

EXPERIMENTAL STUDY OF TURBINE FUEL THERMAL
STABILITY IN AN AIRCRAFT FUEL SYSTEM SIMULATOR

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INTRODUCTION

An experimental program has been conducted under contract NAS3-21593 to investigate the thermal stability of aircraft gas turbine fuels. The objectives of this program were (1) to design and build an aircraft fuel system simulator, (2) to establish criteria for quantitative assessment of fuel thermal degradation, and (3) to measure the thermal degradation of Jet A and an alternative fuel. Accordingly, an aircraft fuel system simulator has been built and the coking tendencies of Jet A and a model alternative fuel (No. 2 heating oil) have been measured over a range of temperatures, pressures, flows, and fuel inlet conditions.

TEST APPARATUS

A complete fuel coking assembly, consisting of fuel delivery system, simulator unit, and controller was designed and constructed under this program. The entire apparatus is shown schematically in Fig. 1. The fuel delivery system, shown schematically in Fig. 2, provided the option of preheating or deoxygenating fuel with storage at ambient or elevated temperatures. A heat exchanger charged with steam at 1.04×10^6 to 2.07×10^6 Pa (50 to 100 psi) was used to preheat the fuel which was stored in an insulated tank. Deoxygenation was conducted at room temperature in the holding tank by sparging for 12 hours or longer with nitrogen gas supplied by boil-off from liquid nitrogen. Run pressures of 6.9×10^5 to 2.07×10^6 Pa (100 to 300 psig) were set by Grove regulators; flows were measured with calibrated turbine meters.

The simulator test unit shown in Fig. 3 was designed to represent an aircraft nozzle/strut assembly, and incorporated provisions for (1) an isothermal wall, (2) variable test parameters, and (3) convenient change of specimens used for characterization of deposit rate by weight gain. Experience at United Technologies Research Center had shown that the weight gain of metal specimens immersed in thermally stressed fuel can be determined accurately, even for short test periods. Resolution of $1 \mu\text{g}$ is easily attained with an electrobalance. In order to apply this method to the present problem, a means of placing preweighed specimens in the heated wall was devised which does not cause

the flow to be disturbed significantly. This requirement was satisfied by using a rectangular channel and flat specimens. Various materials and surface characteristics can thus be examined.

A schematic representation of the fuel nozzle/strut simulator design is shown in Fig. 3. Two closely fitted blocks of high conductivity Beryllco[®] form a channel of nearly constant wall temperature. Upper and lower block temperatures are regulated independently. The channel flow may be laminar or turbulent, and the fuel can be heated to 533 K in either case. The heated fuel flows through a transition section and nozzle and subsequently dumps into a large cavity (not shown). The cavity walls are fitted with windows to allow photographing the spray. Nozzles are removable and can be inspected after each run. Deposit formation rate is determined quantitatively by measuring the weight gain of the implanted metal discs. The discs are clamped between two plates in a modular arrangement, and the entire assembly is bolted to the lower heating block. Four discs spaced uniformly along the duct allow the axial dependence of coking rate to be determined. Mounting and dismounting of the discs can be done away from the apparatus. Disc diameter is set by the minimum weight gain predicted for a four hour test at 422 K. The entire test assembly was nickel plated at a thickness of ~ .001 inch and overplated with gold to a thickness of ~ 50 microinch. Only working surfaces were subject to a thickness specification, but the entire assemblies were plated. Except for outer-surface wear due to handling, no gold was lost from test areas. Sample discs were 302 stainless steel.

The control system utilizes the following system blocks: (1) two flow-meter conditioners, (2) two pressure transducer conditioners, (3) a Fluke data logger with printer, (4) control and interlock panel, (5) three temperature controllers, and (6) three SCR heater power controllers with transformers. The data logger was programmed to print run conditions every five minutes. The print included date, time, two metered flows and pressures and readings from 28 thermocouples which monitored temperatures of each of the two blocks (7 axially distributed thermocouples), the four modules, fuel at a number of locations, and heater and storage tank and ambient air. Additional full prints or continuous monitoring of individual parameters were also optional. The eight heaters were 0.61 meters (24 inch) long x .01 meters (.375 inch) in diameter Chromalox units rated at 1500 watts each. Four were inserted into each half of the test assembly. Each bank of four was controlled by one time-proportioning LFE controller in the console. A single thermocouple at the geometric center of the cover or base furnished a control signal. The rate of heating depended upon desired temperature and flow rate; heating rate was approximately 0.5 K/sec.

