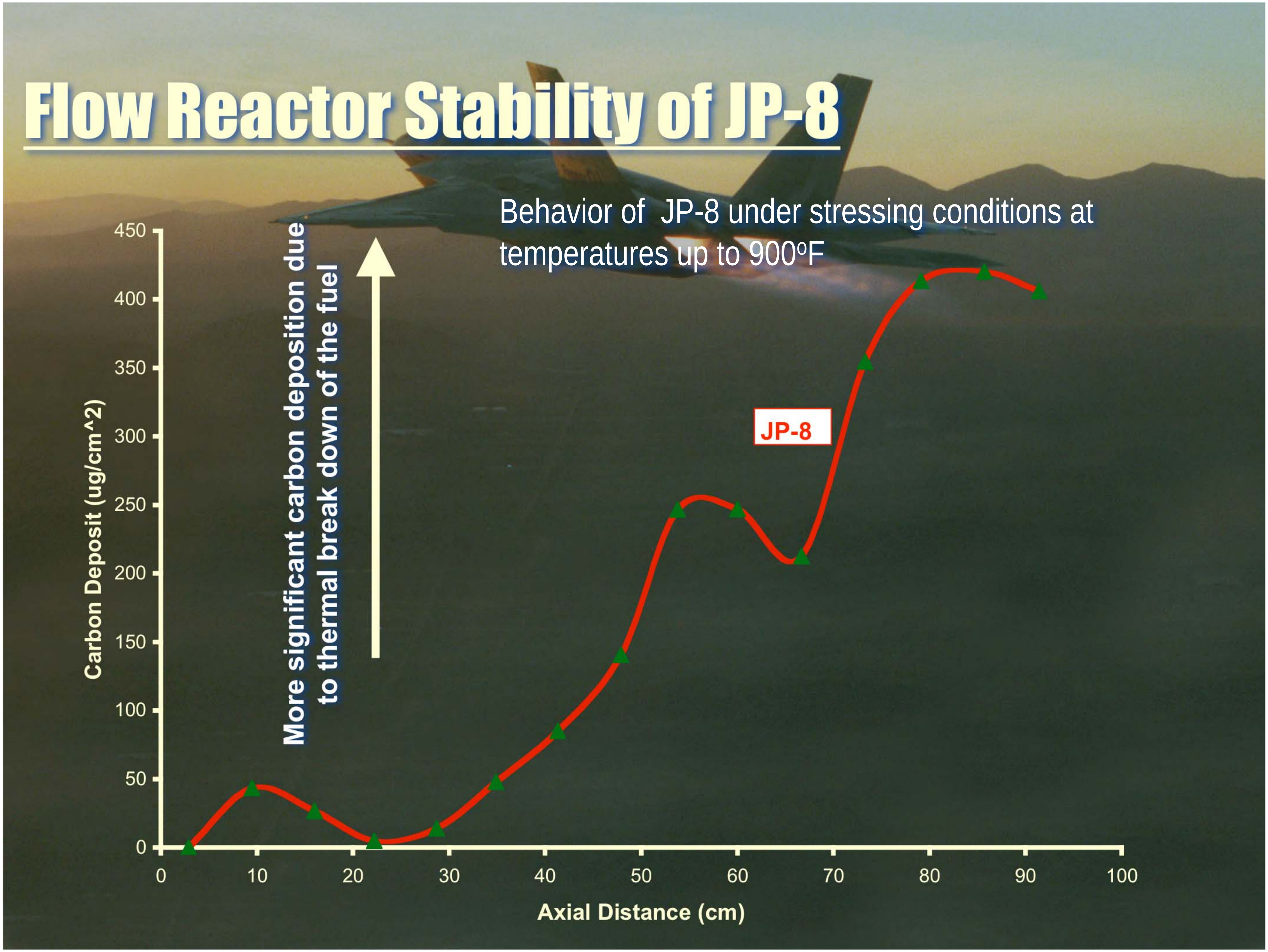
Comparison of stressed jet fuels

JP8
Before After

JP8+100
Before After

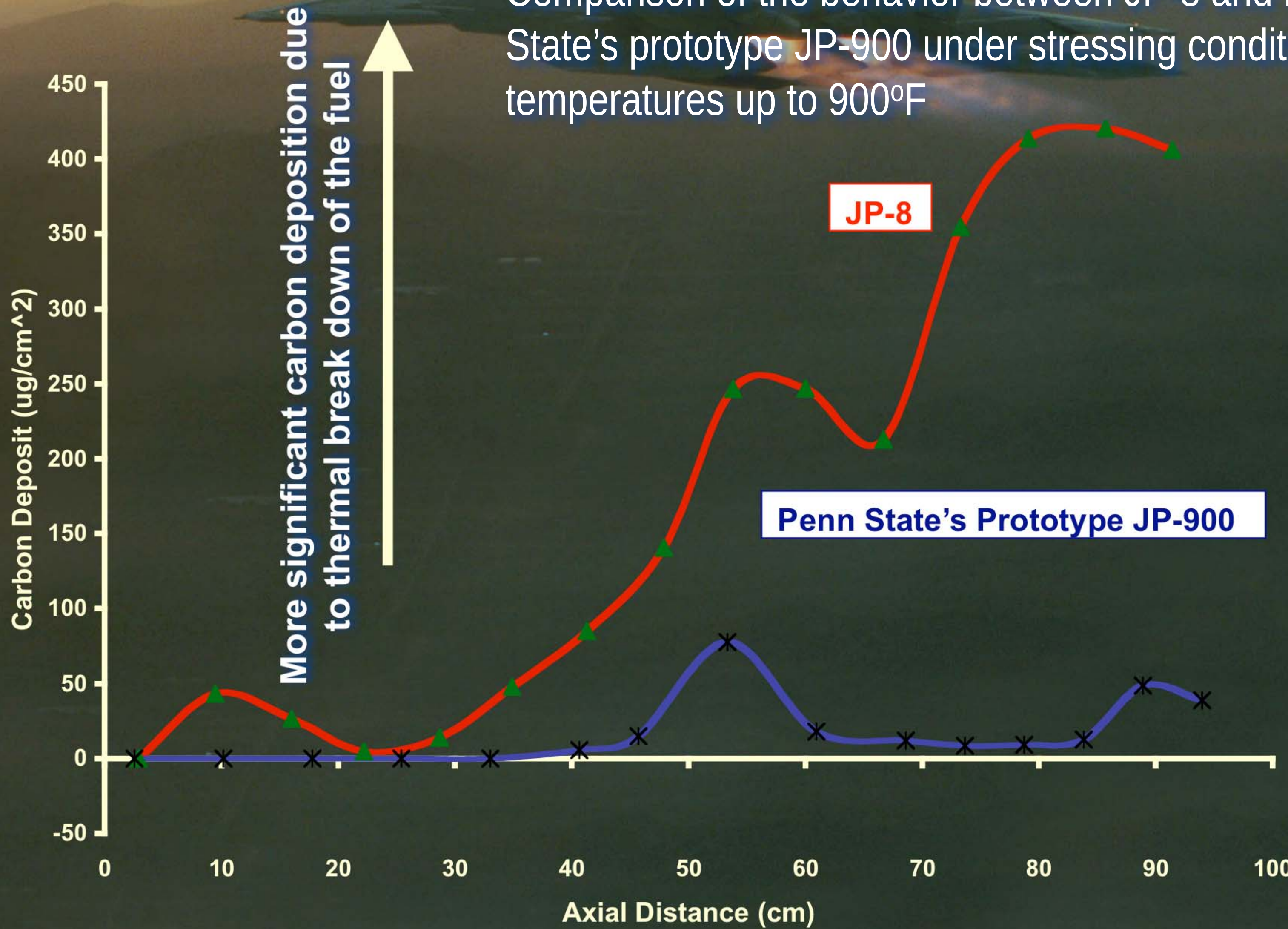
JP900
Before After

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-8
Behavior of JP-8 under stressing conditions at temperatures up to 900ºF
More significant carbon deposition due to thermal break down of the fuel
JP-8
Carbon Deposit (ug/cm^2)
0
50
100
150
200
250
300
350
400
450
Axial Distance (cm)
0
10
20
30
40
50
60
70
80
90
100

