NASA Conference Publication 2307

Assessment of Alternative Aircraft Fuels

Proceedings of a conference held at
NASA Lewis Research Center
Cleveland, Ohio
November 2-3, 1983

NASA

NASA Conference Publication 2307

Assessment of Alternative Aircraft Fuels

Proceedings of a conference held at
NASA Lewis Research Center
Cleveland, Ohio
November 2-3, 1983

NASA
National Aeronautics
and Space Administration

**Scientific and Technical
Information Branch**

1984

FOREWORD

Over the past several years, interruptions in crude oil supplies and subsequent rapid escalation of crude oil prices have led to large increases in aviation fuel prices. This has had an especially adverse impact on the commercial airline industry, which saw fuel costs rise significantly to become the major operating cost of the aircraft. In addition, forecasts have shown a decrease in the expected quality of crudes by the end of the century. Thus, even if crude oil prices stabilized, aviation turbine fuel prices could continue to rise, as refinery costs rose to force lower quality crudes to meet present day fuel specifications. Fuel availability, even at higher prices, was also open to question. All these factors have led industry and the government to consider the possibility of using a broadened property fuel as a suitable aviation turbine fuel.

The purpose of this symposium is to provide representatives from industry, government, and academia concerned with the availability and quality of future aviation turbine fuels with recent technical results and a status review of DOD and NASA sponsored fuels research projects. The symposium has included presentations on the potential crude sources, refining methods, and characteristics of future fuels; the effects of changing fuel characteristics on the performance and durability of jet aircraft components and systems; and the prospects for evolving suitable technology to produce and use future fuels.

We hope that this symposium has met its objectives and has proven informative and useful to those involved.

Jack Grobman
Chairman

CONTENTS

Page

SESSION I - AVIATION FUEL PROPERTY TRENDS

SESSION II - COMBUSTOR RESEARCH AND TECHNOLOGY

SESSION III - FUEL SYSTEM RESEARCH AND TECHNOLOGY

TRENDS OF JET FUEL DEMAND AND PROPERTIES

Robert Friedman
National Aeronautics and Space Administration
Lewis Research Center

Petroleum industry forecasts predict an increasing demand for jet fuels, a decrease in the gasoline-to-distillate (heavier fuel) demand ratio, and a greater influx of poorer-quality petroleum in the next two to three decades. These projections are important for refinery product analyses. The forecasts have not been accurate, however, in predicting the recent, short-term fluctuations in jet fuel and competing product demand. Changes in petroleum quality can be assessed, in part, by a review of jet fuel property inspections. Surveys covering the last 10 years show that average jet fuel freezing points, aromatic contents, and smoke points have trends toward their specification limits.

HISTORIC AND PROJECTED JET FUEL DEMAND

The most obvious trend in jet fuels has been that of increasing price. Figure 1 shows the average fuel price reported by U.S. domestic airlines (monthly averages from "Fuel Cost and Consumption," Civil Aeronautics Board, Washington, DC 20428). Average fuel prices show a threefold increase in the 1973-4 and 1979-81 time periods, each followed by relatively stable periods. Average fuel price has, in fact, decreased by about 20 percent in the last two years. The projected price trends, shown by broken lines in figure 1, illustrate how difficult it is to forecast price by extrapolation. Swihart and Minnick (ref. 1) used the 1977 projection to show how badly prices can be underestimated by extrapolating a trend of slowly rising prices. Unfortunately, the same authors' extrapolation based on 1979 price trends is shown by hindsight to be equally inaccurate in overpredicting present prices.

Refinery property optimization studies require product demand forecasts. These forecasts, however, need not be highly accurate to be useful in guiding the analyses. Figure 2 is a comparison of historic jet fuel demand and four demand forecasts. The data are the average daily demand for jet fuel in the United States as summarized annually in the Oil and Gas Journal. (Refs. 2 and 3 are the latest articles.) The forecasts project jet fuel demand starting from 1976 to 1978, depending on the forecast, to 2000 or beyond. The Exxon and ICF forecasts are estimates based on reviews of several petroleum industry predictions, to be used as inputs to refinery-model studies (reports to be published in the future). The Bonner and Moore forecast is an independent estimate compiled by a petroleum consulting organization (ref. 4). The UCLA forecast is the result of a mathematical-statistical technique (ref. 5), which extrapolates the demand for jet fuel by determining the influence of a number of social, economic, and energy-demand factors. The UCLA forecast shown in the figure uses a scenario of continued moderate energy growth (ref. 6). The forecasts in figure 2 all agree in predicting an increase in jet fuel demand, with average compounded annual rates ranging from 1.3% for Exxon to 2.1% for

UCLA. The absolute demand levels of the forecasts can vary greatly at times. The historic data in the figure, from 1976 to 1983, shows short-term variations that are not consistent with the forecasts. Except for the UCLA technique, however, the forecasts are not intended to predict the short-term details of demand.

Refinery property studies also require overall product distribution forecasts. Figure 3 is a comparison of historic and forecast data for the gasoline-to-distillate volume ratio, G/D, of U.S. refineries. Distillate fuels include kerosine, jet fuels, diesel and home heating oil. The historic data are daily averages calculated from the Oil and Gas Journal demand summaries (refs. 2 and 3). The forecasts are from the three industry and consulting sources noted for figure 2; the UCLA technique was not applied to this forecast. The forecasts all agree in predicting a decrease in future G/D, from the present 1.6 to below 1.0 around 2000. The decreasing ratio is a prediction that gasoline demand will decrease and distillate demand, particularly for diesel, will increase. The short-term historic data, however, shows a slight increase for the average G/D in the past seven years. It remains to be seen when, and if, the predicted decrease in G/D will occur.

FUEL PROPERTY TRENDS

Crude Feedstocks and Fuel Properties - Jet fuels at present are generally manufactured from refinery streams not subjected to chemical processing. Hence, the properties of jet fuels can reflect the qualities of the crude petroleum and their change with time.

It has been noted (refs. 7 and 8, for example) that, in recent years, U.S. feedstocks tend to have a greater proportion of heavier, more aromatic, and higher sulfur-content petroleums. The trends in feedstock quality, however, will not be examined in this paper, but the trends in selected jet fuel properties will be reviewed instead. Average freezing point, aromatics content, and smoke point have been shown by the author (ref. 9) to have recognizable changes during the past decade. These are key properties for refining analyses, design, and performance predictions. Their changes in average values with time may reflect a response to shifting refining and market conditions as well as to the deterioration in petroleum quality.

Freezing Point - Figure 4 shows the trends of average freezing point for U.S. commercial jet fuel, Jet A, determined from inspection survey reports published by the Department of Energy. (Ref. 10 is the latest survey.) Average values are shown as both a mean and median, calculated from the annual set of 60 to 67 samples. The median freezing point increases overall from -46° to -44°C for the decade. Shorter-term variations are less consistent. From 1976 to 1979, the median increased nearly 3°C, but from 1980 to 1982 (the most recent data), it decreased by a degree. The mean freezing point is usually about a degree lower than the median. Thus, the median values are closer to the specification limit of -40°C maximum (ASTM D1655-83).

The reasons for the difference between the mean and median Jet A freezing points may be seen on a distribution plot. Figure 5 is a histogram, plotting freezing points of the 10-year samplings as probabilities for discrete intervals of one degree each. The distribution is highly skewed. Low-probability samples with very low freezing points weight the mean to lower values than the 50-percent probability (median). The skewed, bimodal distribution may be a consequence of the combination of two categories of samples (ref. 9): those controlled by near-specification freezing point clustered near the -40°C limit, and those controlled by other properties (aromatics, for example) with a greater spread of freezing points.

Aromatics and Smoke Points - Figures 6 and 7 show the trend of average Jet A aromatics content and smoke point, respectively, from the Department of Energy annual inspection reports. Aromatics are benzene-ring compounds whose presence is limited in jet fuels because of poor combustion characteristics. Largely as a consequence of the increasing aromaticity of petroleum feedstocks, it has been noted that the aromatics contents of jet fuels is increasing (ref. 11). This is confirmed by the quantitative trend in figure 6 which shows a steady increase in median aromatics over the decade, from 17% to 18.5%. Mean values are generally 0.5% below those of the median. The specification limit for aromatics content is 25% maximum, although fuels with aromatics content above 20% must be reported as such by the supplier to the user.

Figure 7 shows that the median smoke point of Jet A fuels has decreased from 23 to 21.5 mm in the period of observation. Smoke point is a measurement of the maximum flame height for clean combustion in a lamp apparatus. Mean values are generally 0.5 mm above the median; as with the other key properties, the median values lie closer to the specification limit, which is 18 mm mimimum for smoke point. Fuels with smoke points below 20 mm must also be reported as such by the supplier.

Comparison of Property Trends - The property trends illustrated in figures 4 to 7 are derived from limited samplings (ref. 10 and earlier reports), generally accepted as representative of U.S. jet fuel quality. For certain properties, it is possible to confirm the trends by comparison with independent, large-sampling surveys. Figure 8 presents the trends of jet fuel aromatics content for four surveys: the Department of Energy (DOE) (figure 6), United Airlines (UAL), the International Air Transport Association (IATA), and the U.S. Navy. The UAL data are those reported by Campbell (refs. 12 and 13) supplemented by a communication from M. P. Hardy to the ASTM Committee D-2. These data are quarterly averages from a data bank covering 50 to 70 percent of fuel deliveries to U.S. airlines. The averages are volume-weighted; that is, each sample is weighted in proportion to the portion of the U.S. manufacturing volume represented by its refining source. The IATA data are analogous averages for jet fuel deliveries to international airlines, as reported in a private communication from N. G. Baz to the ASTM Committee D-2. The Navy data are volume-weighted analyses for domestic and foreign purchases, reported in ref. 14.

The fuels compared in figure 8 are all kerosine-based fuels and nearly interchangeable in properties, but they do not have identical specifications. Jet A-1 (IATA) has a lower freezing point limit, and JP-5 (Navy) has lower freezing point and higher flash point limits than Jet A (DOE and UAL). These small differences should have no effect on an aromatic-content comparison. All four surveys show averages within a band of about 1.5% aromatics content. All agree on an increasing trend of about 0.25%/year.

Another comparison, which shows more sensitivity to trends, is that of the fraction of "reportable" fuel. It was noted in the discussion covering figures 6 and 7 that, if aromatics or smoke point values are within a prescribed near-specification band, the supplier must report this fact to the user. Figure 9 compares the trends of the fraction of fuels with reportable values of aromatics and/or smoke point. The DOE data were calculated from the inspection data. The UAL and IATA data are statistics on airline deliveries of reportable fuel, from the same sources cited for figure 8. There is no reporting requirements for military fuel; hence, Navy data are not included in figure 9. All three surveys show an increasing trend in reportable fuel, which corresponds to the increase in aromatics (and decrease in smoke point) over the reporting period. The rate of increase differs considerably among the surveys. UAL shows a rapid increase in reportable fuels, reaching 35% by the third quarter of 1981, the latest reporting period. IATA shows a much smaller increase in reportable deliveries. The DOE survey data are intermediate to those of the two airline surveys. The differences among the surveys in the rate of increase of reportable fuel are much greater than those, if any, observed for the trends of aromatics content in figure 8.

Summary of Property Trends - A further means of describing the trends of jet fuel properties is illustrated in figure 10. The 10-year collection of DOE inspection data is plotted to show the distribution of samples by controlling properties. Each sample was characterized by the properties that were near-specification, that is, within a tolerance established by the standard test method. The controlling near-specification property is the one property (if any) nearest to its specification limit (ref. 9). Figure 10 shows that the proportion of Jet A samples controlled by near-specification aromatics has increased during the past decade. This is consistent with the increasing trend of average aromatics contents. One the other hand, smoke point and freezing point-controlled samples show little overall change. Figure 10 also shows the fraction of fuel samples with no properties within the near-specification band. The proportion of these "premium" fuels has been decreasing with time, to about 10% of the samples in the most recent year.

CONCLUDING REMARKS

This paper is an introduction to the subject of refinery property-relaxation analyses, reviewing the historic and projected trends of jet fuel demand and key properties. Detailed interpretations cannot be made from this statistical study, but some observations are warranted. Jet fuel demand trends have short-term variations that are beyond the capability of forecasting, but long-term trends may be amenable to skilled projections. Trends in average jet fuel aromatics contents and smoke points, derived from accepted inspection sources covering the last decade, show shifts toward the specification limits. This is probably due to the recognized deterioration in petroleum quality. Long-term average freezing points also show an increase toward the specification maximum. The reasons for this trend are uncertain, although the increase may reflect refining changes to meet shifting jet and competing fuel demands.

REFERENCES

1. Swihart, John W.; and Minnick, Jack I.: A Fresh Look at Aviation Fuel Prices. Astronautics & Aeronautics, Vol. 18, No. 3, March 1980, pp 34-35.

2. Beck, Robert J.: Forecast and Review - Demand, Imports to Rise in '83. Oil & Gas Journal, Vol, 81, No. 5, January 31, 1983, pp 71-98.

3. Beck, Robert J.: Midyear Forecast - U.S. Demand, Imports to Edge Down, Production Rising. Oil & Gas Journal, Vol. 81, No. 31, July 25, 1983, pp 115-133.

4. Dickson, J.C.; Frederick, F.P.; and Sipowicz, W.W.: Impacts of Alcohol Fuel on the U.S. Refining Industry. DOE/CS/50007-1, November 1983.

5. Ayati, M.B.; Liu, C.Y.; and English, J.M.: Forecast of Future Aviation Fuels: The Model. NASA Contractor Report 165486, September 1981.

6. Ayati, Mohammad B.; and English, J. Morley: A Methodology for Long Range Prediction of Air Transportation. SAE Paper 800768, May 1980.

7. Strauss, K.H.: Future U.S. Jet Fuel - A Refiner's Viewpoint. AIAA Paper 81-0770, May 1981.

8. Sefer, Norman R.; and Moses, Clifford A.: Crude Sources and Refining Trends and Their Impact on Future Jet Fuel Properties. SAE Paper 811056, October 1983.

9. Friedman, Robert: Recent Trends in Aviation Turbine Fuel Properties. NASA Technical Paper 2056, October 1982.

10. Shelton, Ella Mae; and Dickson, Cheryl L.: Aviation Turbine Fuels, 1982. DOE/BETC/PPS-83/2, March 1983.

11. Grobman, Jack; and Reck, Gregory M.: The Impact of Fuels on Aircraft Technology Through the Year 2000. AIAA Paper 80-0896, May 1980.

12. Campbell, P.P.: Jet Fuel Properties. A 1978 Viewpoint. Shell Aviation News, No. 449, 1978, pp 26-31.

13. Campbell, P.P.: Current Jet Fuel Trends, in "Aircraft Research and Technology for Future Fuels." NASA Conference Publication 2146, July 1980, pp 11-14.

14. Grabel, Lawrence: Physical and Chemical Properties of JP-5 Fuel, 1977-1980. NAPC-PE-70, January 1983.

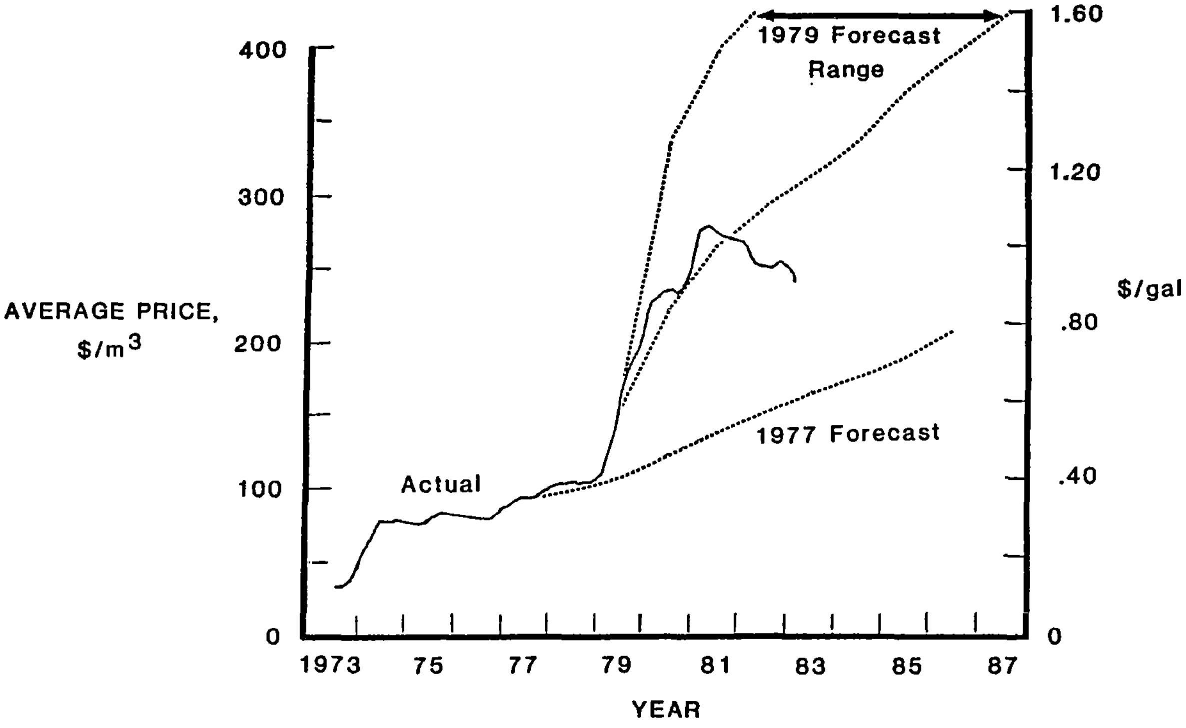


Fig. 1. - Domestic jet fuel price.

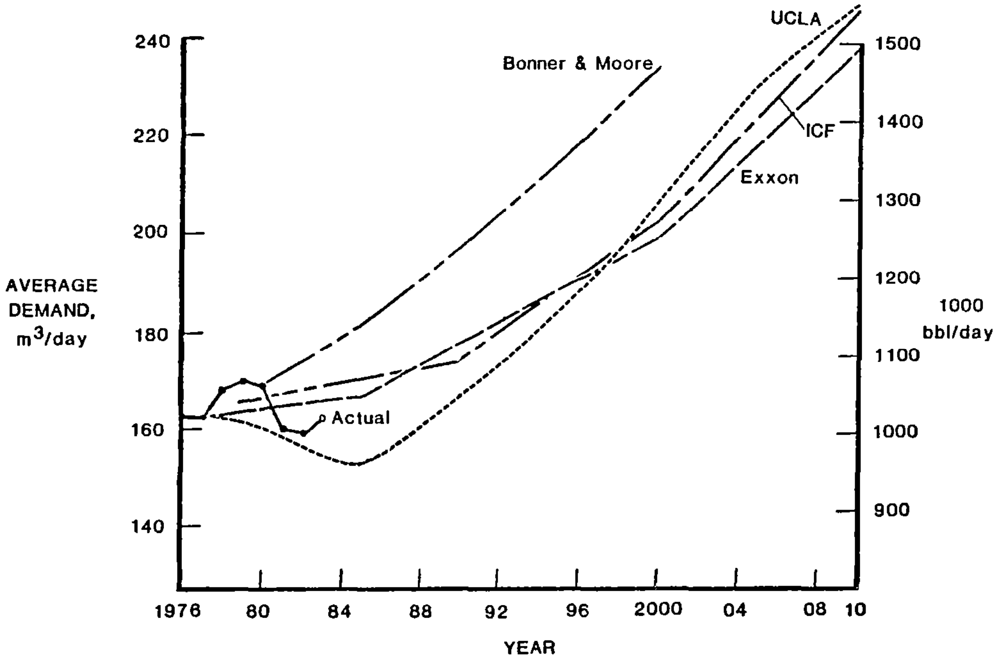


Fig. 2. - U. S. jet fuel demand and forecasts.

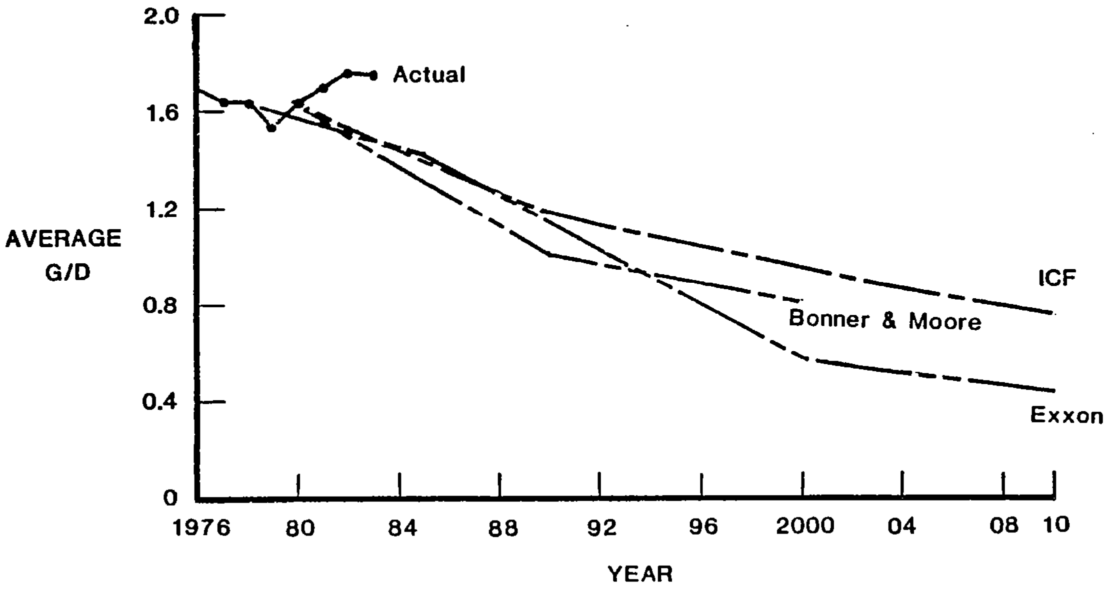


Fig. 3. - U. S. gasoline-to-distillate fuels demand ratio and forecasts.

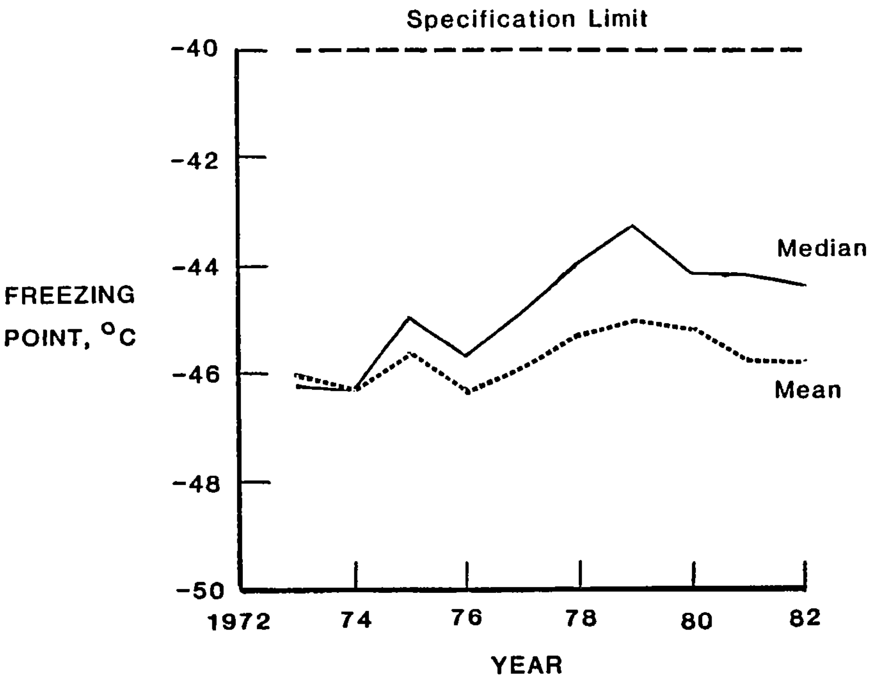


Fig. 4. - Average Jet A freezing points, from Department of Energy inspection reports.

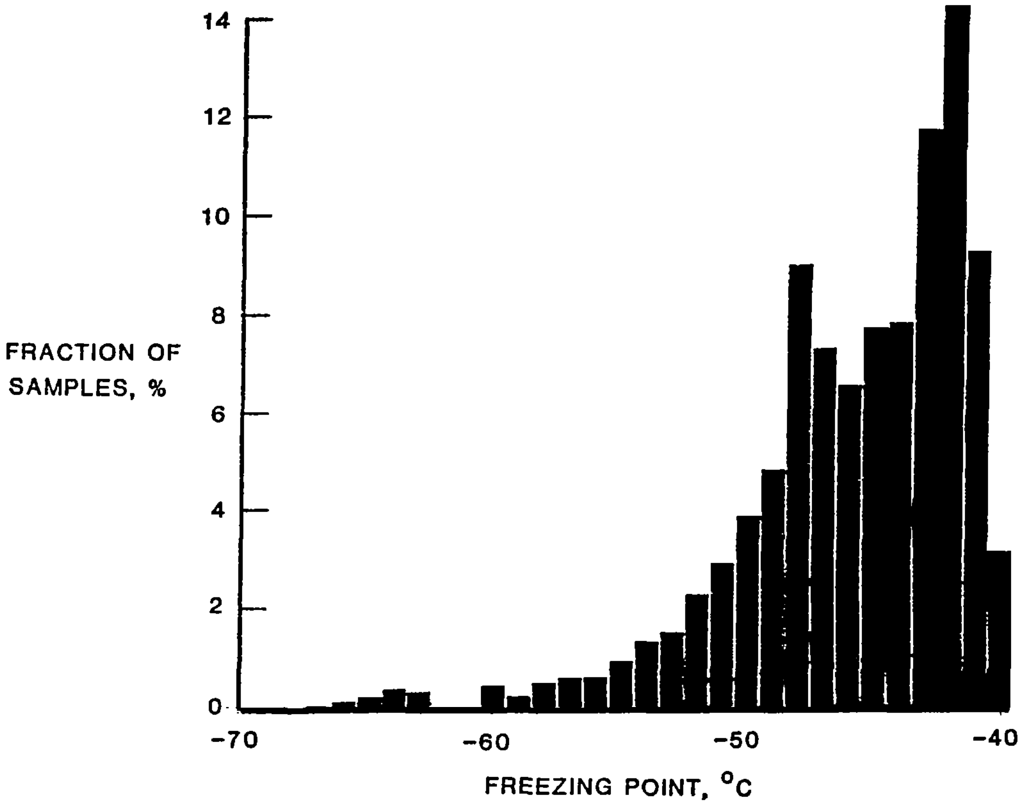


Fig. 5. - Distribution of Jet A freezing points, from Department of Energy 1973 to 1982 inspection reports.

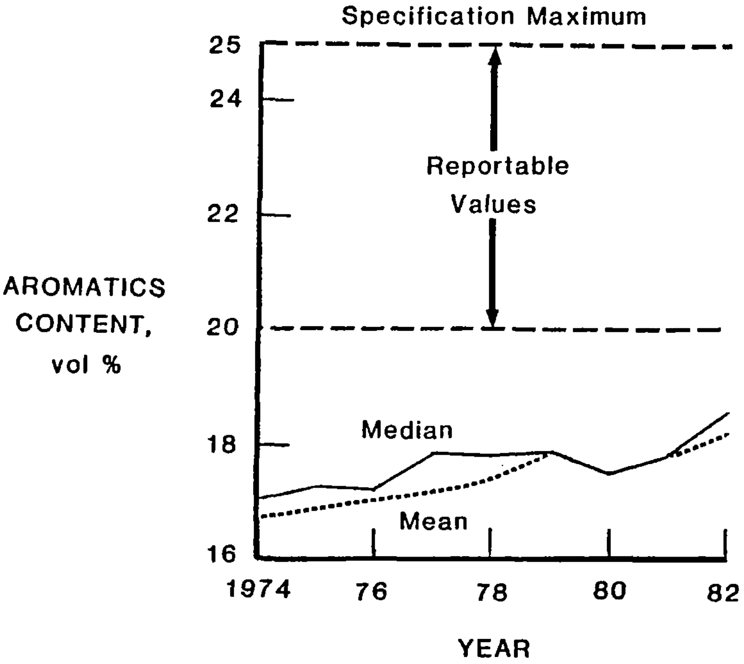


Fig. 6. - Average Jet A aromatics contents, from Department of Energy inspection reports.

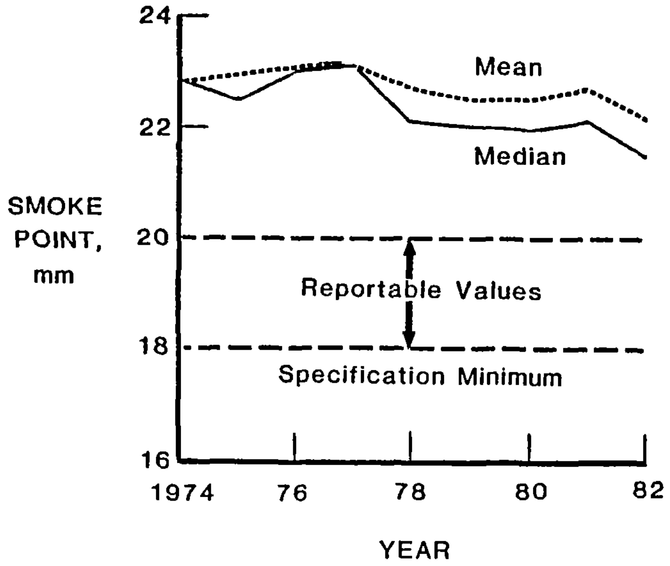


Fig. 7. - Average Jet A smoke points, from Department of Energy inspection reports.

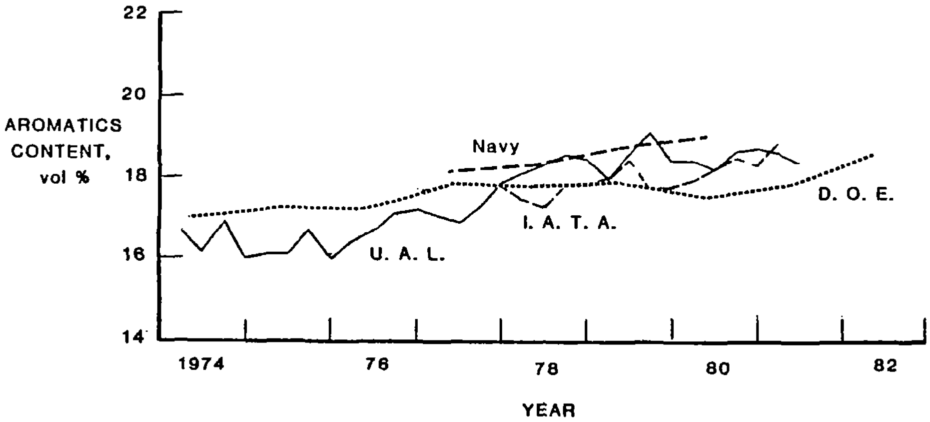


Fig. 8. - Comparison of average jet fuel aromatics contents, from several inspection sources.

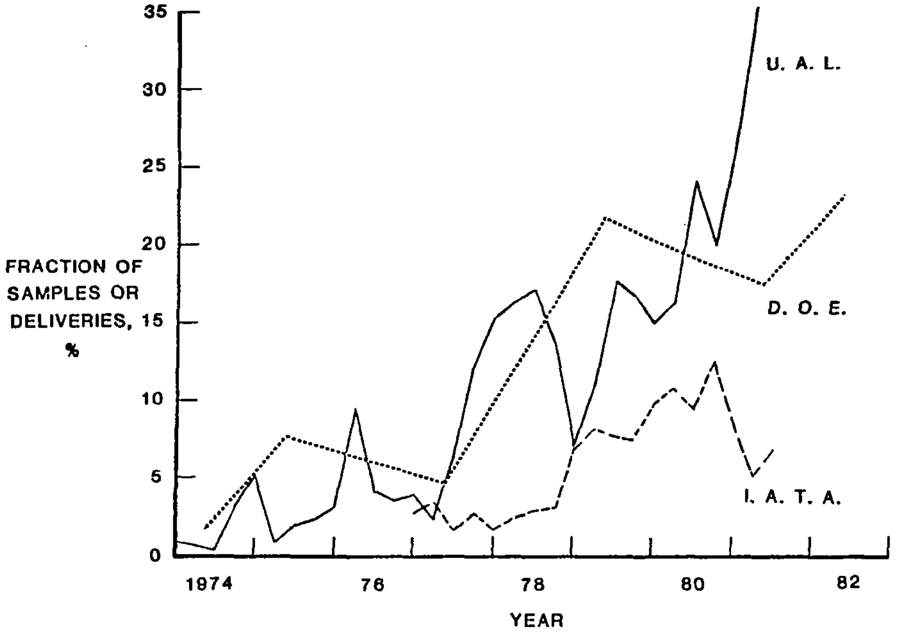


Fig. 9. - Comparison of jet fuels with aromatics and/or smoke points in the reportable range.

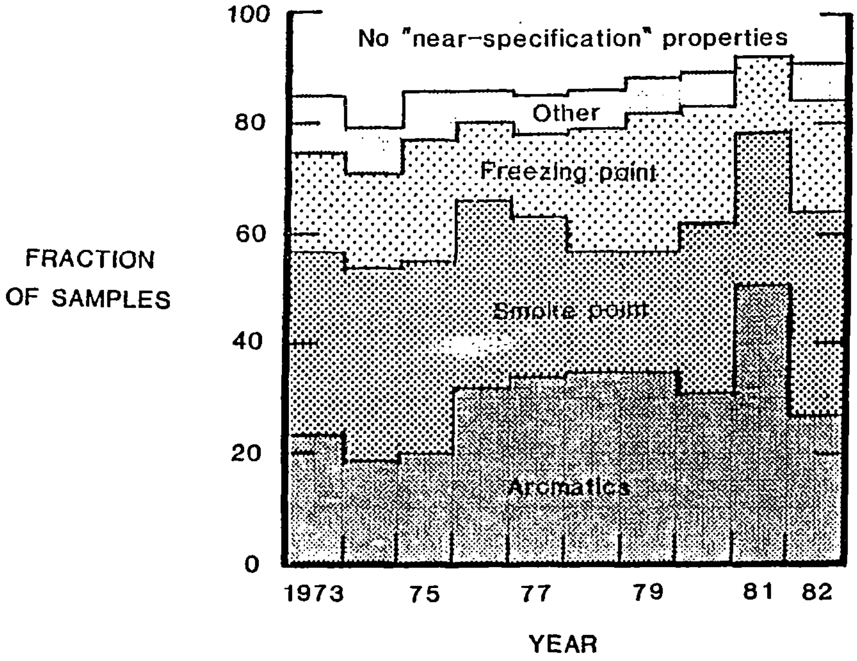


Fig. 10. - Distribution of Department of Energy inspection samples by controlling, near-specfication property.

THE EFFECT OF PROPERTY CHANGES ON JET FUEL PRODUCIBILITY AND COST

G. M. Varga, Jr., A. R. Cunningham, J. F. Gorgol,
A. J. Graf and G. A. Oliver
Exxon Research and Engineering Company

An investigation of the effect of property relaxation on Jet A producibility and cost in the U.S. has been completed under NASA sponsorship by Exxon Research and Engineering Company. This presentation reviews the results obtained.

Linear programming optimization models have been used. Model input included petroleum product demand and property data, estimates of crude qualities, and information on refinery processes. The time period considered was 1978 to 2010.

Projections from a variety of published sources show the demand for kerosene jet fuel and diesel fuel increasing over the study period, while the demand for gasoline, heating oil and heavy fuel oil decline (Figure 1). Five jet fuels were studied to determine property effects (Table 1). The base fuel (TF-1) has typical 1978 properties. The four additional fuels (TF-2 through 5) represent various levels of aromatics content, smoke point and freeze point and the use of cracked stocks, such as those from hydrocracking, catalytic cracking and thermal cracking processes. While cracked stocks are not excluded by specifications, they are now rarely used because of negative impacts on certain specs.

For this study, the U.S. was divided into an eastern and western region which are different in product demand slates and crude qualities. Future crude mixes have been projected for both regions to become heavier and higher in sulfur content with time. In the West less low sulfur crudes are available and they will be heavier than in the East (Figure 2).

An important part of the study was to look at jet fuel property relaxation effects for individual refineries running specific crude quality. Three types of refineries were considered (Table 2). The hydroskimmer is essentially an atmospheric distillation unit with hydrotreating capability. The low conversion refinery adds to the hydroskimmer catalytic cracking and vacuum distillation capability. The high conversion refinery has the ability to convert all of its residuum to lighter, more valuable products and therefore includes residuum destruction facilities. All refineries could invest in severe kerosene hydrotreatment (aromatics saturation) and aromatics extraction if economically warranted. These processes were not in widespread use in 1978.

Both conversion refineries were able to invest in certain advanced processes if economically desirable (Table 3). Included were resid conversion processes, such as Flexicoking and resid hydroconversion as well as processes for hydrogen recovery (pressure swing adsorption) and hydrogen production (partial oxidation). Both conversion refineries could also invest in a hydrocracking process which emphasized jet fuel production, rather than the production of naphtha.

Jet fuel producibility was determined using individual refinery-crude models, which were operated to minimize refining cost. In making these runs, the sum of gasoline plus distillate was held constant, diesel and heating oil were at an 85/15 ratio and other products were held constant. The TF-1 marginal cost (the cost of the last barrel made) of jet fuel was set at 5¢/gallon over diesel, and the value was held constant for all jet fuel relaxations.

Jet fuel production for a typical eastern refinery running medium sulfur heavy crude with resid conversion capability can increase about 20% at gasoline/distillate ratios (G/D) projected for the future when aromatics and freeze point are relaxed (Figure 3). At current gasoline/distillate ratios, increases of about 60% are obtained. When cracked stocks are blended into jet fuel, larger producibility gains are realized even with current levels of aromatics and freeze point. Once the option for using cracked stocks is exercised on economic grounds, relaxation of jet fuel properties yield little further producibility gains (TF-2 vs. TF-5). Hydrocracking is the method of choice, yielding blend stock that is high in quality and not affected by aromatics or freeze point limitations. The high conversion refinery running on medium sulfur heavy crude safely meets the average jet fuel yield on crude run for the eastern region when blending to TF-1 quality at current gasoline/distillate ratios. It can meet the average jet fuel yield only marginally with this quality at gasoline/distillate ratios projected for the future. Relaxing properties for all virgin jet fuel or when including cracked materials results in jet fuel yields substantially above the regional yield on crude even for future time periods. Excess production of naphtha and the need to meet distillate qualities limited the producibility increases possible at the low G/D. This was typical for most eastern refineries. Hydroskimmers had no flexibility for changing jet fuel producibility as properties changed.

Jet production also increased for a typical western refinery (heavy medium sulfur crude-high conversion refinery) as properties were relaxed (Figure 4). Over the extremes of G/D ratios, about a 30% increase in jet fuel yield was achieved when aromatics and freeze point were relaxed from the base even without using cracked components. With cracked components, large producibility increases were possible even at base quality, particularly at G/D ratios corresponding to future years. The model invested in jet hydrocracking at the lowest G/D ratio. Although this refinery would have no difficulty in meeting the average jet fuel yield anticipated for 1985 in the West, it would be unable to meet that anticipated for 2010 without property relaxation.

For other models, producibility changes attributable to property relaxation were found to be a function of refinery-crude type and G/D (Table 4). Considering first the low sulfur crude used by eastern refineries, the hydroskimmer exhibited no increase in jet fuel production with property relaxation at G/D 0.9 where the ratio of naphtha and distillate in this crude allowed this refinery to operate. The low conversion refinery increased jet yield by 14%, and 34% at G/D of 2.0 and 1.2, respectively, and the high conversion refinery exhibited increases of 78% and 69% at the same G/D. No producibility increase occurred for either conversion refinery at G/D 0.9. The eastern high sulfur heavy-high conversion refinery increased jet production by 134%, 65% and 4% at G/D 2.0, 1.2 and 0.9.

In the west, the low sulfur crude-low conversion refinery performed similarly to the eastern conversion refineries. The hydroskimmer running heavy high sulfur crude at G/D 2.6 exhibited a small but meaningful increase in producibility with property relaxation.

The heavy high sulfur crude-high conversion refinery exhibited large producibility increases with relaxation. Here, however, the increases became greater as the G/D declined. At the low G/D, the model invested in hydrocracking for jet fuel. The disposal of excess naphtha was not a problem as it was in the east because this crude had only about one-half of the naphtha of the crudes in the east. At high G/D the model invested in processes that emphasized gasoline production and increases in jet quality distillate were limited. The western refinery example shown in Figure 4 also exhibited large increases in jet producibility at low G/D for the same reasons.

In general, relaxation of aromatics and freeze point or use of cracked stocks increased jet fuel producibility for conversion refineries (Table 5). However, at $G/D < 1$, producibility was limited by the need to meet specifications of distillate fuels and excess naphtha production. Property relaxation generally increased producibility most for high conversion refineries but had only a small effect for hydroskimmers. Hydrocracking for jet fuel was needed in the low G/D cases for distillate volume and quality. This process is, however, costly and the development of improved distillate-oriented processes would be advantageous.

The cost savings associated with property relaxation were determined using regional models composed of the individual refinery-crude models linked together. The individual models competed for available crude, process capacity and product markets. Since every refiner does not produce jet fuel, the crude from which jet fuel could be made was limited to about 70% of the total crude run. Investment was required for processing not available in 1978. Cost savings were determined in 1981 dollars. Except for one crude in each region, neither crude cost nor product values were used for calculating savings due to property relaxation since crude and product volumes were the same for all cases. Before being used, both regional models were verified against 1978 data (Figure 5). The model successfully predicted over 97% of crude usage and in most cases did not exceed the available process capacities while meeting product demand. The model used more vacuum distillation capacity than was available because a 650°F cut point between gas oil and residuum was assumed. In practice, many units employ higher cut points, reducing the need for vacuum distillation.

Cost savings within each region tended to be relatively similar for each relaxation relative to base quality (Table 6). Savings increased with decreasing gasoline/distillate ratio, i.e., time, and ranged from 0.5 to 1.6¢/gallon for the eastern region and 3.4¢/gallon and above for the west. Jet fuel production in the west was made more difficult by the smaller quantity of kerosene available in most crudes, a lower total naphtha/total distillate product ratio, and the large jet yield required. As a consequence, property relaxation and participation in jet fuel production by all refiners was required to meet the 2000 demand (Table 7); but, by 2010, even these conditions were insufficient, and a new fuel, TF-1A, must be used. TF-1A has properties identical to TF-1 except that hydrocracked stocks are allowed. Calculations were made using TF-1A in time periods beyond 1990.

Cost savings of 3.5¢/gallon were calculated for the western region for producing jet fuel in the 1990 time period to TF-4 properties rather than base quality. For the year 2000 and beyond, savings at least as large can be estimated compared to a base case in which the maximum amount of TF-1 is produced and the remainder of the jet fuel demand is met using TF-4 or a TF-1 quality fuel prepared from hydrocracked stocks. The latter will, however, require investment in such processing.

The investment in jet hydrocracking required in the west in 2000 is shown in Table 8. Two cases were considered in formulating these values: one in which all refiners made jet fuel and all crude was available for jet fuel production, and the other where it was assumed that only 75% of the crude could participate in jet fuel production. TF-1A as formulated by the model contained the greatest amount of jet hydrocrackate and required the greatest investment, 120M$ in the full participation case. If all refiners produced the maximum amount of TF-1 and the remainder of the demand was satisfied using hydrocrackate, the investment declined to 20M$. If all refiners produced jet fuel, all jet demand could be met using relaxed property TF-4 and no hydrocracking investment would be required. Limiting participation increases investment in hydrocracking in the west to 290M$, 210M$ and 170M$, respectively, for the same three examples noted above. These data illustrate that freeze point and aromatics relaxations can reduce hydrocracking investment levels.

The use of regional models has shown that all-virgin jet fuel yield of current quality may be insufficient to meet projected demand in the post 2000 time period. Increasing jet fuel aromatics and freeze point and/or introduction of cracked components increases producibility sufficiently to meet demand and results in savings up to 3.8¢/gallon compared to jet fuel meeting current property levels (Table 9).

In addition to providing information on jet fuel cost and availability, the regional models utilized also provide information on fuel properties. Data showing the percentage of the jet pool which is critical (i.e., at the designated property value) in the east for base period TF-1 and two relaxed property fuels as a function of time are shown in Table 10. Freeze and aromatics are about equally critical over time for TF-1. However, with our relaxations, the percentage of the pool which is aromatics critical drops sharply. For TF-2 this is due to the use of hydrocrackate and for TF-4, the aromatics levels of the kerosene cuts was less than the TF-4 aromatics property level. Yet, after these relaxations, a large portion of the pool still remained freeze critical. One reason for this is that freezing point is not amenable to processing solutions as are aromatics. The use of another kerosene stream with different cut points might make a smaller percentage of the jet pool freeze critical. This is an option which is available to refiners but which was not modeled.

Refinery modeling has been used to show (Table 11) that meeting future jet fuel demand will become increasingly difficult if virgin fuel of current quality is required. Relaxation of aromatics and freeze point was found to increase producibility in conversion refineries, substantially meeting demand projections. Investment in hydrocracking for jet fuel production permits the meeting of future jet demand, even at current levels of aromatics and freeze point. And, cost savings of several cents/gallon can be realized for property relaxation and the use of cracked components.

Table 1

JET FUEL QUALITY LEVELS CONSIDERED

Fuel	Components Allowed	Aromatics Vol % Max	Smoke Point mm Min	Flash Point °C Min	Freeze Point °C Max
Specification	—	20	20	38	−40
TF-1 Base Period	Virgin Only	18	21.5	43	−43
TF-2	Virgin and Cracked	18	21.5	43	−43
TF-3*	Virgin and Cracked	$\boxed{23}$	20	43	−43
TF-4	Virgin Only	$\boxed{33}$	$\boxed{14}$	43	$\boxed{-29}$
TF-5	Virgin and Cracked	$\boxed{35}$	$\boxed{13}$	43	$\boxed{-29}$

*East Only.

Table 2

CURRENT PROCESSES AND REFINERY TYPES

Process	Hydro-Skimmer	Low Conversion	High Conversion
Atmospheric Distillation	X	X	X
Vacuum Distillation		X	X
Naphtha Reforming	X	X	X
Catalytic Cracking		X	X
Hydrotreating			
- Mild Kerosene H/T	X	X	X
- Severe Kerosene H/T	[X]	[X]	[X]
- Naphtha H/T	X	X	X
- Gas Oil H/T	X	X	X
Alkylation			X
Visbreaker			X
Delayed Coking			X
Hydrocracking for Naphtha			X
Aromatics Extraction	[X]	[X]	[X]
Steam Reforming-H,	X	X	X
Sulfur Plant	X	X	X

[ ] Model can invest in process if economically warranted.

Table 3

ADVANCED PROCESSES

Process	Hydro-Skimmer	Low Conversion	High Conversion
Hydrocracking For Jet		X	X
Flexicoking			X
Resid Hydroconversion			X
H_2-Pressure Swing Adsorption		X	X
H_2-Partial Oxidation		X	X

Model must invest if it chooses to use these processes.

Table 4

PRODUCIBILITY CHANGES DUE TO PROPERTY RELAXATION VARY STRONGLY FOR DIFFERENT REFINERY CRUDE TYPES

	% Yield Increase For G/D		
East	2.0	1.2	0.9
Low Sulfur-Hydroskimmer	—	—	0
Low Sulfur-Low Conversion	14	34	0
Low Sulfur-High Conversion	78	69	0
High Sulfur-High Conversion	134	65	4
West	2.6	1.9	1.2
Low Sulfur-Low Conversion	91	36	14
High Sulfur-Hydroskimmer	9	—	—
High Sulfur-High Conversion	40	109	167

Table 5

PRODUCIBILITY SUMMARY

- RELAXATION OF AROMATICS AND FREEZE POINT OR USE OF CRACKED STOCKS INCREASED JET FUEL YIELD FOR CONVERSION REFINERIES FROM 10% TO 35%.
  - — At G/D < 1 Producibility Limited by Specifications of Distillates and Excess Naphtha Production.
- PROPERTY RELAXATION HAD LITTLE OR NO EFFECT ON PRODUCIBILITY IN HYDROSKIMMERS.
- HYDROCRACKING FOR JET FUEL NEEDED IN LOW G/D CASES FOR DISTILLATE VOLUME AND QUALITY.
  - — Development of Improved Distillate Processes Needed.

Table 6

AVERAGE COST SAVINGS RELATIVE TO TF-1, ¢/GALLON

	TF-2		TF-4		TF-5	
	East	West	East	West	East	West
1985	0.5	3.4	0.6	3.4	0.6	3.7
1990	0.8	3.5	0.9	3.5	1.0	3.8
2000	0.8	*	0.9	*	1.0	*
2010	1.5	*	1.5	*	1.6	*

*Demand cannot be met with TF-1.

Table 7

RELAXATION OR HYDROCRACKED STOCKS NEEDED TO MEET PROJECTED DEMAND IN WEST

	Percentage of Demand Met			Savings Due to Property Relaxation
Year	TF-1	TF-4	TF-1A*	¢/Gallon
1990	100	100	100	3.5
2000	94	100	100	≥3.5*
2010	79	86	100	≥3.5**

*Same properties as TF-1 but hydrocracked stocks permitted.

**Savings relative to TF-1 cannot be calculated directly at the demand level but savings shown are for maximum TF-1 supply.

Table 8

FREEZE POINT AND AROMATICS RELAXATIONS SAVE ON HYDROCRACKING INVESTMENT IN 2000

	Hydrocracking Investment, M$	
	100% Crude Available	75% Crude Available
TF-1A	120	290
TF-1 (Max Virgin)	20	210
TF-4 (Max Virgin)	0	170

Table 9

COST SAVINGS SUMMARY

- SAVINGS FROM 0.5 TO 3.8¢/GALLON CAN RESULT FROM RELAXATIONS IN JET FUEL AROMATICS AND FREEZE POINT.
- PROPERTY RELAXATION OF VIRGIN JET FUEL OR USE OF HYDROCRACKED STOCKS RESULTED IN SIMILAR SAVINGS ON A REGIONAL BASIS.
- INVESTMENT IN HYDROCRACKING IS REQUIRED AT LOW GASOLINE/DISTILLATE RATIOS TO MEET DEMAND.

Table 10

FREEZE POINT LIMITATION MORE RESTRICTIVE THAN AROMATICS LIMITATION

	% of Pool Critical for Property in East					
	TF-1		TF-2		TF-4	
	Freeze	Aromatics	Freeze	Aromatics	Freeze	Aromatics
1985	68	32	100	33	0	0
1990	53	47	71	32	96	0
2000	51	52	100	2	79	0
2010	100	100	100	4	0	0

Table 11

CONCLUSIONS

- MEETING FUTURE JET FUEL DEMAND WILL BECOME INCREASINGLY DIFFICULT IF VIRGIN FUEL OF CURRENT QUALITY IS REQUIRED.
- RELAXATION OF AROMATICS AND FREEZE POINT INCREASES PRODUCIBILITY IN CONVERSION REFINERIES, SUBSTANTIALLY MEETING DEMAND PROJECTIONS.
- HYDROCRACKING INVESTMENT FOR JET FUEL PRODUCTION PERMITS MEETING FUTURE REQUIREMENT EVEN AT CURRENT AROMATICS AND FREEZE POINT.
- COST SAVINGS OF SEVERAL CENTS/GALLON CAN BE REALIZED FOR PROPERTY RELAXATION AND USE OF CRACKED COMPONENTS.