One of the aims of this program was to provide baseline tests with Jet A and comparison tests with ERBS fuel. Properties of Jet A and ERBS are listed in Table I. Principal differences are the higher aromatic and naphthalene content. However, ERBS (Experimental Reference Broad Specification Fuel) is not readily available and a commercial substitute was sought. Number 2 Home Heating oil (No. 2 HH) was estimated to be an excellent representation of ERBS, except for a slightly higher aromatic level. Analyses of Jet A and the No. 2 HH used are shown in Table I. The Jet A complied with all ASTM D-1655 requirements, except for the aromatic content of 21.7%. A temporary waiver to 22% is in force, however, and the experimental fuel thus fulfills all requirements. The No. 2 HH provided good representation of ERBS, with thermal stability lying between Jet A and ERBS.

The range of variables employed in the tests is given in Table II. Fuel flows were varied from 2.14×10^{-3} to 21.4×10^{-3} kg/sec (2.5 to 25 gal/hr), temperatures from 422 to 672 K (300 to 750 F), and pressures from 6.9×10^5 to 2.07×10^6 Pa (100 to 300 psig) for as-received fuels. In addition, fuels were preheated to 422 K and stored, or were deoxygenated before use. Samples of fuel were collected after passage through the test section; little difference was found in composition compared to inlet fuels. Reynolds numbers ranged from 800 at the inlet (for flow of 2.14×10^{-3} kg/hr and ambient temperature fuel) to 34,290 at the outlet (for flow of 2.14×10^{-3} kg/sec with preheated fuel).

RESULTS

Experiments with Jet A Fuel

Experiments were conducted to investigate the effects of fuel type, wall temperature, flow rate, pressure, deoxygenation, and preheating on coking rate. The coking rate for Jet A fuel is shown as a function of wall temperature, flow rate, and axial position in Fig. 4; the results of deoxygenation are also included for comparison. Inlet temperature for these tests is approximately 294 K. For the lowest temperature and flow rate, curve (a), maximum coking rate is found at the location of the second sample disc. The maximum rate is approximately twice the minimum. With increasing temperature and velocity, curve (b), the maximum rate is found at the next position downstream, and the rate is greater. Large increases in temperature at low flow produce even higher rates, curve (c). The highest rate occurs before the first sample disc because of the very rapid change in rate with temperature. Thus, no maximum rate is indicated. Deoxygenation of fuels produces very low coking rates with a relatively flat distribution.

The dependence of maximum coking rate on temperature is given in an Arrhenius plot in Fig. 5. Curves are shown for flows of 2.14×10^{-3} and

6.85×10^{-3} kg/sec. The overall activation energy at 2.14×10^{-3} kg/sec is 9 kcal/mol, in reasonable agreement with previous work (Ref. 1). The point at 672 K has not been used in placing the curve since the maximum rate actually occurred prior to the first sampling location, as shown above. As expected, the indicated point lies below the curve. It is seen that at higher flow rate, the coking rate is lower at the same wall temperature, yet the dependence on temperature (activation energy) is approximately the same. The lower rate at increased flow points out the importance of liquid-phase heating and homogeneous reaction effects on the formation of deposits. In both cases the magnitude of activation energy suggests a surface-catalyzed process. Taken together, the two curves of Fig. 5 suggest that an Arrhenius expression is reasonable for the description of coking rate over the range of temperature indicated. Therefore, it appears that the effect of preheating the fuel to 422 K (300 F) for 1 hour, as indicated by a single point, is to lower the coking rate. No conclusive explanation for this result is available, but it is possible that deposit precursors are removed in the fuel system prior to exposure to the hotter reaction surface or that bulk phase reactions are not important at this temperature level. The results in Fig. 5 may also be compared with the results of previous "isothermal" tests conducted at UTRC, where the fuel was rapidly heated before reaching the working section, and coking was measured at conditions of equal wall and fluid temperatures. The UTRC results lie well below the present results, although the temperature dependence is nearly the same. Because of the bulk fluid heating effect which occurs in the present experiments, and the difference in surface to volume ratio, the two experiments are not directly comparable. For these reasons the magnitude of coking rate should not be comparable. However, the agreement in activation energies (slope of curves) is encouraging.