Flow Reactor Stability of JP-900

Comparison of the behavior between JP-8 and Penn State's prototype JP-900 under stressing conditions at temperatures up to 900°F

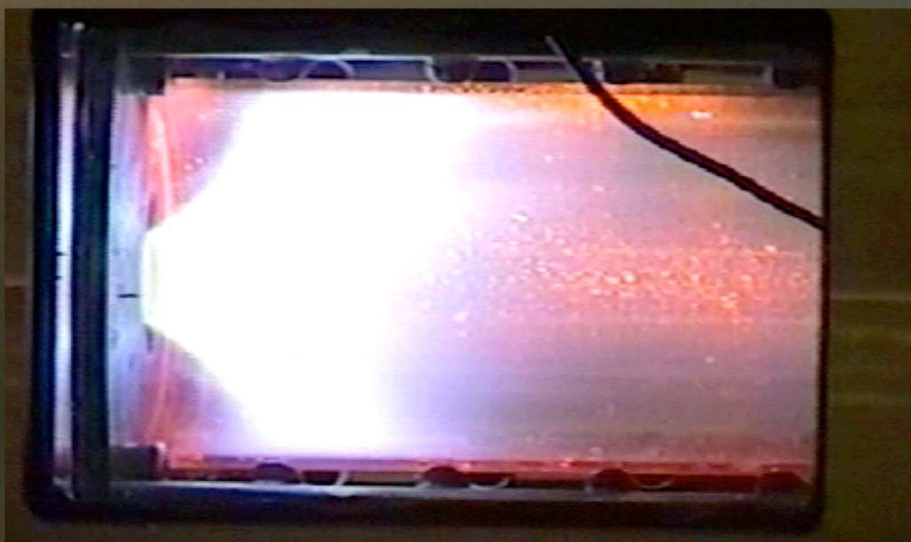


Fuel Combustion Studies

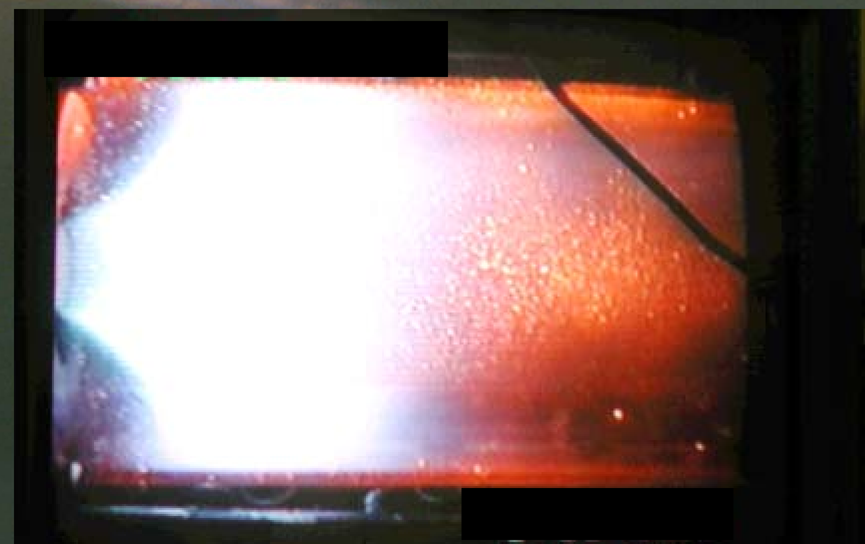
- Current tests are being done in gas-turbine simulator at PSU.
- We have completed a test in a T-63 helicopter engine and in a gas-turbine simulator at AFRL.Joint AFRL/PSU/UDRI manuscript submitted to journal.
- The long-term goal was a full-scale engine test.