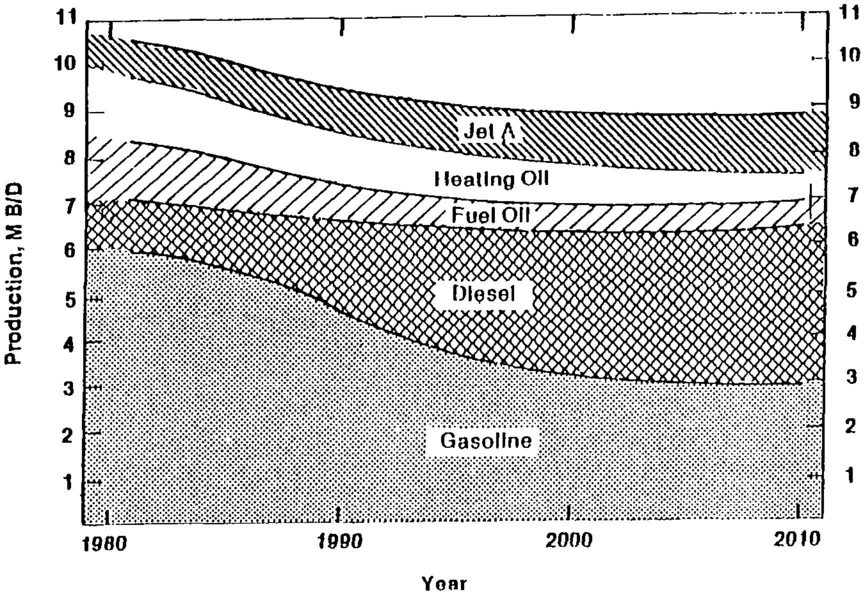


Figure 1. Published U.S. Low Fuel Demand Outlook Used In Study.

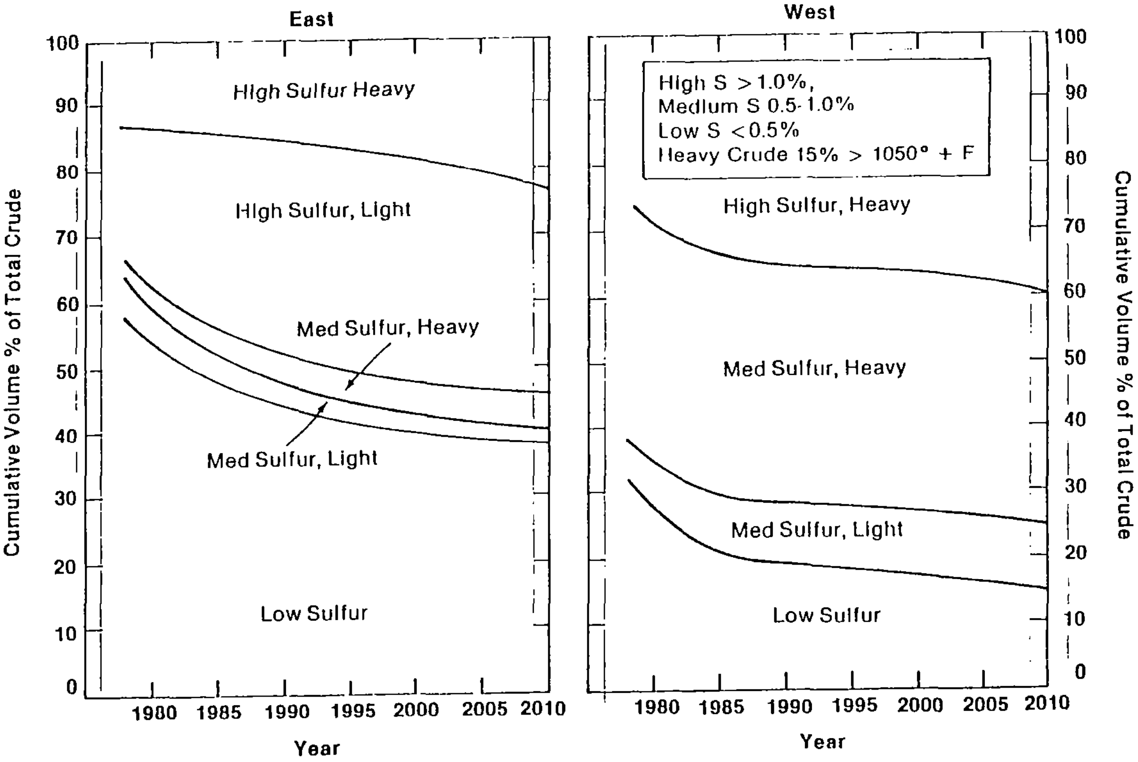


Figure 2. Crudes Projected to Become More Sour, Heavier and Poorer Quality in the West

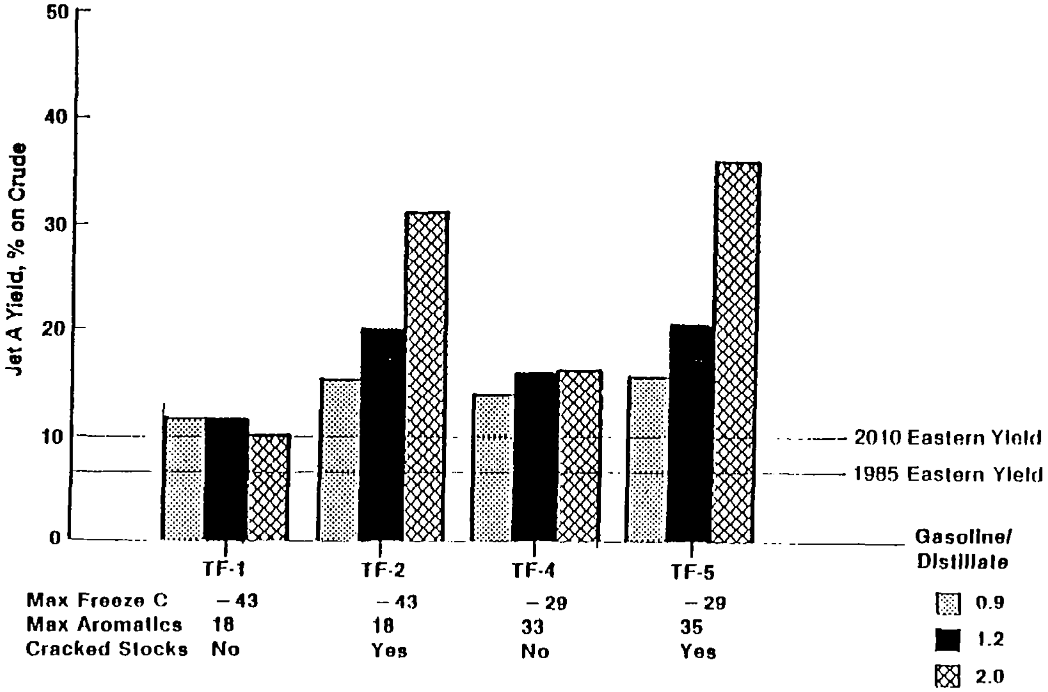


Figure 3. Jet Fuel Producibility for Eastern U.S. Conversion Refinery Exceeds Regional Average Jet Fuel Yield with Property Relaxation

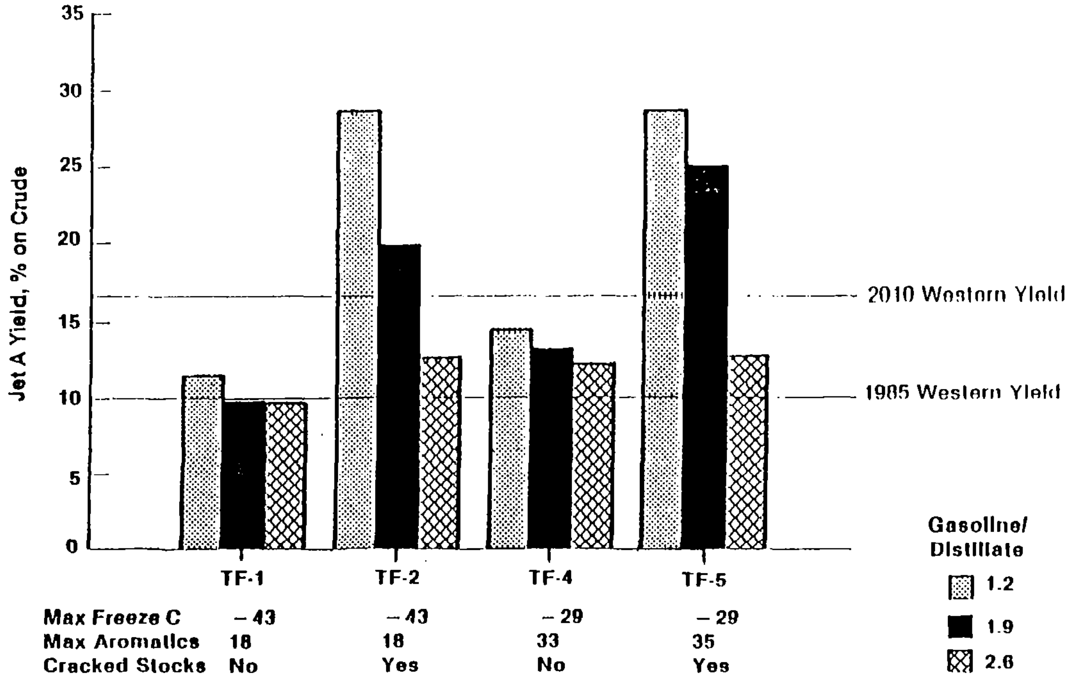


Figure 4. Jet Fuel Producibility Increases for Typical Western U.S. Conversion Refinery with Relaxation of Properties

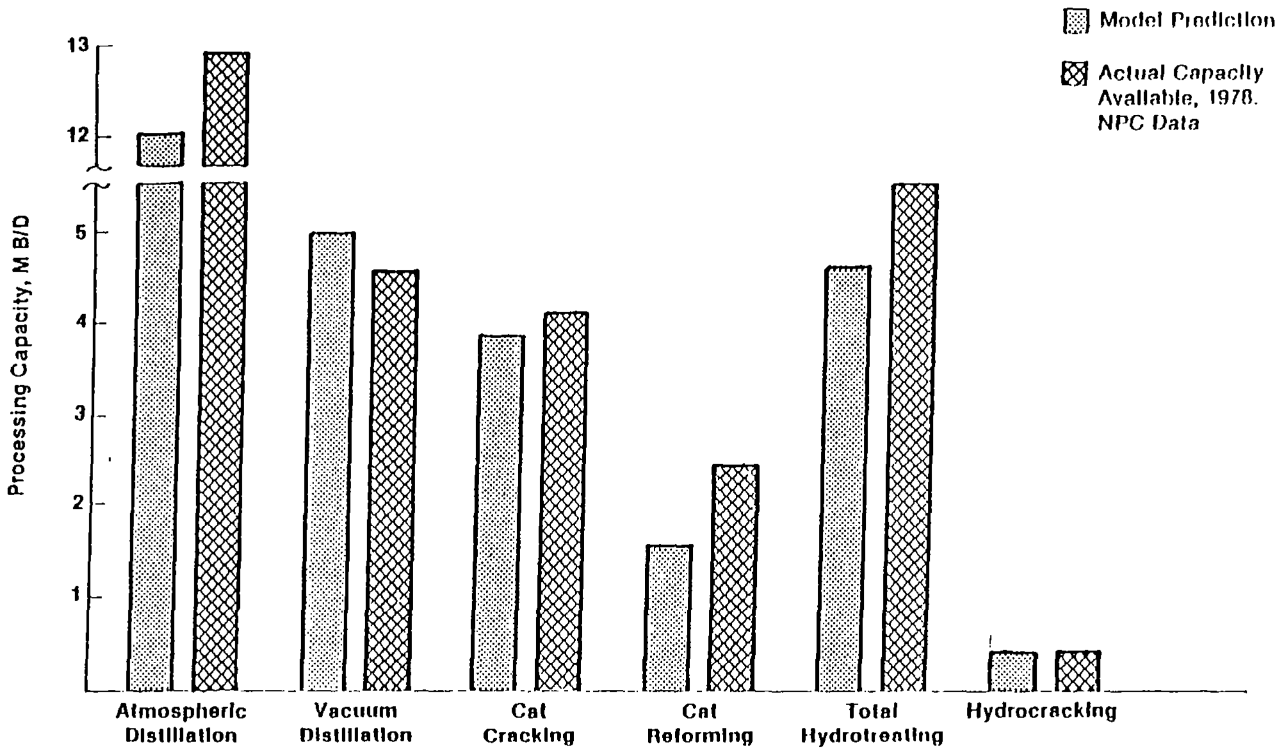


Figure 5. Eastern Regional Model Simulates
Actual Capacities Available in 1978

USAF SHALE OIL PROGRAM STATUS

Charles L. Delaney
Air Force Wright Aeronautical Laboratories

The test and evaluation program on shale derived fuel being conducted by the Air Force is intended to accomplish the minimum amount of testing necessary to assure both the safe use of shale oil derived turbine fuels in operational USAF aircraft and its compatibility with USAF handling systems. The elements of this assurance program were defined by an Air Force ad hoc Working Group for Fuels composed of personnel from the Air Force Logistic Center, Aircraft System Project Offices, Aero Propulsion Laboratory and the Materials Laboratory. This program, which was designed to take advantage of existing R&D testing programs, began in 1981. However, due to a problem in acquiring the necessary fuel, the testing program was suspended until July 1983 when an additional sample of shale derived fuel was received.

Tentatively, the Air Force is planning to make three relatively minor revisions to the procurement specifications requirements for the production shale derived fuel. These are:

Aromatic Contest (min) - 9% (by volume)
Nitrogen (max - 20 ppm by weight)
Antioxidants - 9.1 g/100 gal (U.S.)

The rationale for these specification changes are primarily based upon prior testing of shale derived fuels and experience by the military services in the use of certain fuels which have some specific characteristic which is expected to be similar to some aspect of the shale derived fuel.

SHALE OIL VALIDATION

- PMD L-Y 0106(1) ISSUED 18 SEPTEMBER 1980
  - AFLC IMPLEMENTING COMMAND
  - AFSC-PARTICIPATING COMMAND
- UNION SHALE WILL PROVIDE FUEL FOR VALIDATION PROGRAM - 1 DEC 1983
- AFSC RESPONSIBILITIES BY 1984
  - *UNDER PE 63215F ASSURE SAFE USE OF FUEL IN AIRCRAFT*
  - ASSIST IN PLANNING, SCHEDULING AND TECHNICAL ASSISTANCE
  - PROVIDE TECHNICAL REQUIREMENTS FOR PROCUREMENT SPECIFICATION
  - CONDUCT TOXICOLOGY STUDY ON FUEL
  - CONDUCT SYSTEM SAFETY ANALYSIS ON EACH A/C TO USE FUEL EXCLUSIVELY
  - *MEASURE EMISSIONS AND SUPPORT ENVIRONMENTAL ASSESSMENT*
  - ESTABLISH A QUALITY ASSURANCE PROGRAM FOR FUEL

SHALE OIL VALIDATION CONT'D

AFLC RESPONSIBILITIES

- PLAN VALIDATION PROGRAM
- COORDINATE ON PHASED SCHEDULE TO ASSURE PREVALIDATION TESTING COMPLETION BEFORE OPERATIONAL USE OF FUEL IS STARTED
- REVIEW AND REVISE TECHNICAL MANUALS IF REQUIRED
- PROVIDE TECHNICAL ASSISTANCE TO PARTICIPATING COMMANDS
- ESTABLISH FUEL REQUIREMENTS TO DFSC
- ACCOMPLISH DATA ANALYSIS AND COMPARE RESULTS ON EQUIPMENT TAKING PART IN VALIDATION PROGRAM
- MAKE AN ENVIRONMENTAL ASSESSMENT OF THE USE OF FUEL
- ESTABLISH A QUALITY ASSURANCE PROGRAM TO ASSURE THAT FUEL MEETS REQUIREMENTS OF MIL-T-5624

AIR FORCE SHALE OIL FUEL ACCEPTANCE PROGRAM

PROGRAM FORMULATION

AD HOC COMMITTEE FORMED BY AFWAL/PO

- REPORTS TO ASD/EN AND AFWAL/PO
- MEMBERSHIP
  - ASD-ENGINEERING / SPO'S
  - AFWAL - MATERIALS/TURBINE ENGINES/ POWER
  - AFLC - ENGINEERING
- RESPONSIBILITIES
  - FORMULATE BASIC PROGRAM
  - MONITOR PROGRESS
  - ASSIST IN LOCATING TEST RESOURCES

FUEL SPECIFICATION DEVELOPMENT - SHALE

PROGRAM OBJECTIVE

ACCOMPLISH THE MINIMUM AMOUNT OF TESTING NECESSARY TO ENSURE BOTH THE SAFE USE OF SHALE OIL DERIVED TURBINE FUEL IN OPERATIONAL USAF AIRCRAFT AND ITS COMPATIBILITY WITH FUEL HANDLING SYSTEMS

PROGRAM APPROACH

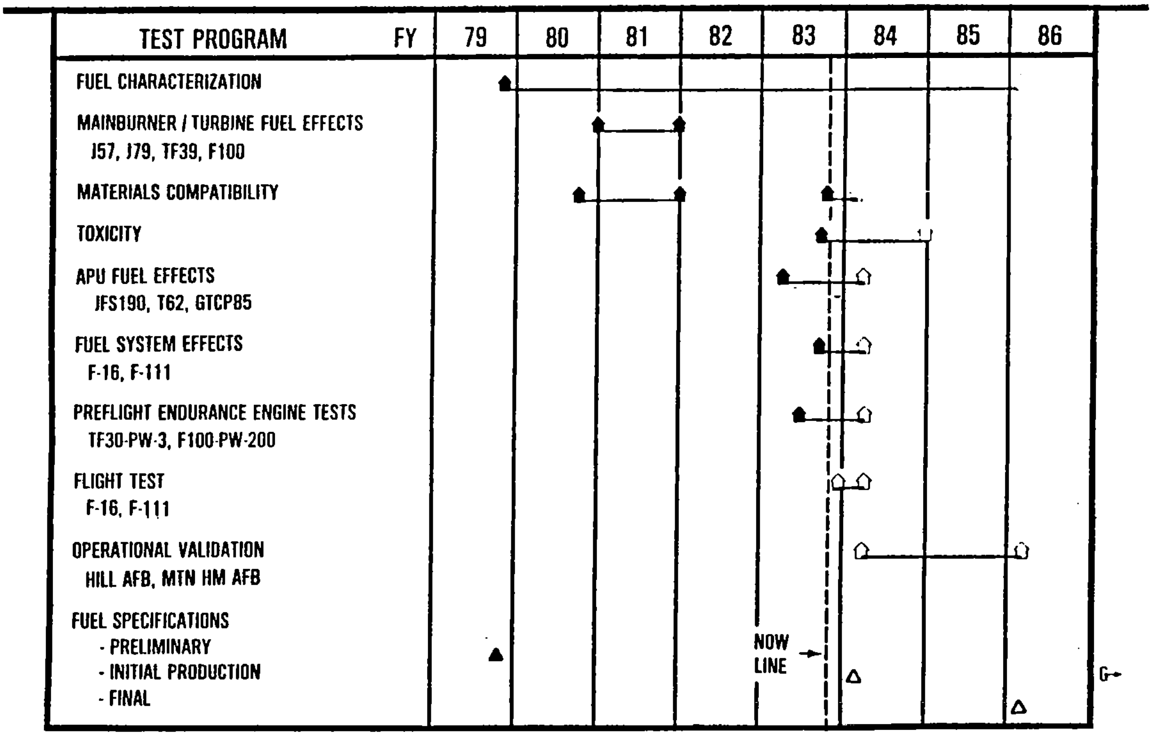
- CONSIDER ALL A/C AT BASES WHERE VALIDATION PROGRAM IS TO TAKE PLACE
- UTILIZE EXISTING COMPONENT TEST PROGRAMS WHERE POSSIBLE
- SUPPLEMENT EXISTING PROGRAMS WITH UNIQUE SHALE OIL FUEL TESTS WHEN NECESSARY
- CONDUCT ENGINE PREFLIGHT CLEARANCE & CYCLIC ENDURANCE TESTS USING ACCELERATED MISSION TEST PROCEDURES
- LIMITED FLIGHT TESTS (PIGGYBACK)

FUEL PROPERTY COMPARISON

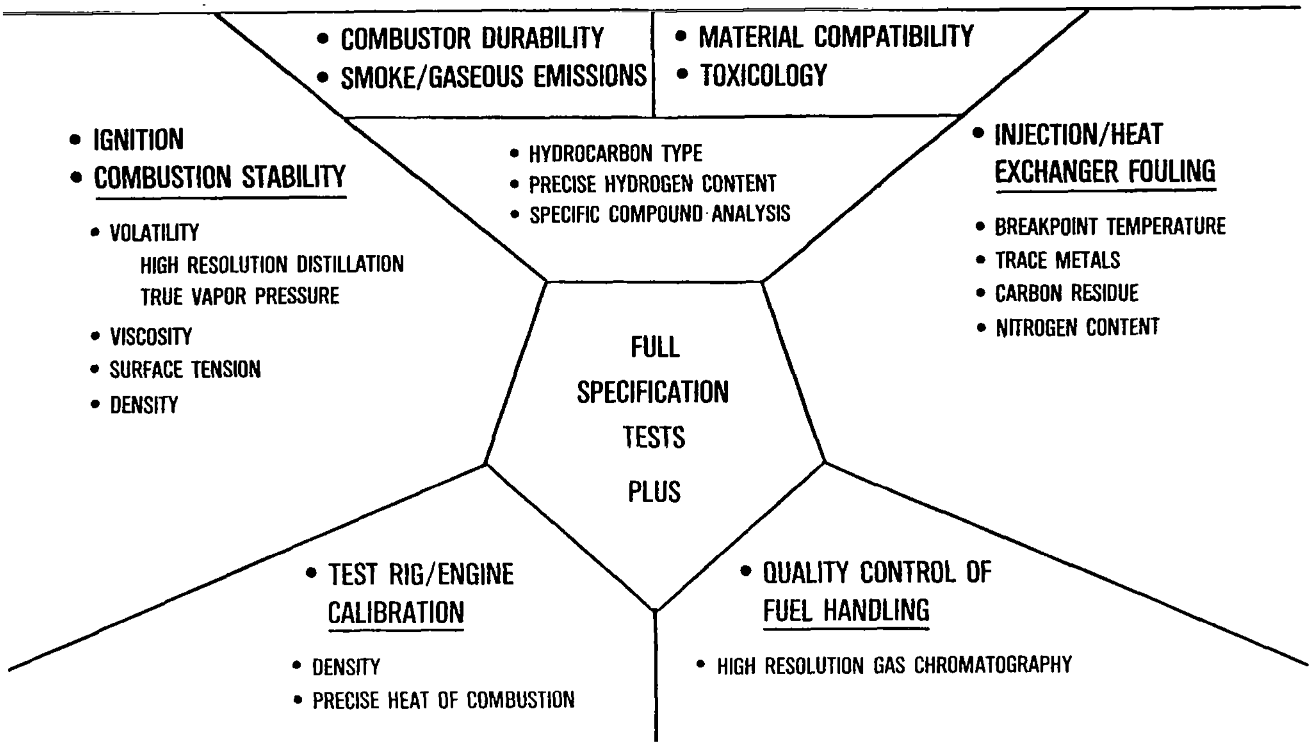
SALIENT PROPERTIES		JP-4 LIMIT	CURRENT EXPERIENCE	EXPECTED JP-4 SHALE LIMIT
AROMATICS (VOL %)	MAX	25	12-15	25
	MIN	–	–	9
FREEZE POINT (°F)		-72	-72	-72
REID VAPOR PRESSURE (PSI)		2-3	2.2	2-3
THERMAL STABILITY BREAKPOINT (°F)		500	500	500
NITROGEN (PPM)			5	20
ANTIOXIDANT (G/GAL)		.091 (OPTIONAL)-MAX		.091

AIR FORCE SHALE OIL ACCEPTANCE PROGRAM

PROGRAM SCHEDULE



FUEL CHARACTERIZATION



- COMBUSTOR DURABILITY
- SMOKE/GASEOUS EMISSIONS

- MATERIAL COMPATIBILITY
- TOXICOLOGY

- IGNITION
- COMBUSTION STABILITY
  - VOLATILITY
    HIGH RESOLUTION DISTILLATION
    TRUE VAPOR PRESSURE
  - VISCOSITY
  - SURFACE TENSION
  - DENSITY

- HYDROCARBON TYPE
- PRECISE HYDROGEN CONTENT
- SPECIFIC COMPOUND ANALYSIS

- INJECTION/HEAT EXCHANGER FOULING
  - BREAKPOINT TEMPERATURE
  - TRACE METALS
  - CARBON RESIDUE
  - NITROGEN CONTENT

FULL SPECIFICATION TESTS PLUS

- TEST RIG/ENGINE CALIBRATION
  - DENSITY
  - PRECISE HEAT OF COMBUSTION

- QUALITY CONTROL OF FUEL HANDLING
  - HIGH RESOLUTION GAS CHROMATOGRAPHY

ADDITIVE EVALUATION

OBJECTIVE

EVALUATE EFFECT OF VARIOUS ADDITIVES ON THE STORAGE AND PERFORMANCE CHARACTERISTIC OF SHALE DERIVED JP-4 FUEL

PROGRAM APPROACH

SELECT A SUFFICIENT NUMBER OF EACH ADDITIVE TYPE TO EVALUATE RELATIVE EFFECTIVENESS AND QUANTITY REQUIRED

ADDITIVE	NO. TESTED	ADDITIVE AMOUNT	TEST TIME
• ANTIOXIDANTS	8	17.1→48.0 MG/L	0, 3, 9, 15 MONTHS
• CORROSION INHIBITOR	4	11.4 MG/L	0, 3 MONTH (LUBRICITY)
• CONDUCTIVITY	2	1 PPM	SPOT CHECK
• FSII	1 (ONLY APPROVED)	0.10-0.15 VOL %	SPOT CHECK
• METAL DEACTIVATOR	1 (2 CHEMICALLY SIMILAR)	5.8 MG/L	0, 3, 9, 15 MONTHS
• JFA-5	1 (APPROVED FOR JP-TS)	11.6 MG/L	0, 3, 9, 15 MONTHS

APU / JFS TEST PROGRAM

OBJECTIVE

DETERMINE IMPACT OF SHALE FUEL ON THERMODYNAMIC PERFORMANCE / DURABILITY OF A/C APU'S

SELECTED HARDWARE

- SOLAR T-62T-40-8 (F-16 ON BOARD ENGINE STARTER)
- GARRETT GTCP-85-180 (M32A/60 GROUND CART)
- GARRETT JFS-190-1 (F-15 ON-BOARD ENGINE STARTER)

TEST PROGRAM

- COMBUSTOR
- STEADY STATE (S. L.→ MAX)
- TRANSIENT (S. L.→MAX)
- IGNITION (S. L.→SPEC LIMIT)

- ENGINE
- ENDURANCE
- START ENVELOPE
- RAPID STARTS
- HOT SOAKS (160°F)
- COLD SOAKS (-65°F)

- MISCELLANEOUS
- FUEL NOZZLE FOULING
- SYSTEM COMPATIBILITY
- EROSION RATES

FUEL SYSTEM EFFECTS

OBJECTIVE

STUDY EFFECTS OF USING SHALE JP-4 IN THE F-16 AND F-111 A/C

TESTING PROGRAM

- MATERIALS COMPATIBILITY
- F-16 FUEL QUANTITY SYSTEM
- COMPONENT ENDURANCE TESTS
  - BOOST PUMP
  - FUEL FLOW PROPORTIONER
  - WING TRANSFER PUMP
  - FUEL FLOWMETER
- F-16 EXPLOSION SUPPRESSION SYSTEM
- SYSTEM SAFETY ANALYSIS
- ASSESSMENT OF EFFECTS ON F-16 SUPPORT EQUIPMENT
- EFFECT ON A/C DEPLOYMENT

ENGINE DURABILITY TESTS

OBJECTIVE

ASSESS LONG TERM PERFORMANCE, OPERABILITY AND DURABILITY EFFECTS OF USE OF SHALE DERIVED TURBINE FUEL IN USAF AIRCRAFT

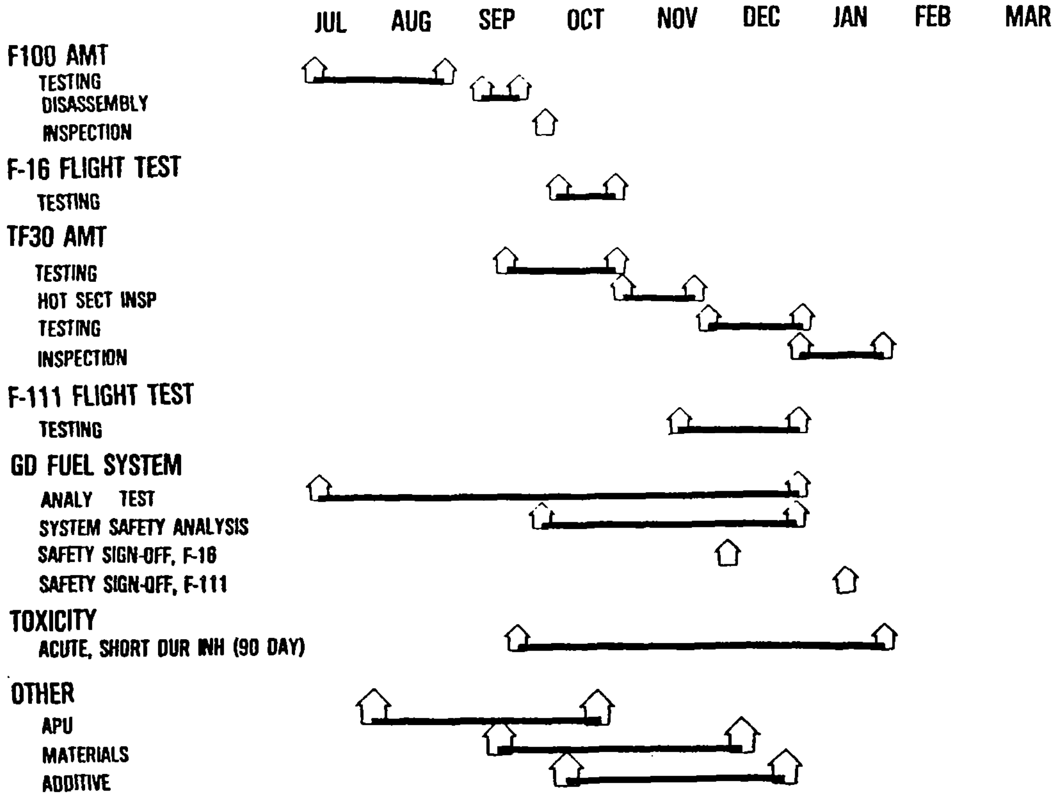
PROGRAM APPROACH

- SELECT ENGINES POWERING A/C BASED AT VALIDATION PROGRAM LOCATION
- INCLUDE VINTAGE AND CURRENT TECHNOLOGY
- UTILIZE ACCELERATED TEST PROCEDURES TO MINIMIZE COST
- SELECT TEST TIME / CYCLES CONSISTENT WITH ENGINE OVERHAUL CRITERIA
- EVALUATION CRITERIA-PERFORMANCE DATA, EXTENSIVE PRE, POST–TEST INSPECTION

TEST PROGRAM

- F100-P-200~1800 CYCLES
  - START 11 JUL 83
- TF30-P-3A~350 CYCLES
  - START 15 SEP 83

SHALE JP-4 RDT&E SCHEDULE



AIR FORCE
SHALE FUEL SPECIFICATION DEVELOPMENT

SUMMARY / CONCLUSIONS

- PROGRAM FORMULATION
  - WIDE VARIETY OF INPUTS / REVIEWS
  - BROAD BASE OF EXPERIENCE INVOLVED
  - SPECIFIC SYSTEMS BEING INVESTIGATED
  - BROAD BASE TESTING APPLICABLE TO ALL SYSTEMS
- TRANSIENT AIRCRAFT REFUELING AT SELECTED BASES NOT OF CONCERN
- THE AIR FORCE'S TESTING PROGRAM SHOULD PRECLUDE THE POSSIBILITY OF AN OPERATIONAL PROBLEM
- THE NECESSITY FOR A SPECIFICATION REVISION WILL BE DETERMINED AT THE COMPLETION OF THE TESTING PROGRAM

INFLUENCE OF FUEL CHEMICAL PROPERTIES ON GAS TURBINE COMBUSTORS

Thomas J. Rosfjord
United Technologies Research Center

The ASTM "Standard Specification for Aviation Turbine Fuels" (ASTM D-1655) defines acceptable limits for many properties of turbine engine fuel for civilian use. Fuels satisfying these limits will have characteristics acceptable to current gas turbine combustors. In particular, desirable combustion characteristics are assured by bounding the aromatic and naphthalenic hydrocarbon contents and the smoke point. Previous studies have been conducted in an attempt to identify which of these properties (or others) influence the performance, emissions and heat load of the combustor. Fuel hydrogen content, which is not a specification parameter, has been cited as a global indicator of fuel effects. These earlier studies, however, did not purposefully emphasize the fuel chemical properties; the combined influence of both physical and chemical properties was likely observed. Additionally, the burners were not always representative of current aircraft practice and the range of fuel properties studied was often limited.

In an attempt to rigorously study the fuel chemical property influence, UTRC (under contract to NASA Lewis Research Center) has conducted an experimental program using 25 test fuels. The burner was a 12.7-cm dia cylindrical device consisting of six sheet metal louvers. A single pressure-atomizing injector and air swirler were centrally mounted with the conical dome. Fuel physical properties were de-emphasized by using fuel injectors which produced highly-atomized, and hence rapidly-vaporizing sprays. A substantial fuel spray characterization effort was conducted to allow selection of nozzles which assured that such sprays were achieved for all fuels. The fuels were specified to cover the following wide ranges of chemical properties: hydrogen, 9.1 to 15 (wt) pct; total aromatics, 0 to 100 (vol) pct; and naphthalene, 0 to 30 (vol) pct. They included standard fuels (e.g., Jet A, JP4), specialty products (e.g., decalin, xylene tower bottoms) and special fuel blends. Included in this latter group were six, 4-component blends prepared to achieve parametric variations in fuel hydrogen, total aromatics and naphthalene contents.

Two test phases were conducted. First, fuel-effects tests were performed during which data were acquired for all 25 test fuels using a single burner configuration. Second, configuration-effects tests were performed using three fuels and two additional burner configurations which produced either higher or lower primary zone equivalence ratios than achieved with the fuel-effects configuration. Results for only the fuel-effects tests will be included in this presentation. Combustor heat load was documented by full-hemispherical-sensing radiometers mounted on the dome and by 39 liner thermocouples. Three narrow-angle radiometers mounted on the combustor case were used to sense shifts in the axial distribution of radiation. Arrays of thermocouples and sampling probes at the combustor exit were used to document the temperature pattern factor, and to acquire gaseous and particulate specie samples. The characteristic particle size and number density of the exhaust soot on the combustor centerline were determined by an optical technique which interpreted scattered light signals according to Mie theory. All data were acquired at a single airflow condition which simulated high-power operation of a gas turbine combustor--namely, combustor pressure = 1.3 MPa and inlet air temperature = 700K. Each test fuel was combusted at 3 fuel-air ratios which were specified to achieve combustor exit temperatures of 1246K, 1346K and 1473K. Repetitive data points were acquired to determine the statistical consistency of the measurements.

The combustor operated in a consistent manner for all tests. Combustion efficiencies greater than 99.9 pct were always achieved; the exit temperature pattern factor was typically less than 0.15. The output from the case-mounted radiometers indicated that for each test condition, the reaction zone structure was not significantly altered by any of the test fuels. Hence all fuels were similarly atomized and distributed in the burner. For every fuel, both exhaust smoke number and particle number density decreased with increasing combustor fuel-air ratio (increasing exit temperature), while the characteristic particle size remained constant. Indeed, the particle size was also independent of fuel properties; the indicated size was always 0.20 ± 0.02 μm. The smoke number/number density trends indicated that the soot oxidation mechanism dominated the overall process of soot production. That is, despite an increasingly fuel-rich primary zone at higher overall fuel-air ratios, lower levels of exhaust soot were produced because of enhanced oxidation at higher exit temperatures. These consistent trends also revealed a correlation between smoke number and soot number density.

The principle influence of fuel chemical properties on the combustor behavior were reflected by the radiation, liner temperature and exhaust smoke number (or equivalently, soot number density) data. The measured dome radiative heat transfer rates appear to correlate well with fuel hydrogen content. Used in this manner, however, the hydrogen content is a global indicator of the fuel property influence since it is accompanied by variations in total aromatics and naphthalenes. Results from tests with fuels which offered parametric variations in hydrogen, total aromatics and naphthalenes indicated that naphthalene content strongly influenced the radiative heat load while parametric variations in total aromatics did not. The hydrogen parametric test results indicated that, in a pure sense, hydrogen content does not influence the radiation load; only a global sense (i.e., with variations of hydrocarbon molecular structure) is a hydrogen content influence observed. Regression analyses were performed on data from tests with all fuels in an attempt to identify the individual influences of the chemical properties. These analyses confirmed the importance of naphthalene content; a regression parameter containing both hydrogen and naphthalene content tracked the data significantly better than a parameter containing hydrogen content alone. For the range of chemical properties encompassed by Jet-A and ERBS, both the hydrogen and the naphthalene content variations would contribute similarly to a variation in radiative heat load. It was also observed that fuel smoke point correlated the data as well as the two-property parameter. Hence smoke point, an existing fuel specification parameter, appears to be an adequate global indicator of fuel chemical property influences. Similar fuel effects were also observed for liner temperature rise and exhaust smoke number.

Objective

Quantify fuel chemical property influences
- Performance
- Heat load

Scope

Perform well-documented tests
- Fuel spray characterization
- Combustor airflow calibration
- Combustor operation

Twenty-five test fuels

RD410TX.002

COMBUSTION QUALITY FUEL ANALYSES

Property	ASTM Jet A specification
• Aromatics	20 vol pct (max)
• Smoke point or naphthalenes	25 mm (min) 3 vol pct (max)
• Hydrogen	Not a specification

RB324TX.003

TEST FUELS

- Standard fuels (8)
  - Jet A
  - JP4
  - JP4-shale
  - JP4-high aromatic
  - JP5
  - JP7
  - ERBS
  - No. 2
- Specialty products (6)
  - Gulf seal oil
  - Xylene tower bottoms
  - Blending stock
  - Decalin
  - Tetralin
  - Paraffinic solvent
- Blends (11)

  Attempt to achieve parametric variation of hydrogen, aromatic and naphthalene contents

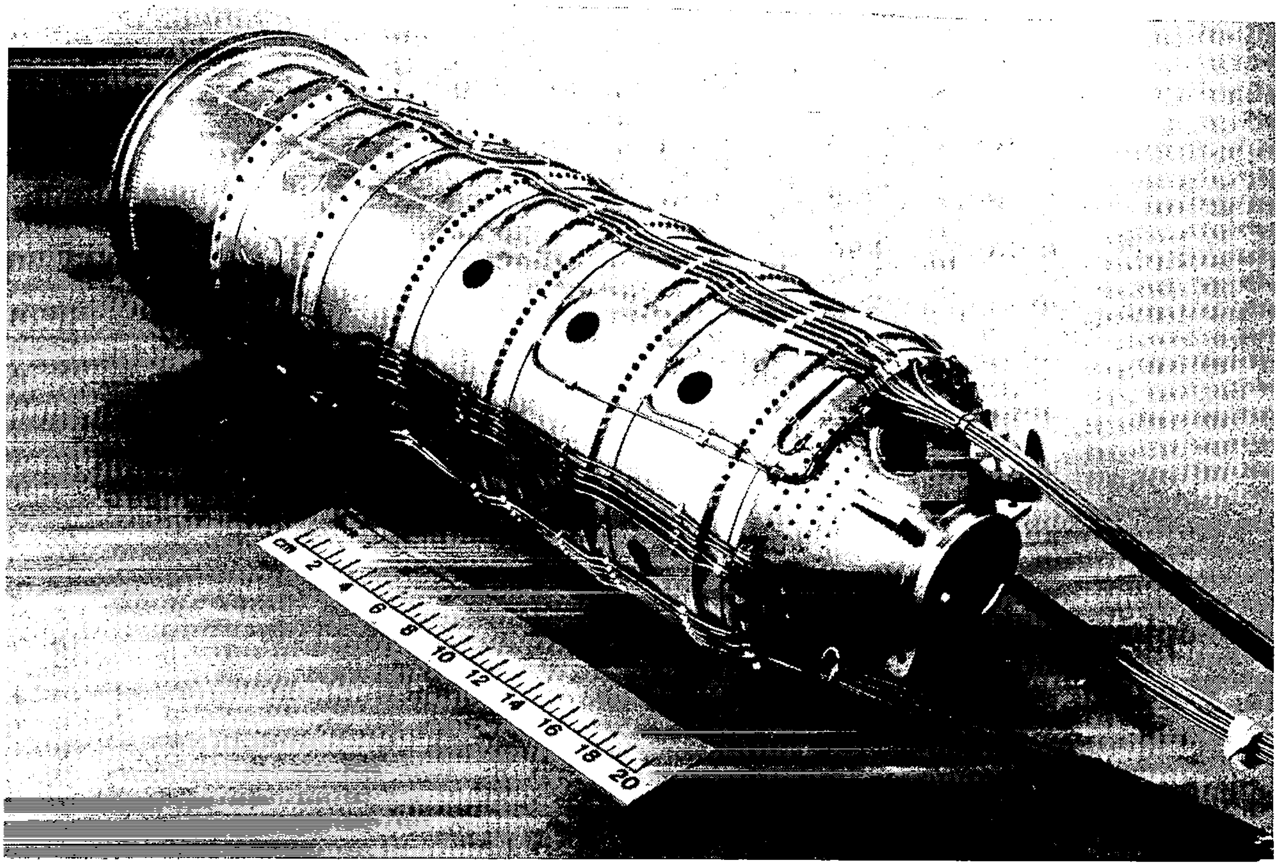
R8410TX.008

TYPICAL FUEL BLEND PARAMETRIC

Blend	Components	Blend properties		
	(Vol fraction)	H	Arom	Naph
ERBS	ERBS (1.00)	12.95	28.39	13.45
UTRC 9A	Jet A (0.50) JP7 (0.20) M naph (0.20) Decalin (0.10)	12.92	28.47	0.99
UTRC 9B	Jet A (0.40) No. 2 (0.45) ERBS (0.10) Decalin (0.05)	13.01	28.27	7.15

R8410TX.004

GENERIC COMBUSTOR



TEST PROGRAM ELEMENTS

- Combustor calibration
  - C_DA for liner
  - Primary airflow split
- Fuel spray characterization
  - Nozzle selection
  - Spray correlation
- Combustion test
  - Fuel-effects tests
  - Configuration-effects tests

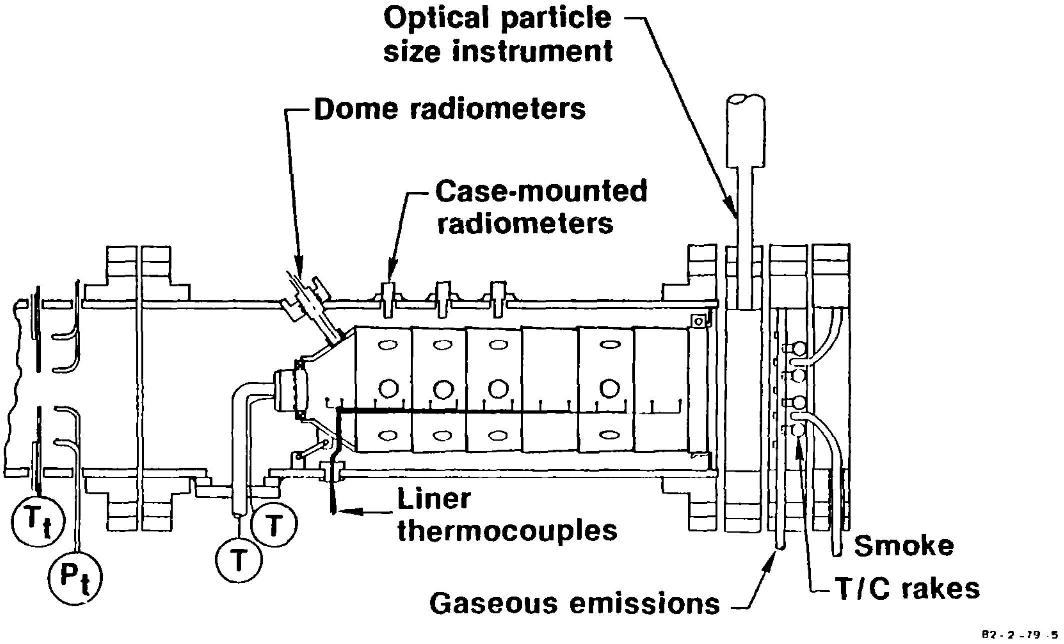
RD410TX.004

OPERATING CHARACTERISTICS

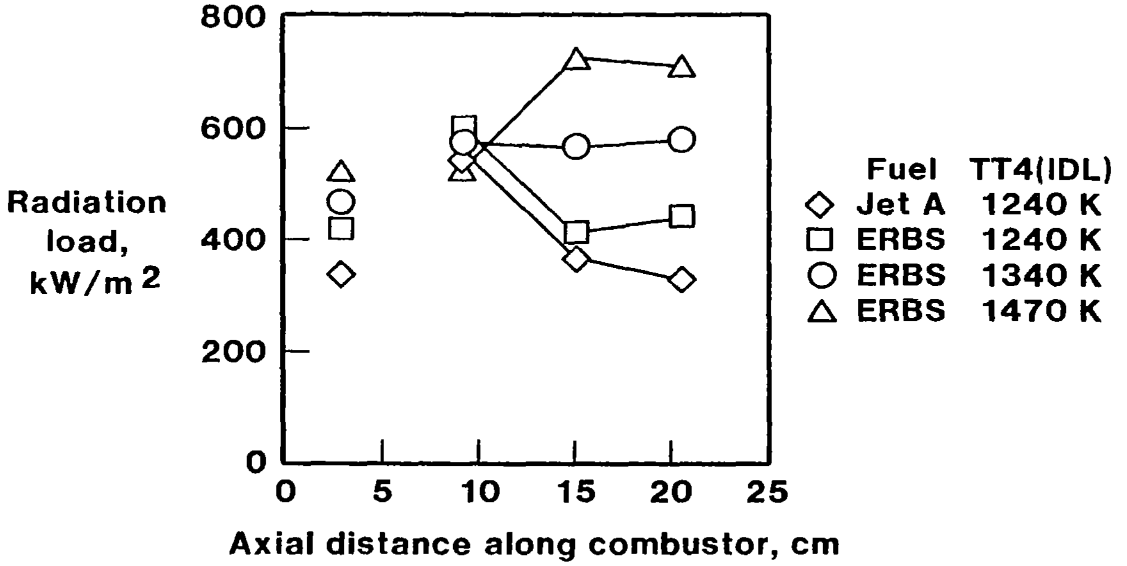
- Test condition
  - P3 = 1.3 MPa
  - T3 = 700 K
  - W_{AIR} = 2 Kg/S
  - T4 = 1240, 1340, 1470 K
- Combustor characteristics
  - $\eta_c \approx 100$ pct
  - $u_{REF} = 25$ m/s
  - $(\Delta P/P)_{LINER} = 2$ pct
  - PF < 0.2