The effect of pressure on coking rate for both Jet A and No. 2 heating oil is shown in Fig. 6. It is seen that in both cases coking rate increases with pressure. For the given temperature, 533 K, the static pressure exceeds the vapor pressure; therefore, the results are not attributable to phase change. A possible explanation is that dissolved oxygen comes out of solution at lower pressures, thereby lowering the rate of liquid-phase fuel-oxygen reactions.

No. 2 Oil Tests

Coking rate distributions for No. 2 oil at low flow and 603 K are shown in Fig. 7, curve (a); a sharp maximum occurs at the second sampling location. At the same temperature but higher flow rate, curve (b), the maximum value is considerably smaller and is shifted downstream. In this sense, the behavior parallels that observed with Jet A fuel. At lower temperature (533 K), curves (c,d,e) the effect of flow is reversed, and it is seen that increased flow leads to an increased coking rate. This may be attributed to more rapid heating of the fuel as a result of the transition from laminar to turbulent flow

or this may signal a change in mechanism whereby coking occurs primarily at the surface at lower surface temperature. In the latter case the coking rate would be augmented by higher mass transport rates. The effect of flow rate is summarized in Fig. 8.

The temperature dependence of coking rate for No. 2 oil is shown in Fig. 9. No simple Arrhenius function is observed. There appears to be no effect of fuel preheating at 533 K (500 F). In view of the observed dependence of coking rate on flow rate at higher temperature level, the single point at 602 K (625 F) and 7.70×10^{-3} kg/sec might show an increased coking rate relative to the unheated condition at the same temperature and lower flow. This result would be in accord with the hypothesis that the bulk heating effect is more important at higher temperature. On the basis of the results shown in Figs. 8 and 9 it is suggested that there may be two regimes of coke formation, a low temperature, surface-dominated regime having low activation energy and a high temperature, bulk-reaction dominated regime having higher activation energy. In the low temperature regime, increased flow increases coking rate, while the reverse is true at high temperature. Additional tests are required.

REFERENCE

1. Vranos, A.; Marteney, P. J.; and Knight, B. A.: Determination of Coking Rate in Jet Fuel. International Conference on Fouling of Heat Transfer Equipment, R.P.I., Troy, N.Y., Aug. 1979.

TABLE I
FUEL PROPERTIES

| | <u>Jet A</u> (ASTM D-1655) or nominal | <u>ERBS</u> (Specification) or nominal | <u>Jet A</u> (Analysis) | <u>No. 2 HH</u> (Analysis) |
|--------------------------|---|--|----------------------------|-------------------------------|
| Specification Gravity | 0.7753-0.8398 | 0.8438-0.8448 | 0.8128 | 0.8478 |
| Viscosity, 80 F, CS | | | 1.79 | 3.36 |
| Sulfur, % Wt. | 0.3 | 0.05 | 0.06 | 0.23 |
| Aromatics, % Vol. | 20* | 35 | 21.7 | 30.4 |
| Olefins, % Vol. | 0.3 | 0.3 | 0.3 | 0.3 |
| Napthalenes, % Vol. | 3.0 | 7.5 | 2.0 | 12.3 |
| Hydrogen, % Wt. | 13.7 | 13.0 | 13.75 | 12.9 |
| H/C Ratio | | | 1.91 | 1.78 |
| Breakpoint Temperature F | 500 | 460 | 500 | 392 |

*Temporary waiver to 2.20

TABLE II
TEST VARIABLES

| | |
|-------------------|--|
| Fuel Flow Rate | 2.5 to 25 gal/hr (2.14×10^{-3} to 21.4×10^{-3} kg/sec) |
| Test Temperature | 300 to 750 F (422 to 672 K) |
| Test Pressure | 100 to 300 psig (6.9×10^5 to 2.07×10^6 Pa) |
| Reynolds Numbers | inlet - 800 to 27,000 outlet - 6,000 to 34,290 |
| Preheated Fuel | 422 K, stored 1 hour before use |
| Deoxygenated Fuel | sparged with nitrogen 16 hours |