Coal-derived Fuel Combustion

JP8/Air



JP-900 prototype/Air



FLOW →

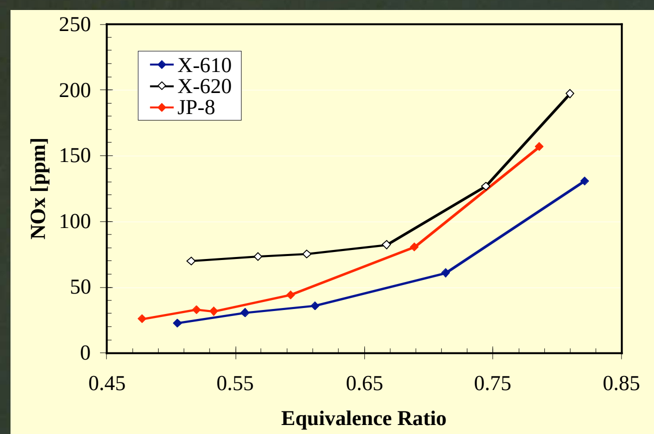
Combustion at 5 Atm Pressure for a Swirl Injector in an Optically-accessible Gas Turbine Chamber at PSU.

Emissions from JP-900 Combustion

Sulfur oxides

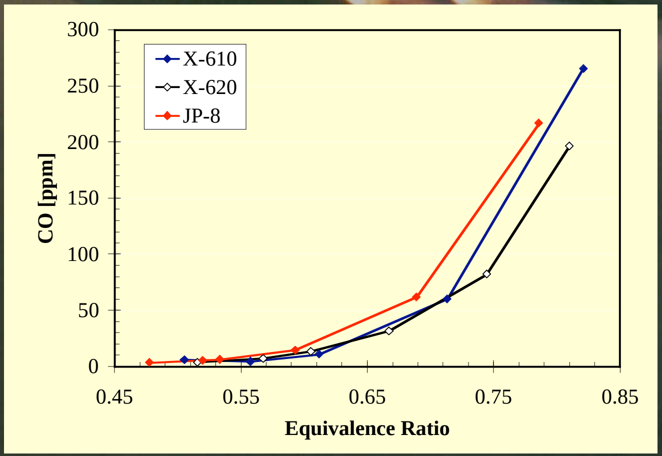
- JP-900 sulfur content (3–7 ppm) is substantially below present JP-8 specifications.

Nitrogen oxides



Emissions from JP-900 cont'd.