RC410TX.008

TEST SECTION INSTRUMENTATION

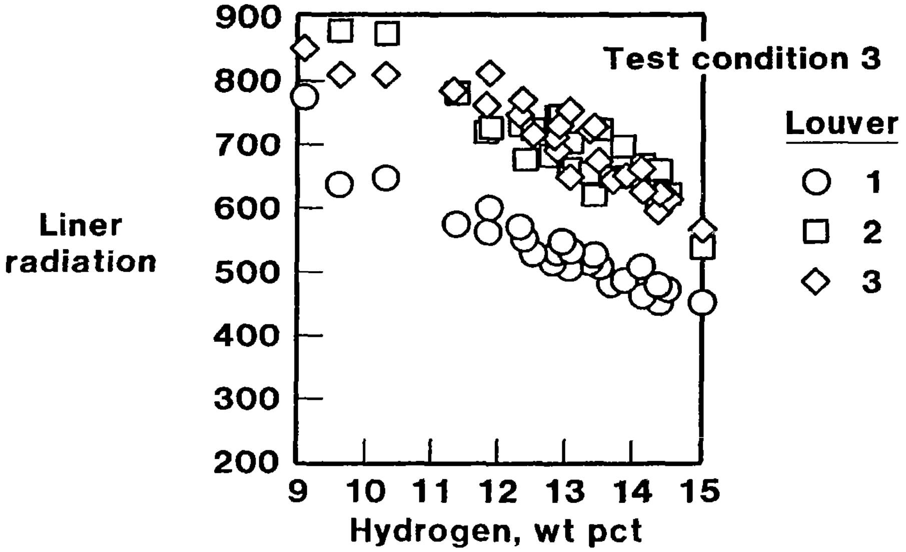


AXIAL DISTRIBUTION OF RADIATION



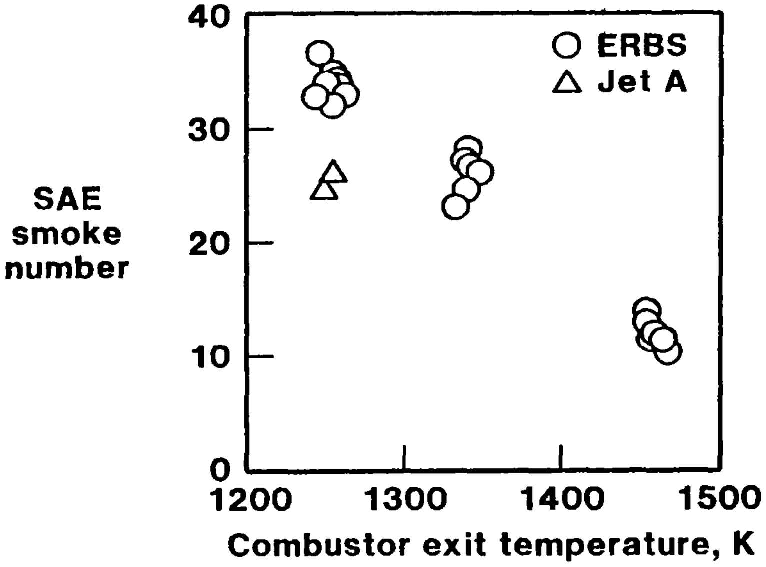
RB324TX.001

INFLUENCE OF FUEL PROPERTIES ON REACTING FLOW STRUCTURE



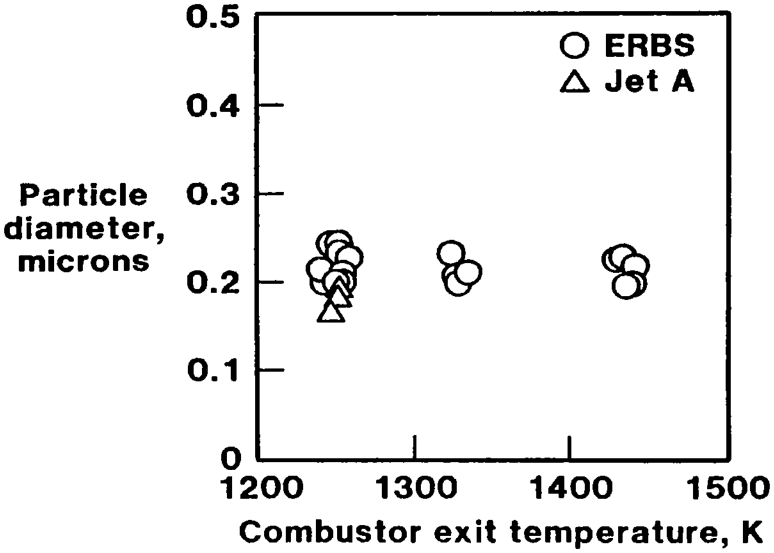
RB324TX.006

INFLUENCE OF OPERATING CONDITION ON SMOKE NUMBER



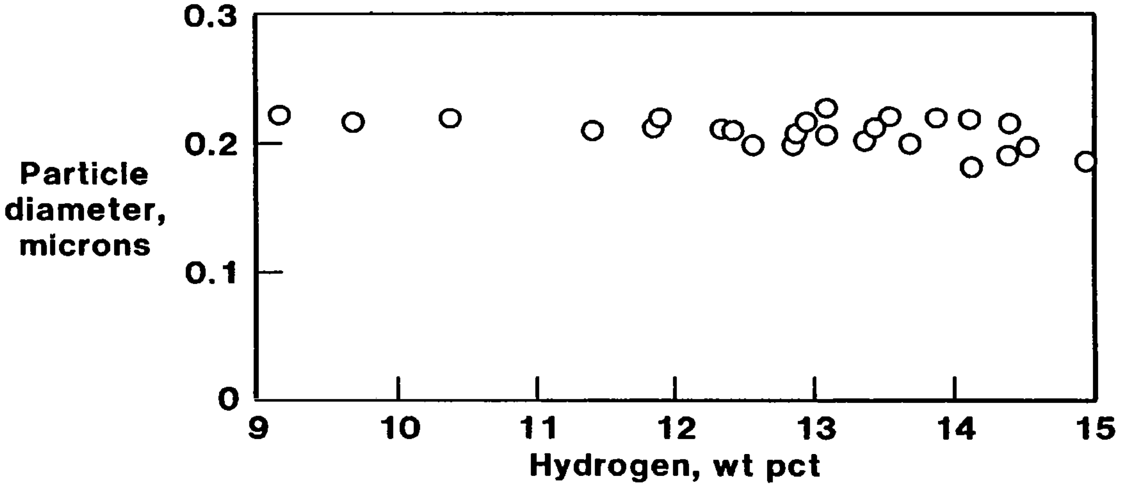
RC410TX.002

INFLUENCE OF OPERATING CONDITION ON PARTICULATE DIAMETER



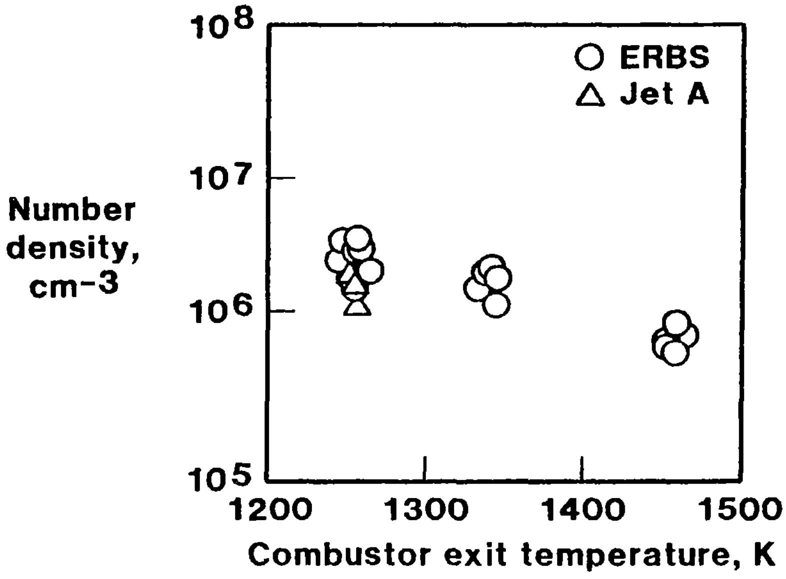
RC410TX.003

INFLUENCE OF FUEL PROPERTY ON EXHAUST PARTICULATE SIZE



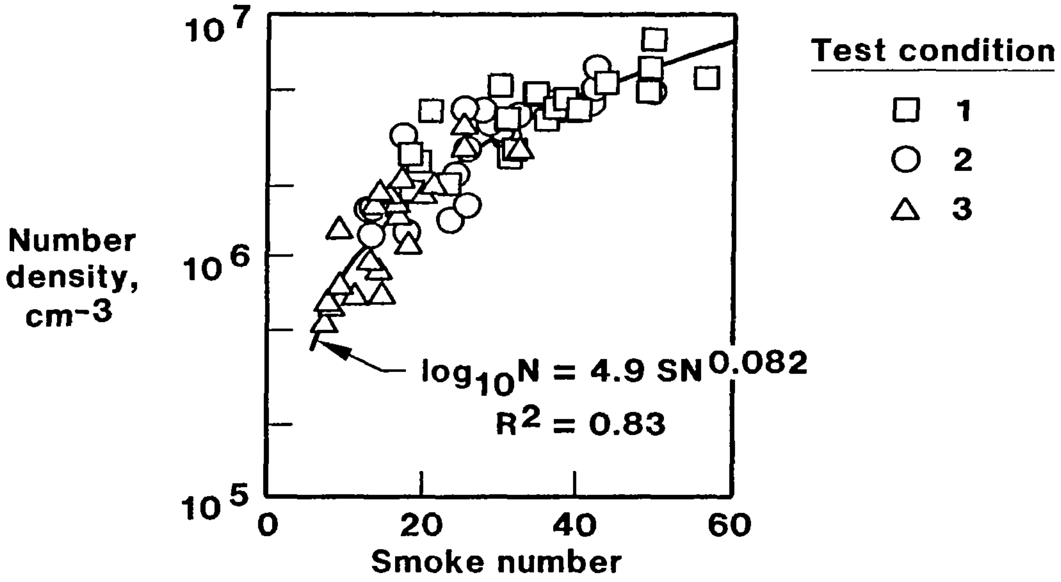
RD410TX.007

INFLUENCE OF OPERATING CONDITION ON PARTICULATE NUMBER DENSITY



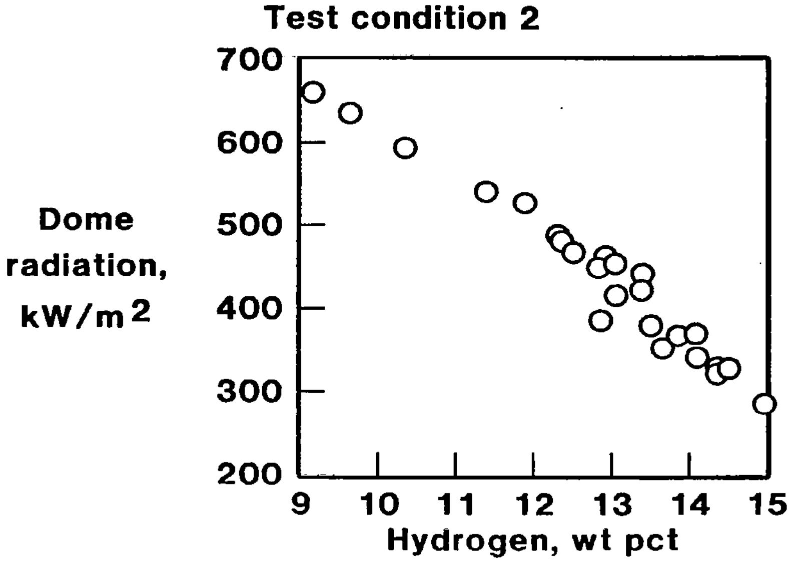
RC410TX.004

SOOT NUMBER DENSITY CORRELATED WITH SMOKE NUMBER



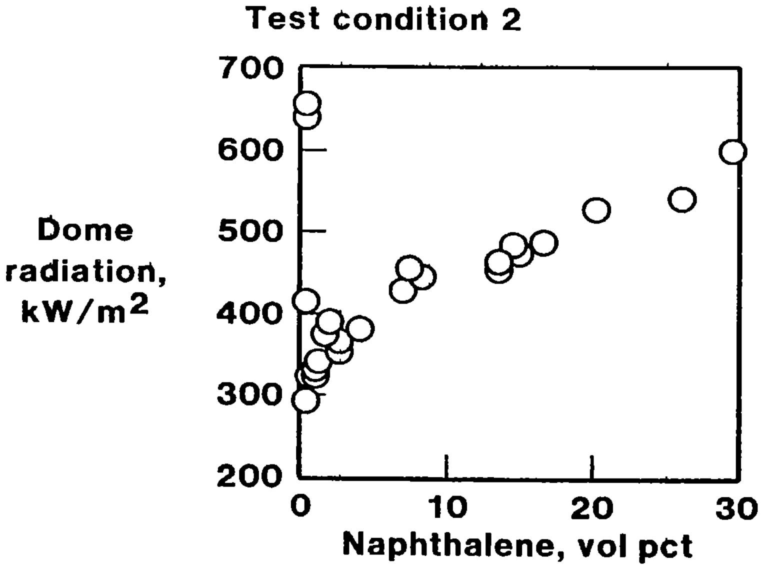
RB324TX.007

DOME RADIATION DEPENDENCE ON FUEL HYDROGEN



RA324TX.002

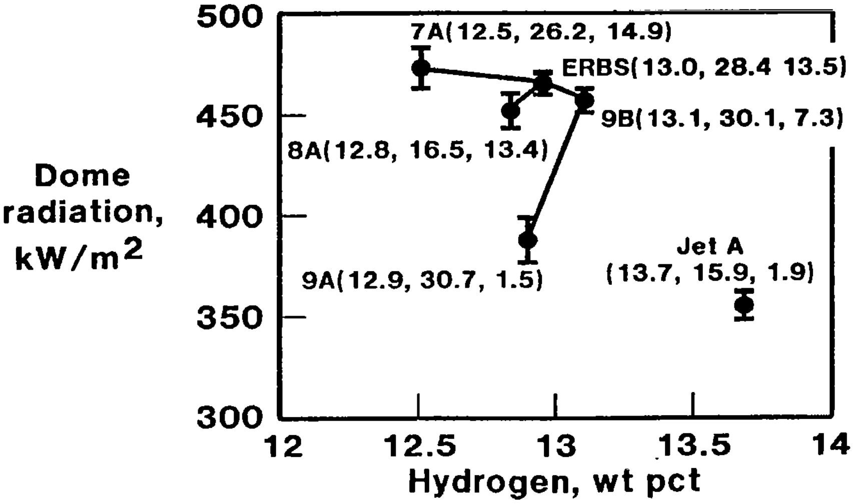
DOME RADIATION DEPENDENCE ON FUEL NAPHTHALENE



RB324TX.005

INFLUENCE OF PARAMETRIC FUEL PROPERTY VARIATIONS ON DOME RADIATION

Test condition 2



RE410TX.001

FUEL PROPERTY CORRELATION GROUPS

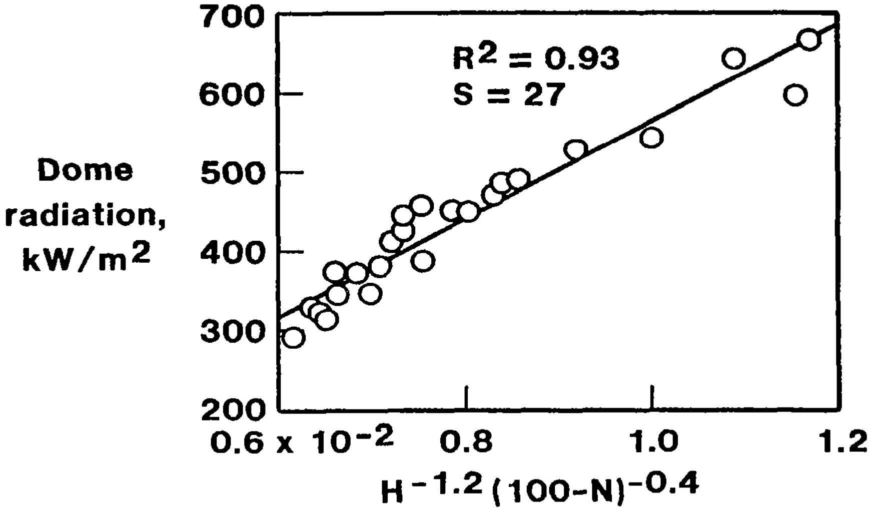
- H^{C1}
- $H^{C1} A^{C2} N^{C3}$
- $H^{C1} (100 - N)^{C2}$
- $H - N^{C1}$

Where: H = Hydrogen (wt pct)
A = Total aromatics (vol pct)
N = Naphthalene (vol pct)

RA324TX.001

CORRELATION OF DOME RADIATION WITH FUEL HYDROGEN AND NAPHTHALENE

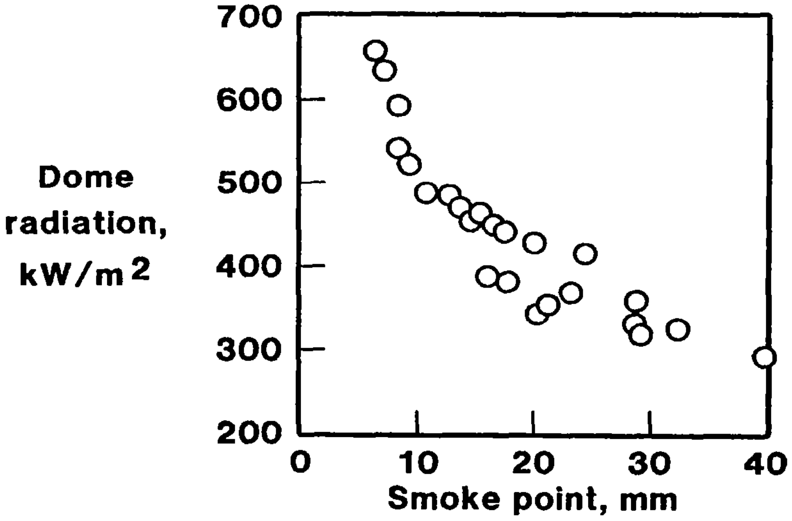
Test condition 2



RA324TX.003

DOME RADIATION DEPENDENCE ON SMOKE POINT

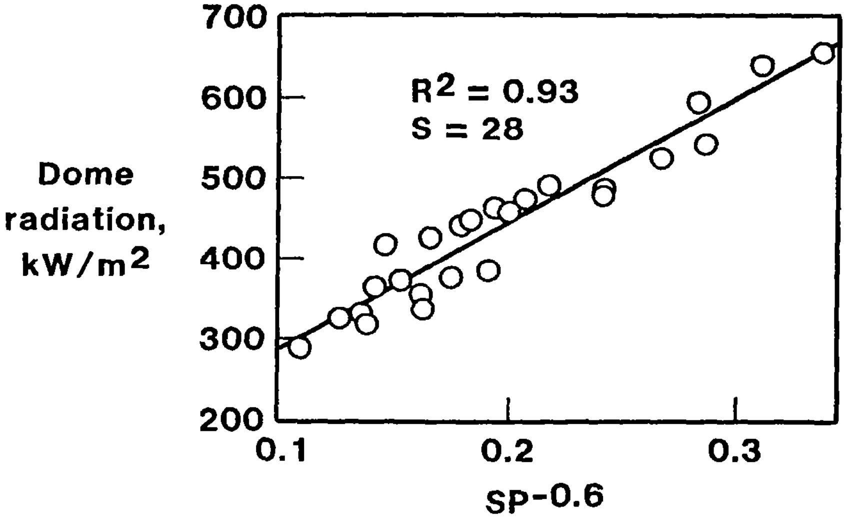
Test condition 2



RA324TX.004

CORRELATION OF DOME RADIATION WITH SMOKE POINT

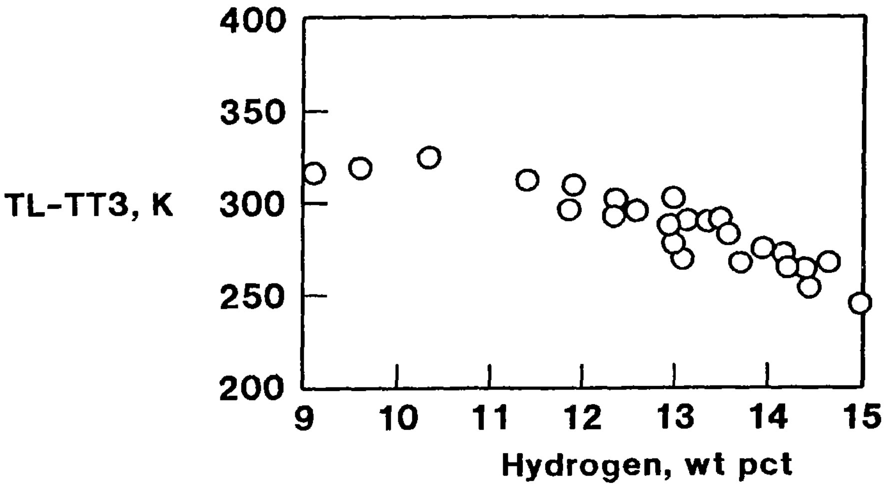
Test condition 2



RA324TX.005

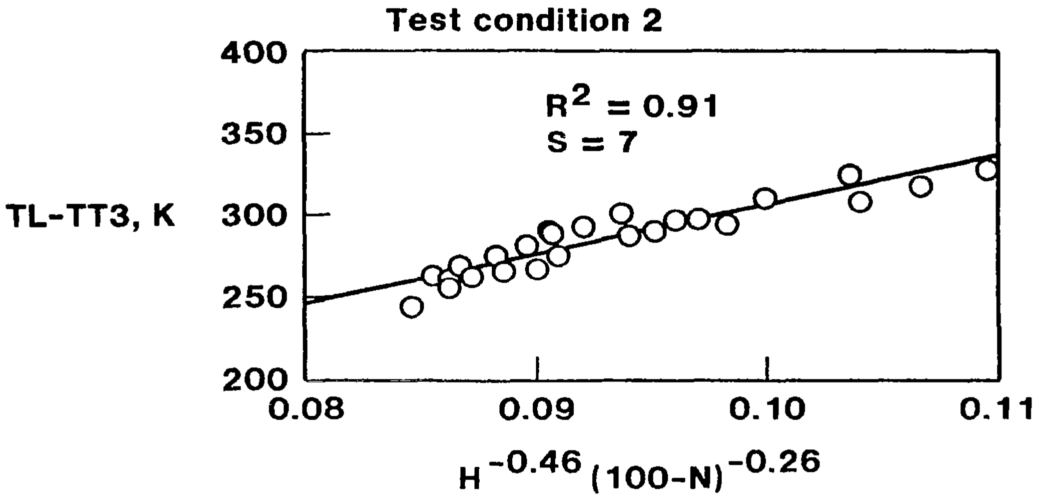
LINER TEMPERATURE RISE DEPENDENCE ON FUEL HYDROGEN

Test condition 2



RA324TX.006

CORRELATION OF LINER TEMPERATURE RISE WITH FUEL HYDROGEN AND NAPHTHALENE



RA324TX.007

CONCLUDING REMARKS

- Comprehensive, well-documented test programs are required to identify fuel property effects

- Combustor heat loads depend on fuel properties in a complex manner

  Both fuel hydrogen and naphthalene contents are important. Heat load data also correlate with smoke point

- Light scattering techniques to characterize exhaust particulates are compatible with a test cell environment

FUEL PROPERTY EFFECTS ON USAF GAS TURBINE ENGINE COMBUSTORS AND AFTERBURNERS

Curtis M. Reeves
USAF Wright Aeronautical Laboratories

Since the early 1970s, the cost and availability of aircraft fuel have changed drastically. These problems prompted a program to evaluate the effects of broadened specification fuels on current and future aircraft engine combustors employed by the USAF.

Phase I of this program was to test a set of fuels having a broad range of chemical and physical properties in a select group of gas turbine engine combustors currently in use by the USAF. The combustors tested were:

J79-17A
F101
TF41
J79-17C
J85-21
TF39-1A
F100
TF33

The fuels ranged from JP4 to Diesel Fuel number two (DF2) with hydrogen content ranging from 14.5 percent down to 12 percent by weight, density ranging from 752 kg/m^3 to 837 kg/m^3, and viscosity ranging from 0.830 mm^2/s to 3.245 mm^2/s. In addition, there was a broad range of aromatic content and physical properties attained by using Gulf Mineral Seal Oil, Xylene Bottoms, and 2040 Solvent as blending agents in JP4, JP5, JP8, and DF2. These Phase I tests produced a large database of information on broad specification fuels and their effects on specific engine combustors with regard to operability, performance, and durability. Information on Phase I work can be found in references 1 to 6.

The objective of Phase II was to develop simple correlations and models of fuel effects on combustor performance and durability. The major variables of concern were fuel chemical and physical properties, combustor design factors, and combustor operating conditions. In addition, Phase II would identify voids in the Phase I developed database and address research needs in these areas. Phase II was accomplished through a dual award contract with Purdue University and Pratt and Whitney Aircraft (P&WA).

A summary of the Purdue effort as follows, is taken directly from their Task I Technical Report [7].

The method followed was to study each aspect of combustion performance from as fundamental a viewpoint as possible. Meaningful relationships were sought, not on the basis of statistical techniques, but from an understanding of the fundamental physical and chemical processes involved. The general approach was either to enhance existing correlations or to replace them with new correlations based on a firmer scientific footing.

It was concluded that fuel chemistry has a significant effect on flame radiation, liner wall temperature and smoke emissions. However, its influence on ignition performance, weak extinction limits, combustion efficiency, pattern factor, and CO and NO_x emissions, is quite small, and stems from the effects of slight variations in lower calorific value on combustion temperature. The physical properties that govern atomization quality and evaporation rates affect light-up characteristics, weak extinction limits, combustion efficiency, and CO emissions. Other important performance parameters, such as NO_x emissions, smoke emissions and liner wall temperature are sensibly independent of physical properties over the range of fuels studied.

The most serious impediment to this study was a lack of accurate information on fuel spray characteristics, especially mean drop size. It is strongly recommended that in future experimental studies on fuel effects, every effort should be made to determine mean drop size and drop size distribution for all fuels over wide ranges of combustor operating conditions.

A summary of the P&WA effort as follows, is again taken directly from their Task I Technical Report [8].

The approach taken in the study was to first develop fuel effect correlations for specific combustor configurations, then to tie together these correlations using engine design parameters, thereby allowing prediction of fuel effects in any current or future aircraft gas turbine combustion system. More specifically, the approach consisted of using statistical analysis to correlate the dominant fuel properties which effect combustor operation for individual combustors, and then to cross correlate the individual combustor relationships against those combustor design and operating parameters that were found to influence their response to fuel differences.

The fuel relationships which were developed included (1) a fuel correlation parameter and combustor operating parameter used to predict altitude relight performance, and (2) a vaporization index used to correlate other vaporization limited parameters such as groundstart fuel flow, combustion efficiency and pattern factor.

Smoke and radiation related parameters were found to correlate well with hydrogen content. The effect of fuel atomization and naphthalene concentration on smoke formation were also evaluated. It appeared that atomization might have a secondary effect at some conditions, but the effect was too small relative to the data scatter to obtain a correlation. Somewhat surprisingly, naphthalene was also shown to have no greater effect on smoke than would be predicted from the change produced in hydrogen concentration. Naphthalene concentration did appear to have a secondary effect on ignition, but this effect was also too small relative to the data scatter to correlate.

A number of approaches to generalizing the individual combustor relationships were evaluated. By-and-large, correlation of fuel effects against combustor operating parameters were not very successful. In most cases, the best correlations were empirical correlations of the sensitivity of the performance effect to fuel property variations, against the value of the performance parameter with some reference fuel (usually JP-4). For example, the sensitivity of smoke number to hydrogen content for most combustors correlates very well with the value of the smoke number with JP-4. Pattern factor and combustion efficiency show similar trends, but a more complete combustion efficiency correlation was obtained using Odgen and Carrier's correlation parameter. An exception to the general trend was the groundstart correlation which was based on primary-zone equivalence ratio and primary-zone entrance conditions.

The Phase II correlation programs were quite successful in producing first approximation correlations for their Task I effort. Task II of Phase II will be conducted only by Purdue University. Its purpose will be to refine the correlations and produce a handbook for their use. Purdue will conduct experiments to measure mean drop sizes from representative pressure-swirl and airblast atomizers under a range of pressures. Additional time will also be spent examining various types of aromatic content effects of fuels on liner wall temperatures along with developing correlations for unburned hydrocarbon emissions.

Fuel effects on aircraft engine afterburners were also conducted after the combustor tests of Phase I to further develop that database. The afterburners tested were of the following engines:

F100
TF30
J79
J85

These test concluded that there is some effect due to atomization quality and volatility in upper left-hand corner efficiency and ignition. Also, there is little or no effect on metal temperatures used by fuel chemical composition. In general, it was found that the afterburners are very fuel tolerant and there is no major degradation in performance or durability caused by the range of broad specification fuels from JP4 to DF2. Information on the afterburner tests is found in references 9-11.

REFERENCES

1. Gleason, C.C.; Oller, T.L.; Shayeson, M.W.; and Bahr, D.W.: Evaluation of Fuel Character Effects on J79 Engine Combustion System, AFAPL-TR-79-2015, June 1979.

2. Gleason, C.C.; Oller, T.L.; Shayeson, M.W.; and Bahr, D.W.: Evaluation of Fuel Character Effects on F101 Engine Combustion System, AFAPL-TR-79-2018, June 1979.

3. Vogel, R.E.; Troth, D.L.; and Verdouw, A.J. : Fuel Character Effects on Current, High Pressure Ratio, Can-Type Turbine Combustion Systems, AFAPL-TR-79-2072, April 1980.

4. Gleason, C.C.; Oller, T.L.; Shayeson, M.W.; and Kenworthy, M.J.: Evaluation of Fuel Character Effects on J79 Smokeless Combustor, AFWAL-TR-80-2092, November 1980.

5. Oller, T.L.; Gleason, C.C.; Kenworthy, M.J.; Cohen, J.D.; and Bahr, D.W.: Fuel Mainburner/Turbine Effects, AFWAL-TR-81-2100, May 1982.

6. Russel, P.L.: Fuel Mainburner/Turbine Effects, AFWAL-TR-81-2081, September 1982.

7. Lefebvre, A.H.: Fuel Effects on Gas Turbine Combustion, AFWAL-TR-81-2081, January 1983.

8. Ernst, R.C.; Andreadis, D.: Fuel Effects on Gas Turbine Combustion, AFWAL-TR-83-2048, June 1983.

9. Lyon, T.F.; Kenworthy, M.J.; Shayeson, M.W.; Burrus, D.L.; and Oliver, W.R.: Fuel Character Effects on USAF Gas Turbine Engine Afterburners, AFWAL-TR-82-2035, June 1982.

10. Russel, P.L.: Fuel Character Effects on USAF Gas Turbine Engine Afterburners Part I - F100 Afterburner, AFWAL-TR-82-2114, November 1982.

11. Russel, P.L.: Fuel Character Effects on USAF Gas Turbine Engine Afterburners Part II - TF30 Afterburner, AFWAL-TR-82-2114, June 1983.

INTRODUCTION

- EIGHT COMBUSTOR RIG TEST PROGRAMS
- TWO ANALYTICAL CORRELATION PROGRAMS
- TWO AFTERBURNER TEST PROGRAMS
- TWO FUEL/ENGINE-AIRFRAME OPTIMIZATION STUDIES

BACKGROUND

- PETROLEUM PROCUREMENT PROBLEMS SINCE EARLY 1970 DUE TO:
    1.) AVAILABILITY
    2.) COST
- THIS PROMPTED BROAD SPEC FUEL TESTING PROGRAM

COMBUSTORS TESTED

COMBUSTOR	TEST GROUP	TECH REPORT
J79-17A	GE	AFAPL-TR-79-2015
F101	GE	AFAPL-TR-79-2018
TF41	DDA	AFAPL-TR-79-2072
J79-17C	GE	AFWAL-TR-80-2092
J79-17A	GE	AFWAL-TR-81-2100
J85-21		
TF39-1A		
F100	P&WA	AFWAL-TR-81-2081
TF33		

FUEL PROPERTY RANGE

FUEL COMPONENTS		HYDROGEN CONTENT	HEATING VALUE	DENSITY	VISCOSITY	SURFACE TENSION	VAPOR PRESSURE
BASE FUEL	BLENDING AGENTS	WEIGHT %	(NET) MJ/kg	$\rho_{300\ K}$ kg/m^3	$\nu_{300\ K}$ mm^2/s	$\sigma_{300\ K}$ mN/m	$P_{300\ K}$ kPa
JP-4	-	14.5	43.603	752.7	0.924	23.27	12.04
JP-8	-	14.0	43.210	799.5	1.849	25.85	2.15
JP-8	GULF MINERAL SEAL OIL	13.9	43.189	801.2	2.071	25.92	1.97
JP-8	2040 SOLVENT	12.0	41.947	852.3	1.809	27.62	1.16
JP-8	XYLENE BOTTOMS	13.0	42.724	813.4	1.428	26.38	1.48
JP-8	XYLENE BOTTOMS	12.0	42.129	827.6	1.160	26.66	1.33
JP-8	2040	13.0	42.556	825.2	1.804	26.42	1.38
JP-4	2040	12.0	42.203	829.7	1.141	25.22	7.38
JP-4	2040	13.0	42.629	796.3	1.028	23.75	8.61
JP-4	XYLENE	12.0	42.196	808.0	0.830	25.21	6.17
JP-4	XYLENE	13.0	42.682	786.5	0.835	24.20	9.06
JP-4	XYLENE & GMSO	14.0	43.366	769.6	1.057	23.45	10.25
2-D	-	13.1	42.691	837.2	3.245	27.35	1.59

UNIVERSAL RESULTS

- **HIGH POWER**

  H_2 RESPONSIBLE FOR:

  - LINER TEMP., LINER LIFE
  - SMOKE
  - RADIATION
  - NOX

- **IGNITION**

  FUEL ATOMIZATION PROPERTIES RESPONSIBLE FOR:

  - COLD DAY START
  - ALTITUDE RELIGHT

RESULTANT NEW AWARDS

- **CONTRACTS AWARDED TO PURDUE UNIVERSITY AND PRATT & WHITNEY AIRCRAFT TO:**

  - CORRELATE FUEL PROPERTIES/ENGINE DESIGN/ OPER. PARAMETERS TO ENGINE COMB. PERF./ HOT SECTION DURABILITY

  - GAIN INSIGHTS ON DATA SHORTCOMINGS OF COMPLETED WORK

FUEL EFFECTS AREAS

- COMBUSTION EFFICIENCY
- LEAN BLOWOUT
- IGNITION
- LINER WALL TEMPERATURE
- EMISSIONS
- PATTERN FACTOR

PURDUE STUDY

- MAJOR PORTION BASED ON EVAPORATION MODEL

- USED PHYSICAL PROPERTIES IN MANY AREAS AS OPPOSED TO CHEMICAL PROPERTIES

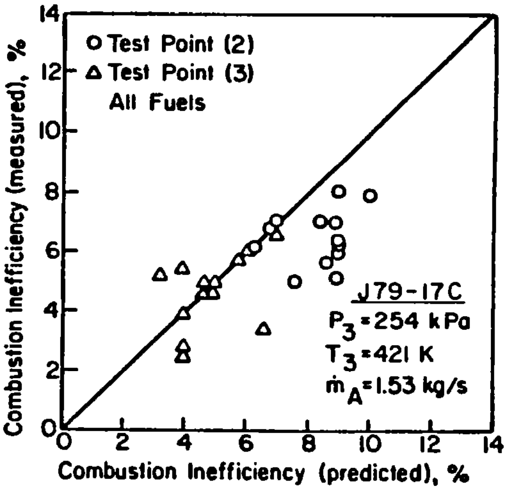
COMBUSTION EFFICIENCY CORRELATION

(PURDUE UNIVERSITY)

$$\eta_c = \eta_{c\theta} \times \eta_{ce}$$

$$\eta_{c\theta} = 1 - \exp\left[\frac{-0.022\, P_3^{1.3}\, V_c \exp(T_c/400)}{f_c\, \dot{m}_A}\right]$$

$$\eta_{ce} = 1 - \exp\left[\frac{-36\times10^6\, P_3\, V_c\, A_{eff}}{T_c\, D_o^2\, f_c\, \dot{m}_A}\right]$$



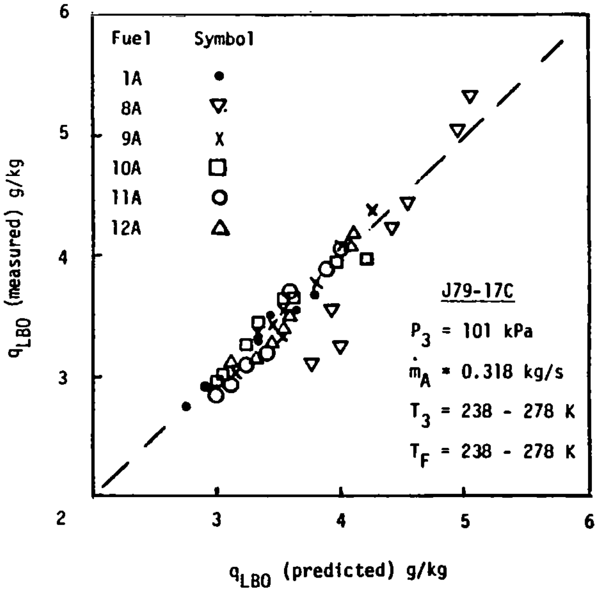
CORRELATION OF LEAN BLOWOUT DATA

(PURDUE UNIVERSITY)

$$q_{LBO} = \left[\frac{A}{\frac{P_3^{1.3} \exp(T_3/300)}{\dot{m}_A}}\right] \times \left[\frac{(D_r)^2}{(\lambda_r)\,(LCV_r)}\right] \times \left[\frac{D \text{ for JP4 at } T_F}{D \text{ for JP4 at } T_0}\right]^2$$

= (reaction rate term) X

(evaporation term) X (correction for fuel temp)



PREDICTION OF LEAN LIGHTOFF LIMITS
(PURDUE UNIVERSITY)

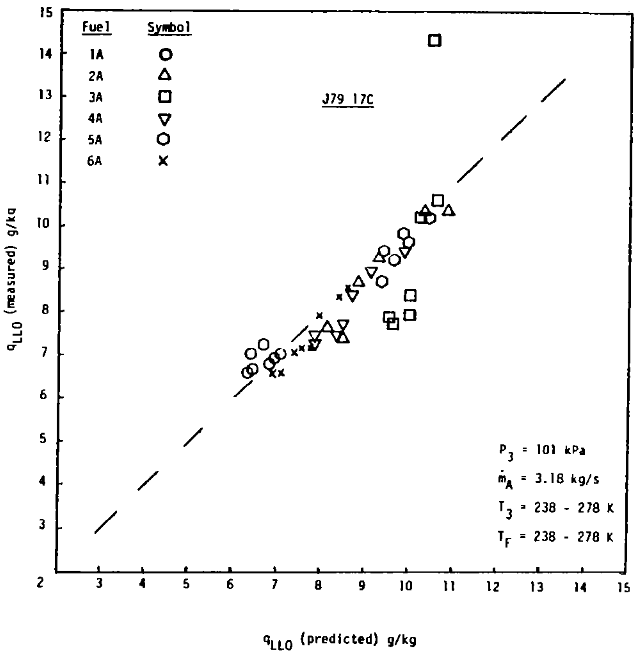
$$q_{LL} = \frac{A}{\left[\frac{P_3^{1.5} \exp (T_3/300)}{\dot{m}_A}\right]} \times \left[\frac{(D_r)^2}{(\lambda r)(LCV_r)}\right] \times$$

$$\left[\frac{D \text{ for JP4 at } T_F}{D \text{ for JP4 at } T_0}\right]^2$$

WHERE q_{LL} = LEAN LIGHTOFF LIMIT, g/kg

T_0 = BASELINE FUEL TEMPERATURE, K

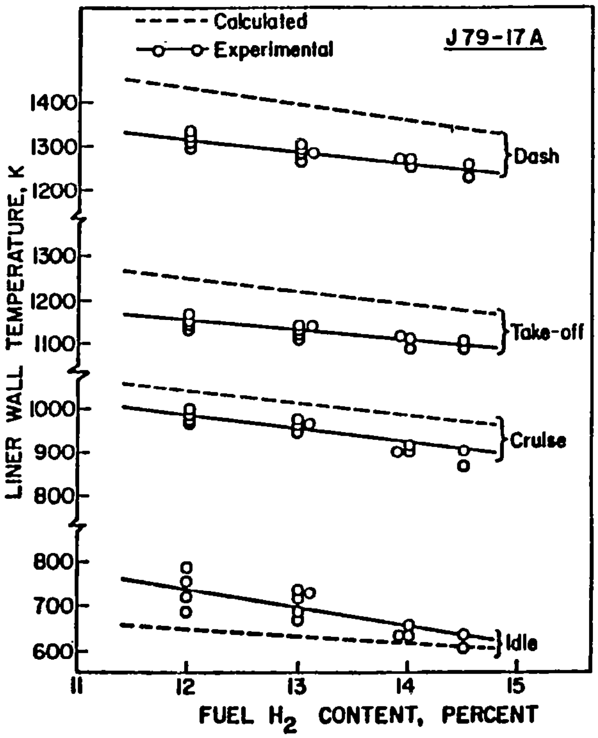
T_F = FUEL TEMPERATURE, K



LINER WALL TEMPERATURE CORRELATION
(PURDUE UNIVERSITY)

$$R_1 + C_1 = R_2 + C_2$$

$$R_1 = 0.5\sigma (1+\varepsilon_w)\varepsilon_g T_g^{1.5} (T_g^{2.5} - T_w^{2.5})$$



NOx CORRELATION
(PURDUE UNIVERSITY)

$$NO_x = \frac{9 \times 10^{-8} P_3^{1.25} V_C \exp(0.01 T_{st})}{\dot{m}_A T_{pz}} \text{ g/kg}$$

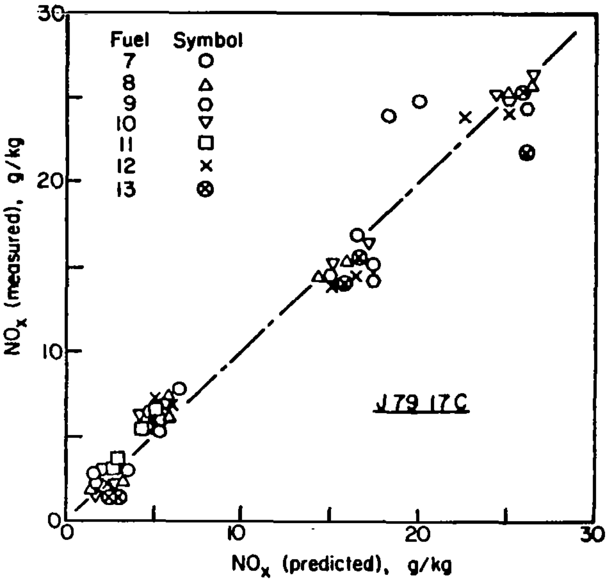
WHERE P_3 = INLET AIR PRESSURE, kPa

m_A = COMBUSTOR AIR FLOW RATE, kg/s

T_{pz} = PRIMARY–ZONE TEMPERATURE, K

T_{st} = STOICHIOMETRIC FLAME TEMPERATURE, K

V_C = PREDILUTION VOLUME, m³



PREDICTION OF PATTERN FACTOR FUEL EFFECTS
(PURDUE UNIVERSITY)

PATTERN FACTOR EQUATION

$$\frac{T_{max} - T_4}{T_4 - T_3} = 1 - \exp - \left[A \left(\frac{\Delta P_L}{q_{ref}} \right) \left(\frac{L_L}{D_L} - \frac{0.55\, U_g\, t_e}{D_L} \right) \right]^{-1}$$

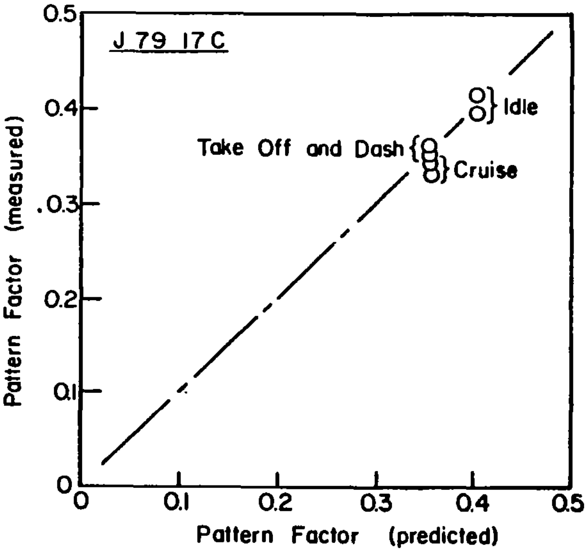
WHERE $(\Delta P_L / q_{ref})$ = LINER PRESSURE LOSS FACTOR

L_L = LINER LENGTH, m

D_L = LINER DIAMETER OR WIDTH, m

U_g = MEAN GAS VELOCITY UPSTREAM OF DILUTION ZONE, m/s

t_e = EVAPORATION TIME, s



PURDUE SUMMARY

- CHEMICAL PROPERTY EFFECTS
  - FLAME RADIATION
  - LINER WALL TEMPERATURE
  - SMOKE
- PHYSICAL PROPERTY EFFECTS
  - IGNITION
  - LEAN BLOW OUT
  - COMBUSTION EFFICIENCY
  - CO

PURDUE STUDY

- TASK II HAS EXPERIMENTAL MEASUREMENT OF SMD
- PURDUE TASK I TECHNICAL REPORT: AFWAL-TR-83-2004

P&WA STUDY

- STATISTICAL ANALYSIS TO CORRELATE DOMINANT FUEL EFFECTS
- CROSS CORRELATING COMBUSTORS SO WE CAN PREDICT EFFECTS ON NEW COMBUSTORS

P&WA CORRELATIONS

Parameter Affected	Governing Factor	Combustor Correlation Used	Basis for Generalized Correlation
Altitude Relight	Spark quenching distance	Fuel Corr. Par. (FCP) Comb. Op. Par. (COP)	Relative change in COP with FCP
Groundstart	Fuel vaporization	Vaporization Index (VI)	Primary zone operating conditions
Combustion Efficiency	Fuel vaporization	Vaporization Index (VI)	Combustion efficiency correlation parameter
Pattern Factor	Fuel vaporization	Vaporization Index (VI)	Relative sensitivity
Smoke and Particulates	Fuel composition	Hydrogen Content	Relative sensitivity
Liner Temperature	Fuel composition	Hydrogen Content	Relative sensitivity

P&WA SUMMARY

- TWO GROUPS OF FUEL RELATIONSHIPS
    - FUEL VAPORIZATION AND EFFECTS FOR FUEL IGNITION AND BURNING RATE
    - FUEL CHEMISTRY FOR SMOKE AND RADIATION
- AGREED WITH PURDUE ABOUT DATA SCATTER
- P&WA TECHNICAL REPORT: AFWAL-TR-83-2048

CORRELATION STUDY APPLICATION

- TASK I DEVELOPED ONLY FIRST APPROXIMATION CORRELATIONS
- TASK II WILL REFINE CORRELATIONS AND DEVELOP HANDBOOK FOR USAGE

FUEL EFFECTS ON AFTERBURNERS

- ENGINE A/B TESTED:

- F100, TF30	TURBOFANS
- J79, J85	TURBOJETS

- TECHNICAL REPORTS:

- F100	P&WA	AFWAL-TR-82-2114, PART I
- TF30	P&WA	AFWAL-TR-82-2114, PART II
- J79, J85	GE	AFWAL-TR-82-2035

FUEL EFFECTS ON AFTERBURNERS - SUMMARY

- ATOMIZATION (SURFACE TENSION, VISCOSITY) AND VOLATILITY AFFECT UPPER LEFT HAND CORNER EFFICIENCY, IGNITION TO VARYING DEGREES
- LITTLE OR NO EFFECT ON METAL TEMPERATURES CAUSED BY FUEL CHEMICAL COMPOSITION
- AFTERBURNERS VERY FUEL TOLERANT

FUEL / ENGINE-AIRFRAME OPTIMIZATION STUDIES

CONTRACTORS:

- GENERAL ELECTRIC CO. (F101/B1, J79/F4, TF39/C5A)
- PRATT & WHITNEY (F100/F16, TF33/B52, J57/KC135)

OBJECTIVE:

- DEVELOP COMPUTER PROGRAM TO PREDICT FUEL PROPERTY EFFECTS ON A/C OPERABILITY, PERFORMANCE, MAINTENANCE, AND LIFE CYCLE COSTS

FUEL AFFECTED PARAMETERS TO BE INCORPORATED:

- ALTITUDE RELIGHT, GROUND START
- ENGINE THROTTLEABILITY
- PAYLOAD AND RANGE
- SMOKE, CO, UHC EMISSIONS
- FREEZE POINT AND FUEL HOLD-UP
- RELIABILITY
- VULNERABILITY / SURVIVABILITY
- OPERATIONAL READINESS
- MAINTENANCE, DURABILITY, SPARE PARTS
- LIFE CYCLE COSTS

FUEL PROPERTY EFFECTS ON USN GAS TURBINE COMBUSTORS

A.I. Masters and S.A. Mosier
United Technologies Corporation
Pratt & Whitney Aircraft

C.J. Nowack
Department of the Navy
Naval Air Propulsion Center

For several years the Department of Defense has been sponsoring fuel-accommodation investigations with gas turbine engine manufacturers and supporting organizations to quantify the effect of changes in fuel properties and characteristics on the operation and performance of military engine components and systems. Inasmuch as there are many differences in hardware between the operational engines in the military inventories, due to differences in design philosophy and requirements, efforts were initially expended to acquire fuel-effects data from rigs simulating the hot-sections of these different engines. Correlations were then sought using the data acquired to produce more general, generic relationships that could be applied to all military gas turbine engines regardless of their origin. Finally, models could be developed from these correlations that could predict the effect of fuel property changes on current and future engines.

This presentation describes some of the work performed by Pratt and Whitney Aircraft, under Naval Air Propulsion Center sponsorship, to determine the effect of fuel properties on the hot section and fuel system of the Navy's TF30-P-414 gas turbine engine.

Page 3. Ignition and combustion are affected by fuel atomization and vaporization characteristics; whereas smoke emissions and thermal radiation are influenced by fuel chemistry effects.

Page 4. Fuel droplet size and volatility have frequently been used to correlate ignition characteristics and combustion efficiency of gas turbine engine burners. Relationships have been developed in the TF30 fuel-effects investigations that include these two fuel variables in a way that satisfactorily weighs their relative importance. Smoke emission and thermal radiation effects from the combustion of hydrocarbon fuels, on the other hand, have been found to correlate consistently with fuel hydrogen content.

Page 5. The bulk of the information presented here is based on data obtained in Navy-sponsored test programs using TF30 combustor rigs. An eight-can, annular rig was used for ignition tests and a single can rig was used for performance tests.

Page 6. Groundstart ignition data were found to correlate very well with a variable defined as the vaporization index. At increased levels of this index, i.e. higher values of fuel viscosity and lower values of fuel volatility, significant increases in fuel flow were needed to effect ignition.

Page 7. Trends similar to those found for groundstart ignition were found for airstart ignition. Heavier, poorer quality fuels reduced altitude relight capability.

Page 8. The reduction in relight capability was found to correlate well with a variable defined as the fuel parameter ratio. This term is the ratio of the fuel characterization, or correlation, parameter obtained for the fuel of interest to the fuel characterization parameter obtained for JP-5 fuel.

Page 9. Turbine life was found to be influenced by changes in thermal radiation resulting from the burning of a fuel and in the temperature distribution of the gas issuing from a combustor (pattern factor). The data used to predict the trend in low-cycle fatigue life for the first-stage vane were acquired during rig tests.

Page 10. Thermal radiation heat fluxes measured within the TF30 combustor during hot-firing tests were found to correlate well with the hydrogen content of the fuels burned over a range of engine operating conditions.

Page 11. Predicted variations in liner durability for engines in the military inventory indicated that some configurations are considerably more sensitive than others.

Page 12. Combustion efficiency at engine-idle operating conditions were found to correlate with vaporization index. As fuel quality decreases, as indicated by increasing values of the vaporization index, low-power combustion efficiency likewise decreases. At higher power levels, combustion efficiency is essentially 100 percent for all modern aircraft gas turbine engines and fuel effects are neglible.

Page 13. Smoke emissions were found to correlate well with the hydrogen content of the fuel burned, as has been observed by many investigators. However, the sensitivity of exhaust smoke level on fuel hydrogen content is not the same with all engine burners.

Page 14. Ignition and combustion efficiency can be correlated with parameters which include atomization and vaporization effects. Efficiency effects are not very important because they only show up at low-power levels. Viscosity is the most important fuel property in these correlations and fuel volatility (particularly in terms of the 10% distillation temperature) is also significant. Fuel hydrogen concentration affects smoke and radiation and, hence, combustor liner life. Reduced turbine life may be the single most important result from use of lower quality fuels, but a better measurement of the effect of fuel properties on pattern factor is needed before this effect can be adequately quantified.