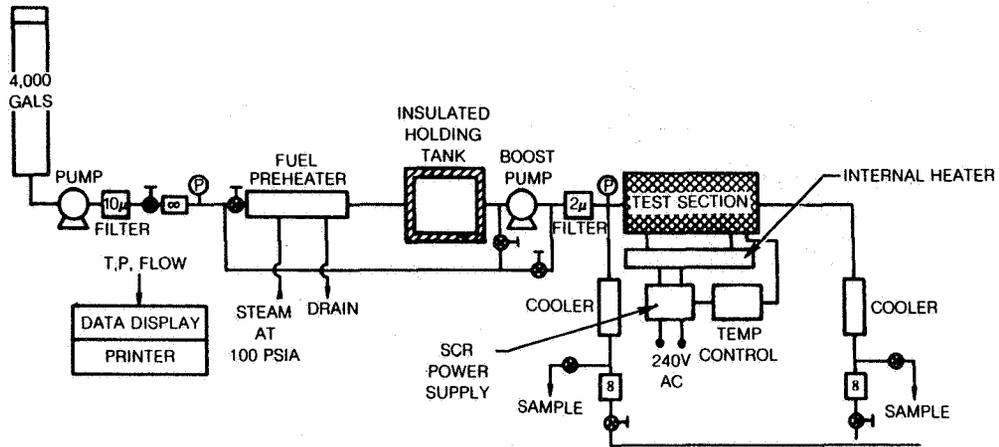


FIG. 1

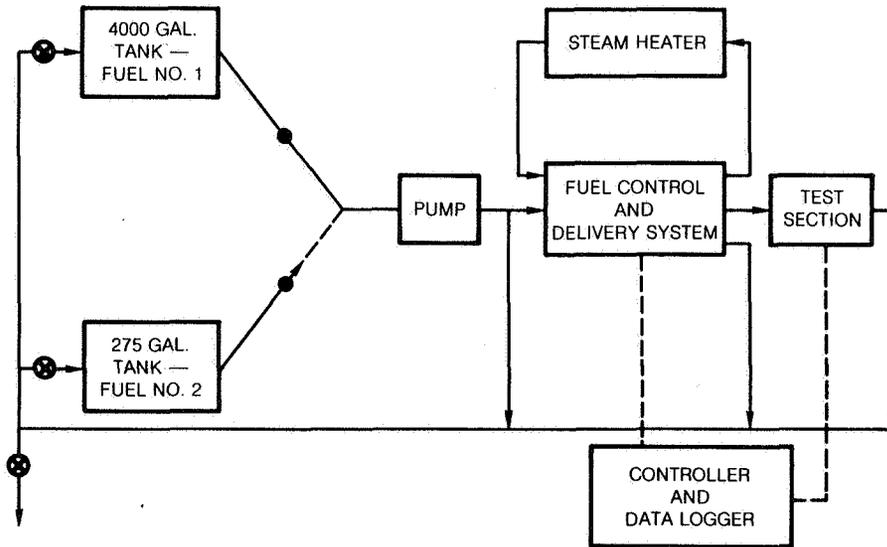


FIG. 2

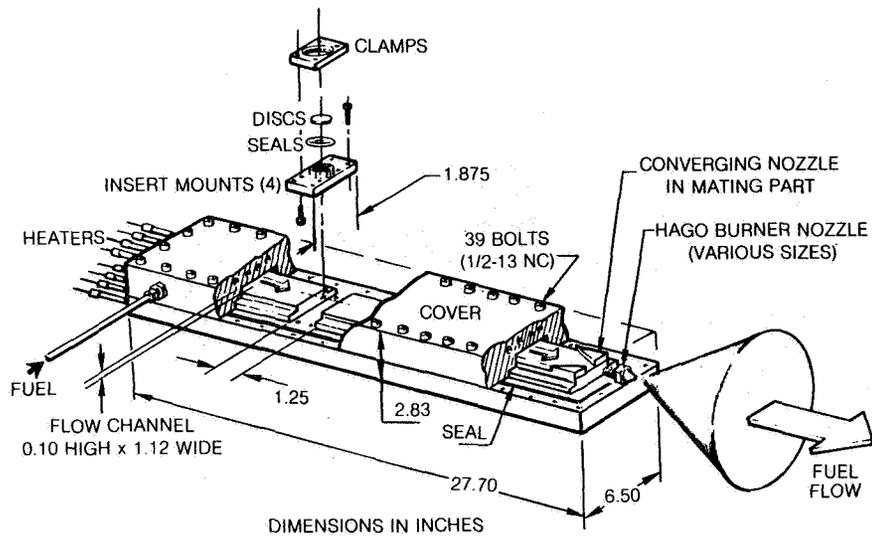


FIG. 3

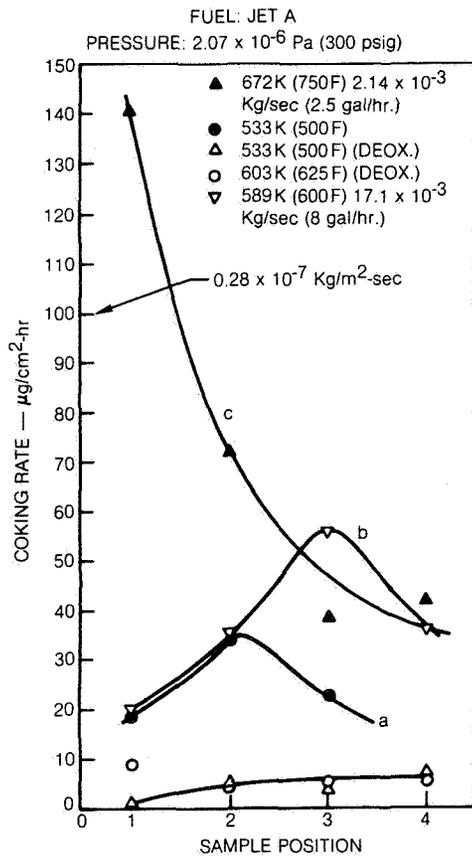


FIG. 4

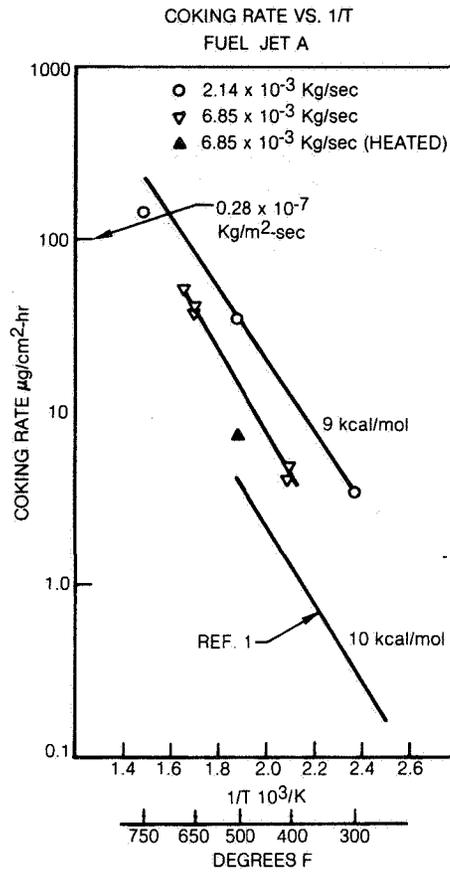


FIG. 5