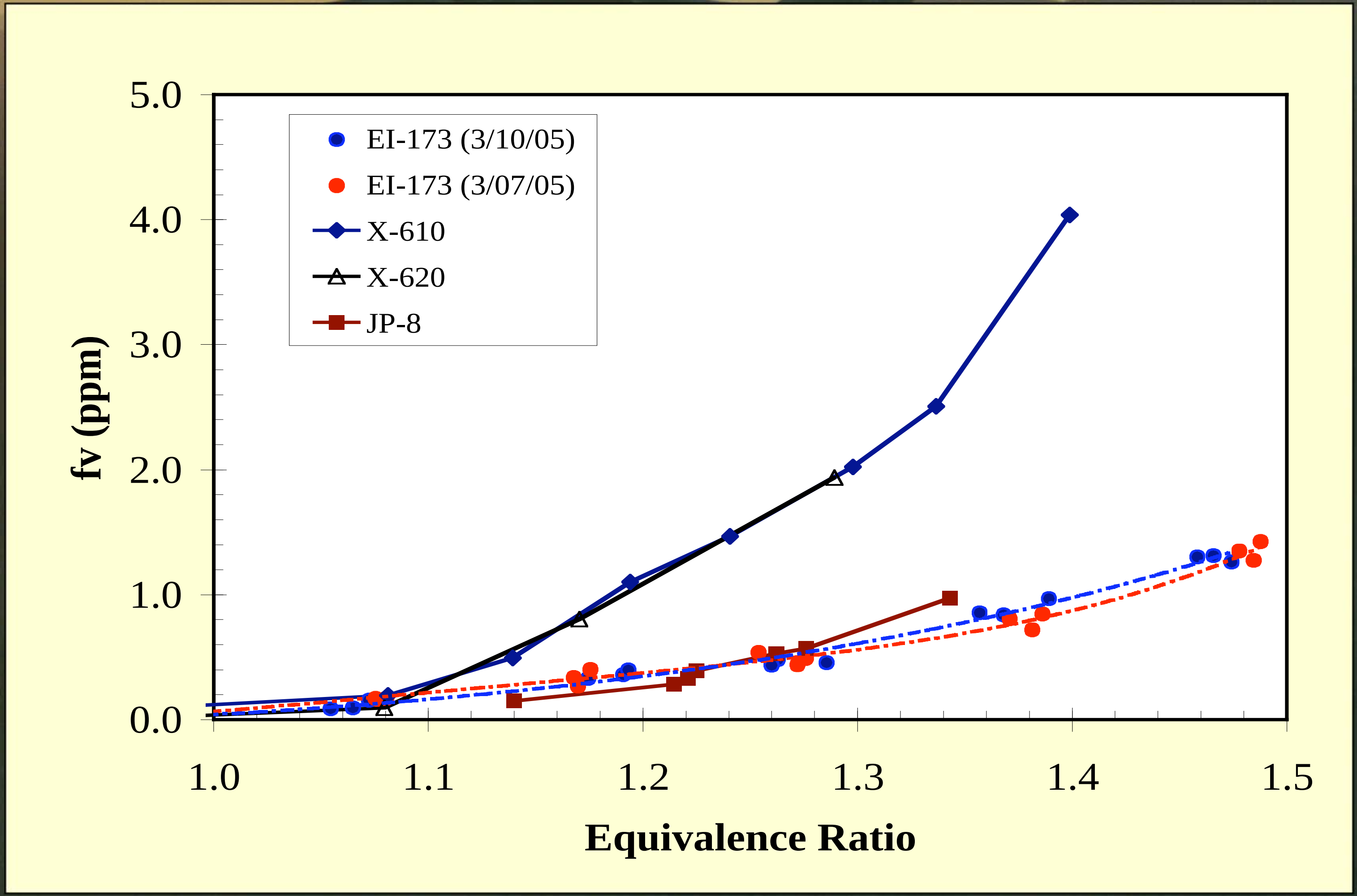
Carbon monoxide



Soot

- Smoke point data from most recent batch of fuel are consistent with JP-8 specifications.

Recent soot data on JP-900



Future Directions: Uni-fuel

- JP-900 has been developed as a gas-turbine engine fuel.
- Preliminary data suggest that, with minor modifications, diesel engines could run on JP-900.
- Preliminary data also show that solid-oxide fuel cells can be run on straight JP-900 (i.e., without a reformer).
- JP-900 could be a universal battlefield or front-line fuel.

JP-900 as fuel for CI engines

- JP-900 fuel will consist of the best combination of thermal stability, smoke point and overall combustion performance for operation in gas turbine engines.

- A JP-900 fuel engineered to meet the smoke point specification should be an adequate diesel fuel, but may require some change in injection timing on the engine or addition of a cetane improver to achieve desirable ignition characteristics.

JP-900 as fuel for SOFCs

- Preliminary tests show roughly 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.