FUEL-AFFECTED HOT-SECTION CHARACTERISTICS

Ignition, Performance, And Component Life Are Impacted By Fuel Quality

- GROUNDSTART IGNITION
- AIRSTART IGNITION
- LINER DURABILITY
- TURBINE DURABILITY
- COMBUSTION EFFICIENCY
- SMOKE

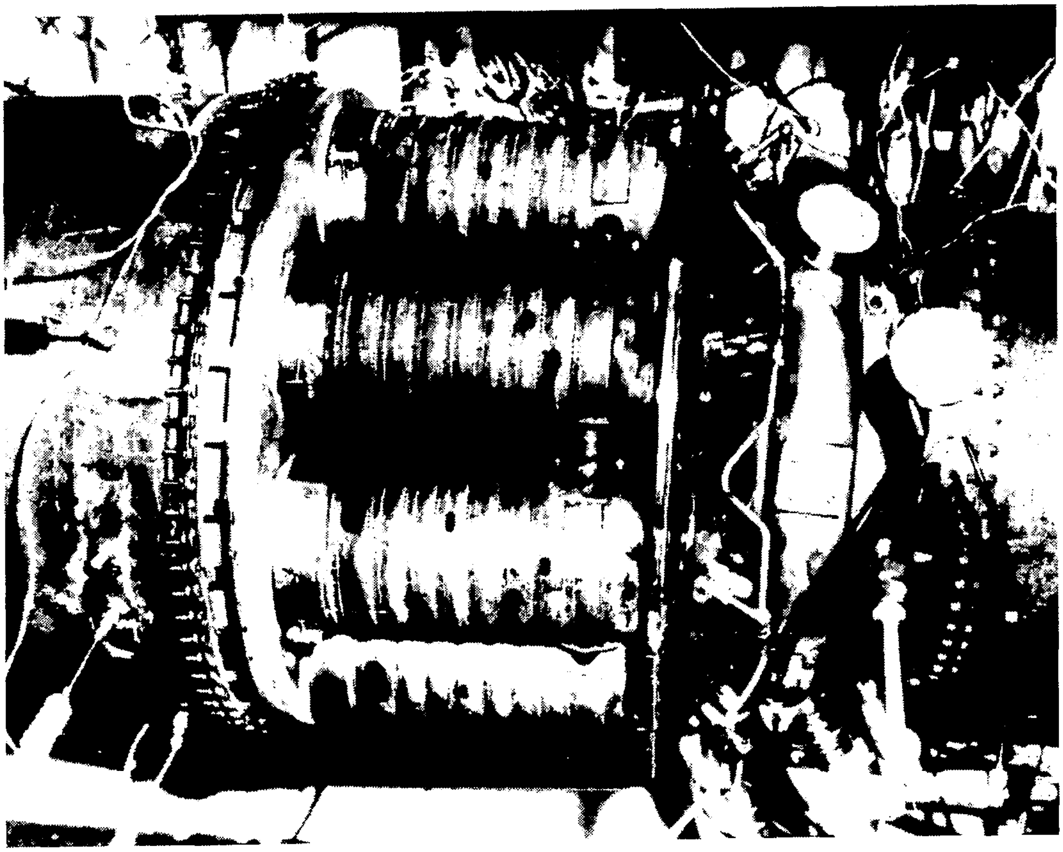
FUEL EFFECT CORRELATIONS

Physical And Chemical Properities Are Incorporated In Key Parameters

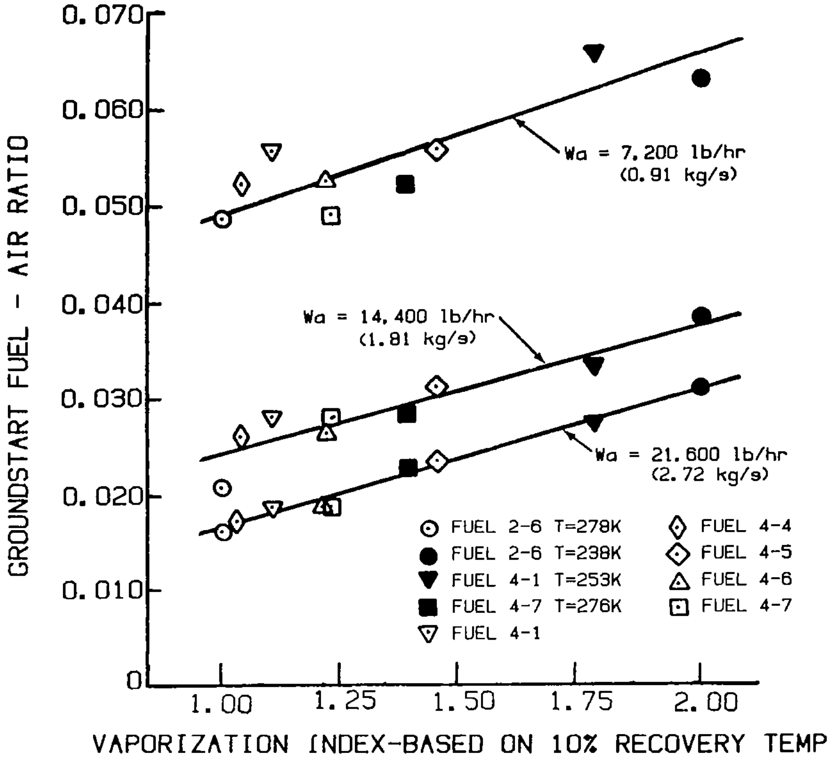
• VAPORIZATION INDEX	$\frac{(RDS)^2 (SG)}{\log(1+B)}$	ATOMIZATION AND VAPORIZATION EFFECTS
• FUEL CHARACTERIZATION PARAMETER	$\frac{(RDS)^{1.5} (SG)}{\log(1+B)}$	
• H CONTENT OF FUEL	Wt.% H	FUEL CHEMISTRY EFFECTS

TF30 COMBUSTION SYSTEM

Comprised Of An Annular Arrangement Of Cans With Pressure-Atomizing Fuel Nozzles

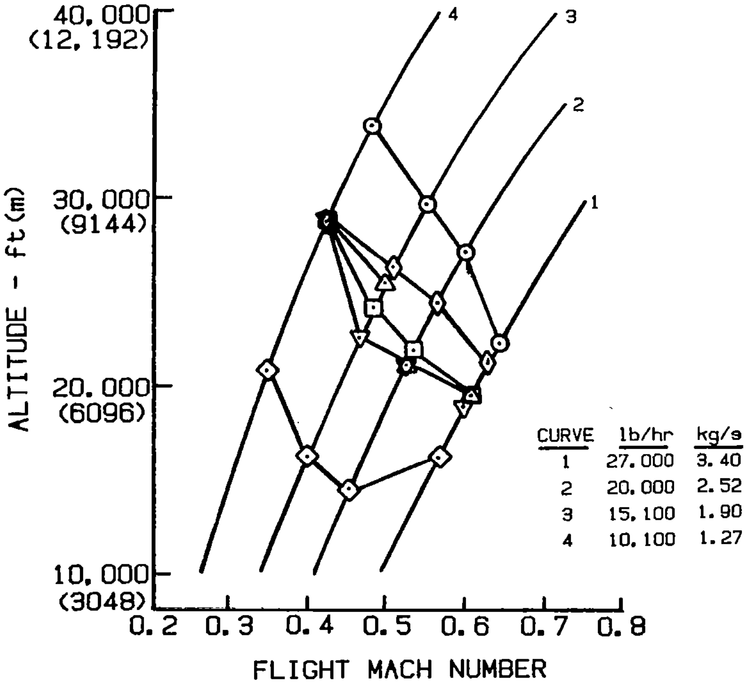


TF30 GROUNDSTART CORRELATION



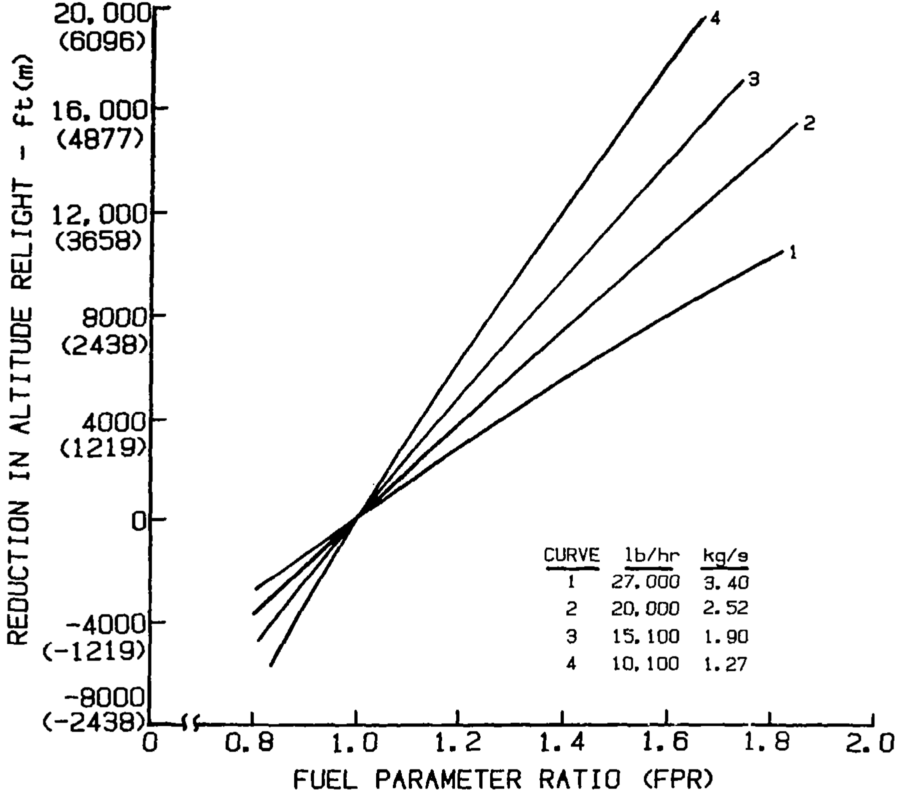
FUEL EFFECTS ON AIRSTART OF TF30 RIG

Airstart Capability Decreases With Decreasing Fuel Quality

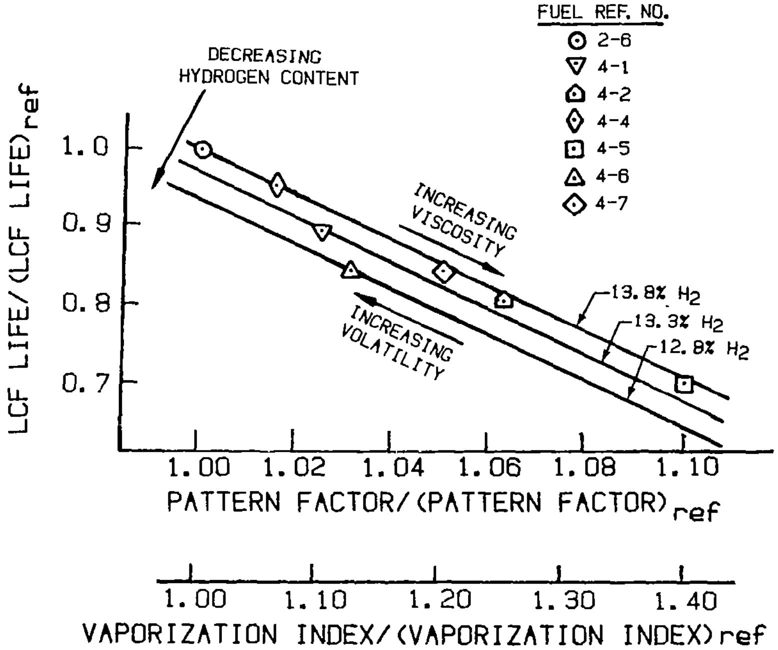


IMPACT OF FUEL PARAMETER RATIO ON RELIGHT ALTITUDE

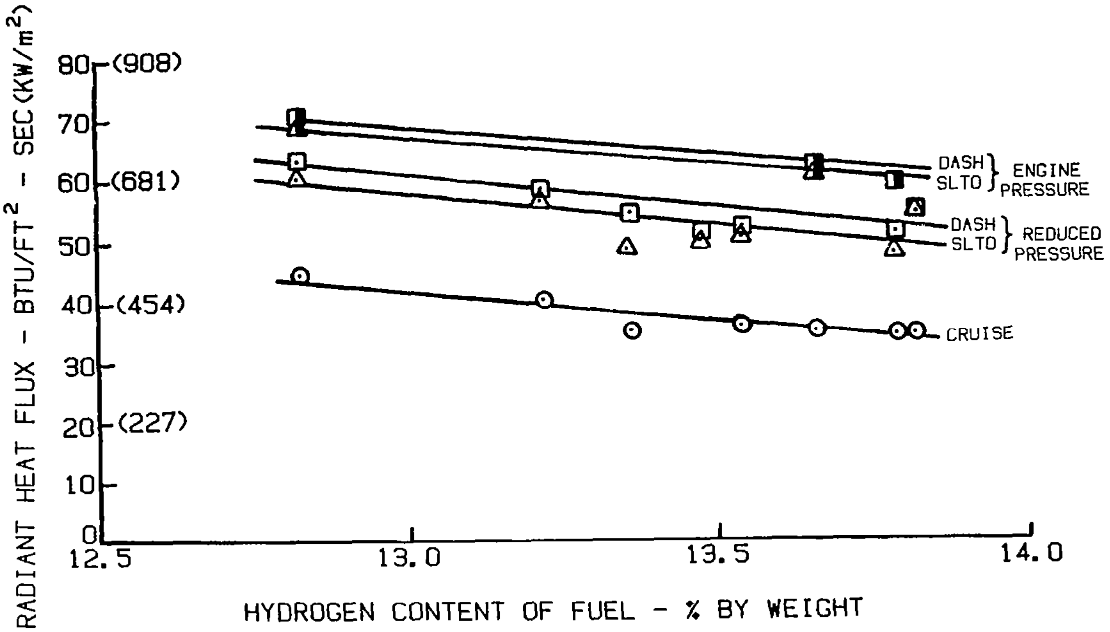
Altitude Relight Capability Decreases With Decreasing Fuel Quality



FUEL EFFECT ON LCF LIFE

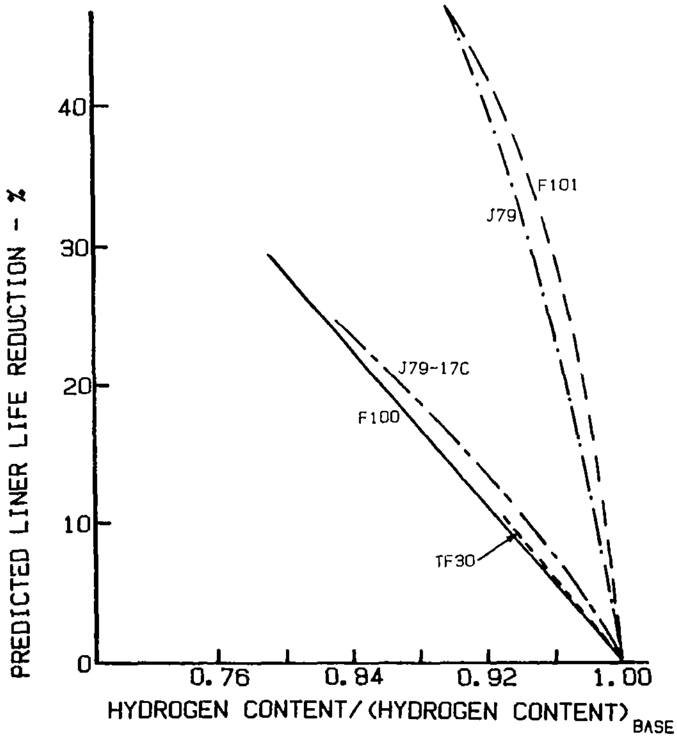


VARIATION IN THERMAL RADIATION RATE

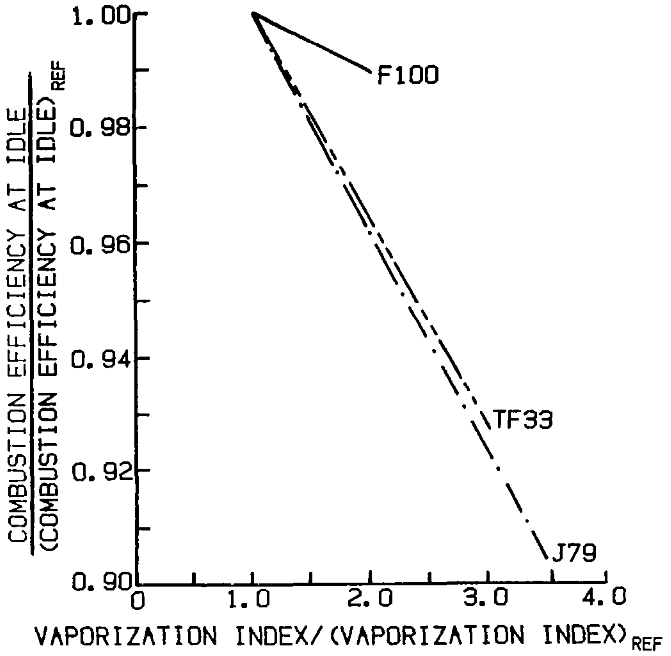


LINER LIFE PREDICTION

Decreasing Hydrogen Content Of Fuel Results In Reduced Liner Life

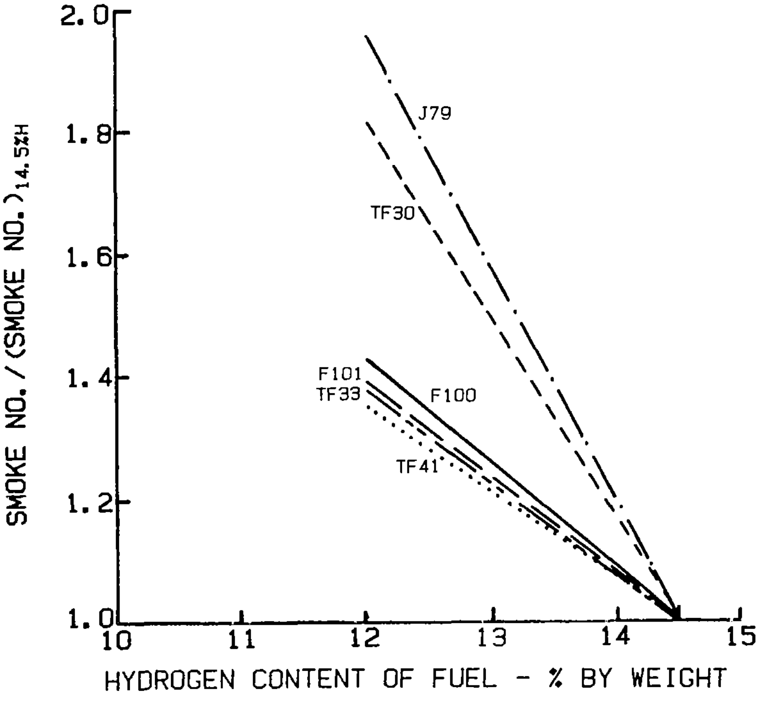


VARIATION IN COMBUSTION EFFICIENCY



FUEL EFFECT ON EXHAUST SMOKE NUMBER

Smoke Level Increases As Hydrogen Content Of Fuel Is Decreased



FUEL-AFFECTED HOT-SECTION CHARACTERISTICS

Ignition, Performance, And Component Life Are Impacted By Fuel Quality

- GROUNDSTART IGNITION
- AIRSTART IGNITION
- LINER DURABILITY
- TURBINE DURABILITY
- COMBUSTION EFFICIENCY
- SMOKE

BROAD PROPERTY FUELS COMBUSTOR RESEARCH AND TECHNOLOGY

Richard W. Niedzwiecki, Chairman, NASA Lewis Research Center
James S. Fear, NASA Lewis Research Center
Willard J. Dodds, General Electric Company
J. D. Cohen, General Electric Company
Robert P. Lohmann, Pratt & Whitney Aircraft Group

NASA BROAD-SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM

James S. Fear
National Aeronautics and Space Administration
Lewis Research Center

The NASA Broad-Specification Fuels Combustion Technology Program was initiated in response to concerns that the supply of high-quality petroleum middle distillates for jet fuel, abundant in the past, would diminish in availability toward the end of the century. This would leave a choice of extensive refining of higher-boiling-point fractions to meet current Jet A specifications, an expensive process, or of modifying the jet engine, in particular the combustion system, to accept fuels with less stringent specifications, a course which would involve large initial expenditures, but which would have the advantage of somewhat lower refining costs over the lifetime of the engine. The Broad-Specification Fuels Combustion Technology Program was undertaken to define the combustion system technology required to accommodate broadened-properties fuels with minimal processing, so that the trade-offs between these two courses of action can be evaluated.

The specific program objective is to evolve the combustion system technology required to use fuels with moderate ranges of broadened properties in the engines used on commercial jet aircraft. The first phase of the program, in which effects of the use of broadened-properties fuels were identified and technology with the potential to offset these effects was also identified, has been completed. The second phase, in which the technology identified in Phase I is being refined, will be completed within the next three months.

Two contractors are involved in both phases of the program, the General Electric Company, using their CF6-80 engine combustion system as a baseline design, and Pratt & Whitney Aircraft, using their JT9D engine combustion system as a baseline design for Phase I; however, with the availability of the more-advanced-design PW2037 engine, a switch was made in Phase II to make it the baseline design.

Each contractor was asked in Phase I to propose three combustion system concepts for screening testing, along with several modifications of each concept. The concepts were to have varying degrees of potential for accomplishing the program goals and were expected to involve correspondingly varying degrees of developmental difficulty and risk. One concept was to involve relatively minor modifications to the baseline production combustion system, the intent being to determine what could be done in the event that current in-service engines were to find it necessary to use broadened-properties fuels. The other two concepts were to be "more advanced" and "highly advanced" designs, which would presumably be used only in entirely new engine designs. All concepts had goals of maintaining baseline engine requirements for performance and durability characteristics and of meeting appropriate emissions requirements. All testing is being done in sector test rigs representing 60 to 75 degrees of full-annular combustors. The test facilities of both contractors are capable of providing true engine pressure, temperature, and airflow conditions for these sectors.

It has been previously stated that the program deals with the effects of "moderate ranges" of broadened fuels properties. The program fuels do cover a rather significant two percent range of hydrogen content but are "moderate" in the sense that they do not get down into the area of coal-derived or other so-called synthetic fuels. Jet A fuel was used for comparison with known baseline engine combustion system data and to establish baseline program data. The main broadened-properties fuel was the Experimental Referee Broad-Specification (or ERBS) fuel established as representative of future broadened-properties fuels. This fuel has a decrease in hydrogen content of approximately one percent from that of Jet A, with a corresponding increase in aromatics content. Two other test fuels, with further reductions in hydrogen content of one-half and one percent, respectively, were made by blending ERBS fuel with a high-aromatics blending stock.

Phase II of this program was originally intended to be used for optimization of the best designs of Phase I in preparation for engine testing in a planned third phase of the program. Because of budgetary and other considerations, Phase III engine testing has been deleted. This has caused Phase II to be redirected, with refinement of the better Phase I designs continuing to be pursued, but with an eye toward even more advanced technology. For example, as mentioned earlier, the baseline combustor design for the Pratt & Whitney program has been changed from the JT9D combustor to the latest-technology PW2037 combustor. Also, an advanced P&WA combustor concept has been incorporated into Phase II testing. In the General Electric Phase II Program, increased emphasis has been placed on innovative fuel injection and mixing techniques. Both contractors have extended the range of fuels properties variations by testing with fuels which are in the same hydrogen content range as the ERBS fuels, but which have considerably increased viscosity and decreased volatility.

PROGRAM OBJECTIVE AND TARGETS

OBJECTIVE

TO EVOLVE THE COMBUSTION SYSTEM TECHNOLOGY REQUIRED TO USE FUELS WITH MODERATE RANGES OF BROADENED PROPERTIES IN COMMERCIAL JET AIRCRAFT WITH ADVANCED HIGH-PRESSURE-RATIO, HIGH-BYPASS-RATIO TURBOFAN ENGINES

TARGETS

- COMPLETE TESTS OF CONCEPTUAL COMBUSTORS AND FUEL SYSTEMS OPERATING WITH EXPERIMENTAL REFEREE BROADENED-PROPERTIES FUELS (PHASE I) - FY 1982
- COMPLETE TESTS OF OPTIMIZED COMBUSTORS AND FUEL SYSTEMS BASED ON BEST PHASE I DESIGNS (PHASE II) - FY 1983

CS-82-1802

PROGRAM STRUCTURE

TWO SEPARATELY-CONTRACTED PHASES INVOLVING PARALLEL EFFORTS BY THE GENERAL ELECTRIC COMPANY (CF6-80 ENGINE COMBUSTION SYSTEM AS BASELINE). AND PRATT & WHITNEY AIRCRAFT (PW2037 ENGINE COMBUSTION SYSTEM AS BASELINE)

CS-82-1803

COMBUSTION SYSTEM CONCEPTS

	TYPE OF DESIGN	APPLICATION
CONCEPT I	MINOR MODIFICATIONS TO PRODUCTION COMBUSTOR	IN-SERVICE ENGINES
CONCEPT II	MORE ADVANCED	FUTURE ENGINES
CONCEPT III	HIGHLY ADVANCED	FUTURE ENGINES

CS-80-1492

COMPARISON OF JET A AND BROADENED-PROPERTIES TEST FUELS

FUEL PROPERTY	JET A	BROADENED-PROPERTIES TEST FUELS		
		ERBS	ERBS	BLENDS
HYDROGEN CONTENT, wt %	13.5-14	12.8	12.3	11.8
AROMATICS CONTENT, vol %	~17	35	40	54
INITIAL BOILING POINT, °C	173	162	163	157
FINAL BOILING POINT, °C	267	328	333	336
VISCOSITY, cS, -23° C	5-6	9.2	7.9	7.0

CS-82-1804

NASA/GENERAL ELECTRIC BROAD-SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM

Willard J. Dodds
General Electric Company
Aircraft Engine Business Group

The NASA/General Electric Broad Specification Fuels Combustion Technology Program is being conducted to evolve and demonstrate the technology required to use broadened-properties fuels in current and next generation commercial aircraft engines. The first phase of this program, completed in 1982, involved the design and test evaluation of three different combustor concepts. All combustors were designed for the General Electric CF6-80A engine envelope and operating conditions, using Experimental Referee Broad Specification (ERBS) fuel having a fuel hydrogen content of 12.8% by weight. Several different configurations of each combustor concept were evaluated in a series of high pressure sector combustor component tests. A total of 25 sector tests were conducted during phase I. Combustor metal temperatures, emissions, exit temperature profiles, and radiant heat flux were measured over the full range of steady-state operating conditions using four fuels having nominal hydrogen contents between 11.8 and 14%. During the current phase II program, the two most promising concepts from phase I are being further refined and evaluated. For phase II testing, two additional fuels representing a wider range of fluidity and volatility are also being used in combustion system tests.

Combustor design considerations for broadened properties fuels are described in Table I. Reduced fuel-hydrogen content primarily affects high power operation, where smoke, flame radiation, NO_x emissions, and carbon deposition potential are all increased. Fuel physical properties are more important at low power, where lightoff, blowout, combustion efficiency and related CO and HC emissions all tend to deteriorate as viscosity is increased and volatility is reduced. As shown in Figure 1, a relatively small increase in liner temperature due to increased flame radiation can have a major impact on combustor durability. Therefore, offsetting increased liner temperatures which occur with reduced fuel-hydrogen content is a major design consideration for operation on broadened-properties fuels.

The three combustor concepts evaluated in this study (Figure 2) are: (1) a state-of-the-art single annular combustor; (2) a staged double annular combustor; and (3) a short single annular combustor with variable geometry. The advanced double annular and variable geometry combustors are both designed to provide low velocity, near stoichiometric primary combustion zone conditions at low power for improved ignition and combustion efficiency, and higher velocity, lean combustion conditions for improved high power performance.

The effects of a reduction from 13.8% (Jet A) to 12.8% fuel-hydrogen (ERBS) on smoke, NO_x, and liner temperatures of the baseline (initial) single annular combustor configuration are shown in Table II. The most important effect is the 10% increase in liner temperature differential at takeoff, which corresponds to an estimated life reduction of 33%. As shown in Figure 3, fuel effects on liner temperatures are strongest in the forward portion of the combustor, where flame radiation is most important due to high temperatures and smoke concentrations.

Development progress with the single annular combustor during the phase I program is summarized in Table III. Significant improvements in liner temperatures, smoke, and combustion efficiency were obtained. During phase I, it was concluded that all of the program goals except for NO_x emissions could be met with relatively simple modifications to the single annular combustor. As shown in Figure 4, both absolute liner metal temperatures and sensitivity to changes in fuel-hydrogen content were reduced. Smoke emissions (Figure 5) were also reduced to levels well below the program goal over the range of fuel-hydrogen content under consideration.

The most promising modifications for smoke and liner temperature reduction in the single annular combustor are listed in Table IV. Increased primary dilution significantly reduced smoke levels, while the use of ceramic thermal barrier coatings on the combustor liners was most effective for metal temperature reduction. An advanced fuel injector/swirl cup was used to increase fuel spreading, which significantly reduced smoke levels. However, combustor metal temperatures were increased, apparently due to higher fuel concentrations near the combustor walls. A variation in fuel atomization was also demonstrated which reduced both smoke and average liner temperature.

During the phase I program, promising results were also obtained with the advanced double annular and variable geometry combustor concepts. These results are discussed in detail in reference 2 and 3. In particular, these concepts could be applied in the future to short, ultra high temperature combustion systems; low NO_x systems; and systems designed for a broader range of fuel properties. However, for the CF6-80A engine burning fuels having more than 11.8% hydrogen content, the use of the more complex advanced concepts does not appear to be justified. Of the advanced concepts, the variable geometry combustor was selected for the phase II program because of its superior intermediate power flexibility and because fuel staging (with potential fuel nozzle fouling) is not required.

During the phase II program, work is continuing to define more extensive design modifications for improved fuel flexibility. Particular emphasis is being placed on the development of an improved airblast fuel injector/swirl cup configuration to provide more uniform primary zone fuel-air mixtures for reduction of smoke and local hot streaks, and reduced CO and HC emissions at low power conditions. Low pressure fuel injection systems having large flow passages are being evaluated. It is thought that such systems will have improved capability for using fuels having reduced thermal stability. As shown in Figure 6, substantial reductions in both CO and HC have been obtained with one of the advanced swirl cup designs.

As noted earlier, the phase II program is also placing increased emphasis on fuel viscosity and volatility effects. Two additional test fuels, JP-4 and No. 2 Diesel (DF 2), have been added for this phase II effort. Examples of these effects are shown in Figure 7, where the effects of fuel type and temperature on idle combustion efficiency and pressure blowout at altitude relight conditions are shown. Both efficiency and stability were reduced as viscosity was increased, either by changing fuel type or temperature. As shown in Figure 8, the effects of fuel viscosity and volatility are well correlated using a relative droplet lifetime parameter. Thus, reduction in fuel droplet lifetime (by improving fuel atomization) is a key to operation on broadened-properties fuels. The drop size reduction required for a given fuel can be estimated from droplet lifetime.

Remaining objectives of the phase II program, which is scheduled to be completed in early 1984, are: (1) to demonstrate the single annular combustor at high power conditions with the advanced fuel injector/swirl cup system and an advanced liner cooling configuration currently under development; (2) to demonstrate improved variable geometry fuel injector/swirl cup configurations having reduced leakage at low power conditions with the vanes closed and improved fuel-air mixing with the vanes open; and (3) to evaluate variable geometry combustor with a fixed swirl cup and variable primary dilution flow.

REFERENCES

1. Dodds, W. J., "NASA/General Electric Broad-Specification Fuels Combustion Technology Program - Phase I," Aircraft Research and Technology for Future Fuels, NASA Conference Publication 2146, pp 109-113, 1980.

2. Dodds, W. J., Ekstedt, E. E., Bahr, D. W., and Fear, J. S., "NASA/General Electric Broad-Specification Fuels Combustion Technology Program - Phase I Results and Status," AIAA-82-1089, 1982.

3. Dodds, W. J., and Ekstedt, E. E., "Broad-Specification Fuels Combustion Technology Program - Phase I Final Report," NASA CR-168179, 1983.

Table I

Combustor Design Considerations

Fuel Property Change	Problems	Approach
• Reduced Hydrogen Content/Higher Aromatics	• Increased Flame Luminosity (Increased Liner Temperatures)	• Lean-Well Mixed Combustion at High Power
	• Increased Smoke	• Short Combustor-Reduced Liner Cooling Requirements
	• Increased NOx	
	• Increased Carboning	• Improved Dome/Swirler Designs
• Increased Viscosity/ Reduced Volatility	• Increased Ground Start/Relight Difficulty • Increased Low Power Emissions (CO & HC)	• Rich-Low Velocity Combustion at Low Power • Improved Dome/Swirler Designs
• Reduced Thermal Stability	• Fuel Valve & Nozzle Fouling	• Increase Fuel System Insulation • Increase Fuel System Passage Sizes

Table II

Baseline Single Annular Combustor Fuel Effects

Emission/Performance Parameter	Percent Increase with ERBS Fuel (12.8% Hydrogen) Relative to Jet A (13.8% Hydrogen)	
	Cruise	Takeoff
Smoke	60	0
NOx	9	6
Liner Temperature Differential*		
Max	11	10
Avg	27	11

* Liner Metal Temperature Minus Cooling Air Temperature

Table III

Single Annular Combustor Development Progress

Parameter	Value with ERBS 12.8 Fuel		
	Program Goal	Baseline Test	Final Test
Max Liner Temperature Differential, K	330	331	244
Max Smoke Number	19.2	41.2	9.3
Min Combustion Efficiency, %	99.0	98.6	99.6
Pattern Factor at Takeoff	0.25	0.33	0.29
Idle Blowout f/a, g/kg	7.5	4.2	6.4
Carboning	Light	Light	Light

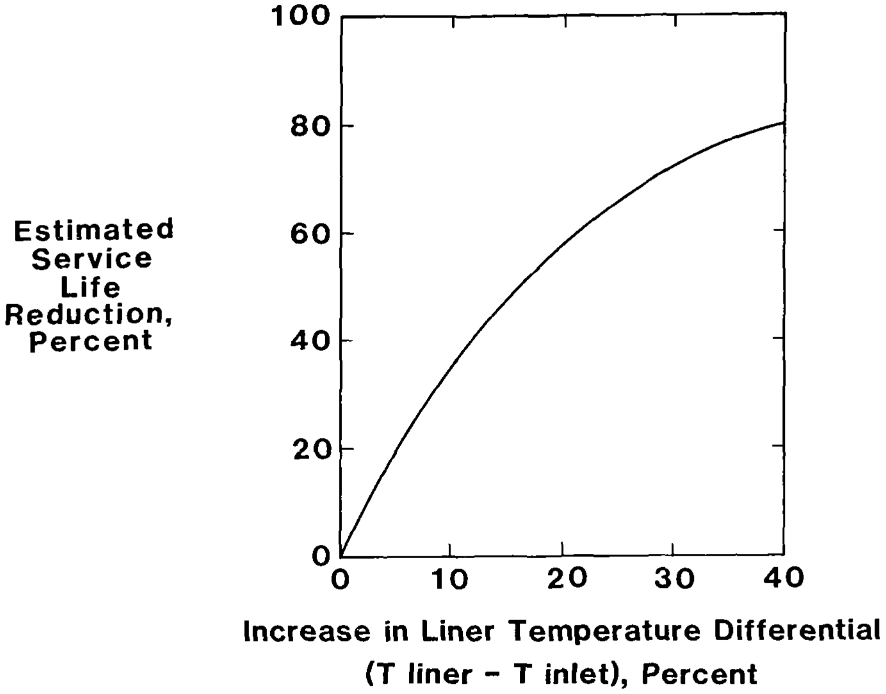
Table IV

Key Single Annular Combustor Modifications

Modification	Effect	
	Smoke	Average Liner Temperature Rise
Increased Primary Dilution	65% Reduction	5% Reduction
Thermal Barrier Coatings	No Effect	15% Reduction
Advanced Swirlers	50% Reduction	45% Increase
Improved Atomization	15% Reduction	10% Reduction

Figure 1

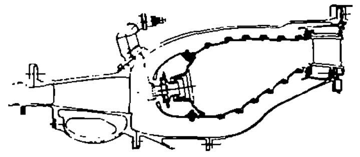
Combustor Life Reduction



Combustor Concepts

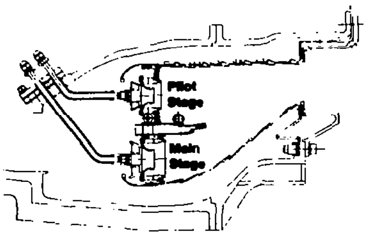
Figure 2

Single Annular Combustor



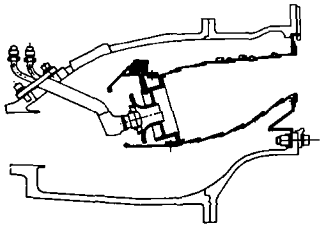
- **Short Single Annular Combustor Design**
- **Counterrotating Dome Swirlers**
- **Advanced Liner Cooling Slot Design**
- **Short Prediffuser**

Double Annular Combustor



- Short Double Annular Combustor Design
- Low Velocity Pilot Stage — Near Stoichiometric Primary Zone Combustion at Idle
- High Velocity Main Stage — Lean Primary Zone Combustion at High Power
- Centerbody Dilution for Improved Mixing
- Utilizes NASA/GE E^3 Swirler Components

Variable Geometry Combustor



- Very Short Single Annular Design
- Dome Swirler Closed for Low Power Operation
  - Low Velocity
  - Rich Primary Zone Combustion
  - Increased Pressure Drop
- Dome Swirler Open for High Power Operation
  - High Velocity
  - Lean Primary Zone Combustion
  - Short Residence Time

Figure 3

Local Liner Temperature Sensitivity

- **Single Annular Combustor**
- **Configuration S-10**

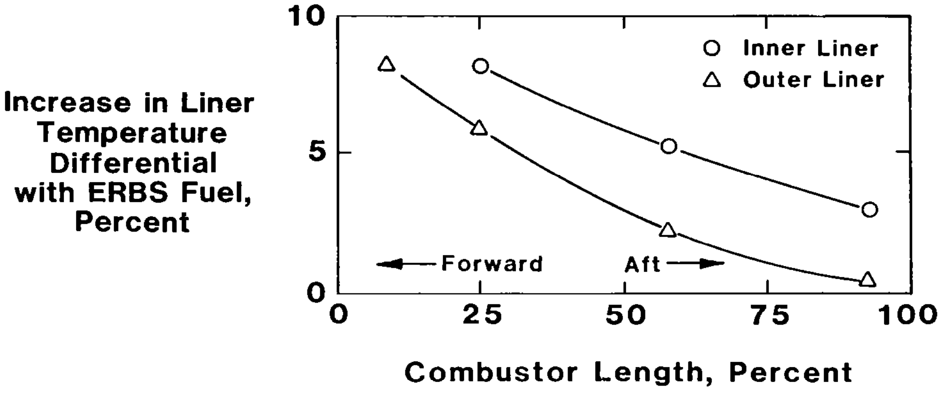


Figure 4

Single Annular Combustor Liner Temperatures

Takeoff Conditions

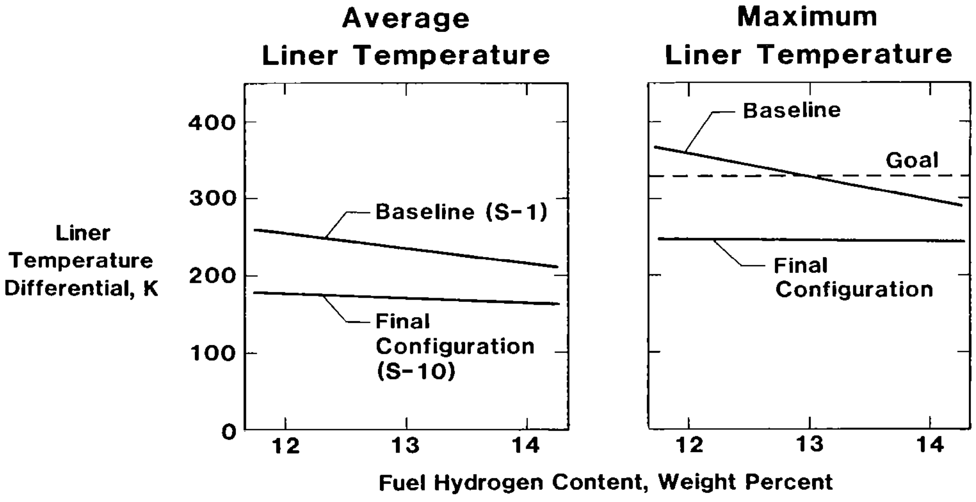


Figure 5

Single Annular Combustor Smoke Emissions

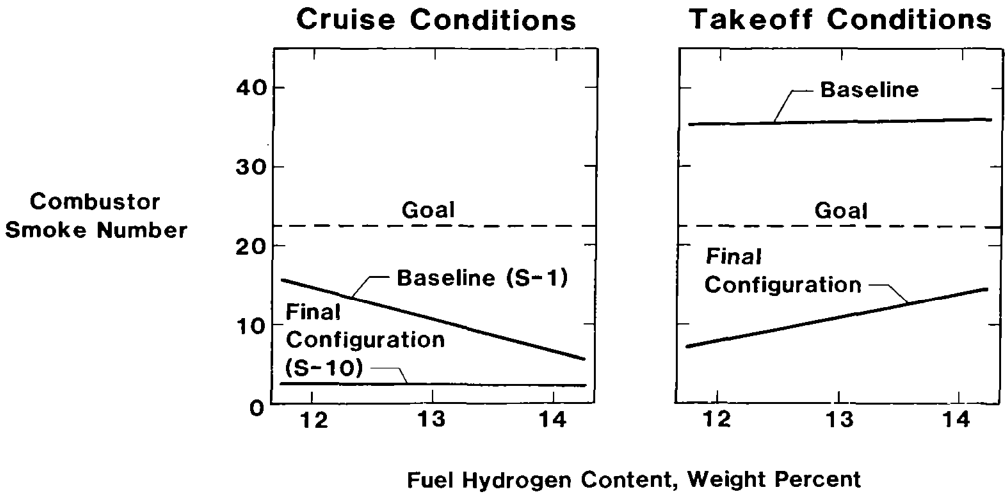


Figure 6

Advanced Swirl Cup Low Power Emissions

- Ground Idle Operating Conditions

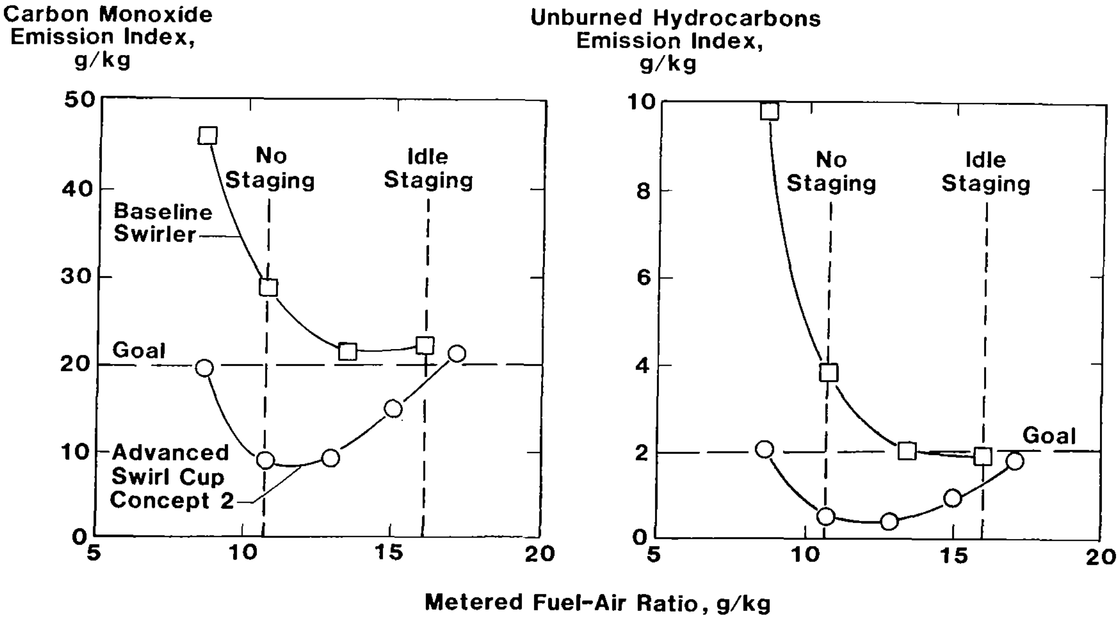


Figure 7

Fuel Viscosity/Volatility Effects

Variable Geometry Combustor

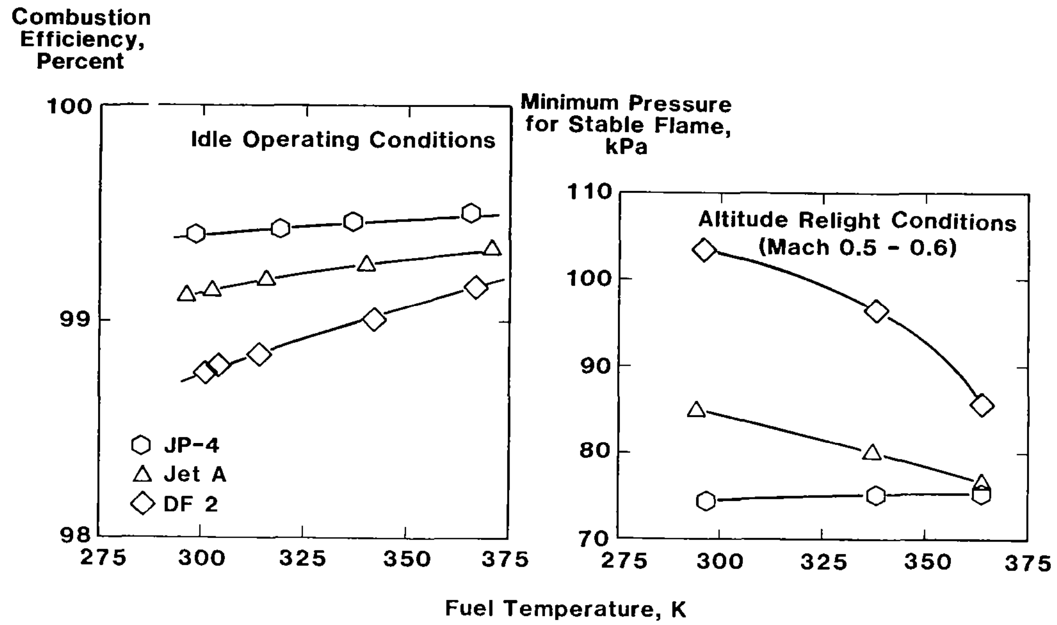
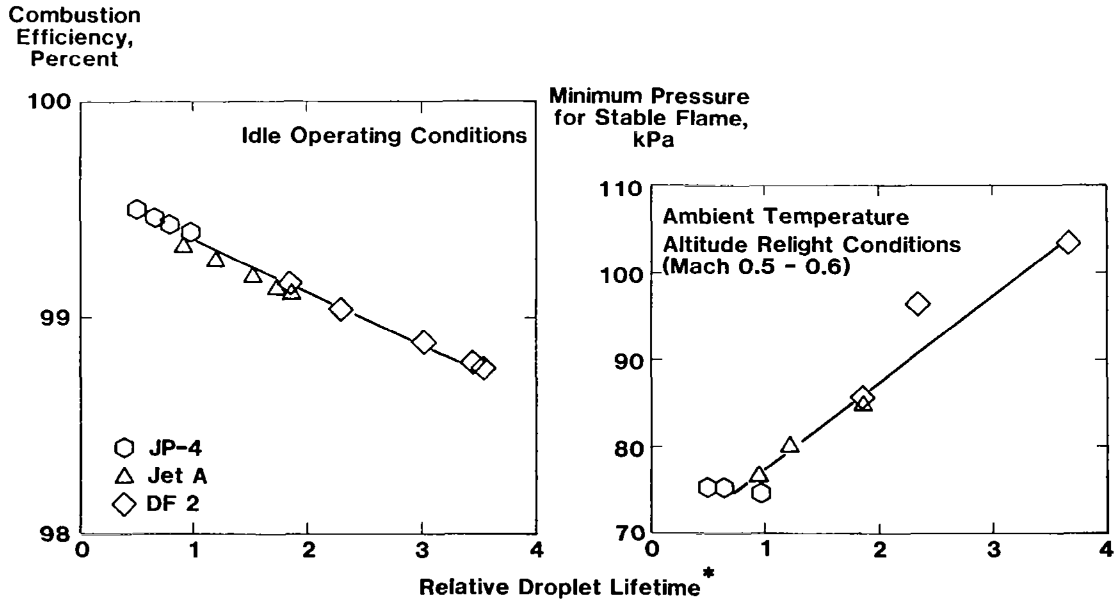


Figure 8

Droplet Lifetime Correlation



*Relative to JP-4 at 297 K (75°F)

ANALYTICAL FUEL PROPERTY EFFECTS - SMALL COMBUSTORS
Phase I Summary

J. D. Cohen
Aircraft Engine Business Group
General Electric Co.

The study performed in Phase I of this program applies only to a T700/CT7 engine family type combustor functioning in the engine as defined and does not necessarily apply to other cycles or combustors of differing stoichiometry. The study was not extended to any of the fuel delivery accessories such as pumps or control systems, nor was there any investigation of potential systems problems which might arise as a consequence of abnormal properties such as density which might affect delivery schedules or aromatics content which might affect fuel system seals.

The T700/CT7 engine is a front drive turboshaft or turboprop engine (Figure 1) in the 1500-1800 shp (1120-1340 kW) class as currently configured with high-power core flows of about 10 lb/sec (4.5 kg/sec). It employs a straight-through annular combustion system (Figure 2) less than 5 in. (12.5 cm) in length utilizing a machined ring film cooled construction and twelve low-pressure air blast fuel injectors. Commercial and Naval versions employ two 0.5 Joule capacitive discharge surface gap ignitors.

The combustor employs a moderately rich primary zone which happens to be relatively sensitive to aromatics fractions carried in the fuel in terms of smoke and flame radiation. The rich primary zone choice arose as a result of trade-off studies done during early T700 development, whereby starts requiring ease of cold day ignition and acceleration were traded against tendency to smoke. In-as-much as smoke requirements are relatively relaxed for small diameter plumes, the choice of primary zone stoichiometry was favorable for this application. Impact of broad fuel specifications was not a consideration at that time.

All combustor concepts and the baseline design were examined for their performance with Jet A and three NASA ERBS fuel types with respect to:

1. Smoke.
2. Emissions (carbon monoxide, unburned hydrocarbons, and oxides of nitrogen).
3. Flame radiation, and as a consequence shell temperature and cyclic durability.
4. The affect of combustion efficiency and pressure drop on specific fuel consumption
5. Complexity and manufacturability.
6. Reliability and maintainability.
7. Engine weight.

Results of the study indicated that smoke and flame radiation were primarily affected by changing the fuel specification. As a result, the proposed redesigns were directed at those two problems.

Interestingly, it was concluded that emissions were insignificantly affected. This is due mainly to low emissions levels in the first place. The low levels are a side effect of a number factors that are favorable in this particular cycle and engine size. NOx is limited at high power due to modest pressure ratio (17 instead of 25-30) and very short residence time, due to high aerodynamic loading (space heat release rate is approximately 12 x 10^6 Btu/hr/ft^3/atm). Idle emissions (CO and THC) are low due to high idle pressure ratio (3.8) and a somewhat richer than normal primary equivalence ratio at idle (approximately 0.75 - 0.85 at the dome) which is nearly optimum for high combustion efficiency at idle (approximately 98.2% based on tail pipe gas analysis).

ANALYTICAL FUEL PROPERTY EFFECTS - SMALL COMBUSTORS
GENERAL ELECTRIC PROGRAM - PHASE I SUMMARY

- Engine Family Chosen for Study - T700/CT7
  Rated Air Flow - 10 lbs/sec
  Rated Pressure Ratio - 17
  Power Class - 1500-1800 SHP
  SFC Levels - .46 - .51 (Typically)
  Combustor Type - Straight Through Annular
  Fuel Injector Type - Air Blast, 12 Equispaced Axial

- Items Studied

	Smoke
FUEL EFFECTS	*Invisible Emissions*
	Flame Radiation, Shell Temperature, Durability
	Combustion Efficiency/SFC
DESIGN IMPACTS	Complexity and Manufacturability
	Reliability and Maintainability
	Weight

- Significant Fuel Effects
  Smoke
  Flame Radiation, Shell Temperature, Durability

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

ANALYTICAL FUEL PROPERTY EFFECTS - SMALL COMBUSTORS
GENERAL ELECTRIC PROGRAM - PHASE I SUMMARY
(CONTINUED)

- Insignificant Fuel Effects
  Invisible Emissions
  Combustion Efficiency/SFC

- Key Fuel Properties Affecting Performance
  Aromaticity/Hydrogen Content

- Required Design Characteristics for Improved Performance
  Leaner, More Homogeneous Primary Zones
  Improved Shell Cooling

- Methods Proposed
  For Leaner Primary Zones
  1) Advanced Air Blast Fuel Injector with Central Air Core
  2) Variable Area Swirlers

  For Improved Shell Cooling - Enhanced Convection
  1) Impingement/Film, baseline structure
  2) Counter Flow/Film, baseline structure
  3) Impingement/Film, new structure

GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

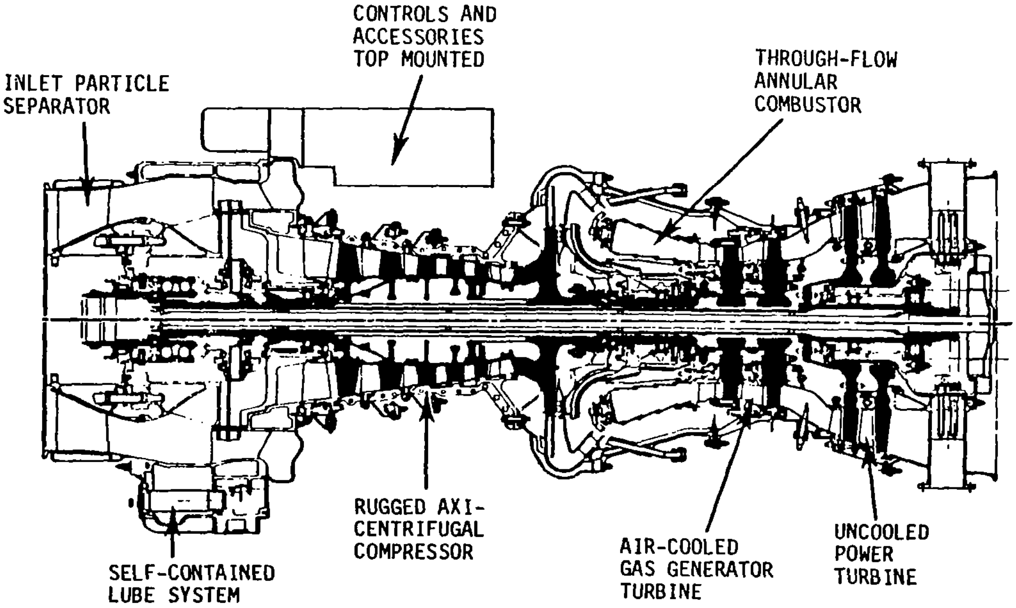


Figure 1. T700 Engine Cross Section.