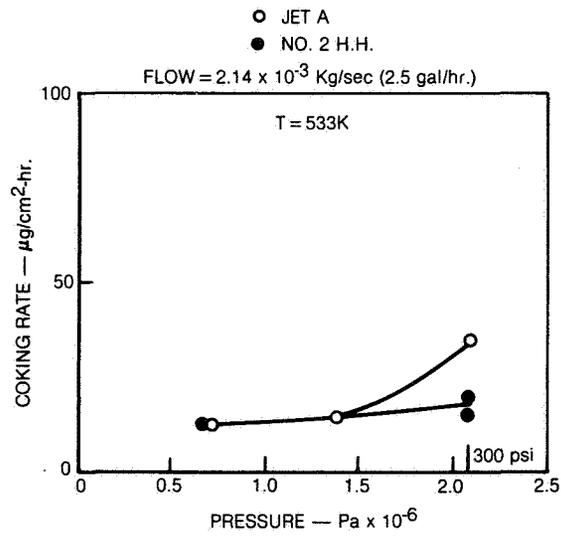


FIG. 6

FUEL: NO. 2 H.H.
PRESSURE: 2.07×10^6 Pa

- 603K (625F) 2.14×10^{-3} Kg/sec (2.5 gal/hr.)
- ▲ 603K 17.1×10^{-3} Kg/sec (8 gal/hr.)
- 533K (500F) 2.14×10^{-3} Kg/sec (2.5 gal/hr.)
- 533K 4.28×10^{-3} Kg/sec (5 gal/hr.)
- △ 533K 15.4×10^{-3} Kg/sec