Future Directions: Universal Jet Fuel

- JP-900 meets or exceeds virtually all specifications for JP-8 tested so far. It could be a drop-in replacement for JP-8 (Air Force and Marines).
- JP-900 has the high flash point characteristic of JP-5 (Navy).
- JP-900 has the thermal stability of JP-7 (specialty fuel for SR-71 Blackbird).
- JP-900 has the high volumetric energy density of JP-10 or RP-1 (missile fuel).

The "Fuel of the Future" Becomes the "Fuel of Now"

A major development of the Penn State Jet Fuel program is the ability to produce coal-based jet fuel using existing oil refinery infrastructure (with some retrofitting). All of the production steps are consistent with current refinery operations.

This means —

- it is not necessary to construct new plants for the liquefaction of coal —a savings of $2 billion per plant;
- it is not necessary to focus on a fuel for which engines have yet to be developed

The "Fuel of the Future" Becomes the "Fuel of Now"

- We can begin to displace conventional petroleum-derived jet fuel with fuel containing 50% (or more) of coal components.
- We can reduce our reliance on imported petroleum.

And, *at the same time*, have a fuel that meets or exceeds the Air Force's most stringent requirements for high-temperature stability.

Why Coal? Why Now?

Science

- Abundant Penn State research results show the fundamental chemical reasons for fuel stability provided by molecules from coal.

National policy

- Increased reliance on coal is consistent with the President’s energy policy.

International tensions

- Both the Middle East and Venezuela are currently in turmoil. These two regions are among our largest sources of imported oil.

Why Coal? Why Now?

Domestic economy

- Currently, $800 million per day flow out of the U.S. economy for oil imports. Every $1 worth of oil imported from the Persian Gulf was said to cost DOD $2 to protect (pre-Afghanistan, pre-Iraq!).

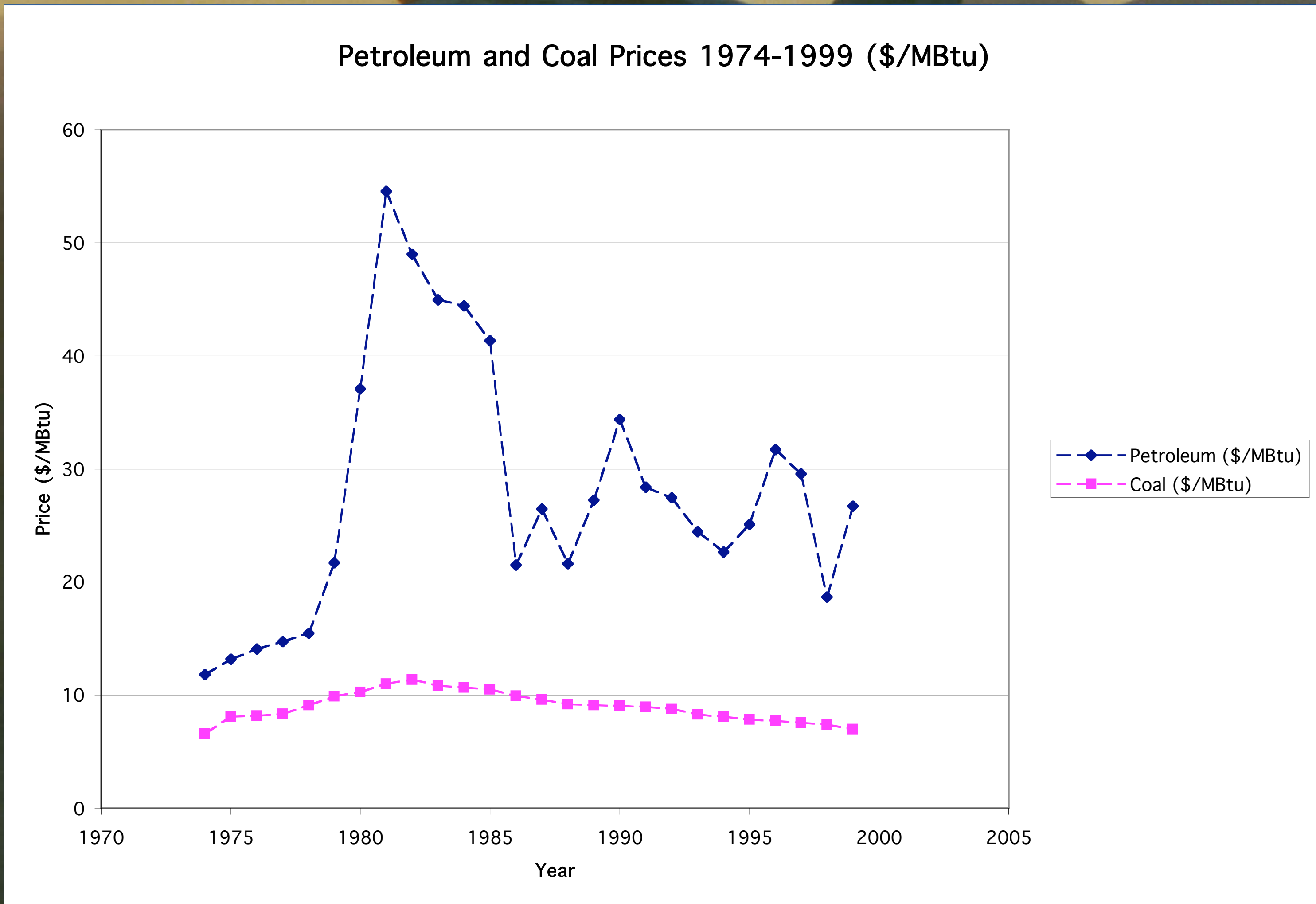
- Locally, a healthy coal industry has a positive economic impact on rural areas and small towns.