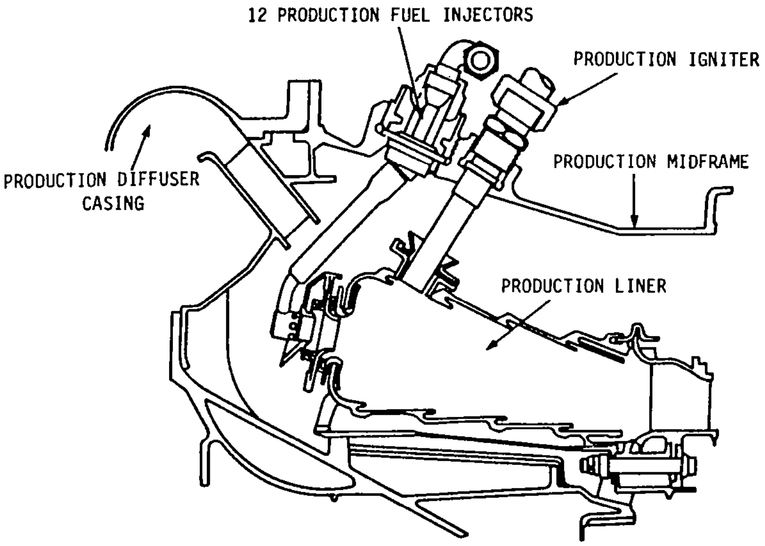
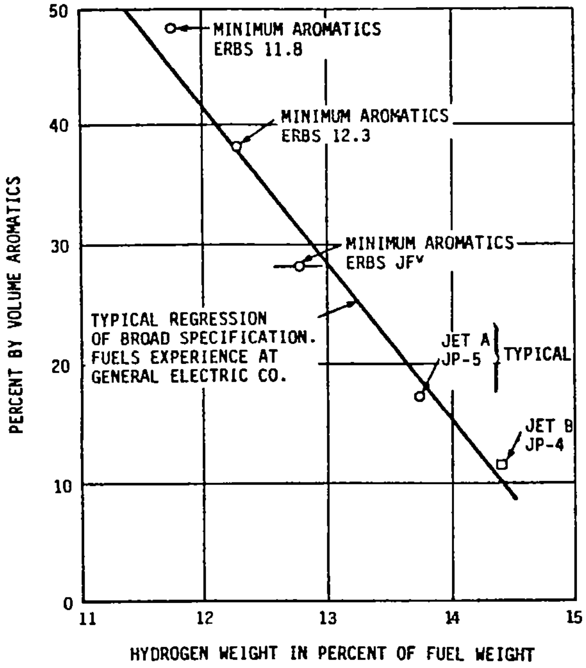
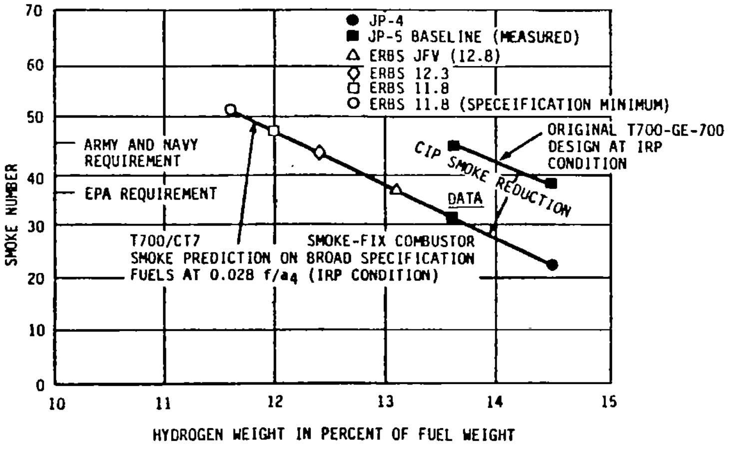


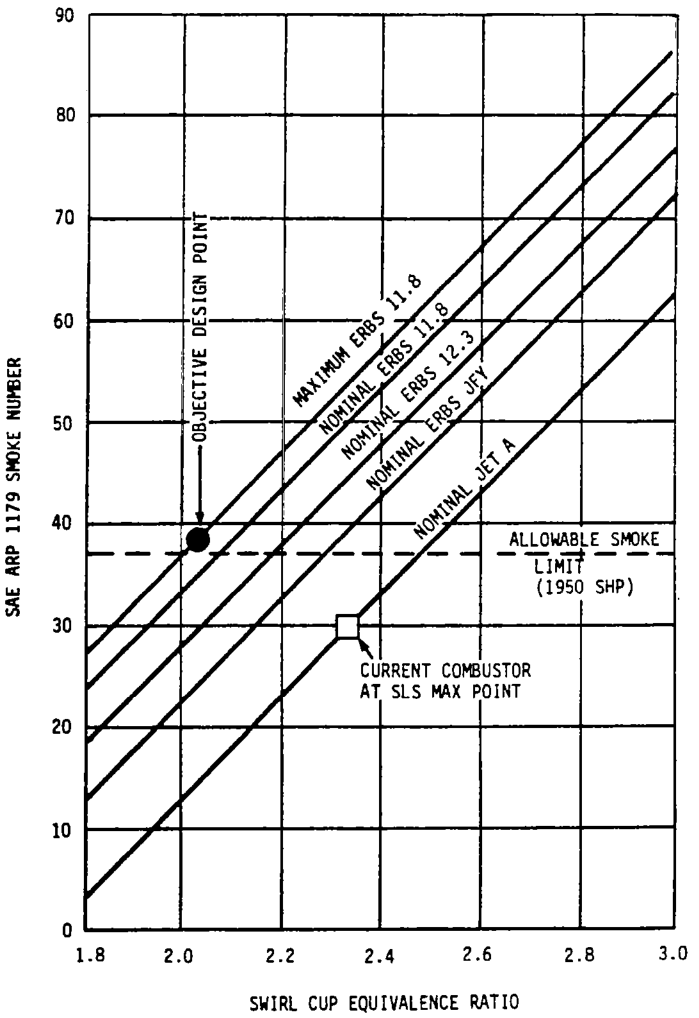
Figure 2. T700-GE-401 and CT7-5 Primerless Combustor.



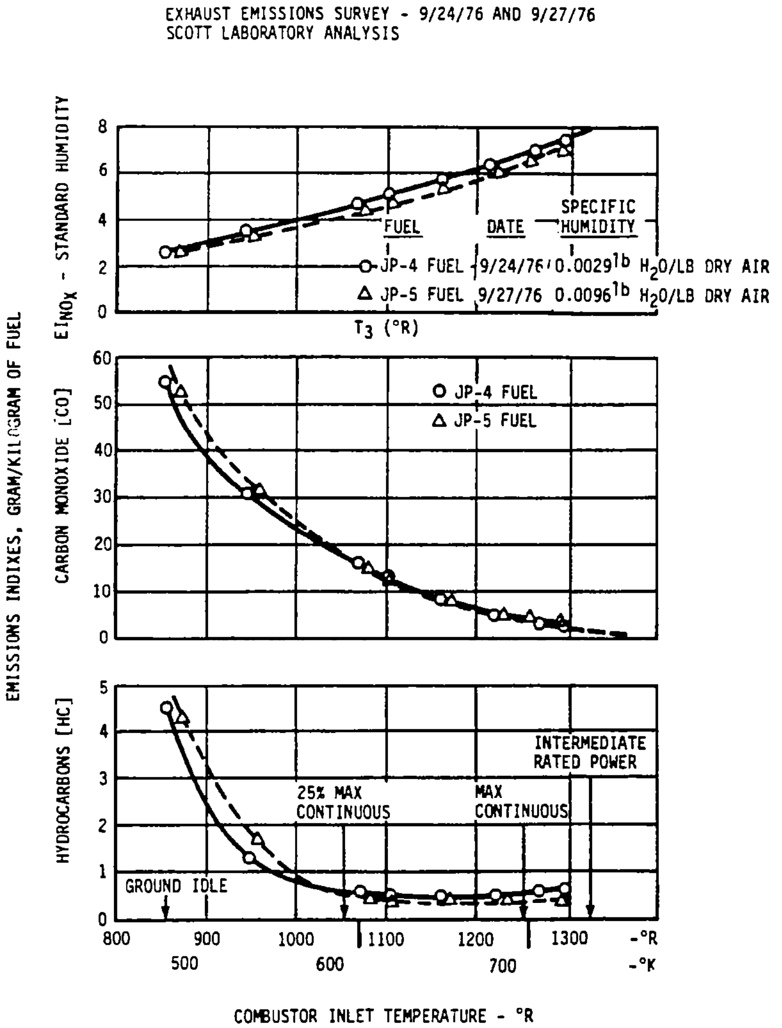
Relationship of Hydrogen Content and Aromaticity.



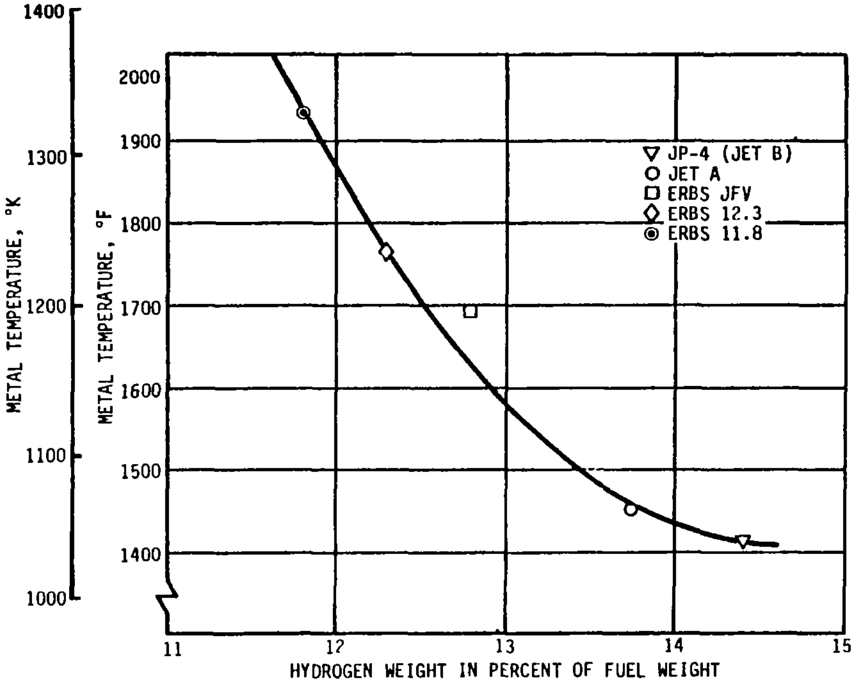
T700/CT7 Engine Smoke Fix Characteristics.



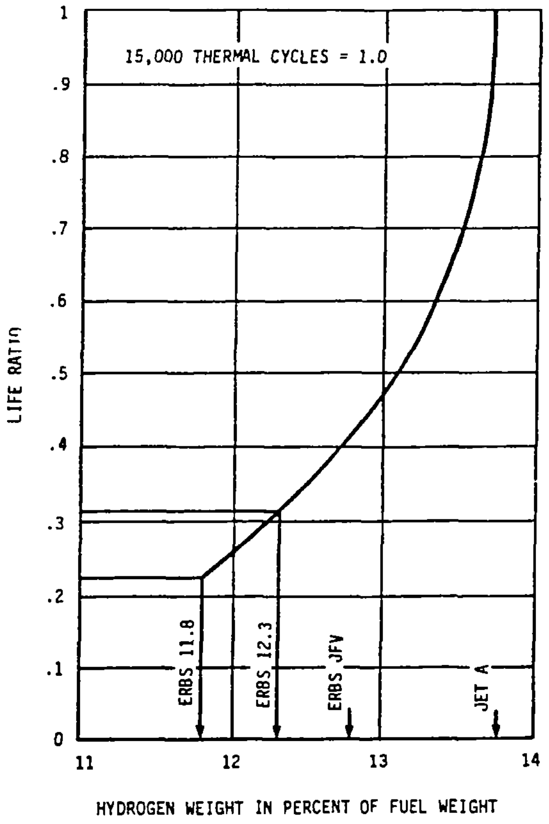
Effect of Swirl Cup and Equivalence Ratio and Fuel Type (Hydrogen %) on Smoke.



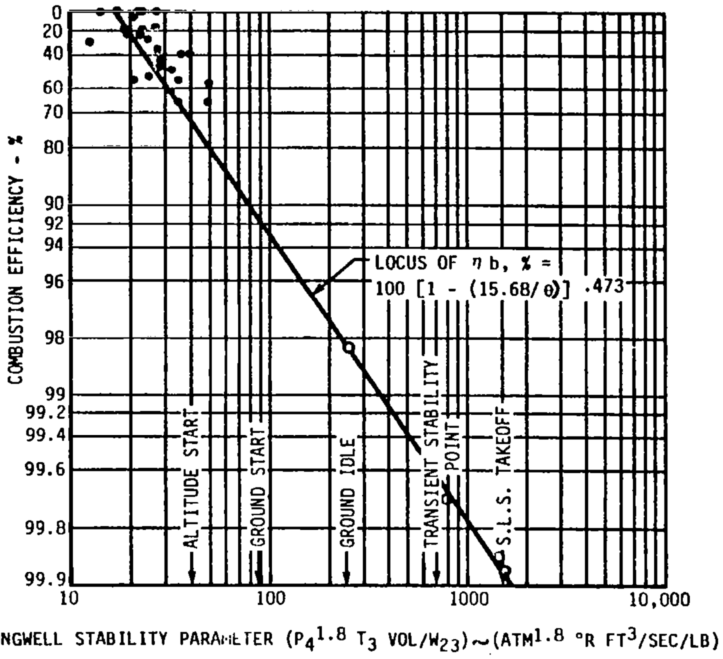
Exhaust Emission Measurements - T700-GE-700
Engine Serial No. 207010-5B.



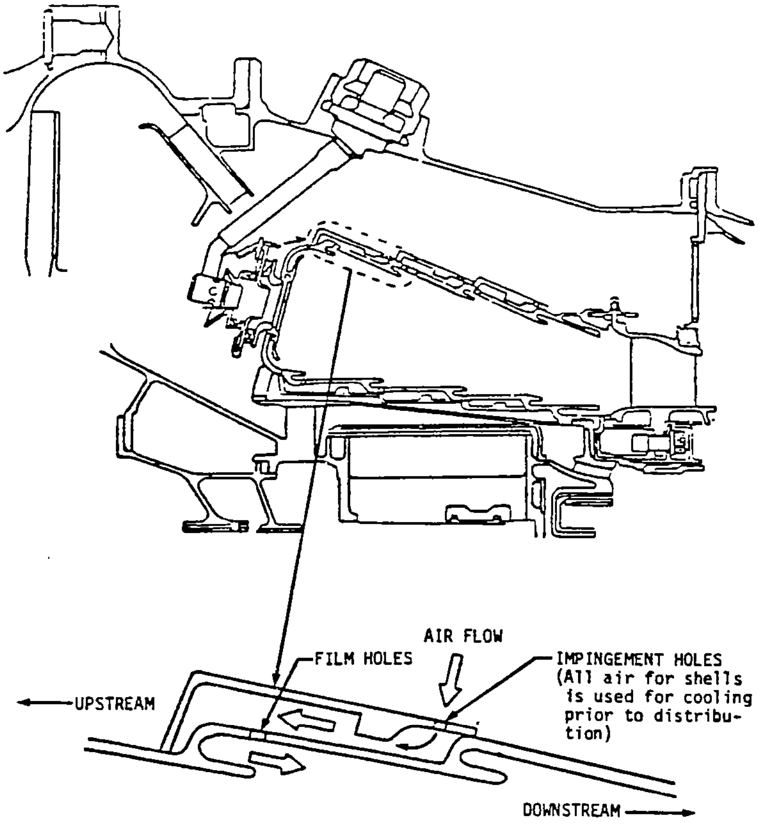
First Panel Metal Temperatures.



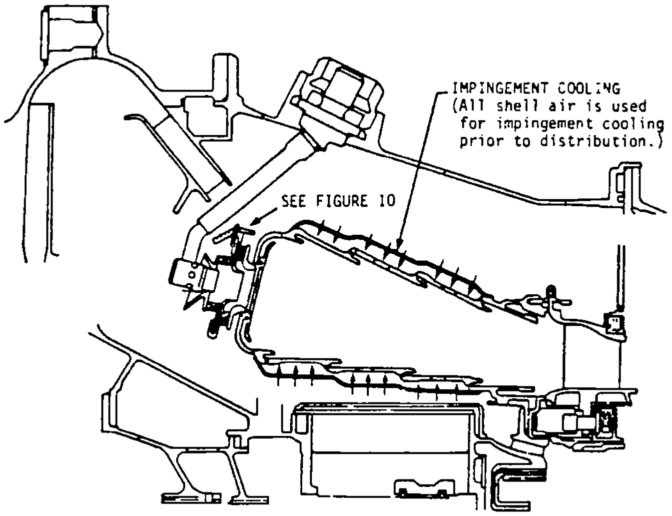
Predicted Life Degradation of Baseline Combustor as a Function of Fuel Properties.



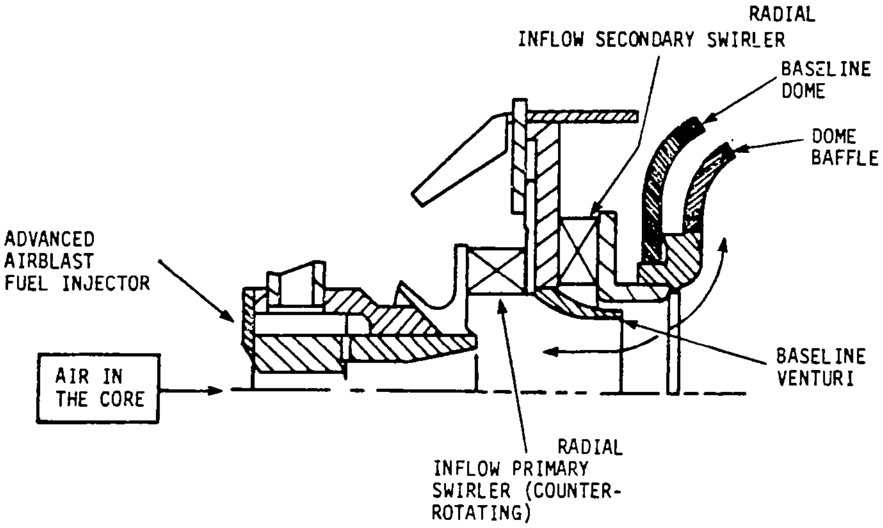
CT7-5 Combustor Efficiency Correlation.



Reverse Flow Convectors with Impingement Stage - Design A.

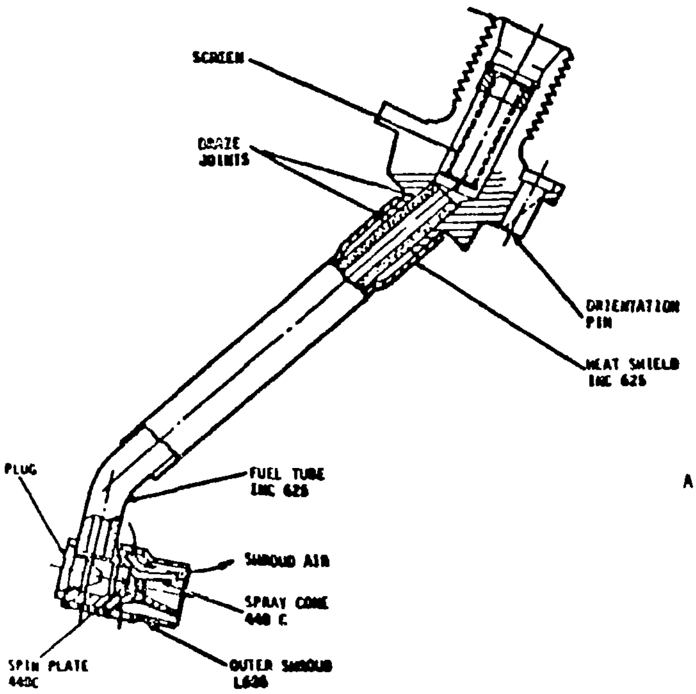


100% Impingement Cooled Shells - Design B.



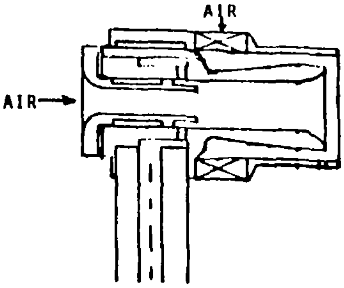
Advanced Air Blast Fuel Injectors - Design B.

PRODUCTION INJECTOR



IMPROVED AIR BLAST INJECTOR

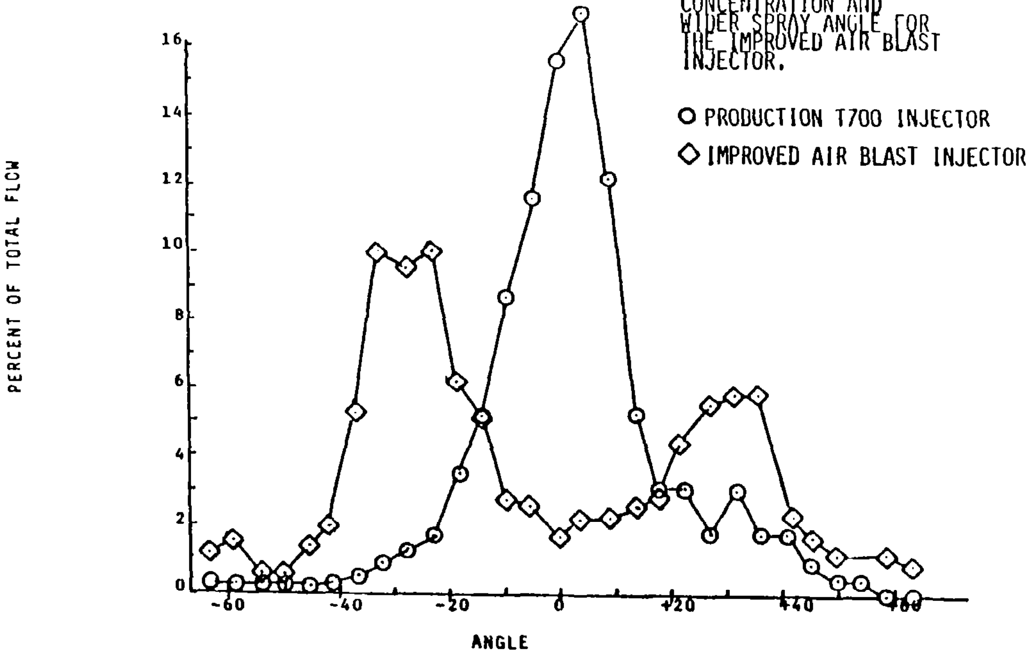
AN IMPROVED AIR BLAST FUEL INJECTOR PUTS AIR ON BOTH SIDES OF THE FUEL INJECTION LOCATION TO IMPROVE ATOMIZATION AND REDUCE PEAK PRIMARY ZONE FUEL-AIR RATIO.



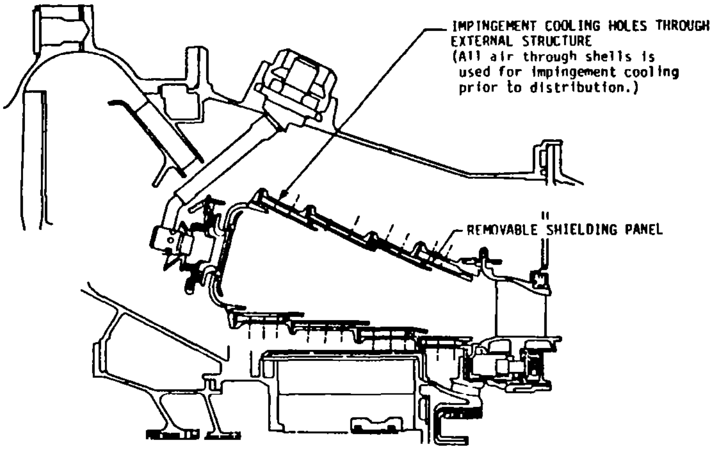
GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP

PATTERNATOR TEST RESULTS

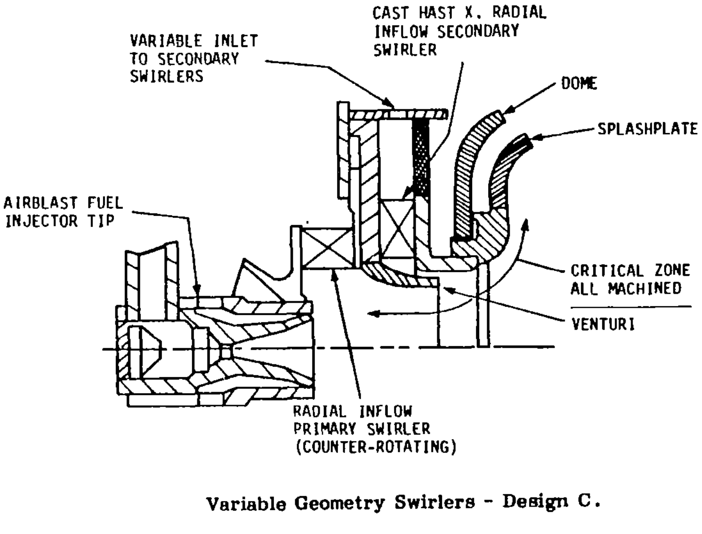
VERIFY A REDUCED FUEL CONCENTRATION AND WIDER SPRAY ANGLE FOR THE IMPROVED AIR BLAST INJECTOR.



GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUSINESS GROUP



100% Impingement Cooled with Replaceable Flame Shields - Design C.



Variable Geometry Swirlers - Design C.

THE NASA BROAD SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM AT PRATT & WHITNEY

Robert P. Lohmann
Pratt & Whitney Aircraft Group
United Technologies Corporation

The objective of the National Aeronautics and Space Administration/Pratt & Whitney Aircraft Broad Specification Fuels Combustion Technology Program is to identify and evolve the technology required to accommodate the use of broadened properties fuels in commercial aircraft engine combustors with minimum impact on the emissions, performance, durability and engine operational characteristics. To accomplish this objective a two phase program, involving extensive combustor rig testing is being conducted. In the first phase emphasis was placed on defining the potential for reducing the fuel sensitivity of the reference combustion system through design refinements and the introduction of more advanced technology combustors. To this end the tests conducted in Phase I included the evaluation of variations of three different combustor concepts representing progressively more advanced technology levels.

The JT9D-7F had been selected as the reference engine and the production burner from this engine became the initial configuration of the single stage combustor concept which was the simplest of the three concepts. The second and subsequent configurations of the single stage concept were variations of the JT9D Advanced Bulkhead combustor which is the production burner in more recent models in the JT9D engine series. A staged combustor, incorporating two distinct combustion zones was selected as the second combustor concept. This burner was the advanced Vorbix combustor that has been evolved under the NASA/PWA Energy Efficient Engine program. A variable geometry combustor was selected as the third and most advanced combustor concept because the capability of shifting the airflow distribution to optimize stochiometry at different power levels offered potential for improving performance and emissions characteristics. However, due to the preliminary or screening nature of the investigation in Phase I, no attempt was made to construct variable combustor components at that time and this concept was assessed in terms of fixed geometry perturbations of the JT9D bulkhead combustor.

The tests fuels for this program consisted of Jet A; Experimental Referee Broad Specification Fuel (ERBS) which has a nominal hydrogen content of 12.8 to 13.0 percent weight as opposed to 13.6 to 13.8 percent typical in Jet A and two other fuels of progressively lower hydrogen content produced by blending a high aromatic content stock with ERBS.

Details on the evaluation of these combustor concepts and their subsequent design modifications may be found in the cited references. Generalizing the results presented therein it has been concluded that Phase I of the program demonstrated that 1) reduced fuel hydrogen content has adverse impacts on current single stage combustors; 2) the best opportunities for reducing the fuel sensitivity of these combustors are through improved fuel injectors and advanced liner cooling and structural concepts and 3) that the advanced technology staged and variable geometry combustor concepts have inherent operational flexibility that can be exploited to accommodate changes in fuel composition.

Based on these conclusions, when the Phase II program was initiated the entire emphasis was placed on the assessment of advanced technology combustor concepts to produce the greatest benefits consistent with the overall program objective. Recognizing that advanced combustor concepts would be more likely to be incorporated in future models and derivatives of the most modern engines rather than retrofit into older engine models, the reference engine was changed to the PW2037 for the Phase II program. All test hardware was sized consistent with this engine and a PW2037 single stage combustor is being evaluated under this phase to establish a fuel sensitivity baseline against which the advanced technology concepts can be compared.

Initially, two advanced technology combustor concepts are being evaluated and refined under Phase II. A variable geometry combustor, capable of airflow modulation during operation, has been constructed and the initial sequence of test configurations has been evaluated. Airflow is shifted in this combustor by actuating valves that pressurize or isolate the cavity behind the combustor hood from which air may enter the primary combustion zone through large swirlers concentric with the aerated fuel injectors. The airflow feed to the fuel injectors is independent of the hood cavity to provide good fuel atomization in both operating modes. Variables addressed during the initial sequence of testing this combustor include the fuel injector geometry, the strength and aerodynamic configuration of the swirlers and the primary zone airloading.

The second advanced technology combustor being evaluated in Phase II is a new concept, designated the Mark. IV, which is a further evolution of the Vorbix combustor approach pursued in the NASA/PWA Experimental Clean Combustor and Energy Efficient Engine programs. This annular combustor incorporates a number of air admission modules protruding through the front of the combustor through which the majority of the combustor airflow enters. The modules feature concentric primary and secondary air paths which deliver swirling airflow to a primary or pilot combustion zone and a downstream secondary combustion and dilution zone respectively. The evaluation of this concept has also proceeded through the testing of an initial series of configurations in which such parameters as the strength, aerodynamics and penetration of the swirlers; the fuel injector size and density and the primary combustion zone airloading and cooling level have been varied.

The initial evaluation effort in the Phase II program, consisting of the testing of six configurations of each of these two combustor concepts, has been completed. These tests were conducted in a facility that was limited to a maximum combustor inlet total pressure of 15 atm. However, it has the advantage of expeditious turnaround between tests which made it more cost effective during the conceptual evolution type of investigation being conducted on both combustor concepts. The next program element, which is currently being started, involves comparative testing of a final or best configuration of each combustor in a high pressure test facility capable of duplicating the full takeoff pressure level of the PW 2037 engine. Based on the results of these tests, the best or most promising concept will be selected for further refinement and a final full engine pressure level demonstration test. While the combustors were only operated with Jet A and Experimental Referee Broad Specification Fuel (ERBS) during the initial evaluation effort, the tests conducted in the high pressure facility are more extensive and involve operation with four test fuels.

These include Jet A, Experimental Referee Broad Specification Fuel, one of the blended low hydrogen content fuels used in Phase I and a commodity fuel selected to extend the variation of the viscosity and volatility of the test fuel matrix.

The technical effort on the Phase II program will be completed early in CY 1984. With the conclusion of this program, the potential of incorporating design refinements and advanced technology approaches to enhance the fuel flexibility of commercial aircraft gas turbine combustors will have been demonstrated.

REFERENCES

1. R. P. Lohmann, R. A. Jeroszko, "Broad Specification Fuels Combustion Technology Program, Phase I", NASA CR-168180, July 1983.

2. R. P. Lohmann, J. S. Fear, NASA Broad Specification Fuels Combustion Technology Program - Pratt and Whitney Aircraft Phase I Results and Status" AIAA Paper 82-1088, 18th Joint Propulsion Conference, June 1982.

PHASE I PROGRAM

- **Objective**

  Identify and evolve combustor technology to accomodate use of broadened properties fuels

- **Reference engine**

  JT9D-7F

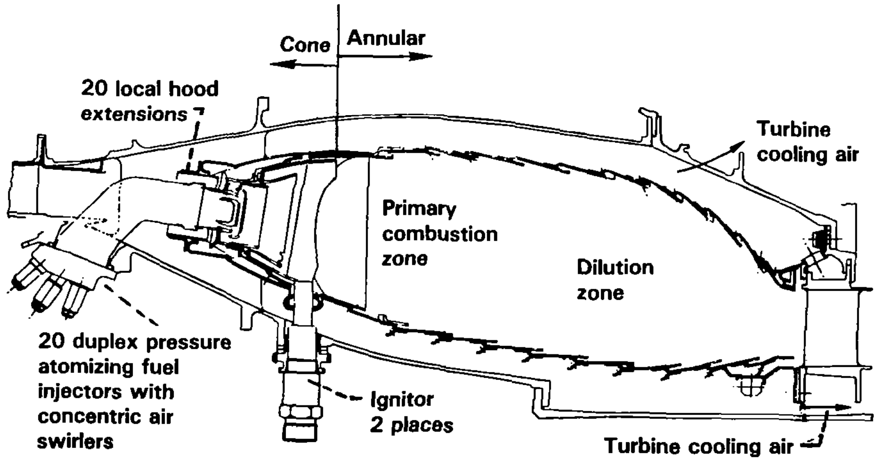
- **Approach**

  Evaluate variations of three combustor concepts of progressively more advanced technology level in rig tests

- **Status**
  - **Program completed**
  - **Reported in NASA CR 168180**

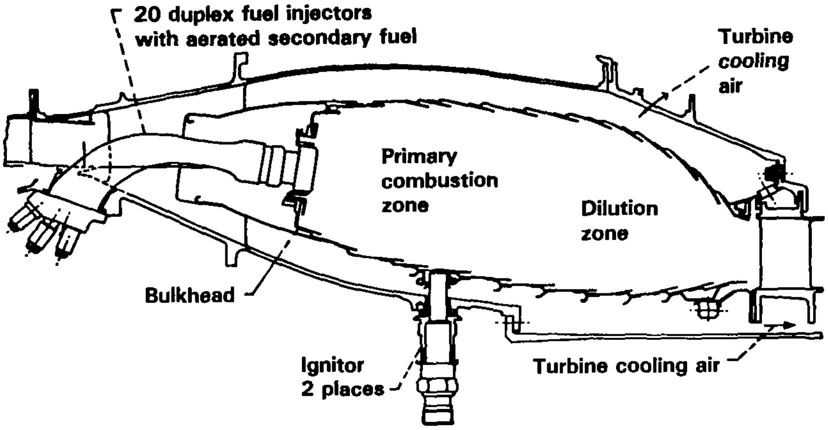
J29076-2
830609 E222

INITIAL SINGLE STAGE COMBUSTOR CONCEPT



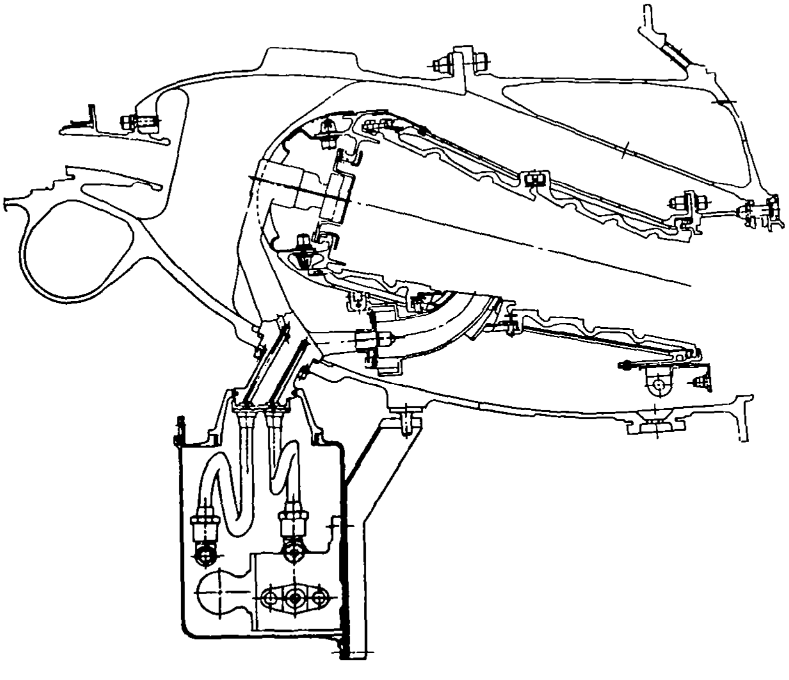
J26864-15
822605 M255

ADVANCED SINGLE STAGE COMBUSTOR CONCEPT



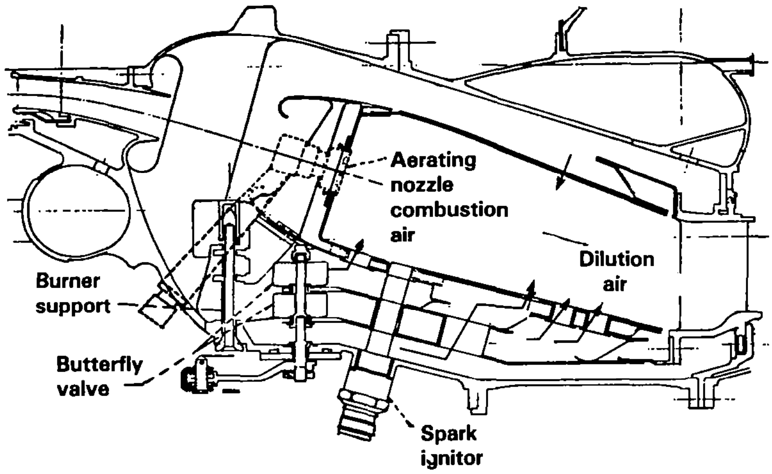
J26864-14
822605 M255

STAGED COMBUSTOR CONCEPT



J26864-17
822605 M255

VARIABLE GEOMETRY COMBUSTOR CONCEPT



J26864-16
822605 M255

TEST FUEL PROPERTIES

Composition	Jet A	ERBS	12.3% Hydrogen	11.8% Hydrogen
Aromatic content — % vol	20.6	31.5	40.4	52.2
Napthalene content — % vol	1.06	11.7	13.5	15.4
Hydrogen content — % wt	13.62	12.93	12.37	11.80
Physical properties				
Viscosity, cs. @ 249°K (−10°F)	5.50	8.57	7.23	6.48
Specific gravity, 289/289°K	0.8184	0.8403	0.8509	0.8623
Smoke point — mm	20	12	11	9
Distillation temperatures — °K				
Initial	422	422	413	420
10%	447	471	453	447
50%	478	498	496	498
Final	544	594	597	603

J26864-5
822105 M254

PHASE I
CONCLUSIONS

- Reduced fuel hydrogen content has adverse impacts on current (single stage) combustors
- Fuel sensitivity of current combustors may be reduced with
  - Improved fuel injectors
  - Advanced liner cooling/structural concepts
- Advanced technology combustor concepts have operational flexibility that can be used to accomodate changes in fuel composition

J26864-4
R830609

PHASE II PROGRAM

- Objective

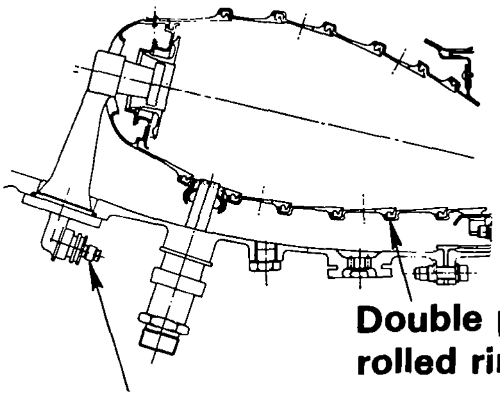
  Refinement of advanced technology combustor concepts for optimum performance with broadened properties fuels
- Reference engine

  PW2037
- Approach

  Parallel evolution of two combustor concepts in rig tests followed by selection and final optimization of one concept
- Status
  - Initial evolution of both concepts completed
  - Testing to be completed in early 1984

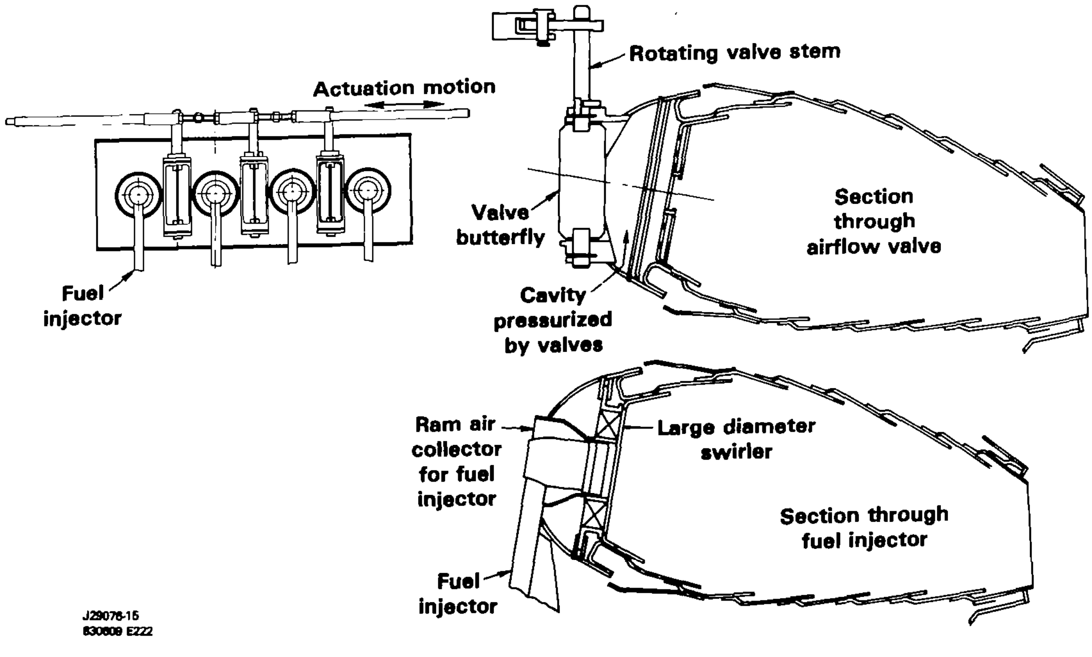
J29076-13
830609 E222

BASELINE PW2037 COMBUSTOR



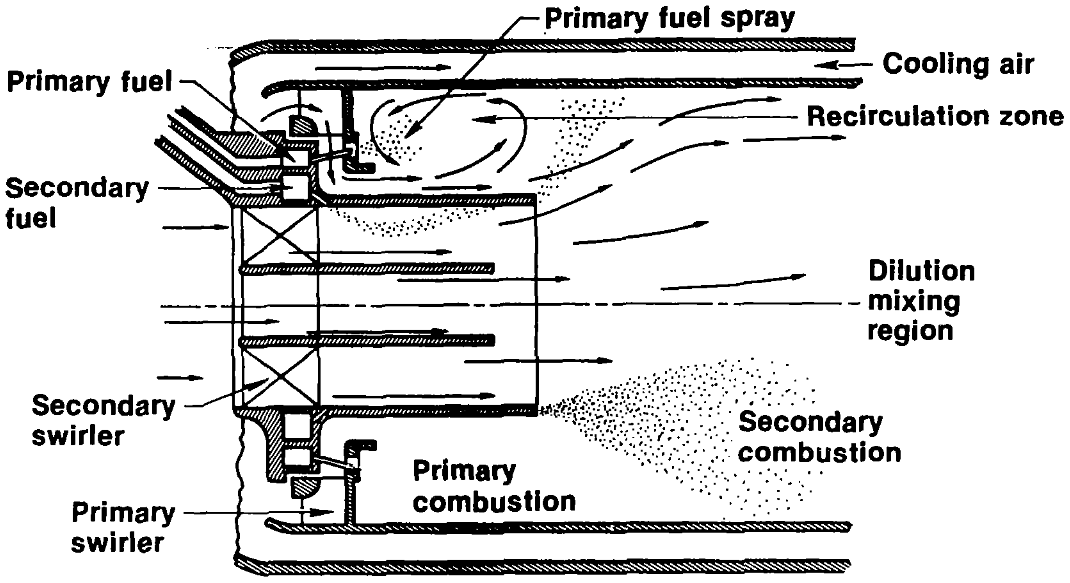
J29076-14
830609 E222

VARIABLE GEOMETRY COMBUSTOR CONCEPT



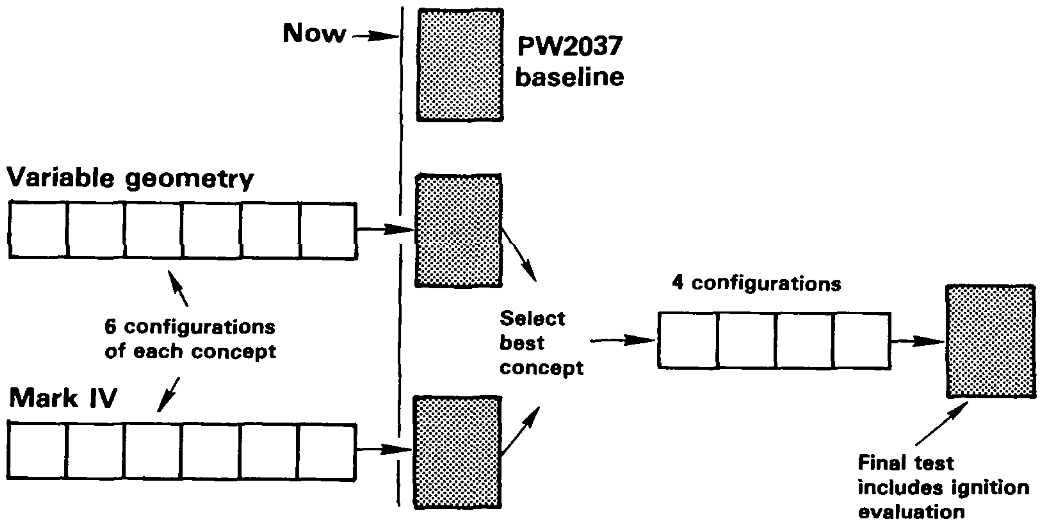
J29076-15
830609 E222

MARK IV COMBUSTOR CONCEPT



J29076-16
830609 E222

PHASE II PROGRAM STRUCTURE



Open – low pressure (15 atm) Jet A and ERBS fuels
Shaded – full pressure, four test fuels

J29076-17
830609 E222

MODIFICATIONS TO COMBUSTORS

Variable geometry	Mark IV
• Alternate fuel injectors	• Fuel injector size and density
• Swirler strength and aerodynamics	• Secondary swirler strength, aerodynamics and immersion
• Primary zone airloading	• Primary swirler strength and airloading
	• Primary zone cooling

J29076-18
830809 E222

EFFECT OF FUEL INJECTOR TYPE ON PERFORMANCE OF VARIABLE GEOMETRY COMBUSTOR

Fuel injector type		A	B	C
Idle — valves closed				
Emissions	CO	83	58	76
indices, gm/kg	THC	31	5	27
Combustion efficency, %		94.3	98.0	94.8
Lean blowout fuel/air ratio		0.0028	0.0071	0.0058
Approach — combustion efficiency				
Valves closed		99.5	—	99.8
Valves open		99.3	99.6	99.2
Cruise — valves open				
Max liner temperature °K above T_{T3}		242	228	267
SAE smoke number		37	21	15

All data with ERBS fuel

J29076-20
830909 E222

EFFECT OF SECONDARY SWIRLER CENTERTUBE AIRFLOW ON PERFORMANCE OF MARK IV COMBUSTOR

Centertube airflow, percent of maximum		0	35	100
Idle				
Emission	CO	107	68	115
indices, gm/kg	THC	87	16	32
Combustion efficiency, %		87.0	96.5	93.0
Lean blowout fuel/air ratio		0.0062	0.0057	0.0040
Approach				
Combustion efficiency, %		96.0	99.8	98.7
SAE smoke number		9	16	38

All data with ERBS fuel

J29076-21
830909 E222

CURRENT STATUS OF MARK IV AND VARIABLE GEOMETRY CONCEPTS

Durability	Both adequate
High power smoke	Both adequate
Exit pattern factor	Mark IV is better
Low power emissions	Both need further improvement
Combustion stability	Both are marginal

J29076-19
830609 E222

FUEL SYSTEM RESEARCH AND TECHNOLOGY - AN OVERVIEW OF THE NASA PROGRAM

Bert R. Phillips
National Aeronautics and Space Administration
Lewis Research Center

Research and technology investigations are being conducted to determine the interactions between the design and operation of aircraft fuel systems and the properties of alternative aircraft fuels. This paper provides an overview of the NASA Lewis program of fuels system research and technology in terms of its rationale, its progress, and future plans. Particular aspects of the program not covered by other speakers in this session will be highlighted.

The rationale for the program can be more readily understood using Figure 1 which indicates the interactions between the fuel system research and technology program and the identification of future fuels, which was discussed in the first session of this symposium; the fundamental aspects of fuels and combustion, which are discussed elsewhere; and the application of information about fuels and aircraft fuel systems to systems analyses and tradeoff studies, which are included within this session. Based on the extensive efforts conducted within those areas mentioned above, the fuel system program has been focussed on two key fuel properties; the fuel freezing temperature and the thermal stability of the fuel.

Program for Studying Effects of Increased Fuel Freezing Temperature

The principal elements of the NASA program are listed in Figure 2 and are based primarily on the results of a 1977 NASA fuels workshop.

Analysis of inflight temperatures has until recently been based on measurements of the bulk fuel temperature and the corresponding static air temperature provided by commercial and military aviation. The resulting data base was limited to a relatively modest amount of route and seasonal variation. Not withstanding those limitations, statistical anayses of the data reveal much useful information. A typical example, taken from a 1979 Boeing study, is shown in Figure 3. The curves shown, while differentiated by aircraft type, might just as well be separated by the aircraft flight Mach number together with some indication of the fuel usage strategy employed on the plane since those two factors have been demonstrated to be of great importance in determining the rate of heat loss from the fuel.

In order to provide a more comprehensive data base on which to base technology efforts, a number of initiatives have been taken both by NASA and others. The NASA initiatives have involved the measurement of ambient air temperatures for a wider range of seasonal and geographic variations, based on GASP program observations and the inflight measurements of the temporal and spatial variation of the fuel temperatures with a commercial aircraft. The result of these studies will be discussed in this session by Roger Svehla.

Design of aircraft fuel systems for use with higher freezing point fuels has emphasized the evaluation of a variety of schemes for heating the fuel to avoid freezing related problems. Concepts have been evaluated using experimental and design analysis approaches. Although the bulk fuel temperature within the wing tanks is only a rough indication of the potential for fuel freezing problems, it can be calculated with some degree of confidence that this type of calculation can be readily incorporated into design analysis studies for a variety of aircraft and mission models. Three separate design studies were initiated which have included the use of fuels with increased as well as conventional freezing temperatures. The results of these studies will be presented during this session by representatives of GE, Lockheed, and Simmonds Precision.

From an experimental viewpoint, the evaluation of fuel heating systems as well as other aspects of the low temperature behavior of fuels have been studied in wing tank simulators. These simulators have been used by NASA Lewis, JPL, Boeing, and Lockheed in the knowledge of this author. Figure 4 is a picture of the simulator used in-house at NASA Lewis. The figure shows the hoses that carry the refrigerant that is used to reduce the temperature of the upper and lower surfaces of the vessel in a manner consistent with flight measurements. At the conclusion of the test, for example, the unpumpable fuel, or holdup, can be readily determined. Efforts are made to correlate holdup with the transient temperature measurements made during the test. The results of a series of tests with a variety of in-tank heaters is shown in Figure 5. The results, presented as the fraction of fuel initially loaded that cannot be pumped out of the tank, indicate that fuel heating can significantly alleviate much of the holdup.

The results obtained to date using the wing tank simulator are quite encouraging with their similarity to flight test data. There are, however, some significant differences, particularly in the details of the near-wall temperature gradients, that need additional study. In order to clarify these issues as well as to develop predictive techniques to anticipate the amount of holdup for a variety of aircraft fuels and fuel systems, additional wing tank simulator testing is planned, both in-house and under contract.

In order to aid in the interpretation of the data and to generate a useful predictive technique, efforts to model the phenomena have been expanded. The required fuel property data base, particularly the transport properties at near freezing conditions, is being acquired. An illustration of the improvements in prediction with a better viscosity model is shown in Figure 6. The dashed line represents the improved model. Prediction of the important temperature profile near the lower wing surface has also been improved as is illustrated by the agreement between analysis and experiment in Figure 7. Additional model improvements including the addition of multidimensional effects are also being investigated.

A rapid and portable measurement of the fuel freezing temperature can be very useful, particularly if applied to the fuel while it is being loaded onto the aircraft. A study of potential methods for performing this measurement is being concluded by Midwest Research Institute under contract to NASA. Two different approaches were evaluated in detail; an optical method based on change in transmissivity when the fuel freezes and a thermal method based on calorimetry. A comparison of the two methods with the ASTM D-2386 laboratory standard is shown in Figure 8. Based on the results of testing, the thermal method has been selected for additional development.