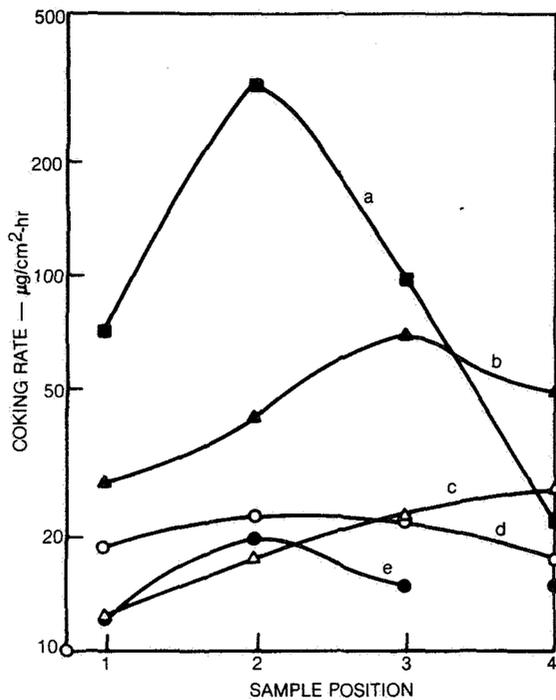


FIG. 7

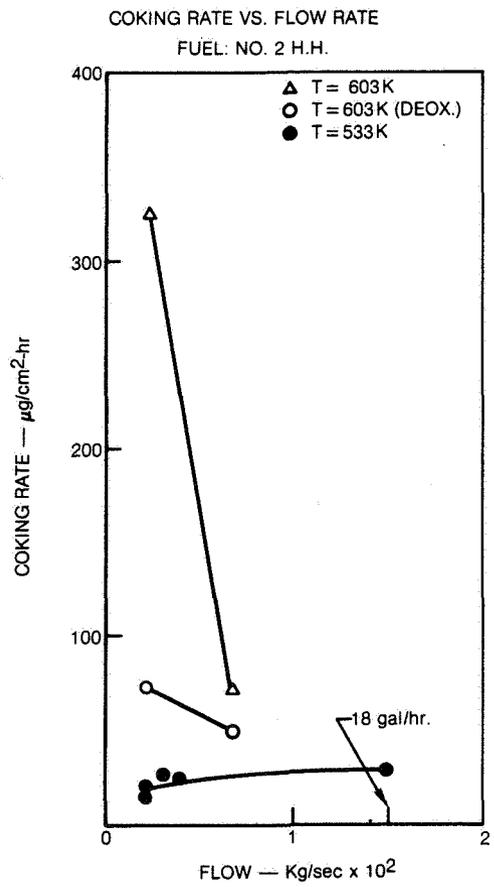


FIG. 8

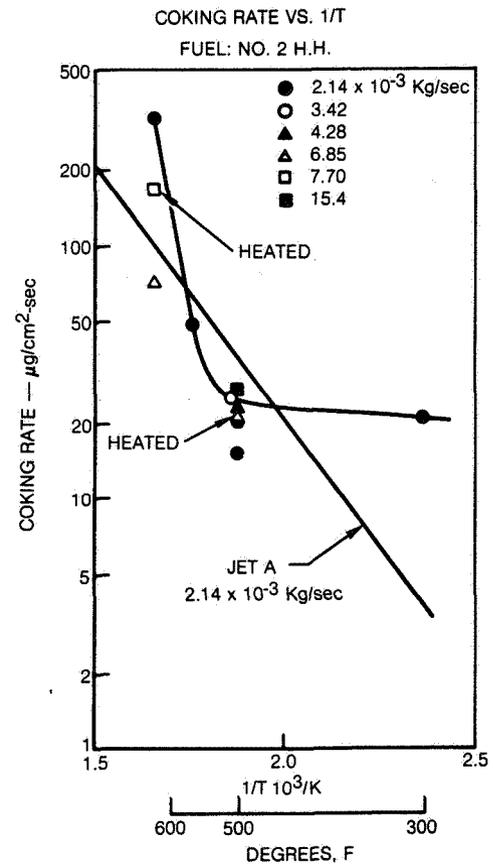


FIG. 9