Coal—Long-term Security at Low Cost

- Coal is cheapest hydrocarbon energy source, on a dollars-per-unit-energy basis. It is also a secure, domestic resource.

- Coal is also the only energy source for which it is possible to obtain long-term supply contracts at guaranteed price. Contracts can be set up for at least 20 years; in some cases, for “life-of-mine.”

Historical Stability of Coal Prices

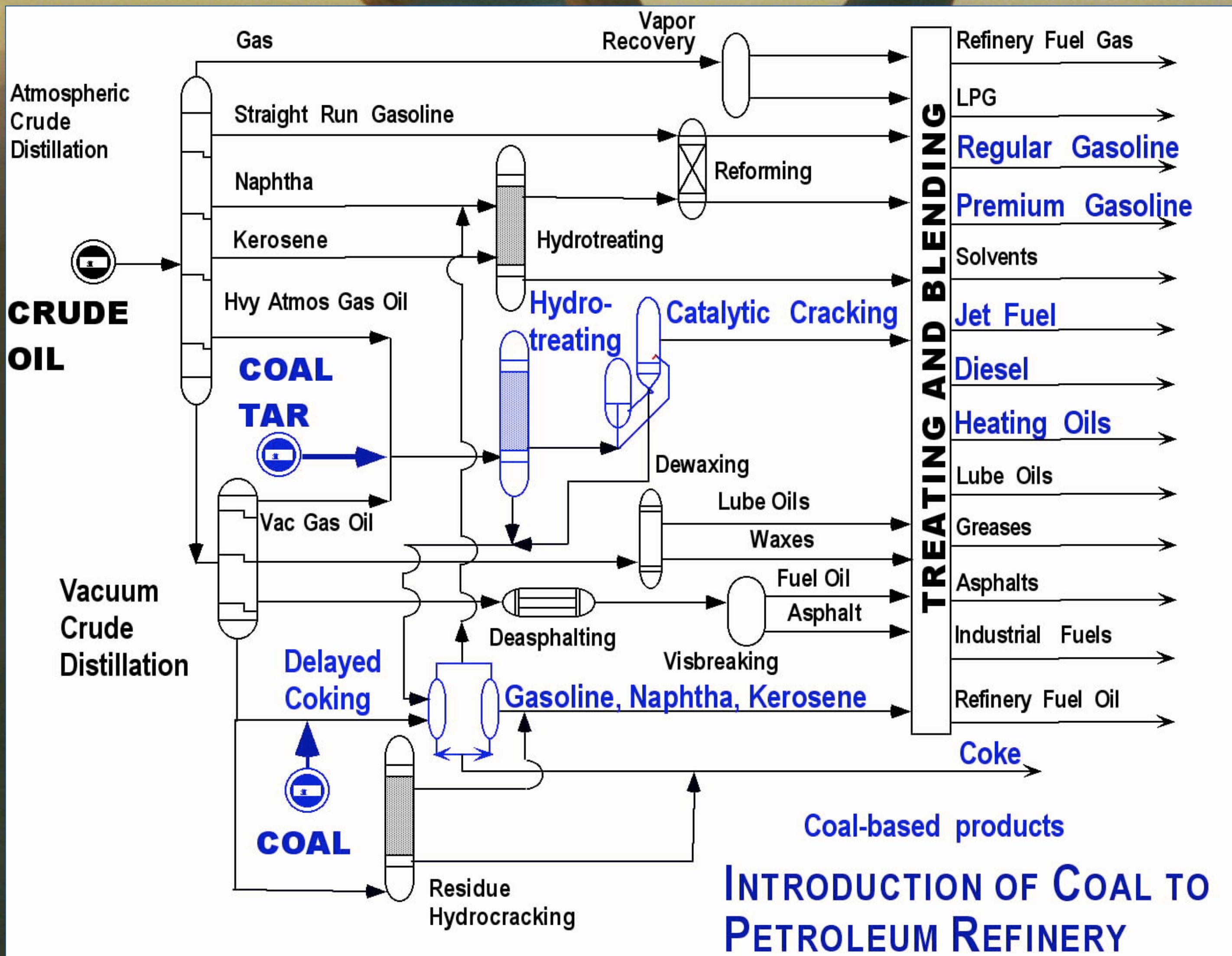


Refinery Integration

- No oil refinery is run just to make jet fuel. Other products include gasoline, diesel fuel, heating oil, and coke.

- To have coal-based fuel production integrated into a refinery, it is important to evaluate the yields, quality, and uses of the other products that come from the JP-900 processes. Can they be incorporated into the normal refinery output? Do they have special value?

Refinery Integration



Refinery Integration Project Scope

The Refinery Integration project seeks to examine the "non-jet fuel" products: gasoline, diesel fuel, heating oil, and coke.

Coke applications being considered at present are aluminum-smelting anodes and synthetic graphite.

Properties of Laboratory-scale Anodes from "Co-coke"

	Sample	Target
Baked density, g/cc	1.53	1.54
Resistivity, μΩm	57.0	55.5
Permeability, nPm	1.76	2.00
Crush strength, MPa	31	40-55
Flex strength, MPa	6.6	11
CTE	4.64	4.5
Thermal cond., W/mK	3.0	4.0
CO_2 wt. loss, %	6	4-10
Air wt. Loss, %	9	8-30

X-ray Parameters of Laboratory-scale Graphitized "Co-coke"

	Samples	Synthetic Graphites
d-Spacing, Å	3.354-3.360	3.354-3.360
Crystallite height, Å	246-310	100-500

Start Now and Grow

Coal-based fuel production can be achieved in existing refineries with minor modification.

Therefore, there is no need for a complete conversion of the aircraft fleet all at once to a new fuel. And, there is no need for the construction of new, large, fuel-production plants.

Rather, the coal-based fuel concept allows us to start even with one refinery and one base, and gradually convert fuel production and fuel logistics as needs dictate.