Additional aspects of the program that have not been mentioned include the evaluation of flow improvement additives to alleviate low temperature flowability problems. As is illustrated in Figure 9, based on tests in a wing tank simulator, additives appear to be as effective as wing tank heating under certain circumstances.

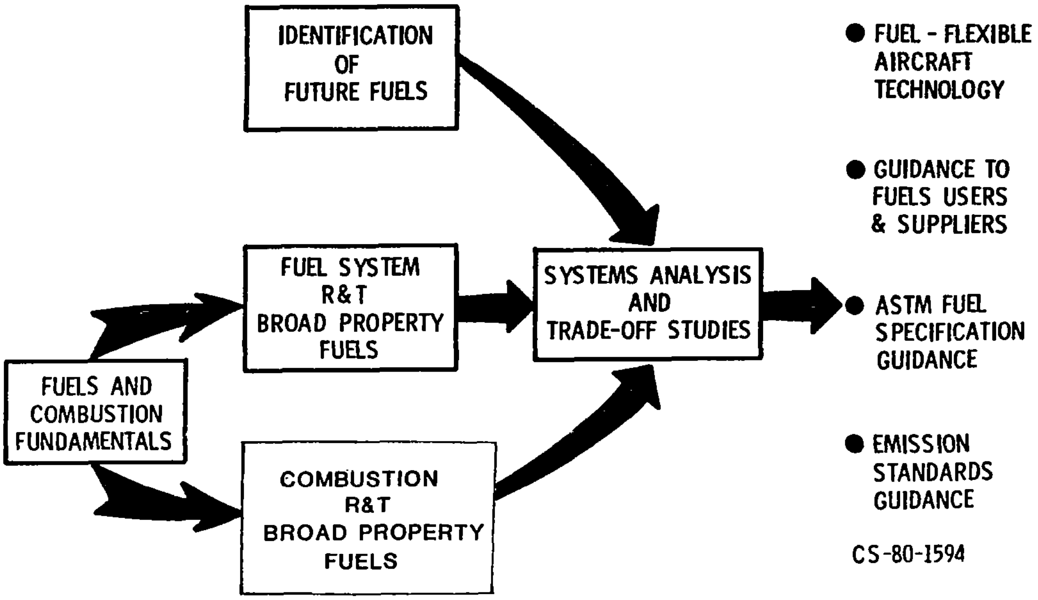
Fuel Thermal Stability Program Overview

During this session, a detailed discussion of the research program for fuel thermal stability will be presented by Charles Baker. It is appropriate to point out that the aforementioned contract design studies have also evaluated fuels with lower thermal stability. Particularly, in the case of the GE study, detailed estimates have been made of the temperature history of the fuel as it flowed through the system. A typical example of the results of those calculations is shown in Figure 10.

Efforts to simulate the high temperature regime of an aircraft fuel system have had to compromise between an effort at realism and the need for quantitative data acquisition in a controlled environment. The approach adopted by NASA is presented in Figure 11. It is, essentially, an effort to provide a uniform temperature environment at conditions representing either the fuel system or some more stressful conditions and to acquire samples of the resulting fuel deposit for detailed measurement. The apparatus is characterized by its large thermal inertia. Alternative approaches have been investigated that provide uniform thermal flux while allowing the local temperatures to vary accordingly. In order to relate the variety of simulator data to one another and to take into account the bewildering variation in chemical effects, an effort to model the deposition process in detail is required. Extensive inhouse and contractual efforts are planned to expand the data base with controlled experiments. An example of some of the nuances of the data obtained by simulators is shown in Figure 12. The important effect of intermediate cleaning of the apparatus on the total deposit formed is obvious.

Other areas of fuel system research that have not been discussed include studies of fuel lubricity, electrical conductivity, materials compatibility, and overall system safety as well as many more. Much of the research in these areas has been supported by other agencies of the government, in particular the Federal Aviation Administration and the Department of Defense. A representative of the Southwest Research Institute that performs a great deal of the fuel system research for the Department of Defense will speak at the conclusion of this session.

AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS



IDENTIFICATION OF FUTURE FUELS

FUEL SYSTEM R&T BROAD PROPERTY FUELS

FUELS AND COMBUSTION FUNDAMENTALS

COMBUSTION R&T BROAD PROPERTY FUELS

SYSTEMS ANALYSIS AND TRADE-OFF STUDIES

- FUEL - FLEXIBLE AIRCRAFT TECHNOLOGY
- GUIDANCE TO FUELS USERS & SUPPLIERS
- ASTM FUEL SPECIFICATION GUIDANCE
- EMISSION STANDARDS GUIDANCE

CS-80-1594

FIGURE 1

FUEL FREEZING POINT PROGRAM

ANALYSIS OF IN-FLIGHT TEMPERATURE DATA

DESIGN OF AIRCRAFT FUEL SYSTEMS FOR USE WITH HIGH FREEZING POINT FUELS

EXPERIMENTAL STUDY OF LOW TEMPERATURE FLOWABILITY

DEVELOPMENT OF RAPID FREEZING POINT METHODS

FIGURE 2

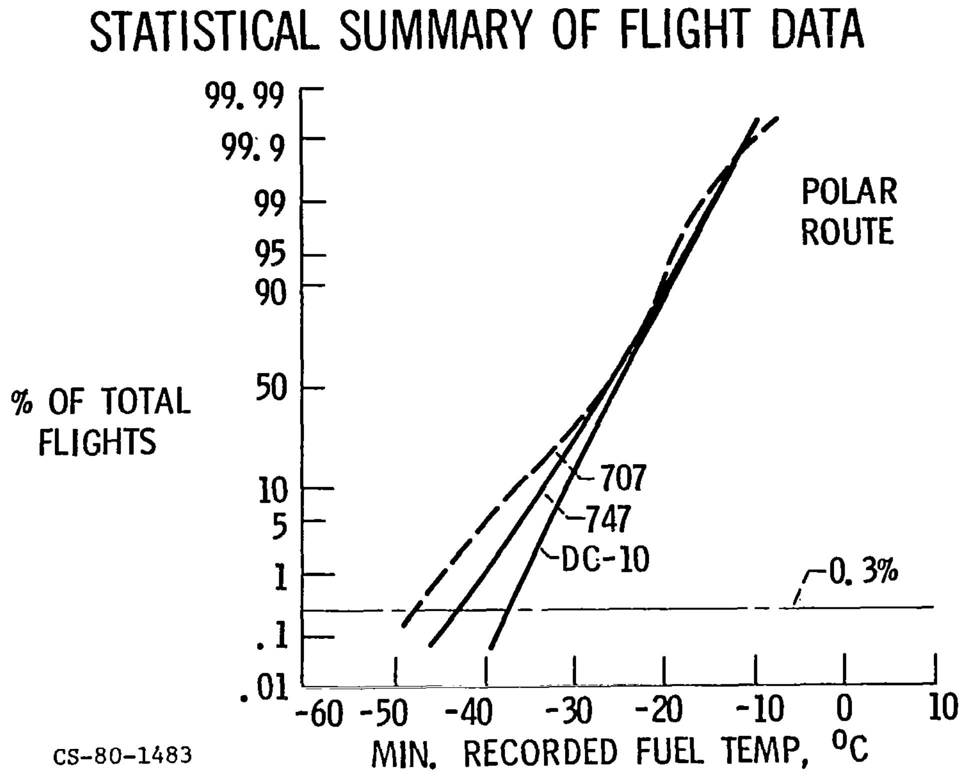

STATISTICAL SUMMARY OF FLIGHT DATA

FIGURE 3

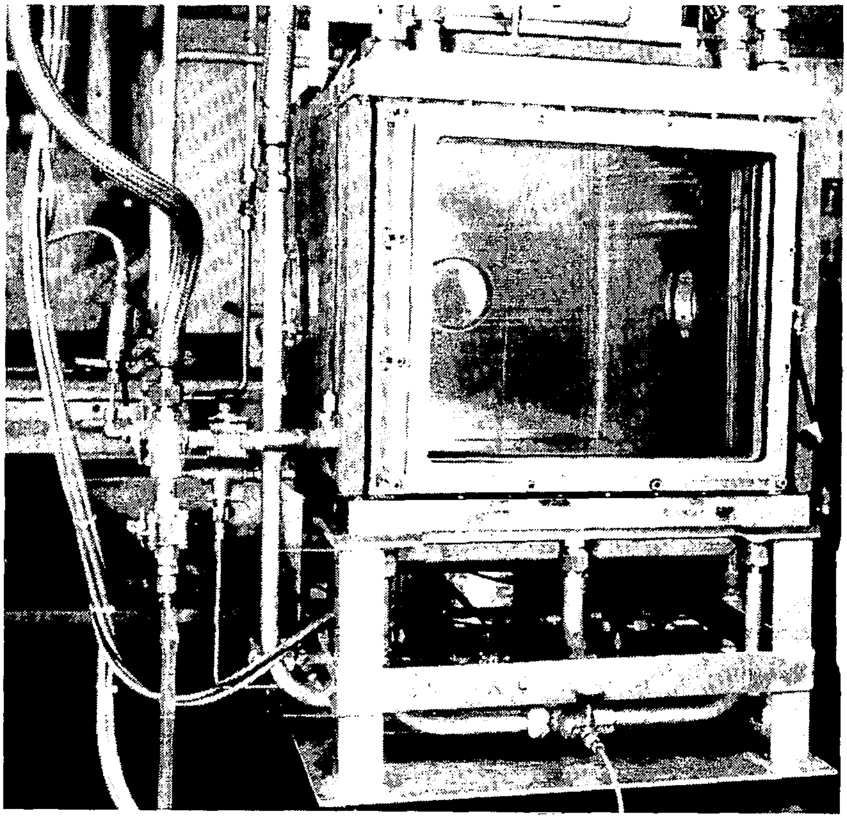


FIGURE 4 - LOW TEMPERATURE FLOW FACILITY

EFFECT OF FUEL HEATING FOR COLD DAY FLIGHT SIMULATION

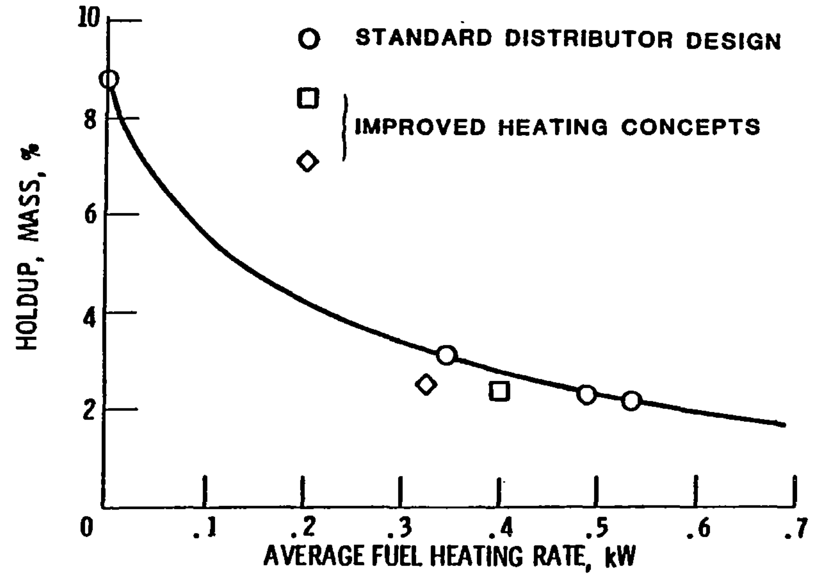


FIGURE 5

BULK TEMPERATURE PREDICTION

FREEZING TEST (4.4% HOLDUP)

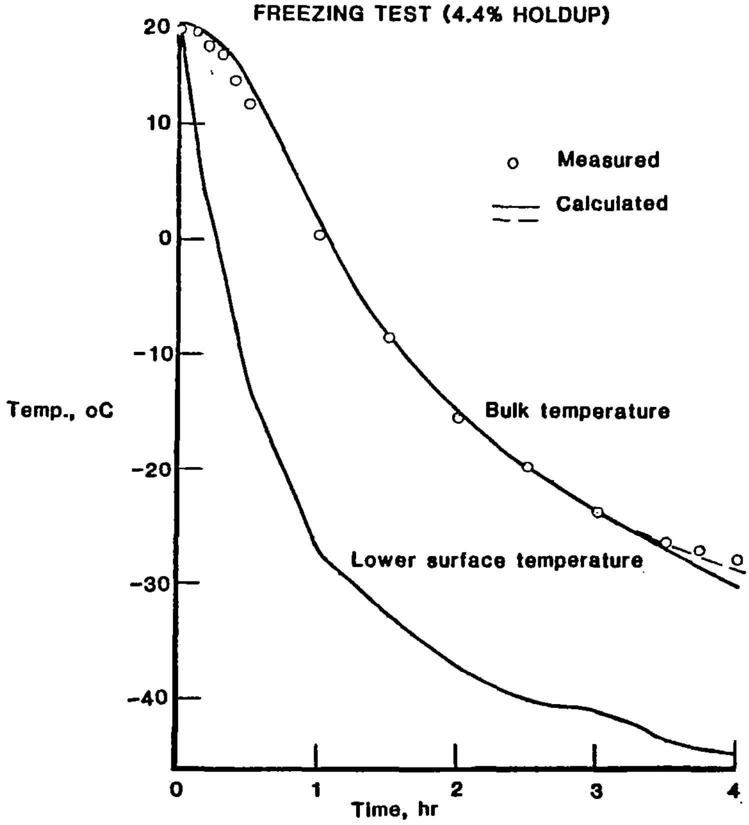


FIGURE 6

TEMPERATURE PROFILE PREDICTION

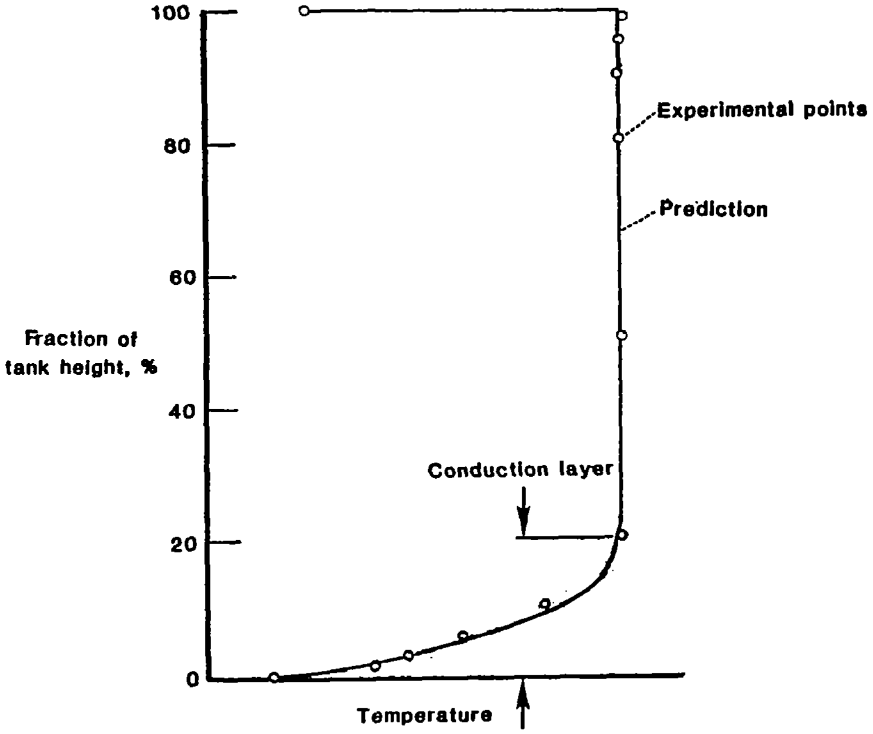


FIGURE 7

COMPARISON OF STANDARD ASTM METHOD WITH CONCEPTUAL METHODS

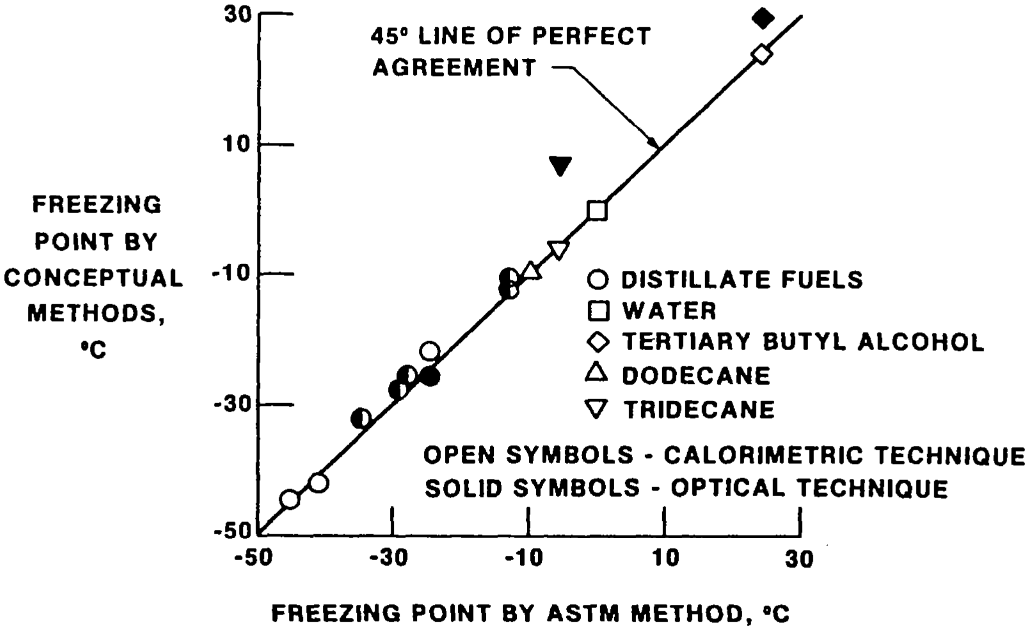


FIGURE 8

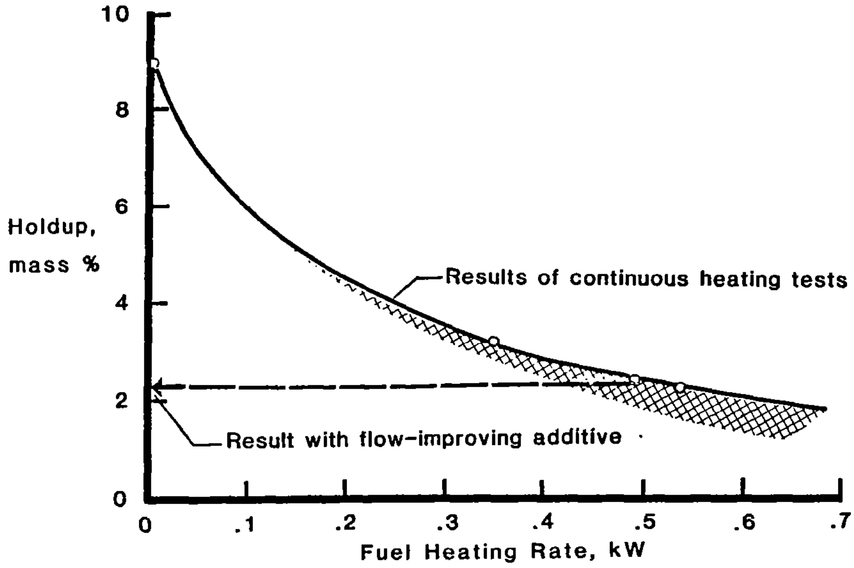


FIGURE 9

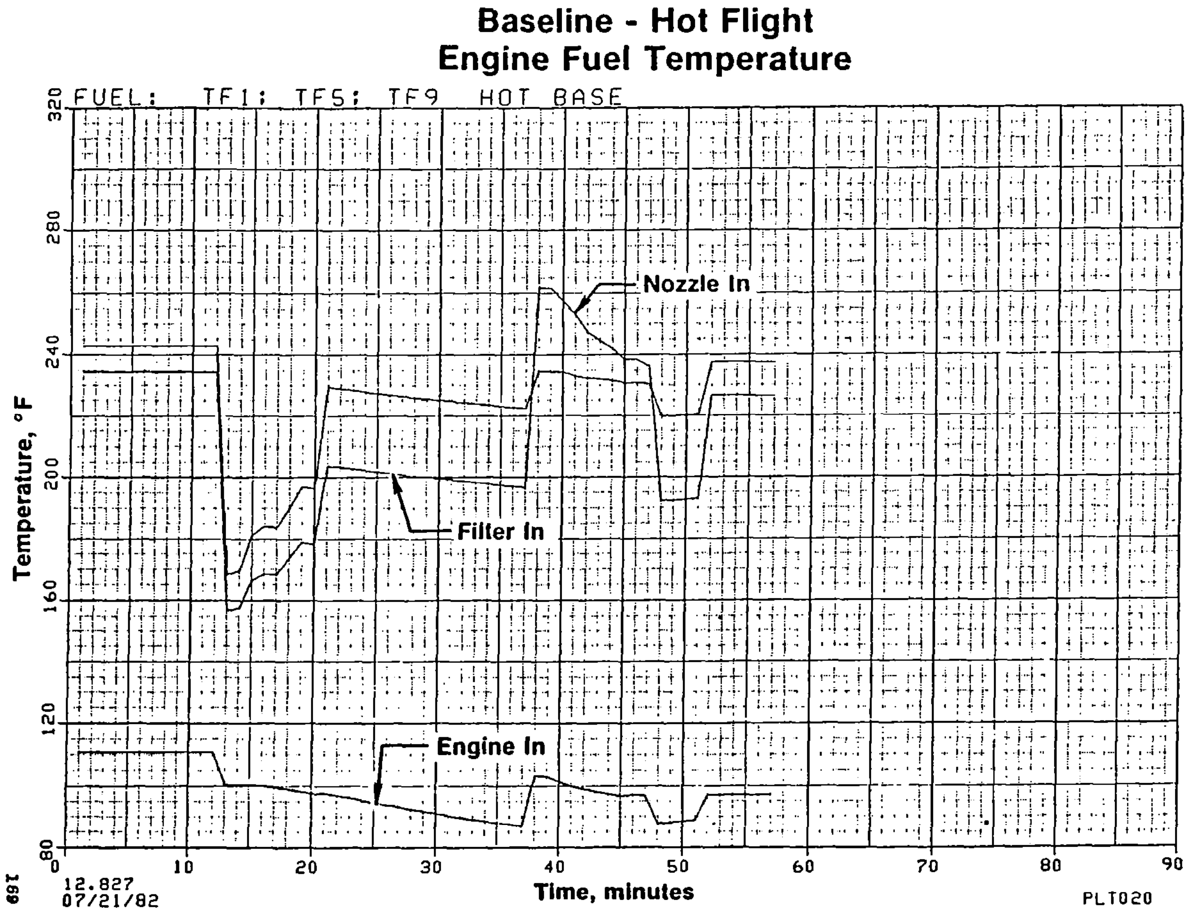
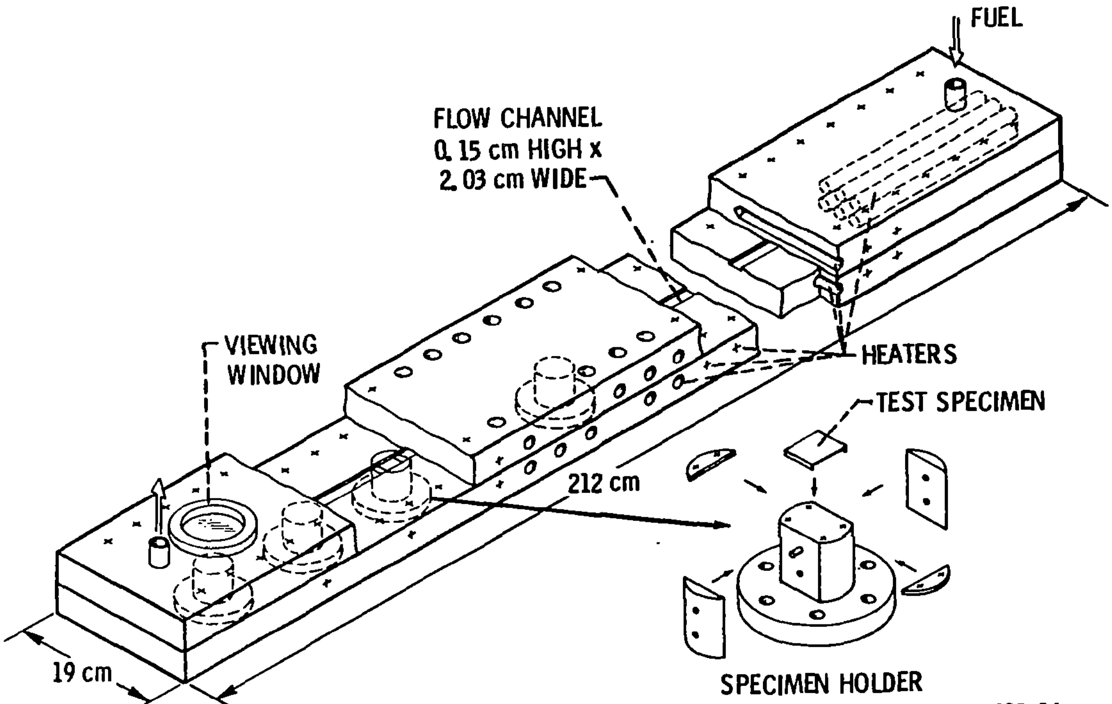


FIGURE 10

NASA THERMAL STABILITY TEST SECTION



CD-12403-34
CS-79-4226

FIGURE 11

EFFECT OF TEST SECTION CLEANLINESS ON DEPOSITION

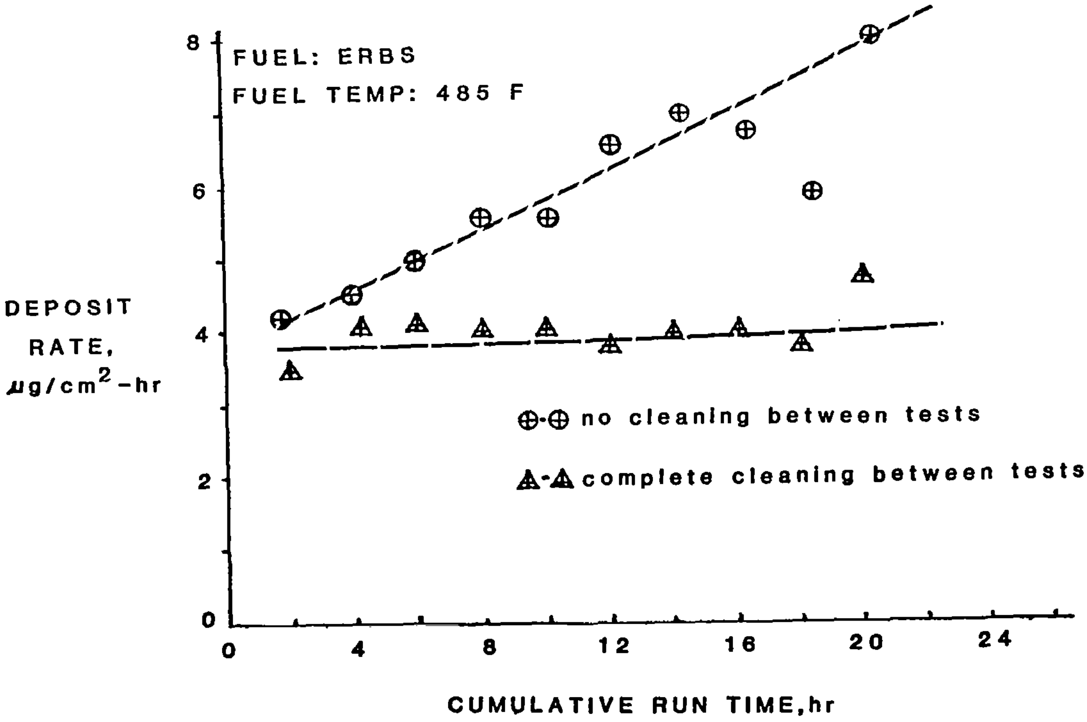


FIGURE 12

RESEARCH ON AVIATION FUEL INSTABILITY

Charles E. Baker, David A. Bittker, Stephen M. Cohen,
and Gary T. Seng
National Aeronautics and Space Administration
Lewis Research Center

The purpose of this report is to define the problems associated with aircraft fuel instability, review what is currently known about the problem, describe the research program sponsored by NASA Lewis, and identify those areas where more research is needed. The term fuel instability generally refers to the gums, sediments, or deposits which can form as a result of a set of complex chemical reactions when a fuel is stored for a long period at ambient conditions or when the fuel is thermally stressed inside the fuel system of an aircraft.

Thermal instability was first identified as a problem in aviation turbine engines in the 1950's. During the 1960's, early studies in the United States on the supersonic transport (SST) gave considerable attention to the problem of fuel instability, because in this SST, the fuel was to be used as a heat sink for the wing surfaces which are heated aerodynamically. It is generally acknowledged that current aircraft turbine fuels do not present a significant problem with regard to fuel instability for current subsonic aircraft. However, turbine fuels with broadened properties or nonpetroleum-derived fuels (from shale, tar-sands, coal, etc.) may have reduced thermal stability because of their higher content of olefins, heteroatoms, and trace metals. (Heteroatoms include nitrogen, oxygen, and sulfur atoms contained in organic compounds.) Moreover, advanced turbine engines may increase the thermal stress on fuels because of their higher pressure ratios and combustion temperatures. Deposition of solids within the fuel systems of aircraft may lead to fouled heat exchangers, plugged fuel nozzles, and/or jammed fuel valves which may result in excessive oil temperatures and non-uniform fuel spray patterns which could cause distorted turbine inlet temperatures (hot spots).

During the past several years NASA Lewis has been engaged in a research and technology program to determine the effects of broadened-property fuels on engine and fuel system components and to evolve the technology needed to use these fuels. Broadening fuel properties may offer the potential for increasing the refinery yield of jet fuel. Moreover, additional energy intensive treatment of poorer quality crudes and syncrudes will be required if jet fuel with current properties is to be produced. One of the major problem areas that must be addressed is fuel instability because of the reasons given in the previous paragraph. In recognition of its importance, NASA Lewis has established a broadly-based research program to better understand the underlying causes of fuel thermal degradation. Our in-house research is supported by grants with universities and contracts with industry. The progress, status, and results for these various activities will be reviewed and discussed in the report, along with some preliminary thoughts on design approaches required to minimize the effects of lowered thermal stability.

The complex chemical and physical processes involved in the degradation of fuels have been studied extensively. The early work was covered by Nixon in a comprehensive review published in 1962 [1]. A thorough literature survey which included reports of investigations since 1962 was recently published [2] by the Coordinating Research Council (CRC), and Peat has summarized the major aspects of fuel thermal stability in a current AGARD advisory report [3]. NASA Lewis sponsored a workshop on jet fuel thermal stability in 1978 [4]. The consensus among the workshop participants concerning what is known about the chemistry and physics of fuel thermal oxidation stability included the following points:

- The initial process is the interaction of fuel and dissolved oxygen.
- The chemistry involves primarily free radical reactions, but polymerization, addition, and condensation reactions are also important.
- Deposit formation rate depends on temperature with the process starting at approximately 100°C.
- Deposit rate is affected by fuel flow parameters (velocity and Reynolds number, residence time).
- The amount of dissolved oxygen in the fuel is important; in general, removal of oxygen significantly improves fuel stability.
- Metals have a significant effect on deposit formation, with copper being the most deleterious metal. Both homogeneous effects (dissolved metals) and heterogeneous (surface) effects have been observed.
- Deposits can form both in the liquid and vapor phases with the presence of both phases causing the greatest amount of deposits.

The fuel deposits that form in aircraft fuel systems may occur as soft gums, as strongly adhering lacquers and varnishes, or as brittle cokes [3]. Studies of the morphologies of these deposits [5,6] indicate that they are generally an agglomeration of microspheres, although plate and rod forms have also been observed. Chemical analysis of fuel deposits has revealed these additional general characteristics: (1) The hydrogen/carbon ratio is lower in the deposits than in the original fuel, (2) oxygen concentration of the deposits is much greater than in the thermally unstressed fuel, and (3) other heteroatoms such as nitrogen and sulfur are highly concentrated in the deposits, with concentrations several orders of magnitude higher than in the fuel [3]. The high concentration of heteroatoms in the deposits relative to their concentrations in the fuel is strongly supportive of the importance of these trace organic impurities in the deposit formation process. The lower hydrogen/carbon ratio in the deposits suggests that aromatic compounds play an important role in deposit formation.

Attempts to measure the amount of deposit produced by a fuel under a given set of conditions have ranged from small-scale glass laboratory devices to full-scale fuel system simulators. These devices have been thoroughly reviewed in ref. 2, and this report will concentrate on the American Society for Testing and Materials (ASTM) test methods for evaluating fuel thermal stability and on the larger dynamic fuel stressing rigs commonly referred to as laboratory simulators.

Research on fuel instability can be classified into two general types: research designed to understand chemical mechanisms and research on the behavior of actual fuels. When the elucidation of chemical mechanisms is the main objective of the research, pure compounds or "model fuels" made up of a mixture of a few pure compounds are usually employed in order to simplify the chemistry. Compounds containing heteroatoms or trace metals are then added in small amounts to determine their effects on fuel stability. Other research efforts concentrate on the deposits produced by actual fuels when they are thermally stressed under controlled conditions. Common to both these types of research is the need to characterize the resulting fuel deposits. A variety of analytical techniques is required to provide information on both elemental and molecular composition. NASA Lewis' current work on fuel stability, both in-house and under grant or contract, will be reviewed according to these three categories of research.

REFERENCES

1. Nixon, A. C., "Autoxidation and Antioxidants of Petroleum," Autoxidation and Antioxidants, Vol. II, Chapter 17, W. O. Lundberg, Ed., New York, New York, Interscience Publishers, Inc., 1962, pp. 695-856.
2. Anon., "CRC Literature Survey on the Thermal Oxidation of Jet Fuel," 1979, CRC Report No. 509.
3. Peat, A. E., "Fuel Thermal Stability," AGARD Advisory Report No. 181, Vol. 2, 1982, Appendix A2.4, pp. 119-141.
4. Taylor, W. F., ed., "Jet Fuel Thermal Stability," 1979, NASA TM 79231, A Workshop held at Lewis Research Center, Cleveland, Ohio, November 1-2, 1978.
5. Schrimer, R. M., "Morphology of Deposits in Aircraft Fuel Systems," Phillips Petroleum Co. Res. Div. Report 5029-68R, August 1968.
6. Schrimer, R. M., "Morphology of Deposits in Aircraft and Engine Fuel Systems," SAE Paper 700258, April 1970.

TABLE I. - MODERN INSTRUMENTATION FOR DEPOSIT CHARACTERIZATION

INSTRUMENT	INFORMATION OBTAINED
SCANNING ELECTRON MICROSCOPE (SEM)	MORPHOLOGY OF DEPOSITS THROUGH HIGH MAGNIFICATION
ENERGY DISPERSIVE ANALYSIS OF X-RAYS (EDAX)	QUALITATIVE AND SEMI-QUANTITATIVE ANALYSIS OF μ-SIZE SAMPLE AREAS
ELECTRON SPECTROSCOPY FOR CHEMICAL ANALYSIS (ESCA)	QUALITATIVE AND SEMI-QUANTITATIVE ANALYSIS OF TOP 100 A OF SAMPLE SURFACE - PROVIDES BONDING INFORMATION
SECONDARY ION MASS SPECTROSCOPY (SIMS)	QUALITATIVE AND SEMI-QUANTITATIVE ANALYSIS OF 25 TO 2500 A LAYER OF SAMPLE PER MASS SCAN
FOURIER TRANSFORM INFRARED SPECTROSCOPY (FT-IR)	DETERMINATION OF FUNCTIONAL GROUPS - SUPERIOR SENSITIVITY TO CLASSICAL IR
RAMAN SPECTROSCOPY	DETERMINATION OF FUNCTIONAL GROUPS - COMPLEMENTS IR
PHOTOACOUSTIC SPECTROSCOPY (PAS)	CHROMOPHORE AND FUNCTIONAL GROUP DETERMINATIONS, AND THERMAL PROPERTIES CHARACTERIZATION
PYROLYSIS/GAS CHROMATOGRPAHY-MASS SPECTROMETRY	PYROLYZED FRAGMENTS FROM DEPOSIT IDENTIFIED - MOLECULAR COMPOSITION OF ORIGINAL DEPOSIT DETERMINED

LOW TEMPERATURE

(BELOW 300° C - AUTOXIDATION)

$$\mathrm{RH} + \mathrm{X} \longrightarrow \mathrm{R}\cdot + \mathrm{HX},\ \text{(INITIATION)} \qquad (1)$$

$$\mathrm{R}\cdot + \mathrm{O_2} \longrightarrow \mathrm{RO_2}\cdot \qquad (2)$$

$$\mathrm{RO_2}\cdot + \mathrm{RH} \longrightarrow \mathrm{ROOH} + \mathrm{R}\cdot \qquad (3)$$

$$\mathrm{RO_2}\cdot + ? \longrightarrow \text{DEPOSITS, GUMS, SEDIMENTS} \qquad (4)$$

INTERMEDIATE TEMPERATURE

(300 - 500° C)

$$\mathrm{ROOH} \longrightarrow \mathrm{RO}\cdot + \mathrm{HO}\cdot \qquad (5)$$

$$\mathrm{RO}\cdot + \mathrm{RH} \longrightarrow \mathrm{ROH} + \mathrm{R}\cdot \qquad (6)$$

$$\mathrm{HO}\cdot + \mathrm{RH} \longrightarrow \mathrm{H_2O} + \mathrm{R}\cdot \qquad (7)$$

$$\mathrm{ROOH} + \mathrm{X} \longrightarrow \text{KETONE} + \mathrm{XH},\ \text{(SECONDARY HYDROPEROXIDE)} \qquad (8)$$

$$\mathrm{RH} \longrightarrow \mathrm{R_1}\cdot + \mathrm{R_2}\cdot,\ \text{(PYROLYSIS)} \qquad (9)$$

ISOMERIZATION AND
DECOMPOSITION OF $R_1\cdot$
AND $R_2\cdot$ TO FORM OLEFINS

Figure 1. - Proposed mechanisms for fuel degradation.

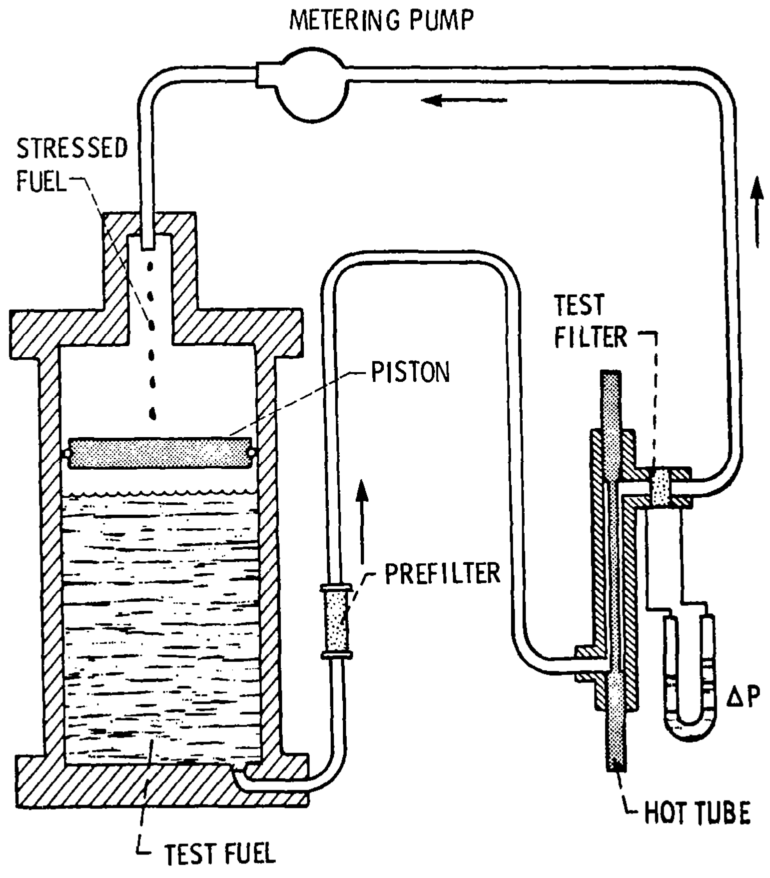


Figure 2. - Schematic of jet fuel thermal oxidation tester (JFTOT).

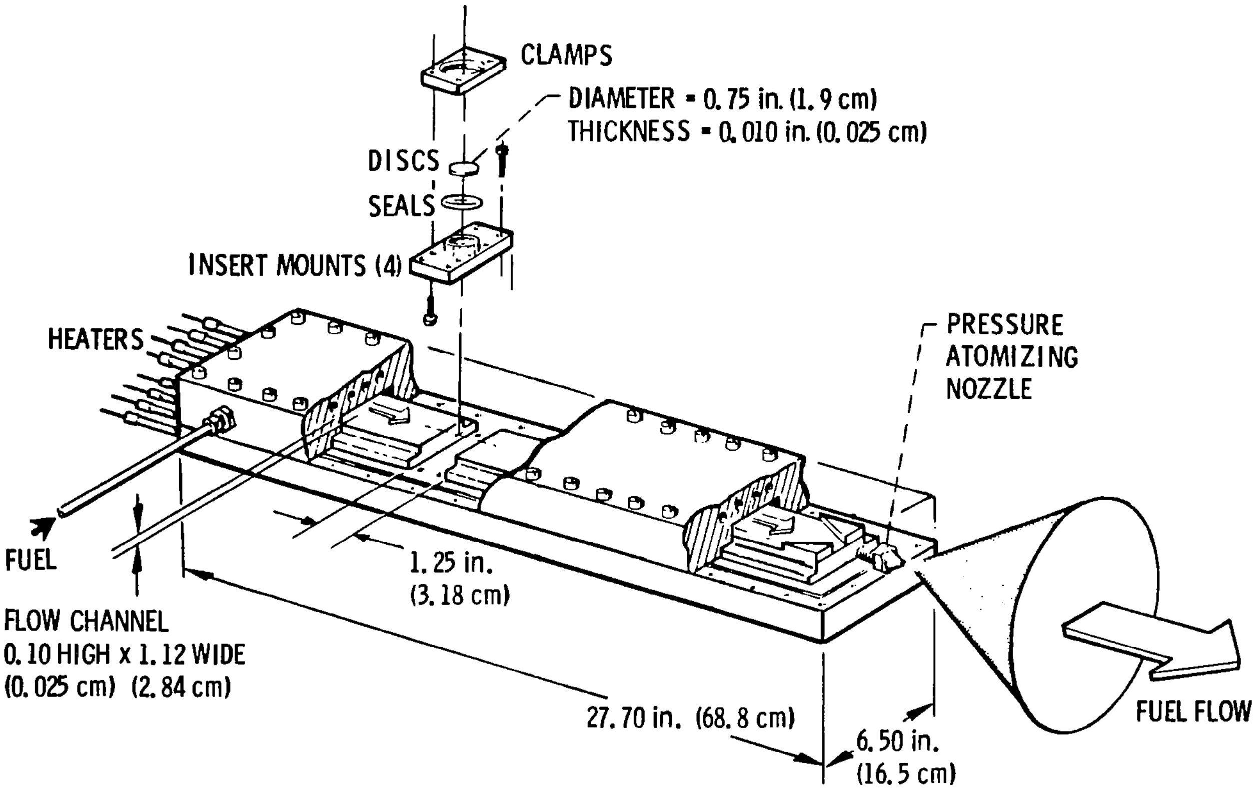
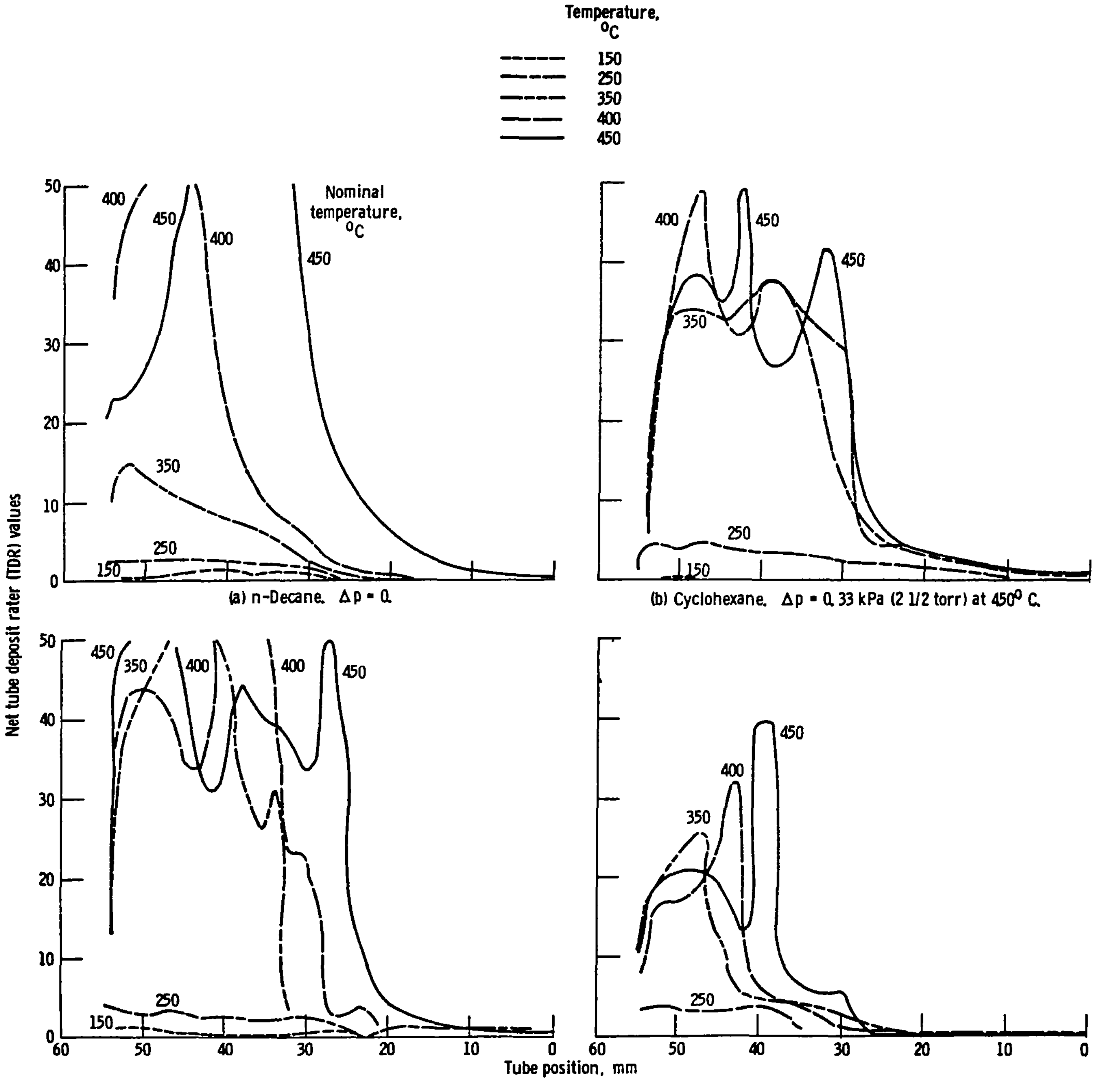


Figure 3. - UTRC thermal stability test section.



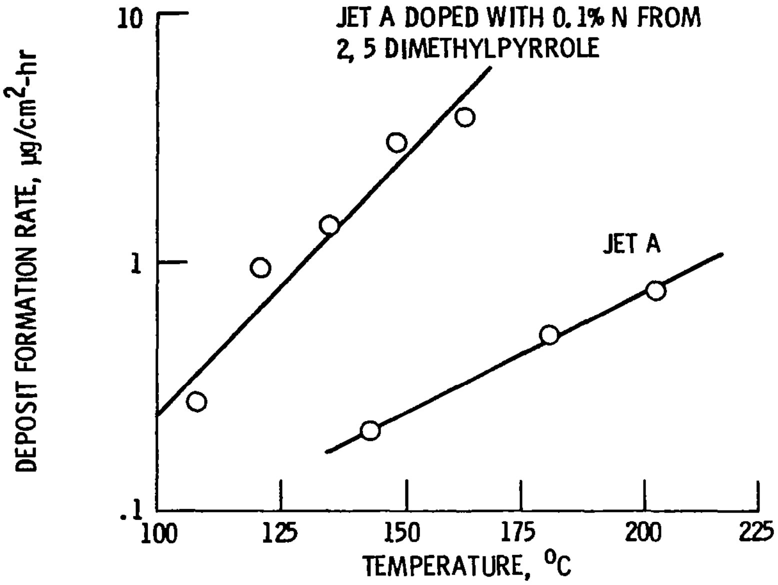
(a) n-Decane. Δp = 0.

(b) Cyclohexane. Δp = 0.33 kPa (2 1/2 torr) at 450° C.

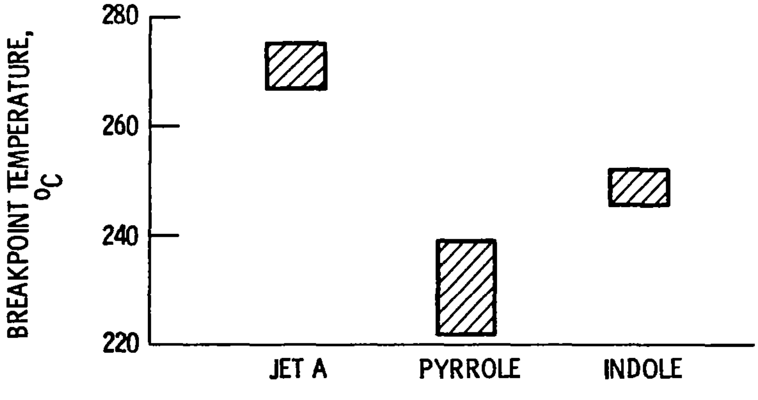
(c) 1-Hexene. Δp = 0.27 kPa (2 torr) at 450° C.

(d) Benzene. Δp = 0.40 kPa (3 torr) at 250° C, 0.80 kPa (6 torr) at 350° C, 1.9 kPa (14 torr) at 400° C, and 2.5 kPa (19 torr) at 450° C.

Figure 4. - Tube deposit and sediment formation for four hydrocarbon fuels.



(a) Effect of fuel nitrogen content on deposit formation rate.



(b) Breakpoint temeratures of Jet-A and solutions of nitrogen compounds in Jet-A ranging from 0.01 to 0.1 weight percent N.

Figure 5. - Effect of fuel nitrogen content on thermal stability.

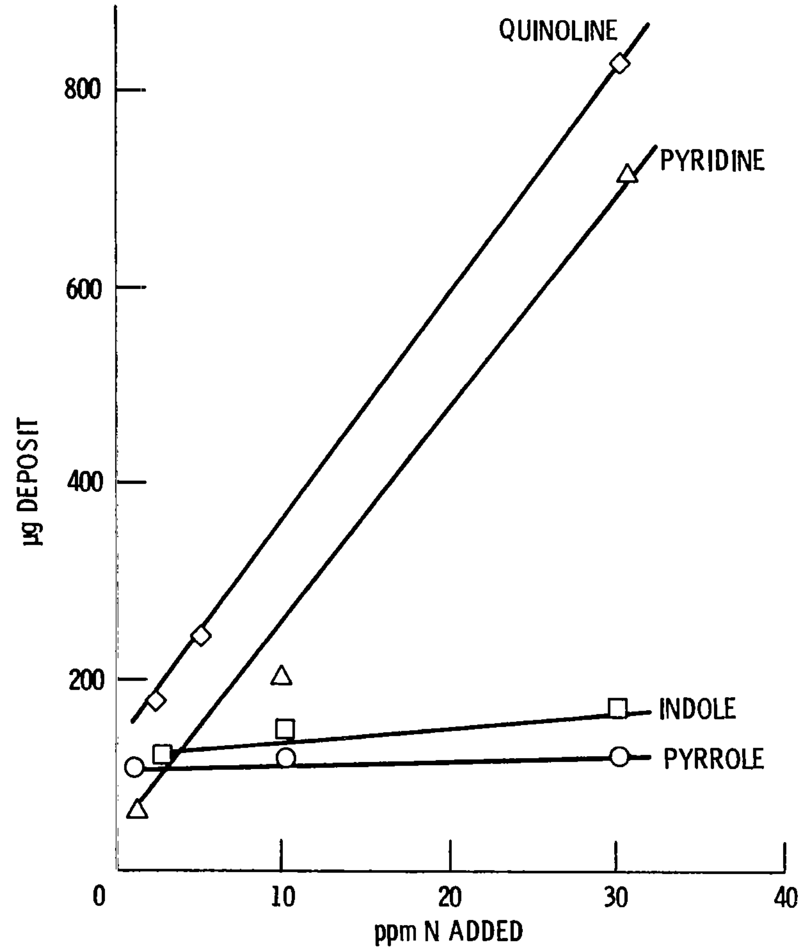


Figure 6. - Effect of added nitrogen concentration on deposit rate at 130° C.

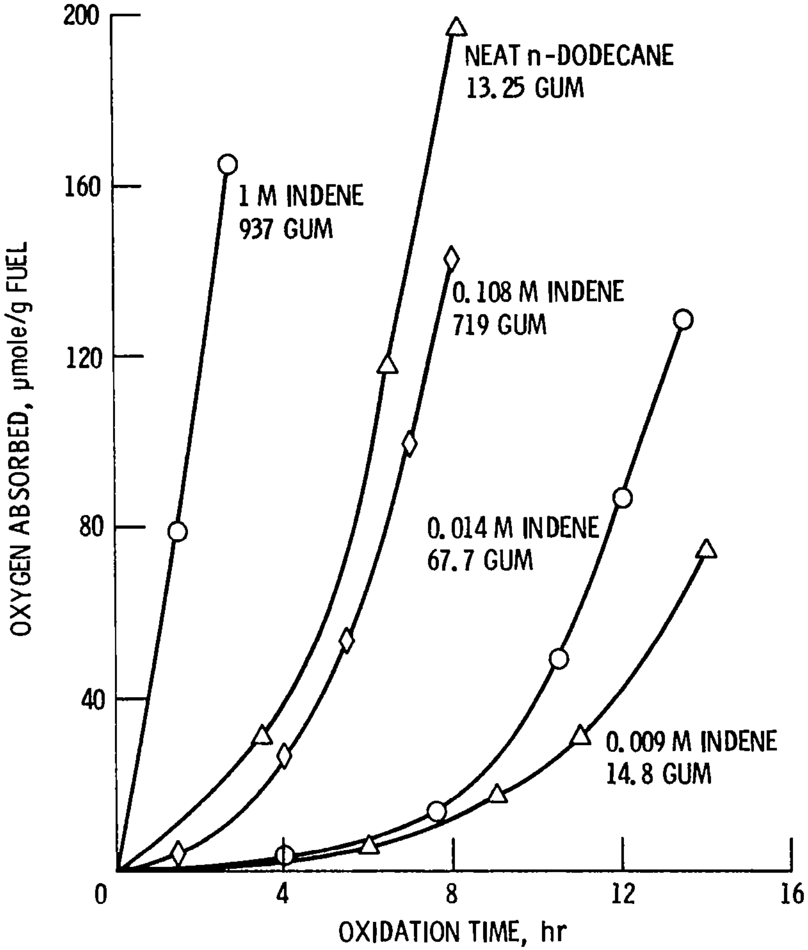


Figure 7. - Oxidations of n-dodecane with indene at 130° C (Gum is in mg/100 g fuel, determined at 100° C).

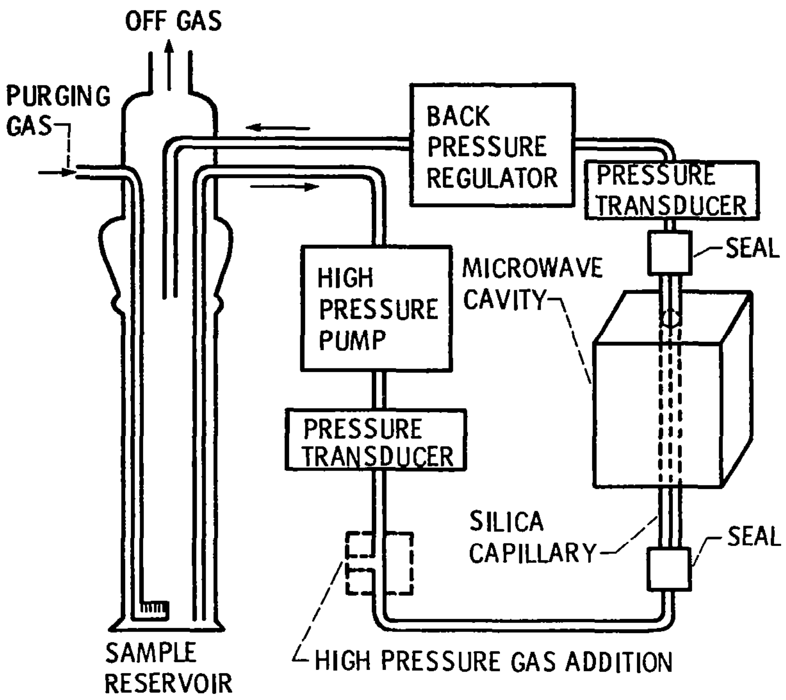


Figure 8. - Flow system for fuel thermal stability studies using electron spin resonance (ESR) spectrometer.

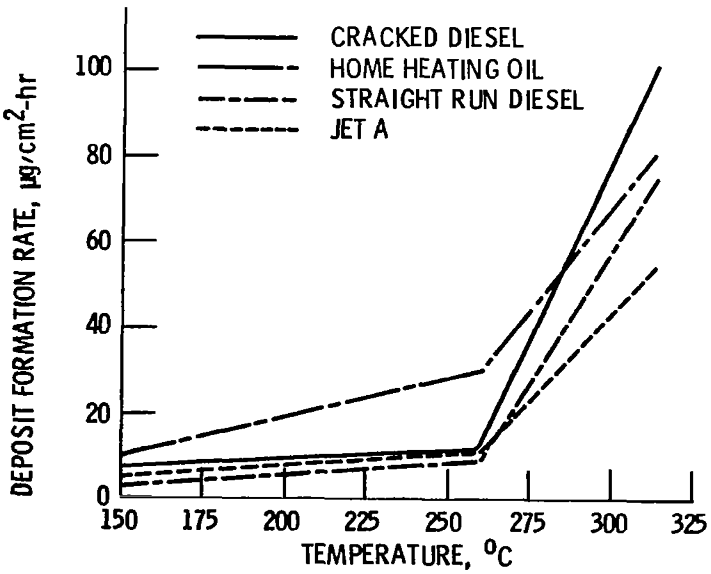


Figure 9. - Deposition rate of various fuels.

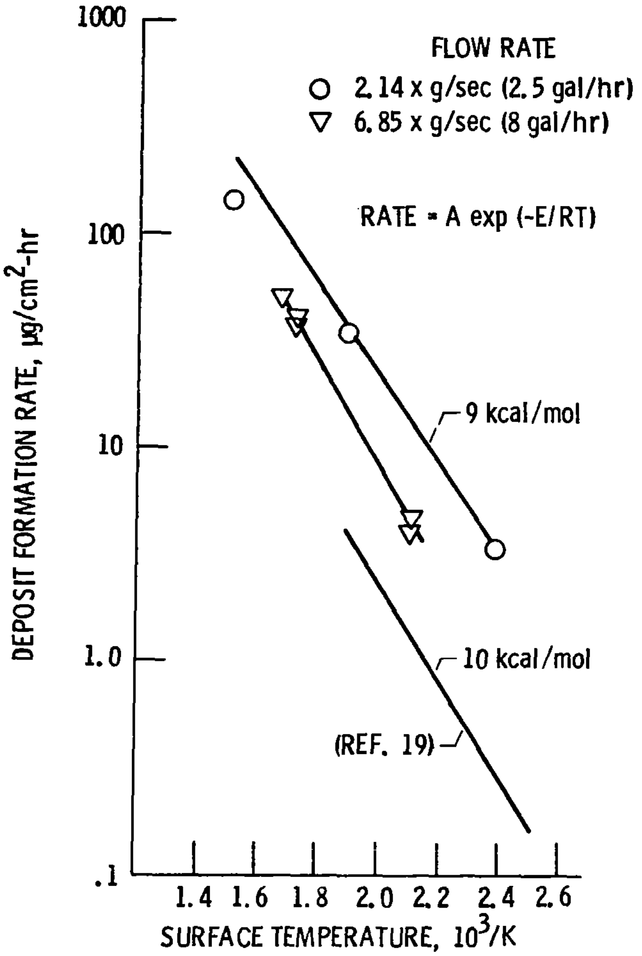


Figure 10. - Arrhenius plot of deposit rate in Jet A.

IN-FLIGHT ATMOSPHERIC AND FUEL TANK TEMPERATURE MEASUREMENTS

Roger Svehla
National Aeronautics and Space Administration
Lewis Research Center

In order to maintain an adequate supply of aviation turbine fuels in the future, fuels may have properties different from those now currently produced. One possible change is an increase in the freezing point temperature. If this should occur, it will be necessary to know the low temperature flow characteristics of these fuels. Studies to date have involved both the use of computer models and subscale fuel tank simulators (Ref. 1-3). They indicate that steep temperature gradients occur near the upper and lower surfaces which can result in freezing at the bottom, even though the bulk fuel temperature is above the freezing point.

There is currently a lack of in-flight data to verify the computer model and simulator results. Only one set of data are known (Ref. 1). To obtain additional measurements, a Lockheed L1011 research aircraft at Palmdale, California was instrumented with a vertical thermocouple rake in an inboard tank and an outboard tank (Figure 1). The tests were conducted with one of the two instrumented tanks maintained full for either two or five hours at altitudes of at least 10668 meters (35000 ft). Other flight parameters such as Mach number, air temperature, fuel quantity, and heading were also recorded.

The program was designed to obtain data during other regularly scheduled research flights in order to avoid the high cost of dedicated flight hours. However, before the program was completed, Lockheed announced termination of L1011 production, which greatly reduced the need for research flights. An additional five-hour flight was still needed with a low ambient temperature and the outboard tank full. The flight was made on a dedicated flight hour basis on March 9, 1983, and concluded the flight program (Figure 2).

Data for three of the long flights are shown in Figures 3-8. These are for the full fuel tank. For each of the flights, two figures are shown. One figure shows the temperature profile during the test period and the other shows a history of the air temperature, lower skin temperature, and temperature at a point near mid-height of the tank. The data is shown only for the test period and does not include takeoff or descent, though data were recorded during the entire flight.

As expected, the outboard tank, being smaller in volume and thinner than the inboard tank, cooled more quickly than the inboard tank. None of the data show that a steady state condition was reached by the end of the test period, although the outboard tank temperature profile becomes nearly flat within about three hours. The flat part of the profile is associated with mixing due to natural convection, and the gradient near the bottom is due to conduction. Computer model calculations and fuel tank simulator measurements indicate that the conduction layer builds up and extends further from the bottom than was found from the outboard tank data (Refs. 1,3). This apparent inconsistency will have to be examined. In contrast, the inboard tank does show some apparent buildup of the conduction zone as the flight proceeds, although some anomalous behavior occurred near the bottom during the first and second hour. At the top of each profile the gradient is sharp due to the large temperature difference between the fuel and upper skin. During normal filling procedures, approximately three percent of the tank is left empty to allow for expansion. It is apparent that the thermocouple in the outboard tank is in a location affected by the ullage. There may also be ullage in the top centimeter of the inboard tank.

Since the fuel temperature is influenced by the air temperature, as well as the duration of the flight, it is useful to examine historical recorded air temperature data. In the Global Air Sampling Program (GASP), four commercial 747 aircraft were instrumented to obtain measurements of aerosols, trace constituents, and meteorological variables. The program ran from 1975 to 1979 with data obtained from 6945 flights covering 273 routes at five-minute intervals. Most of the flights were between the U.S. (including Hawaii) and Japan or Europe. Results of the temperature data have been summarized (Refs. 4,5). Data from a typical long flight from the Persian Gulf to New York are shown in Figures 9 and 10. Figure 9 shows a temperatue history for a specific flight and Figure 10 shows a summary of the minimum air temperatures which occurred during all of the recorded flights. The minimum temperatures do not necessarily occur at the highest altitude.

Another study gives a statistical analysis of recorded fuel and air temperature data from the International Air Transport Association (IATA) member airline flights during the winter of 1977. (Ref. 6). A total of 8125 flights for 12 routes are included. A typical plot illustrating the format of the data is shown in Figure 11. For this 747 route, the lowest static air temperature was -72°C, the lowest total air temperature -41°C, and the lowest fuel temperature -33°C. The coldest flights were from the Polar route where the total air temperature got as low as -53°C and the fuel temperature down to -48°C.

In summary, low ambient air temperatures provide an environment whereby tank fuel can approach the freezing point during extended flights. If an increase in the freezing point should occur, it will be important to have an understanding of fuel flow characteristics. With the acquisition of the L1011 data, there is now a sufficient library of experimental data to support tests for verification of results from fuel tank subscale simulators and computer models.

REFERENCES

1. Tolle, F.F.: High-Freezing-Point Fuel Studies. Aircraft Research and Technology for Future Fuels. NASA Conference Publication 2146. Cleveland, Ohio, April 16-17, 1980.

2. Stockemer, F.J.: Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in A Wing Tank Model. Lockheed-California Company, NASA CR-159615, 1979.

3. Friedman, R.; and Stockemer, F.J.: Temperature and Flow Measurements on Near-Freezing Aviation Fuels in A Wing-Tank Model. ASME Paper 80-GT-63, March 1980.

4. Nastrom, G.D.; and Jasperson, W.H.: Flight Summaries and Temperature Climatology at Airliner Cruise Altitudes from GASP Data. Control Data Corporation, NASA CR-168106, March 1983.

5. Jasperson, W.H.; and Nastrom, G.D.: Temperature Histories of Commercial Flights at Severe Conditions from GASP Data. Control Data Corporation, NASA CR-168247, October 1983.

6. Pasion, A.J.: In-Flight Fuel Tank Temperature Survey Data. Boeing Commercial Airplane Company, NASA CR-159569, 1979.

LOCATION OF THERMOCOUPLE RAKES ON L1011

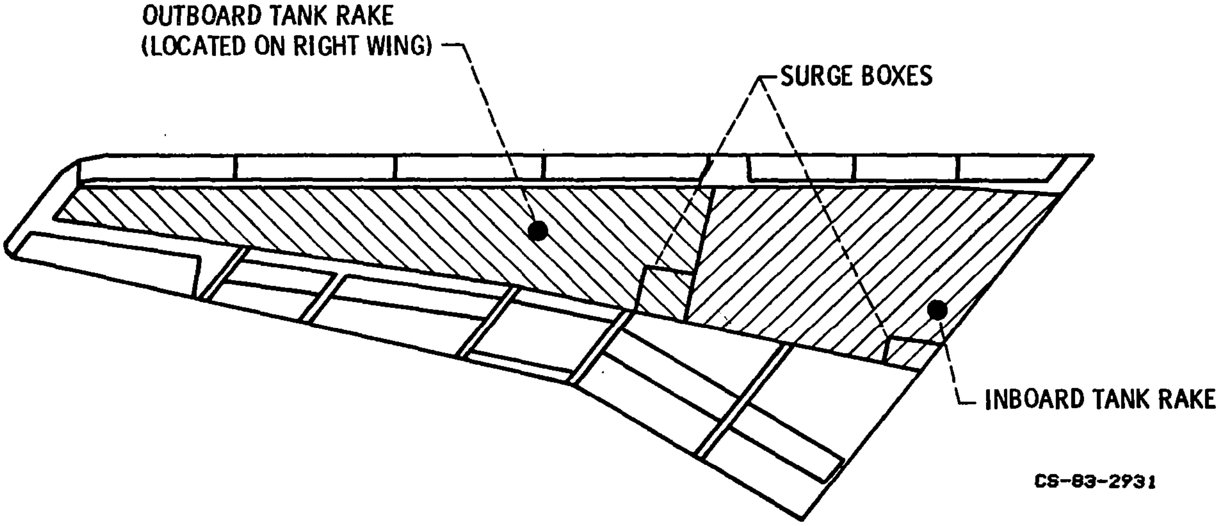


Figure 1.

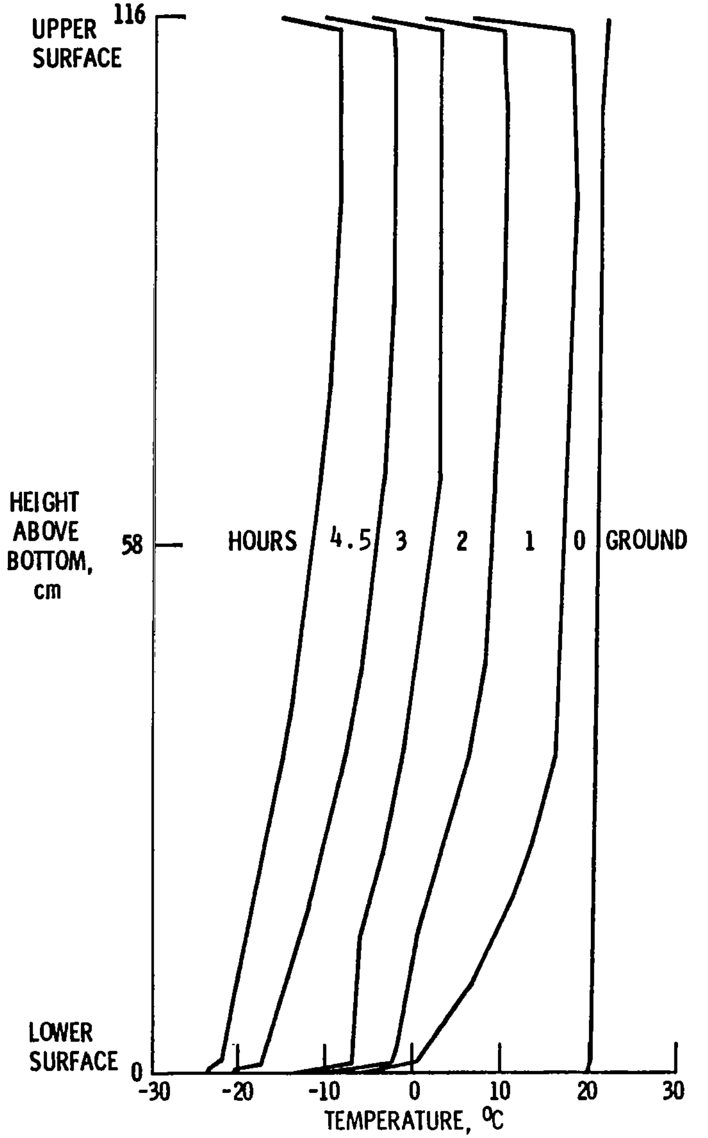
LOCKHEED L1011 FLIGHT HISTORY

DATE	FULL TANK	CRUISE TIME	TOTAL FLIGHT TIME
APRIL 23, 1981	INBOARD	4 hr 28 min	7 hr 11 min
APRIL 30, 1981	OUTBOARD	5 hr 2 min	6 hr 44 min
JUNE 21, 1981	OUTBOARD	5 hr 0 min	6 hr 23 min
JULY 1, 1981	OUTBOARD	3 hr 2 min	4 hr 1 min
AUGUST 1, 1981	OUTBOARD	1 hr 59 min	5 hr 18 min
AUGUST 26, 1981	INBOARD	2 hr 5 min	3 hr 29 min
AUGUST 27, 1981	INBOARD	2 hr 2 min	3 hr 30 min
AUGUST 28, 1981	INBOARD	2 hr 1 min	2 hr 52 min
AUGUST 18, 1982	OUTBOARD	2 hr 6 min	3 hr 30 min
MARCH 9, 1983	OUTBOARD	6 hr 16 min	7 hr 40 min

CS-83-2933

Figure 2.

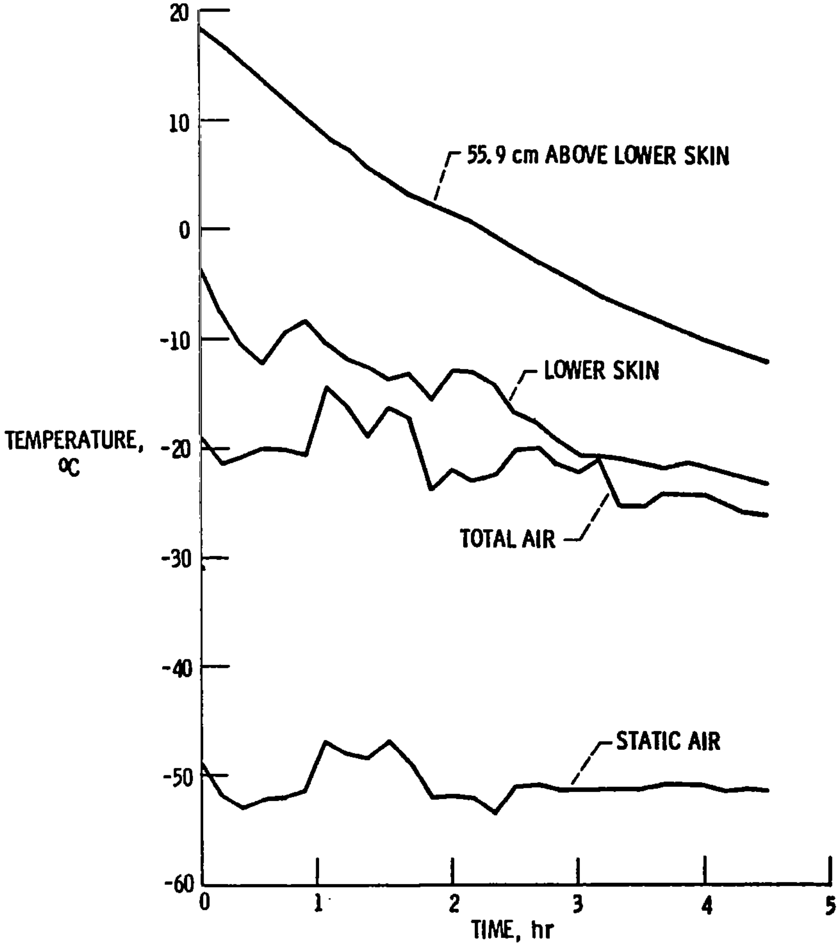
INBOARD TANK TEMPERATURE PROFILE - APRIL 23, 1981



CS-83-2929

Figure 3.

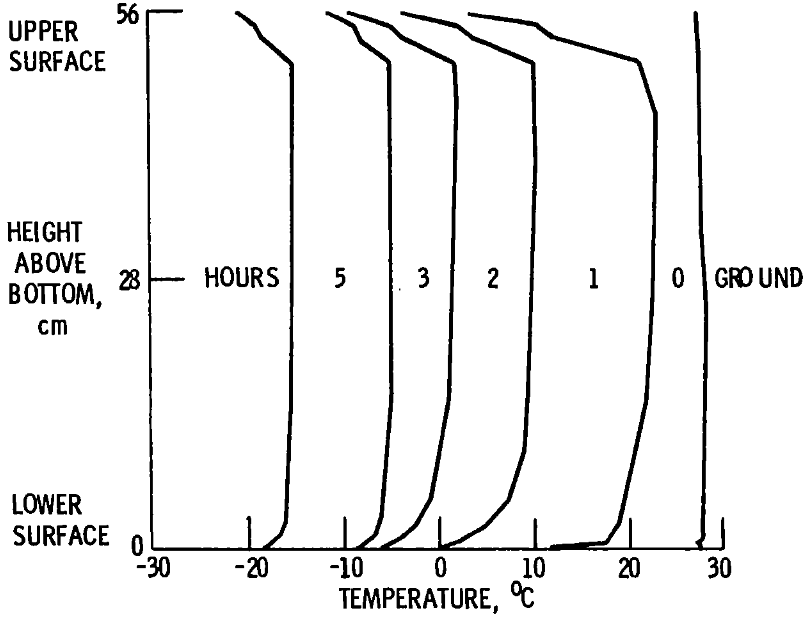
INBOARD TANK TEMPERATURE - APRIL 23, 1981



CS-83-2937

Figure 4.

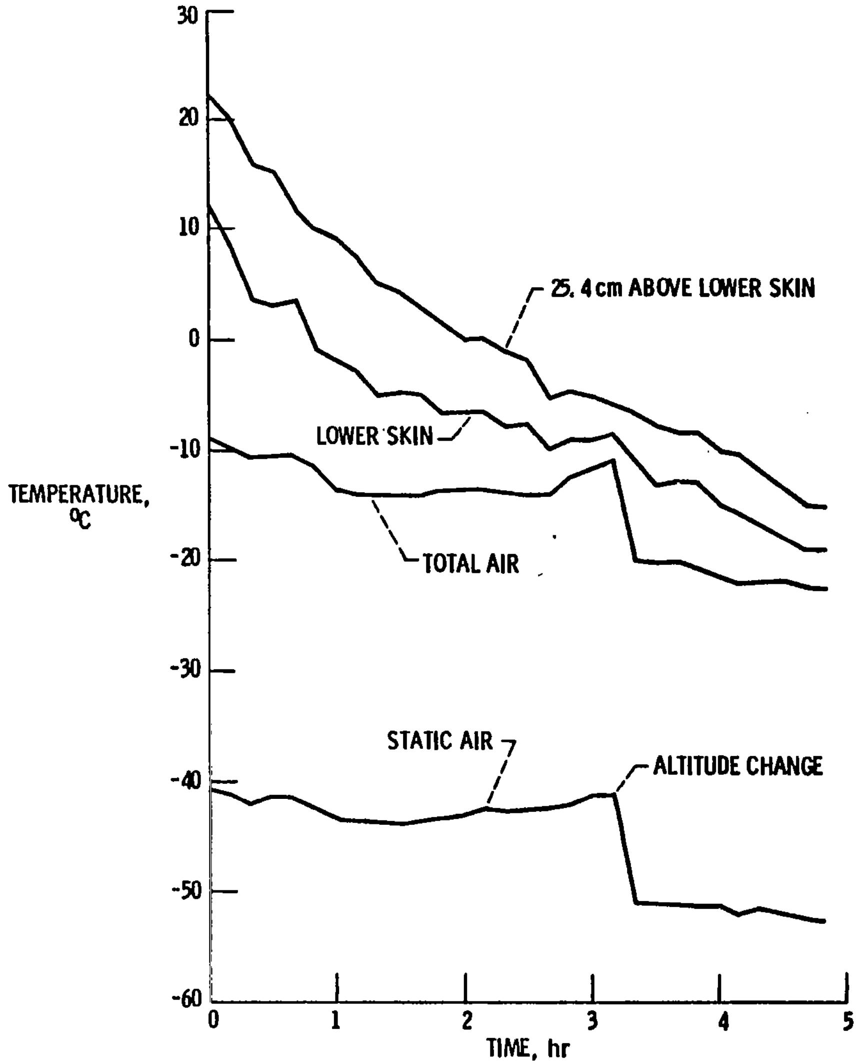
OUTBOARD TANK TEMPERATURE PROFILE - JUNE 21, 1981



CS-83-2927

Figure 5.

OUTBOARD TANK TEMPERATURE - JUNE 21, 1981



CS-83-2928

Figure 6.

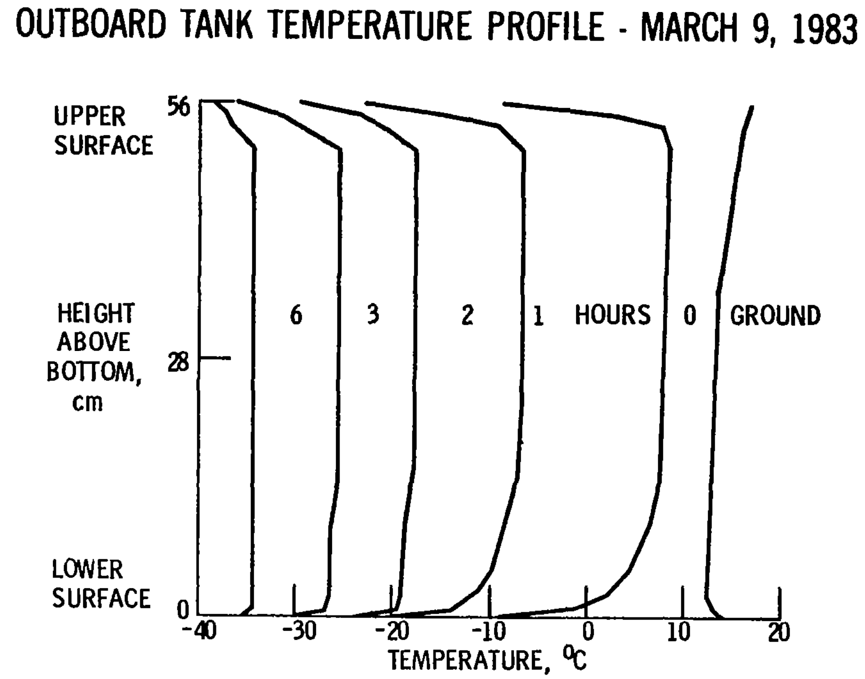


Figure 7. CS-83-2926

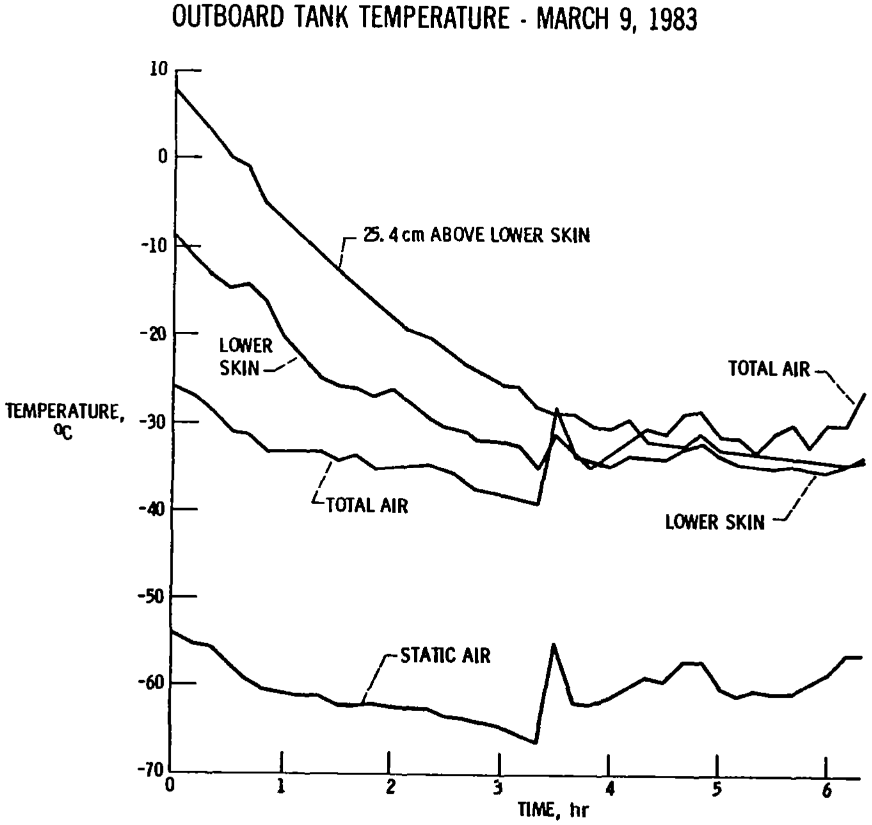
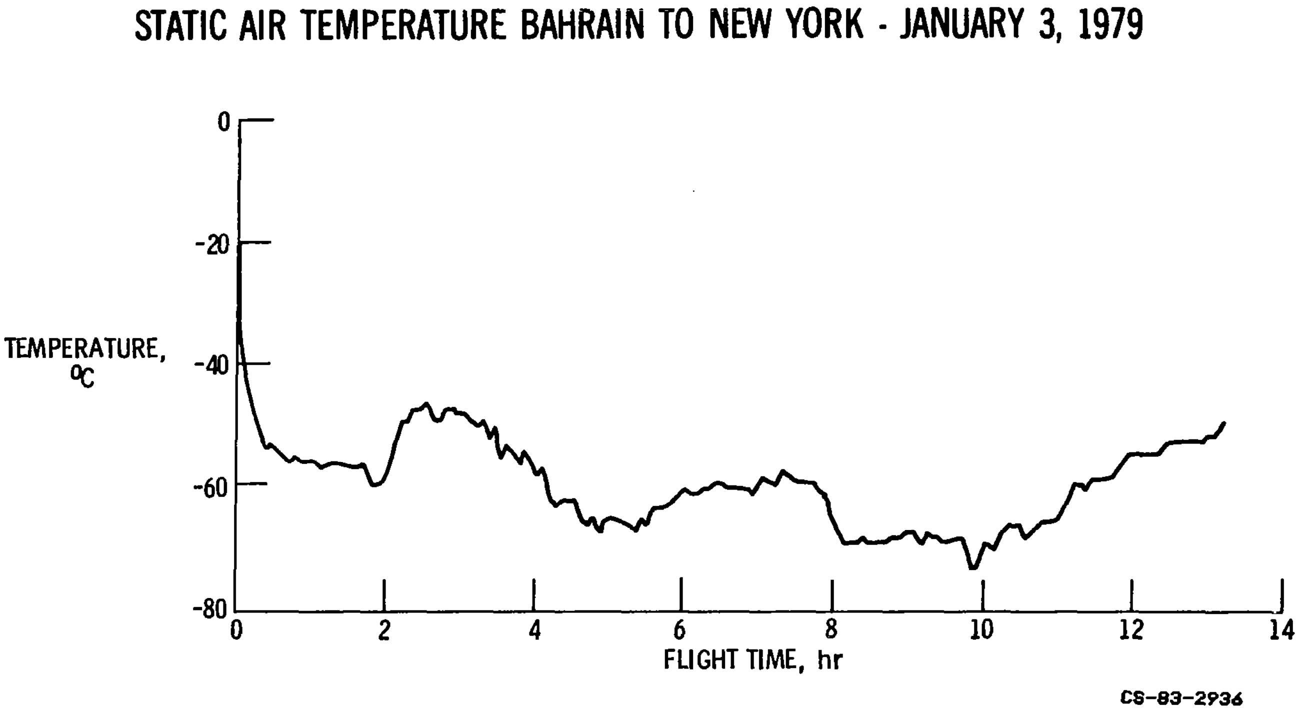
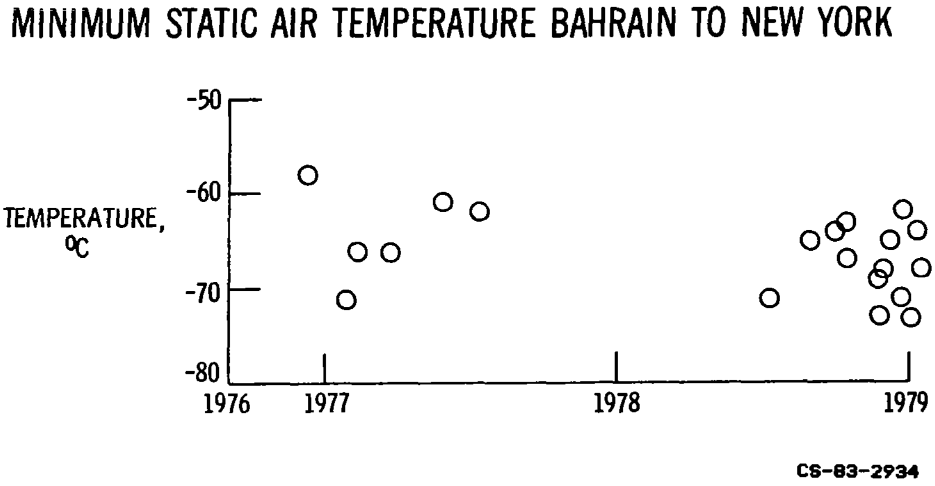


Figure 8. CS-83-2932



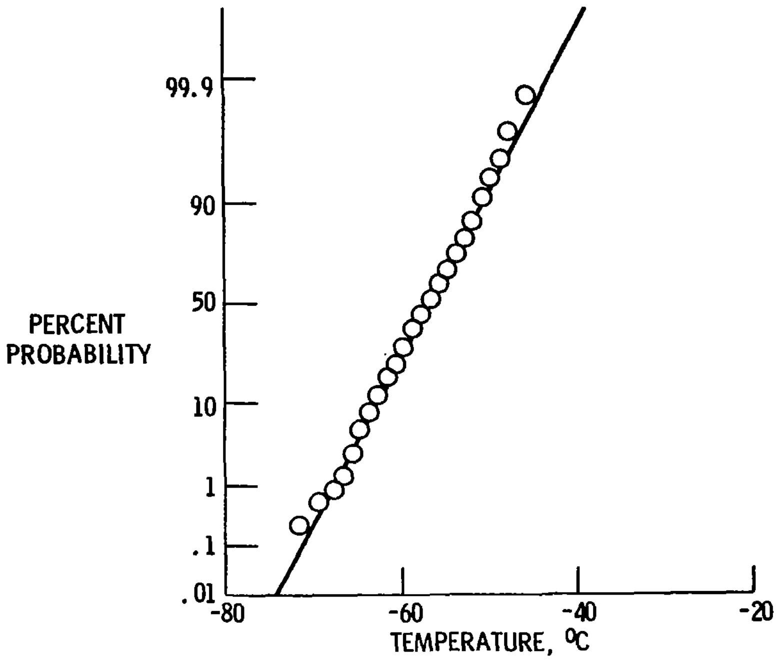
STATIC AIR TEMPERATURE BAHRAIN TO NEW YORK - JANUARY 3, 1979

Figure 9.



MINIMUM STATIC AIR TEMPERATURE BAHRAIN TO NEW YORK

Figure 10.



747 ANCHORAGE TO TOKYO FLIGHTS MINIMUM STATIC AIR TEMPERATURE

CS-83-2935

Figure 11.

ANALYSIS OF FUEL SYSTEM TECHNOLOGY
FOR
BROAD PROPERTY FUELS

George A. Coffinberry
General Electric Company
Aircraft Engine Business Group

An analytical study was performed in order to assess relative performance and economic factors involved with alternative advanced fuel systems for future commercial aircraft operating with broad property fuels. The following discussion highlights significant results from this study with emphasis on design practicality from the engine manufacturers' standpoint.

A computer model was written to represent the aircraft/engine fuel system for the No. 1 engine on the DC10-30 aircraft. The DC10, shown in Figure 1, was chosen for the study because its fuel tank transfer system involves transfer of fuel from the auxiliary (center) tank and No. 2 inboard tank to the No. 1 outboard (wing tip) tank, then to the No. 1 tank and engine. This arrangement of fuel transfer would be expected to produce different rates of fuel cooldown than the simple tank-to-engine fuel feed arrangement typical of other aircraft. The study used the DC10-30 equipped with General Electric CF6-80X engines as a present-generation baseline design from which more advanced fuel systems could be compared in terms of compatibility with broad property fuel and economic impact to the airline user.

The baseline system, shown in Figure 2 was modeled in a computer program. Figure 2 essentially shows the elements of the model. Three advanced systems shown in Figures 3, 4 and 5 were also formulated. Advanced system A provides fuel tank heating by means of recirculating engine lube system heat to the aircraft wing tanks. Advanced system B provides fuel tank heating by means of recirculating electrical generator (IDG) oil heat back to the tanks. Systems A and B also include low pressure air-atomizing fuel nozzles which reduce the level of engine fuel pump pressure rise and thus cause less fuel heating at the nozzles. System B places the nozzle flow divider and check valve on the fuel manifold to futher reduce the likelihood of valve/nozzle fuel coking. Advanced system C provides tank heating by transfer of heat from the engine compressor bleed air heat to tank fuel. This arrangement also eliminated the need for cabin environmental control system (ECS) fan air precooling, and thus improves fuel economy (lowers SFC). A single high-force nozzle divider valve is located in a relatively cooler place on the engine for fuel coking benefit. System C uses a centrifugal fuel pump for lower fuel temperature rise, which further reduces nozzle fuel coking tendencies.

An objective of the study was to determine as accurately as possible the relative merits of each system from the standpoint of compatibility with broad property fuel. Freezing point, thermal stability and lubricity were the key fuel property issues. The study and computer format is shown in Figure 6.

In effect, the computer model (DC10-30 Thermal Model) "flew" simulated airline ticket flights for DC10-30 aircraft now in airline use. Several auxiliary models previously formulated for GE engine analysis, were used and are shown in the flow diagram of Figure 6. Figure 7 and 8 show the simulated "real-world" flights. Airline cold and hot flights were based on one-day-per-year statistical probability. These flights were used to assess cold fuel freezing point and hot fuel thermal stability effects. A nominal (50-percent probability) flight was used to assess fuel burn rate differences associated with direct engine performance and component weight.

Figure 9 summarizes the results during the cold flight (Helsinki to Seattle via polar region). All wing fuel tanks associated with No. 1 engine fuel feed came to within one degree of the wing boundary layer air temperature (recovery temperature T_R). Thus for the baseline design, -45°C (-49°F) fuel can be expected. Tank bulk temperature was used for the model and might be considered conservative except that considerable fuel transfer occurs in the DC10 and particularly the auxiliary wing tip tank. Fuel mixing and less stratification is likely to occur.

The sequence of fuel tank transfer on the DC10 can be seen from Figure 10. For long range flights the auxiliary (center) tank is used first and provides make-up fuel to the outboard and main (wing engine) tanks. After depleting the auxiliary tank, main tank fuel is used by the engine. Then at approximately 180 minutes into the cold flight, fuel is transferred from the No. 2 tank via the outboard tank, to the No. 1 tank. The flight continues using main tank fuel, while the outboard tank is held in reserve. At approximately 560 minutes outboard tank fuel is transferred to the main tank.

The effective heat transfer area of the fuel tanks is dependent on fuel quantity since fuel level determines the wetted surface area of tank walls and conductive stringers. This is shown in Figure 11 for the main tank. Note the increase in fuel level heat transfer area at 200 minutes into the flight.

Figure 12 shows the calculated main tank bulk fuel temperature for the baseline design during the cold flight. Note the decrease in rate of cooling as fuel is being transferred to the tank during the period from 180 to 200 minutes. Fuel quantity increase overcompensates for increase in heat transfer area. Thus the fuel cools more slowly. Figure 12 also shows that JET-A fuel would be unacceptable for this cold flight since at 105 minutes the fuel temperature is within 3°C (5°F) of JET-A freezing point (-40°C/°F). At the end of the high altitude portion of the flight the fuel is down to -45°C (-49°F). For all practical purposes JET-B fuel would be required in order to maintain a safe margin above fuel freezing point.

The question arises as to the best choice of flight profiles and statistical environmental conditions when considering higher freezing point broad property fuels. Note in Figure 13 that for the baseline design during the nominal flights, fuel cools to -28°C (-19°F) and is well above the limit of -37°C (-35°F) for JET-A. Thus a -31°C (-24°F) broad property fuel would be acceptable for half of the DC10-30 flights while retaining the baseline system design. And again, these results indicate that JET-A cannot be considered a universal fuel since it fails to meet the needs of the cold flight.

Considering the multitude of variables involved with aircraft design, fuel tank temperature margin above freezing point is only one measure of comparison. Perhaps a different answer to the fuel freezing question is in order.

This answer is suggested by the cold flight results for the advanced systems. Figure 14, 15 and 16 all show a different mode of tank cooling than that associated with the baseline design. With any means for continuous tank heating a point is reached during the flight where thereafter the tank fuel warms rather than cools. In future studies of similar systems it may be possible by means of fuel transfer management to improve these results. The main point to note is the inherent capability of tank heating systems to reverse the cooling trend associated with non-heated tanks. Instead of faster cooling with lower fuel reserves, the tank heating rate increases. In addition the heated tank would be less prone to fuel holdup associated with temperature gradients. In other words the front end of the fuel freezing problem is inherently avoided by large fuel quantity early in the flight, while tank heating may solve the second (and more critical) part of the problem when low fuel quantity produces fast cooling rates and the likelihood of fuel holdup.

In addition to determining tank fuel temperatures, an objective of the study was to evaluate the effect of the advanced systems on critical engine fluid temperatures. General Electric commercial engines use engine lube heat for fuel ice protection. Figure 17 shows comparative results in terms of fuel temperature at the engine main fuel filter during the cold flight. Only system A fails to provide results comparable to the baseline design. This occurs because lube heat is also used for tank heating. In practice however, this may not be a problem. Lube heat could be directed to the engine for short periods of time to remove ice which had formed on the filter. Furthermore, fuel icing is much less likely to occur with extremely cold fuel. Ice blockage is of greater concern between temperature of -7 to 0°C (20 to 32°F).

The fuel nozzle and nozzle divider value problem is usually assessed on the basis of fuel supply temperature to the nozzle. For one-day-per-year exposure, 149°C (300°F) is an upper limit for JET-A. As shown in Figure 18 all systems except System A yield results comparable to the baseline. System A shows a significant improvement because engine fuel pump and lube heat are partially absorbed by the tank fuel. This improvement shows up later in the study in terms of reduced maintenance for fuel nozzles.

Engine lube oil temperatures are similar for all systems except again for System A. These results are shown in Figure 19. A -8°C (17°F) lube supply temperature could be a real problem causing lube system maldistribution and high oil pressure. Diverting lube heat back to the engine would remedy this problem but at the expense of tank heating capability. From these results, System A and the use of engine lube heat would have to be considered unacceptable.

An assessment was made of the economic impact associated with the advanced systems. It was assumed that advanced systems would be applicable to new aircraft and engines and subsequently have a service life of 15 years. As shown in Figure 20, the economic influences used for the study included maintenance cost, fuel consumption and initial equipment cost. These factors for each system were determined using cold, hot and nominal flight results combined with individual engineering assessments. Maintenance costs were based solely on engine fuel nozzle coking rates. These rates as shown in Figure 20, include both the effect of nozzle design differences and fuel temperature exposure for the hot flight. Fuel consumption differences are for the nominal flight and include all factors such as weight, engine air bleed and fuel heating (to engine combustor). Reduction in initial cost for System A and B is the result of lower-cost fuel nozzles which compensates for the tank heating system.

A computer model was formulated to determine the investment incentive to the airline for each system. Both Present Value and Return on Investment were considered as shown in Figures 21 and 22. Present value is simply a measure of the total savings anticipated (over the life of the investment) at the time the investment is made. This value (saving) less investment cost is the net investment incentive. In other words the anticipated profit before taxes. Rate of Return (ROR) indicates the anticipated annual percentage profit on the investment, which would normally be 10 percent on cash-savings. All calculations were based on constant 1982 dollars but the effect of inflation on investment incentive was included in the formulation. Results were calculated for JET-A and a future broad property fuel. Fuel property differences effect nozzle coking and maintenance cost.

The economic results generally show significant dollar influence as the result of maintenance and fuel consumption. In the case of System A, a $168,000 profitability is projected for airline operation on future fuel. This comes about largely because of lower fuel supply temperature to the nozzles. For System C, block fuel savings of 0.342 percent offsets the higher initial investment of $167,000 and goes on to yield a $207,000 to $281,000 profitability. A problem one may have with these results is their dependency on the accuracy of the overall study. However, these results do suggest that future fuel compatability can be achieved without economic penalty so long as early planning and anticipation is made by the aircraft/engine manufacturer.

The foregoing is but a brief portion of the study performed in 1982 by General Electric for NASA-Lewis under Contract NAS3-23267. Considerably more results will be found in the program final report. In summary, each of the advanced systems provides to a varying degree the desired characteristic of tank thermal recovery (heating) during the most critical period of the flight. That is when reserves are low and fuel holdup may be a problem. With the exception of System A where low oil temperature may be a problem, no other services side effects were noted. The advanced systems appear to be cost effective so long as their introduction is made during the initial design of the aircraft and engine.

REFERENCES

1. Coffinberry, G.A., "Waste Heat Recovery System Design Report - Energy Efficient Engine Component Development and Integration, NASA Contract NAS3-20643", General Electric Co. R81AEG805, December, 1981.

2. Coffinberry, G.A., "Lightweight Fuel Delivery System Phase II Final Report, US Navy Contract N00140-78-C-0059", General Electric Co. R78AEG528, December, 1978.

3. Friedman, R., "High-Freezing-Point Fuels Used for Aviation Turbine Engines", ASME 79-GT-141, 1979

4. Pasion, A.J. and Thomas, I., Preliminary Analysis of Aircraft Fuel Systems for use with Broadened Specification Jet Fuels", NASA CR-135198, May, 1976.

5. "Airport Temperatures", Boeing Document Number W3753, Boeing Commercial Aircraft Company.

6. "Windtemp" Updated Winds and Temperatures Program Licensed by Boeing Computer Services, Inc.

DC-10 Aircraft

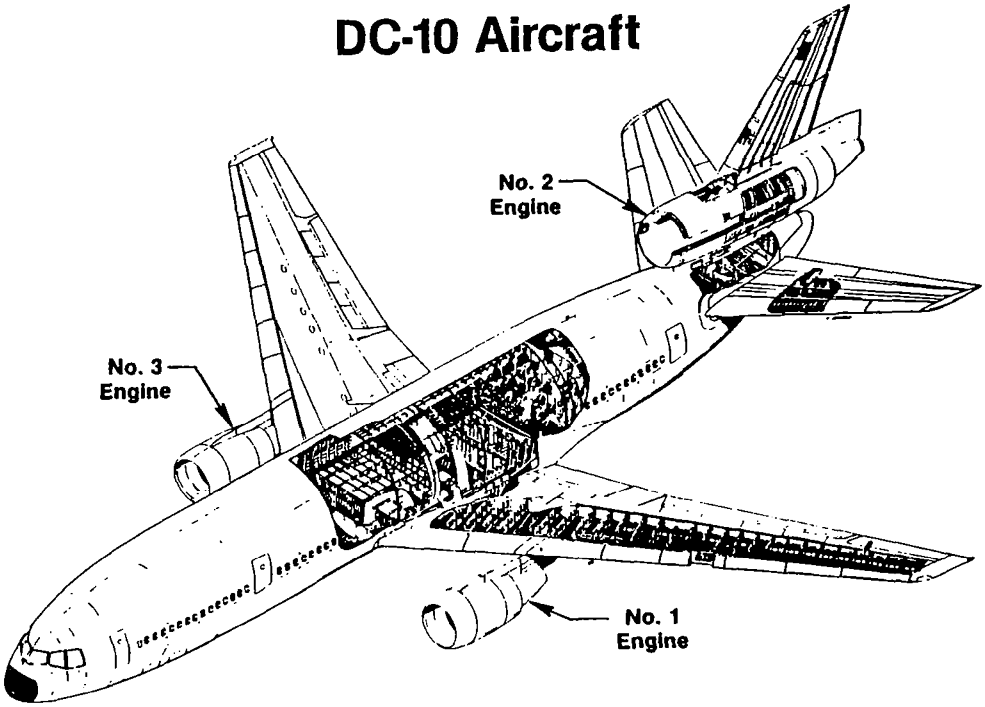


Figure 1

Baseline DC10-30 and CF6-80X

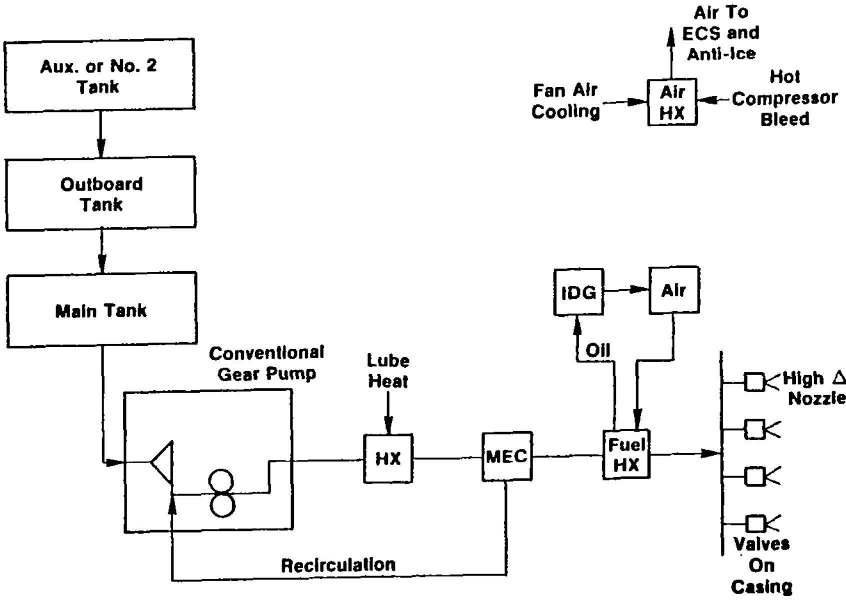


Figure 2

Advanced System "A"

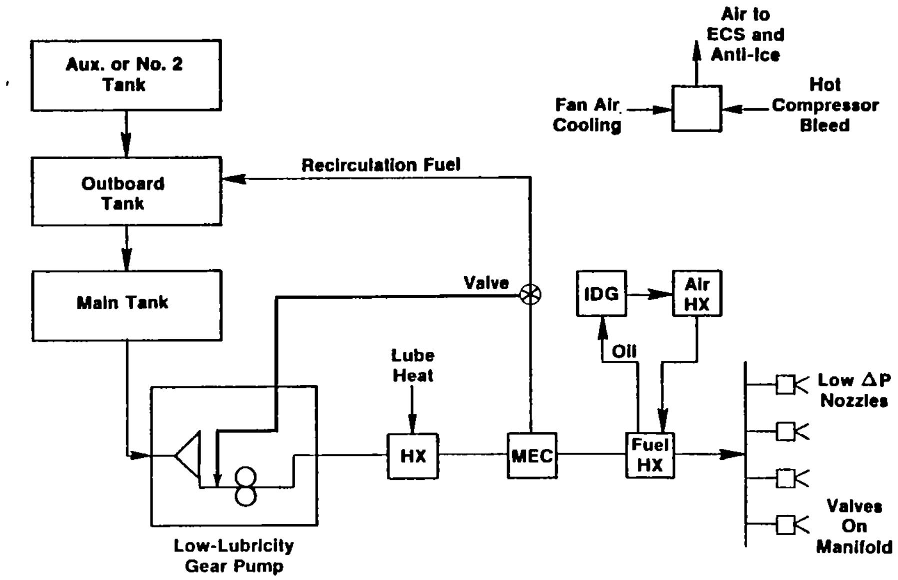


Figure 3

Advanced System "B"

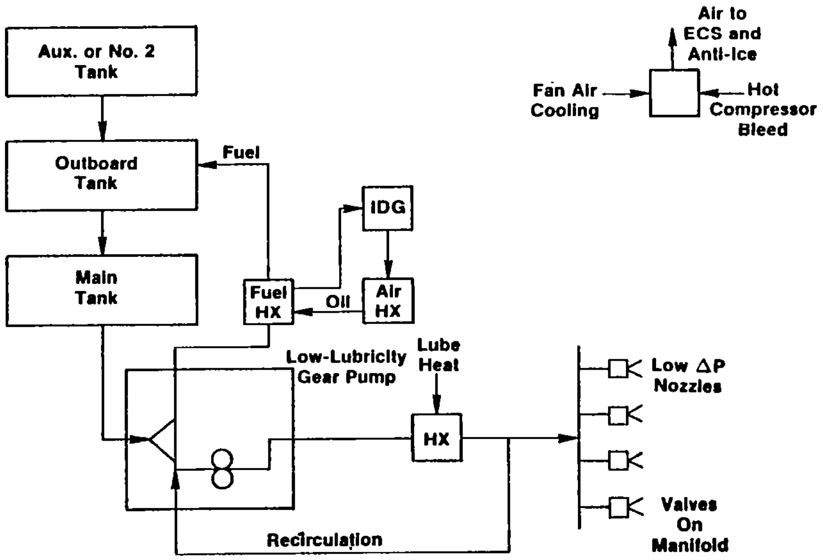


Figure 4

Advanced System "C"

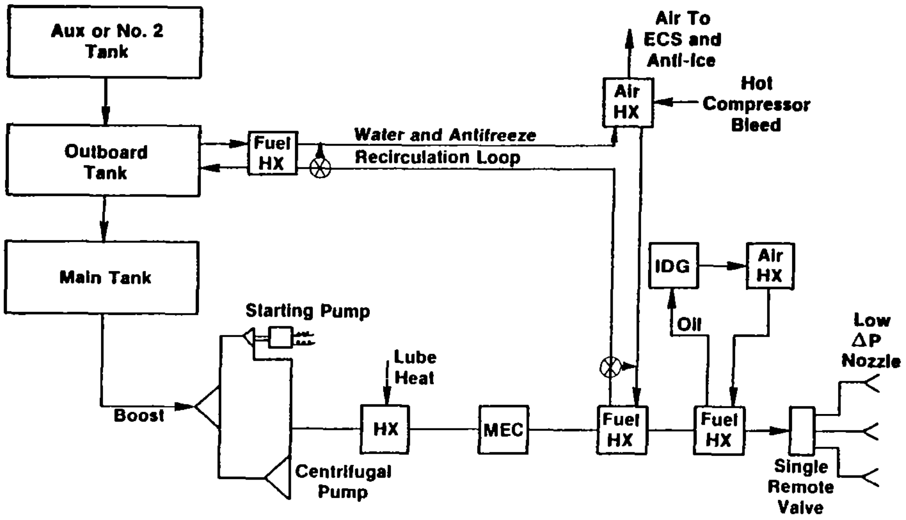
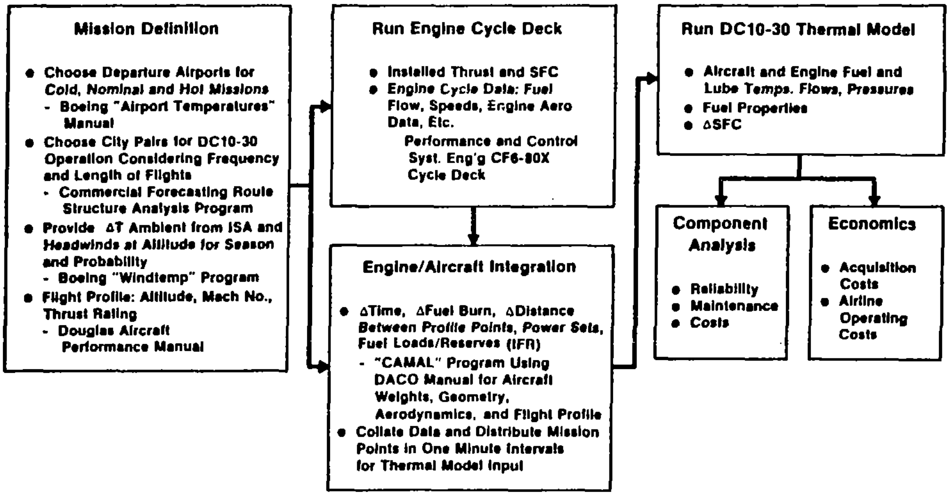


Figure 5

Analysis Flowchart



Mission Definition

- Choose Departure Airports for Cold, Nominal and Hot Missions
  - Boeing "Airport Temperatures" Manual
- Choose City Pairs for DC10-30 Operation Considering Frequency and Length of Flights
  - Commercial Forecasting Route Structure Analysis Program
- Provide ΔT Ambient from ISA and Headwinds at Altitude for Season and Probability
  - Boeing "Windtemp" Program
- Flight Profile: Altitude, Mach No., Thrust Rating
  - Douglas Aircraft Performance Manual

Run Engine Cycle Deck

- Installed Thrust and SFC
- Engine Cycle Data: Fuel Flow, Speeds, Engine Aero Data, Etc.

Performance and Control Syst. Eng'g CF6-80X Cycle Deck

Engine/Aircraft Integration

- ΔTime, ΔFuel Burn, ΔDistance Between Profile Points, Power Sets, Fuel Loads/Reserves (IFR)
  - "CAMAL" Program Using DACO Manual for Aircraft Weights, Geometry, Aerodynamics, and Flight Profile
- Collate Data and Distribute Mission Points in One Minute Intervals for Thermal Model Input

Run DC10-30 Thermal Model

- Aircraft and Engine Fuel and Lube Temps. Flows, Pressures
- Fuel Properties
- ΔSFC

Component Analysis

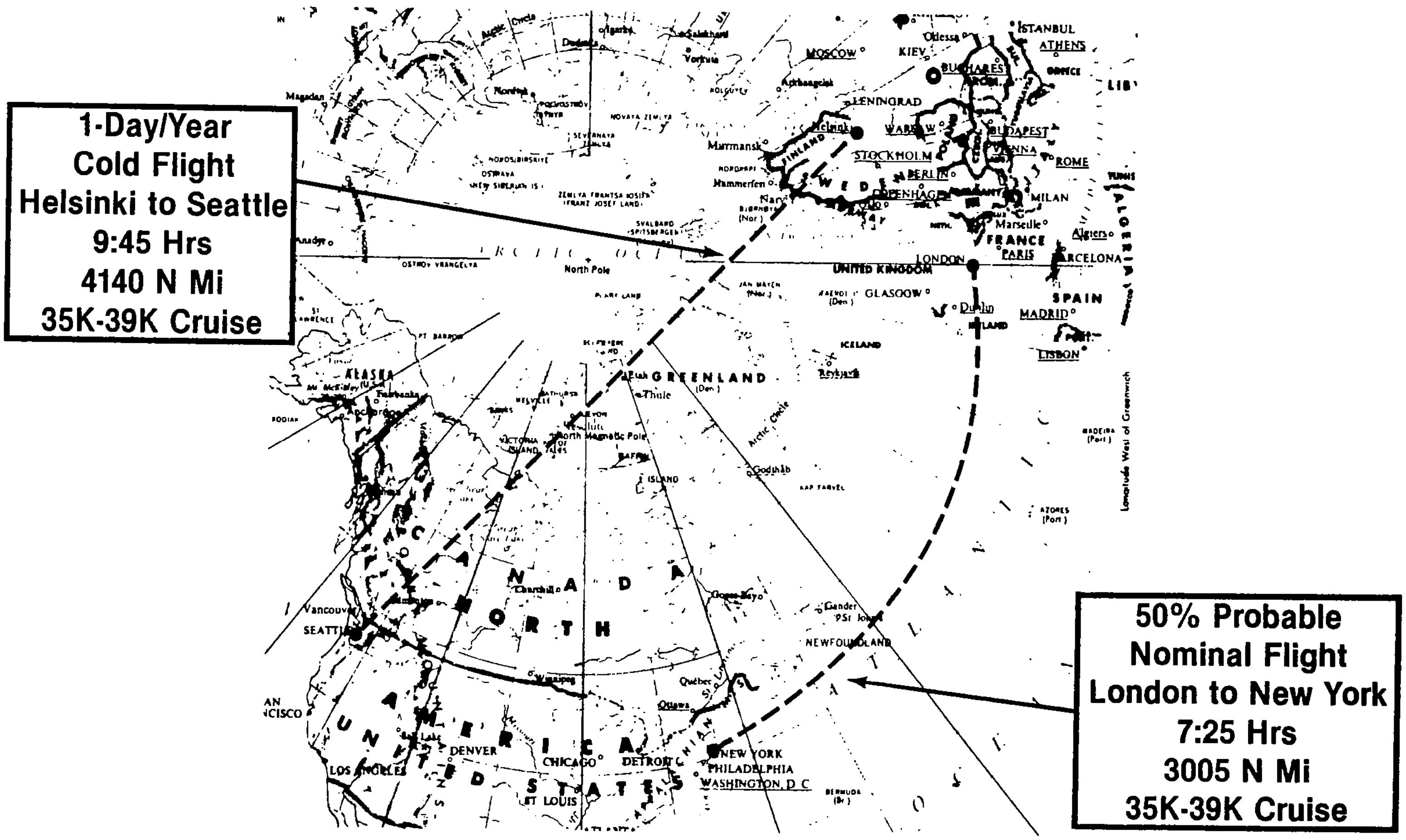
- Reliability
- Maintenance
- Costs

Economics

- Acquisition Costs
- Airline Operating Costs

Figure 6

Nominal and Cold Flights

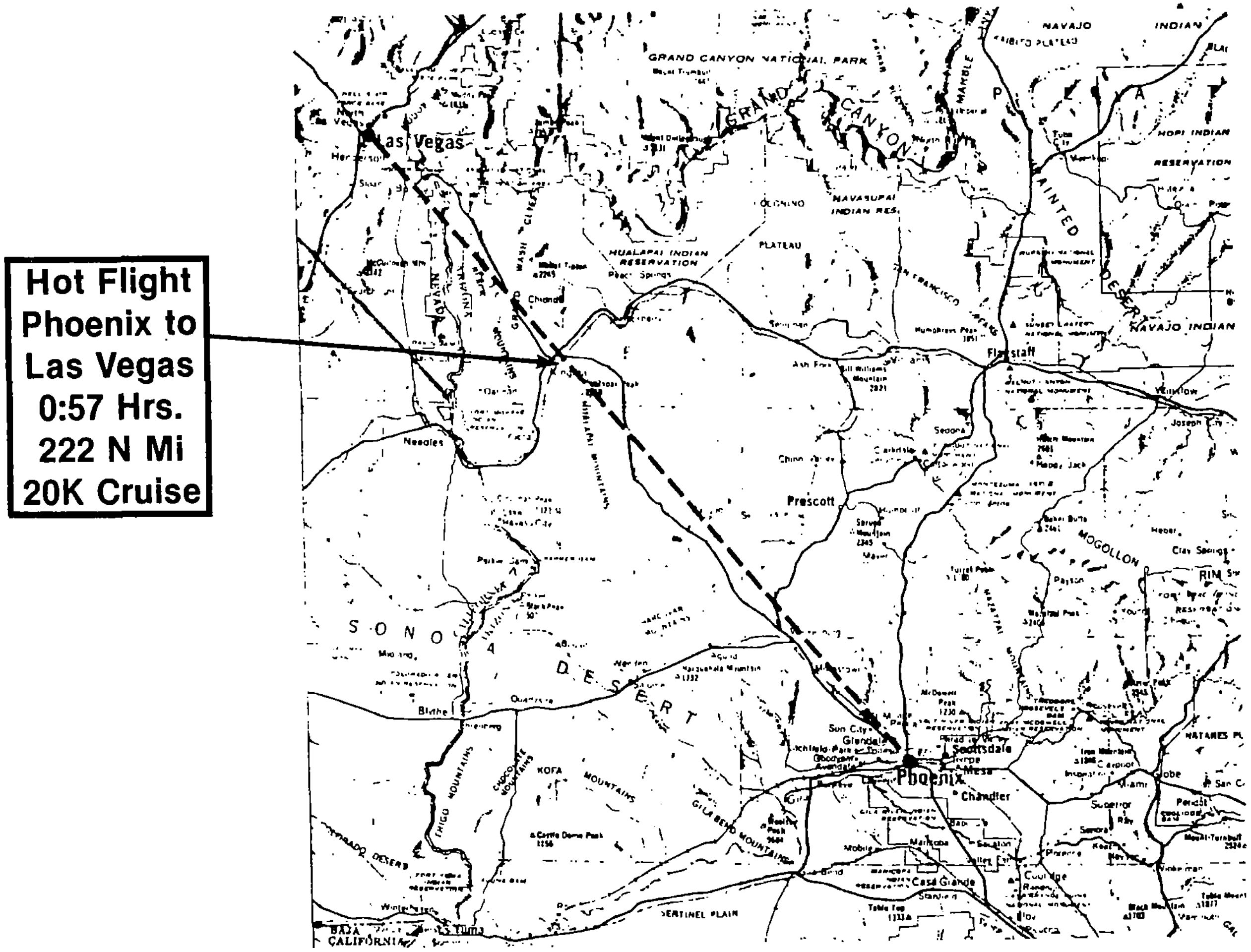


1-Day/Year
Cold Flight
Helsinki to Seattle
9:45 Hrs
4140 N Mi
35K-39K Cruise

50% Probable
Nominal Flight
London to New York
7:25 Hrs
3005 N Mi
35K-39K Cruise

Figure 7

Hot Flight



Hot Flight
Phoenix to
Las Vegas
0:57 Hrs.
222 N Mi
20K Cruise

Figure 8

Cold Flight Tank Temperatures Minimum During Flight — °F

	Baseline	System A	System B	System C
No. 2 Main	-49	*	*	*
No. 1 Main	-49	-29	-43	-26
No. I Outboard	-49	-18	-32	-10

Fuel Loading Temperature = 0° F

Spec Max Freezing Point +5° F	Minimum Air Temperture
Jet-B = -53	T_{Amb} = -94
Jet-A = -35	T_R = -50
	T_2 = -45

*No Advanced Systems on No. 2 Engine

Figure 9

Cold Flight Tank Fuel Level

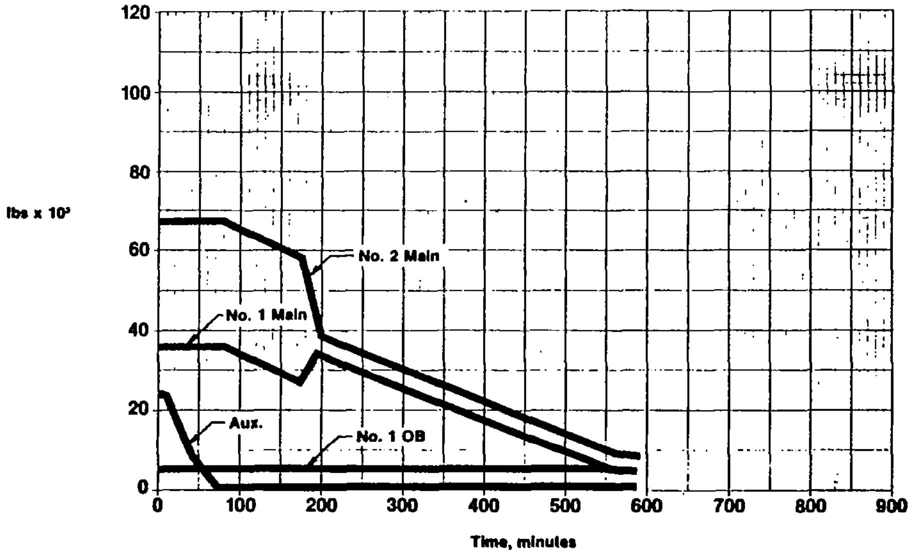


Figure 10

Cold Flight
No. 1 Main Tank Heat Transfer Area

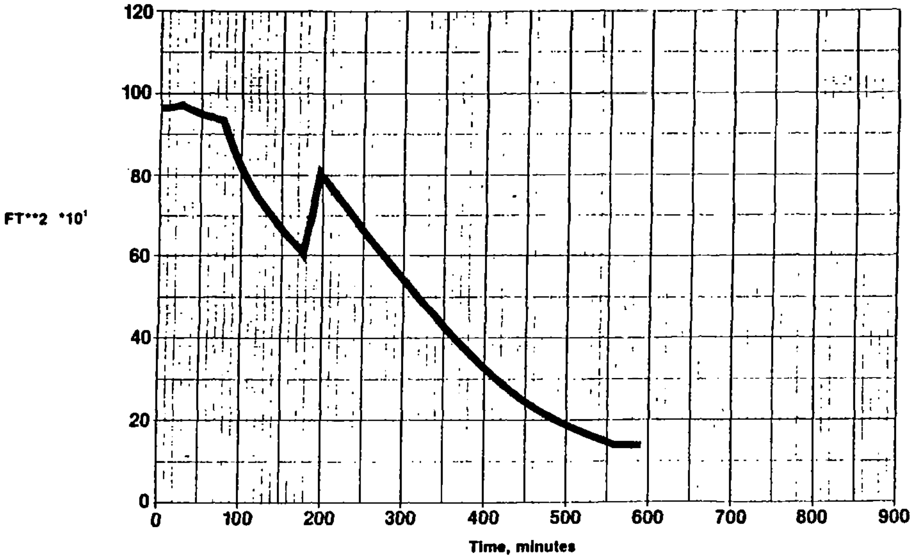


Figure 11

Baseline — Cold Flight
No. 1 Main Tank Temperature

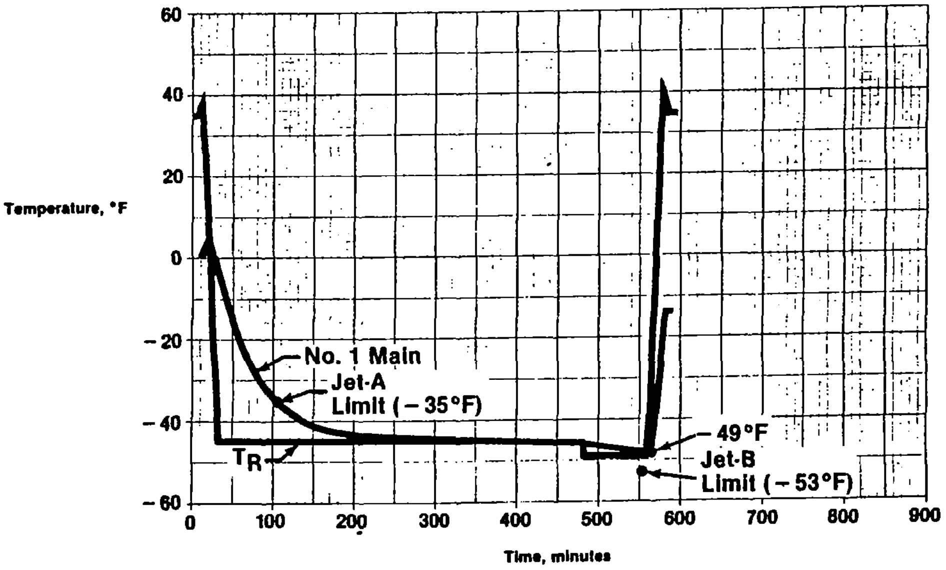


Figure 12

Baseline — Nominal Flight
No. 1 Main Tank Temperature

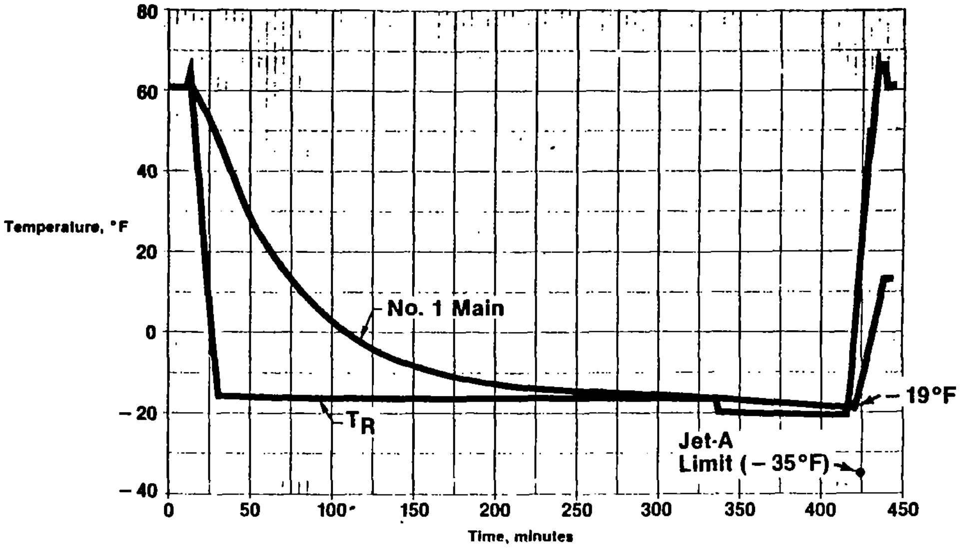


Figure 13

System A — Cold Flight
No. 1 Main Tank Temperature

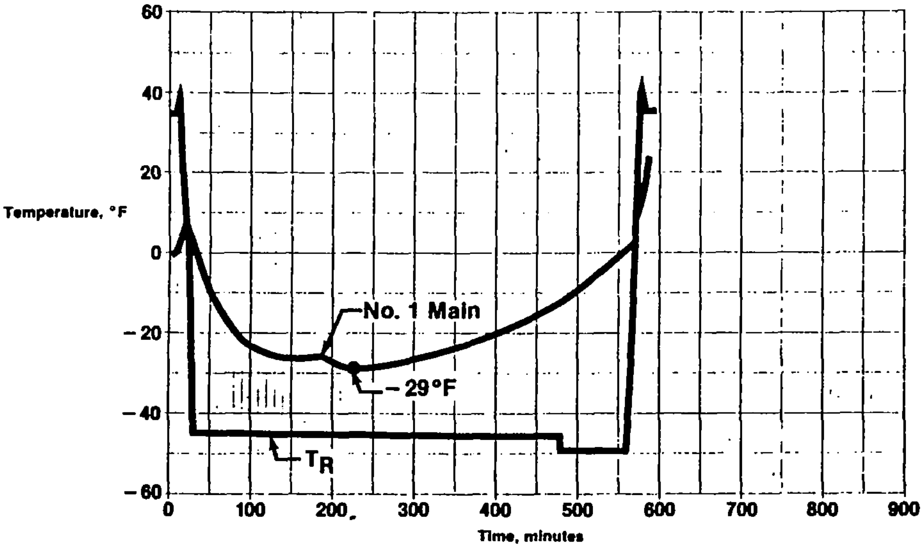


Figure 14

System B — Cold Flight
No. 1 Main Tank Temperature

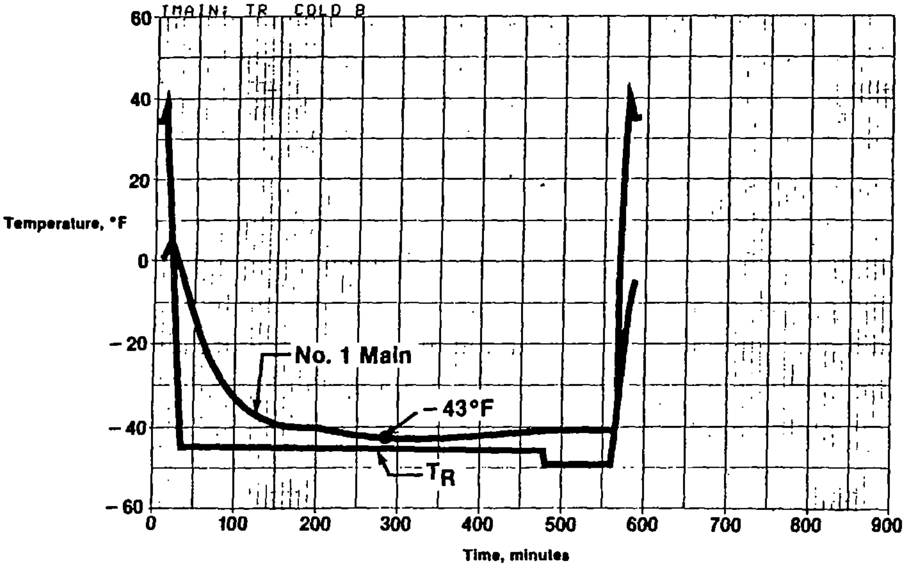


Figure 15

System C — Cold Flight
No. 1 Main Tank Temperature

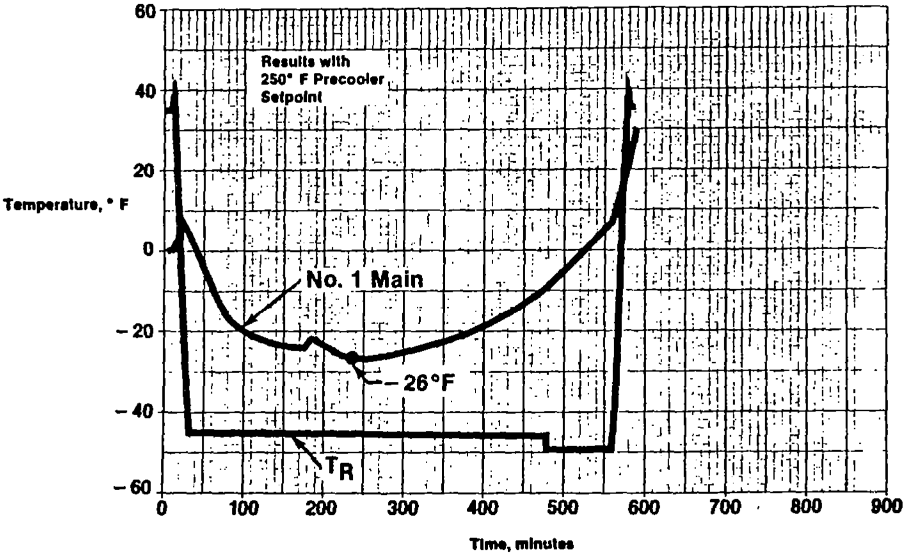


Figure 16

Filter Fuel Inlet Temperature Minimum During Flight — °F

	Baseline	System A	System B	System C
Cold Flight	65	-1*	62	58
Nominal Flight	118	35	116	102
Hot Flight	157	97	155	152

Ice Protection Limit = 32° F

* Problem Avoided with Fuel Return to Engine Instead of Tank

Figure 17

Nozzle Fuel Inlet Temperature Maximum During Flight — °F

	Baseline	System A	System B	System C
Cold Flight	172	90	186	152
Nominal Flight	208	122	216	243
Hot Flight	243	160	252	273

Baseline Nozzle Limit
Jet-A = 300°F (473°F/245°C Break Point)
Study Fuel = 255°F (428°F/228°C Break Point)

Figure 18

Engine Lube Oil Temperature Minimum During Flight — °F

	Baseline	System A	System B	System C
Cold Flight	96	⑰*	95	89
Nominal Flight	133	㊽*	130	123
Hot Flight	177	103	175	168

Baseline Normal Minimum = 90° F

* Problem Avoided with Fuel Return to Engine Instead of Tank

Figure 19

Economic Influences

	Baseline	System A	System B	System C
Maintenance				
• Fuel Nozzle Coking Only				
• Unscheduled Removals (Events/M—Hrs.)				
Jet-A	50	1	15	13
Future Fuel	140	1	41	37
Fuel Burn				
• Δ% Block Fuel	*	+0.231	+0.073	−0.342
Equipment Cost				
• At Airline Cost Level for 3-Engine Aircraft	*	−$1260	−$2760	$167,610
• For New Aircraft				

* Baseline is Reference

Figure 20

Economic Tradeoffs — Future Fuel

	System A	System B	System C
Increased Initial Investment	– 1,260	– 2,760	167,610
Annual Increased DOC			
• Maintenance	– 47,640	– 4,140	– 2,280
• Fuel (1.06/Gal)	25,596	8,088	– 37,896
Net Increased DOC	– 22,044	3,948	– 40,176
Present 1982 Value (15 Yrs. — 10% ROR)	– 167,148	– 31,182	375,372
Net 1982 Investment Incentive	– 168,408	– 28,422	207,254
Recovery of Investment			
• No. Years			3
• Investment % ROR			31.8

Values at Airline Cost and 1982 Dollars for 3-Engines

Figure 21

Economic Tradeoffs — Jet-A Fuel

	System A	System B	System C
Increased Initial Investment	– 1,260	– 2,760	167,610
Annual Increased DOC			
• Maintenance	– 16,800	– 12,390	– 11,910
• Fuel (1.06/Gal)	25,596	8,088	– 37,896
Net Increased DOC	8,796	4,302	– 49,806
Present 1982 Value (15 Yrs. — 10% ROR)	– 67,422	31,566	448,617
Net 1982 Investment Incentive	– 66,162	34,326	281,007
Recovery of Investment			
• No. Years			3
• Investment % ROR			38.4

Values at Airline Cost and 1982 Dollars for 3-Engines

Figure 22

FUEL SYSTEM DESIGN CONCEPTS FOR BROAD PROPERTY FUELS

Edward F. Versaw
Lockheed-California Company

This paper presents the results of a NASA funded study awarded to the Lockheed-California Company for the purpose of assessing the impact of using jet fuel with relaxed specification properties on an aircraft fuel system. The study objectives were (1) identify credible values for specific fuel properties which might be relaxed, (2) evolve advanced fuel system designs for airframe and engines which would permit use of the specified relaxed properties fuels, and (3) evaluate performance of the candidate advanced fuel systems and the relaxed property fuels in a typical transport aircraft. The study used, as a baseline, the fuel system incorporated in the Lockheed Tristar (Figure 1). This aircraft is powered by three RB.211-524 Rolls-Royce engines and incorporates a Pratt and Whitney ST6C-421 auxiliary power unit for engine starting and inflight emergency electrical power.

The fuel property limits examined in this study are compared with commercial Jet A kerosene and the NASA RFP fuel properties in Figure 2. A screening of these properties established that a higher freezing point and a lower thermal stability would impact fuel system design more significantly than any of the other property changes.

The first task in the study involved the development of fuel system designs which could accommodate fuel with a -20°C freezing point. For purposes of analysis a 9260 km flight profile at altitudes up to 12 km for periods in excess of 10 hours was selected (Figure 3). The ambient temperature profile used was developed from a probability analysis of long range flights for which extremely low temperatures were expected.

The areas of the aircraft fuel system identified as being most susceptible to fuel freeze-out were the fuel tanks, the distribution systems for the auxiliary power unit and the engine (when it has been shutdown for an extended period of time inflight.) Fuel freeze-out in the wing will reduce the aircraft range. Freeze-out in the fuel systems of the APU or engine could prevent their operation.

To determine the wing tank freeze-out potential, a computer model was established which would predict bulk and wing tank skin temperatures as a function of time, given aircraft flight speed, fuel quantities, initial fueling temperatures, altitude, and the associated ambient temperatures. Although the analysis showed that all tanks would experience some fuel freeze-out, the most critical tanks were shown to be the outboard compartments of tanks 2L or 2R which have the largest surface-to-volume ratios and hence, cool most rapidly. The results of this analysis are shown in Figure 4. As noted, the bulk fuel and lower surface temperatures are below the -20°C fuel freeze point for almost all of the flight.

To preclude fuel freeze-out, heat must be added to the fuel to maintain its temperature above the freezing point. The heat sources which were considered in this study are engine oil, engine bleed air, engine exhaust gas, or electrical heater. Of these sources, only electrical heating offers both an adequate heat supply and a practicable means of applying the heat. Three systems which used electrical power heating were developed, one with no insulation and two with insulation. Details of these options are illustrated in Figures 5, 6 and 7. The electrical power required to maintain the fuel at -17°C, 3°C above the fuel freezing point, for each of these options is shown in Figure 8.

The electrical generators installed in the Tristar can supply approximately 101.5 kilowatts of electrical power above the aircraft maximum electrical load. This is adequate to meet the fuel heating power requirements, providing the insulation options are used. If insulation is not used, a feasible state-of-the-art option would be to replace the pneumatic engine starters with Sm/Co starter/generators. The power requirements for engine starting make the generator electrical power output compatible with the fuel tank heating requirements.

Fuel freeze-out protection for an inoperative engine and the APU is best provided by the use of bleed air from operating engines. The bleed air would be available to these units from existing manifolds already in place between engines and APU. Thawing of the frozen fuel lines would be accomplished by flow of the hot bleed air in manifolds surrounding the fuel lines and components exposed to the cold slipstream air as shown in Figures 9 and 10.

A summary comparison of the weight penalties and power requirements of these options is presented in Figure 11. Although the weight penalty associated with the use of dedicated starter/generators is significant, it is considerably less than the weight of insulation required.

Commercial Jet A kerosene has a maximum JFTOT rating of 260°C. This study examined a fuel which had a rating reduced to 204°C. This change requires that the operating temperature in the engine be held to 79°C, (i.e., 56°C below the maximum operating temperature of 135°C frequently assumed for today's engines). Figure 12 presents representative fuel temperature test data corrected to a 54°C day for a typical jet engine. As can be seen, fuel entering the HP fuel pump exceeds 79°C at takeoff and during descent while downstream of the HP fuel pump, fuel temperatures exceed the limit by a large margin for almost all of the flight. Accordingly, several methods of reducing the fuel inlet temperature to the engine combustor had to be investigated. A system which is capable of satisfying this requirement is shown in Figure 13. This system includes the use of both fuel and air heat exchangers to cool the engine oil, a variable displacement HP pump to minimize fuel heating by the pump, and oil cooler fuel recirculation to the fuel tank to reject engine oil heat through the wing surfaces.

Three candidate fuel systems which combine the ability to operate with fuels having both a high freeze point and a low thermal stability are described in Figure 14. All candidates employ bleed air to melt fuel freeze-out prior to starting the APU or an inoperable engine.

The effects of incorporating these systems on aircraft weight and engine specific fuel consumption are shown in Figure 15. It is apparent that the OEW change favors Candidate A while Candidate C is favored if the prime concern is SFC. Neither of these changes will affect the aircraft payload capabilities for the 9260 kilometer mission since the maximum increase in TOGW of 1553 kilograms is well within the aircraft weight growth potential even on a hot day as illustrated in Figure 16.

The cost premises used in this study assumed a fleet of 300 aircraft having the operational, economic, and maintenance factors shown in Figure 17. Acquisition costs (i.e., full scale engineering development, installation, and material procurement costs) and direct operating costs (i.e., fuel, insurance, depreciation, and maintenance) are listed in Figure 18. Fuel was the heaviest contributor to direct operating costs. In anticipation of increased fuel costs in the future, the DOC increase resulting from the fuel system modifications for each candidate were evaluated in terms of 1982 dollars assuming fuel costs varying from $1.00 to $2.00 per gallon. At $1.00 per gallon, Candidate A (which uses no insulation but requires dedicated starter/generators for fuel heating) was most attractive. However, after fuel costs exceeded $1.27 per gallon, Candidate B (which added insulation to the lower wing surfaces and used only existing excess aircraft generator power) had the lowest DOC (Figure 19).

FUEL TANK ARRANGEMENT AND CAPACITIES

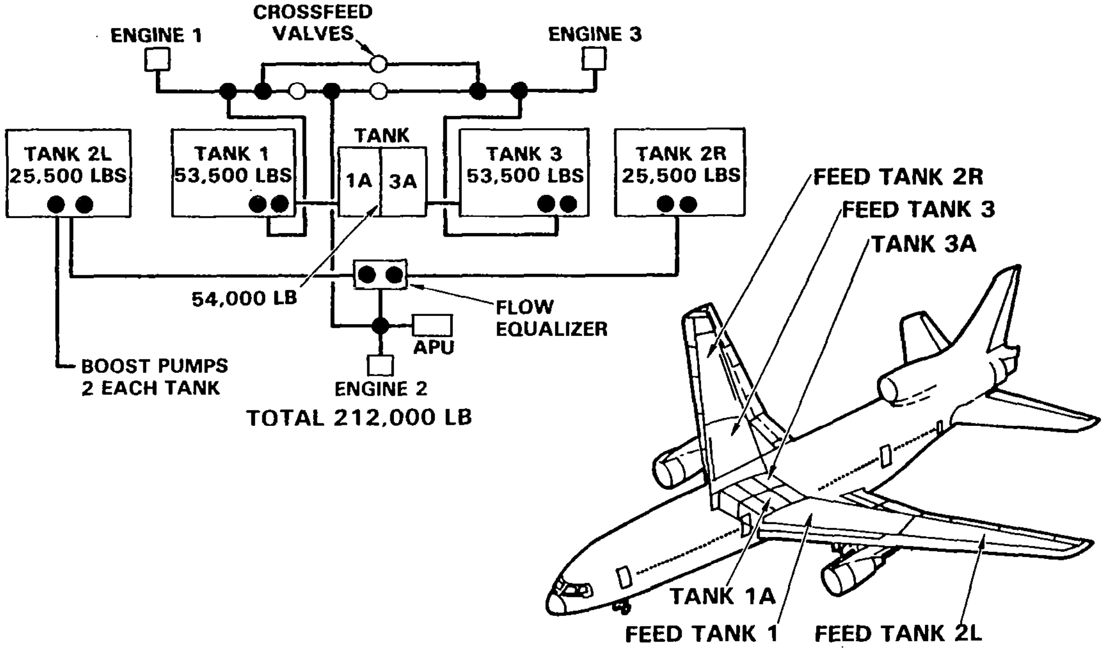


FIGURE 1

REQUIREMENTS

	JET A ASTM-D-1655	AS REQUIRED BY NASA RFP	FUEL PROPERTY LIMITS USED IN THE PRESENT STUDY
FREEZING POINT (°C MIN)	-40	-30	-20
THERMAL STABILITY JFTOT (°C)	260	220	204
FLASH POINT (°C MAX)	37.8	27	27
AROMATIC (VOL. % MIN)	20-25	---	35
VISCOSITY (CST MIN @ -23.8°C)	8.0 (@ -20°C)	12	15
LUBRICITY, WSD, MM	---	TBD	0.45
VAPOR PRESSURE, KPA	13.8-20.7 (JET B)	TBD	13.8
WATER REACTION			
SEPARATION RATING, MAX	2	TBD	---
INTERFACE RATING	1B	TBD	---
ELECTRICAL CONDUCTIVITY, PS/M	---	---	450

FIGURE 2

COLD DAY FLIGHT PROFILE, 9260 KM (5000 N.MI.) MISSION

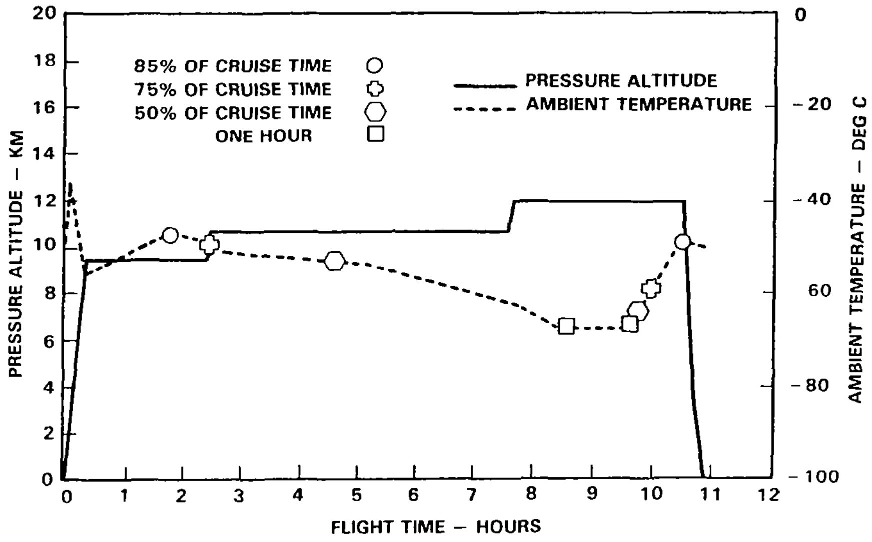


FIGURE 3

TANK-2 OUTBOARD BULK FUEL AND LOWER SURFACE PREDICTED TEMPERATURE – 9260 km (5000 n.mi.) COLD DAY MISSION

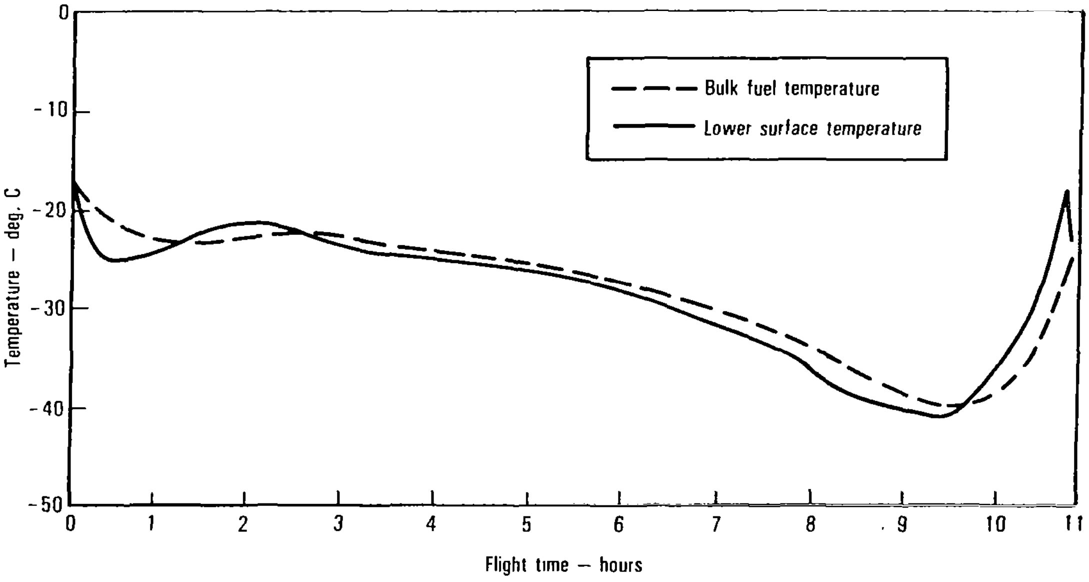


FIGURE 4

FUEL TANK ELECTRIC FOIL HEATERS W/O INSULATION (FOR ALL TANKS)
SYSTEM 1

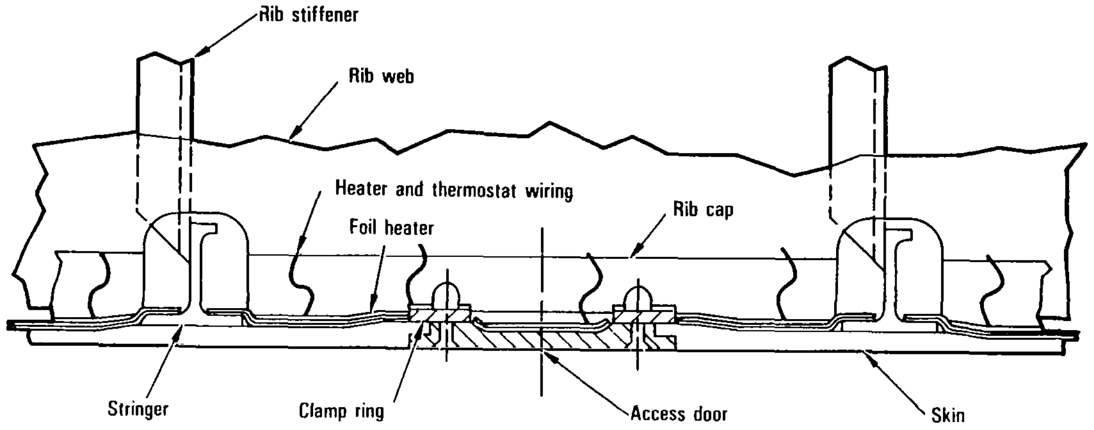


FIGURE 5

FUEL TANK ELECTRIC FOIL HEATERS WITH LOWER SURFACE INSULATION (FOR ALL TANKS)
SYSTEM 2

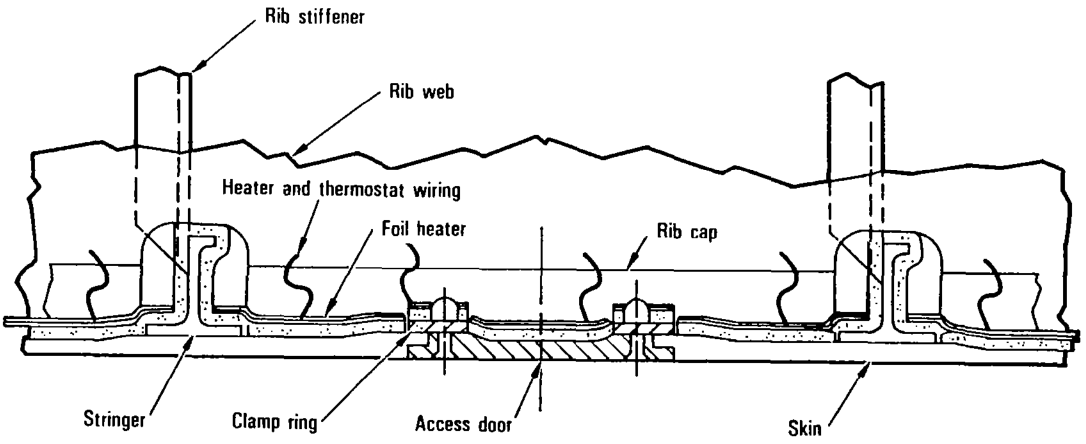


FIGURE 6

SYSTEM 2 PLUS UPPER SURFACE INSULATION (FOR TANK 2-OUTBOARD) SYSTEM 3

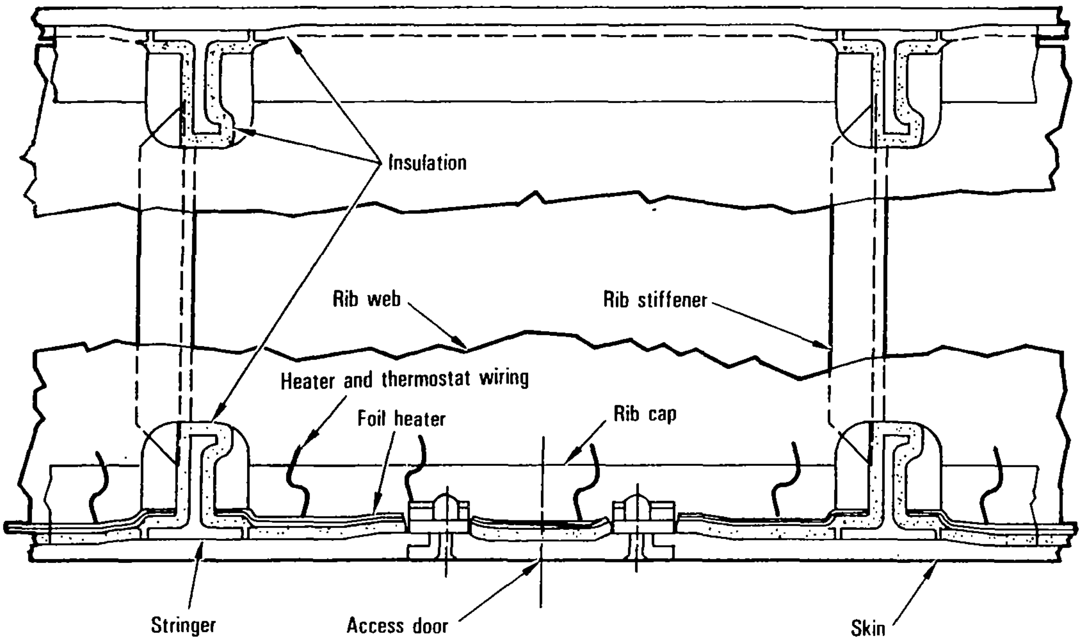


FIGURE 7

PREDICTED FUEL TANK ELECTRICAL HEATING POWER REQUIREMENTS – 9260 km (5000 n.mi.) COLD DAY MISSION

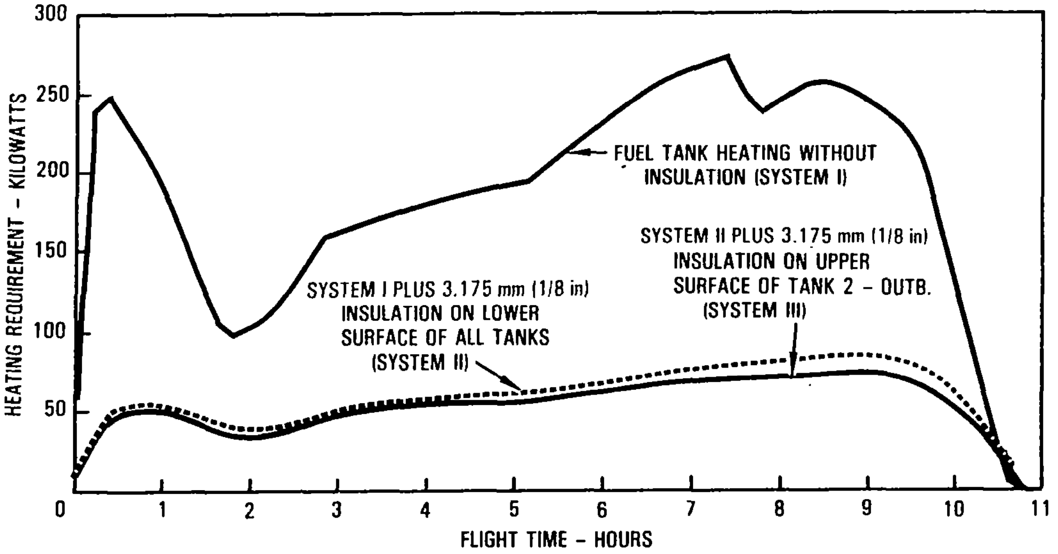


FIGURE 8

ENGINE FUEL SYSTEM HEATING

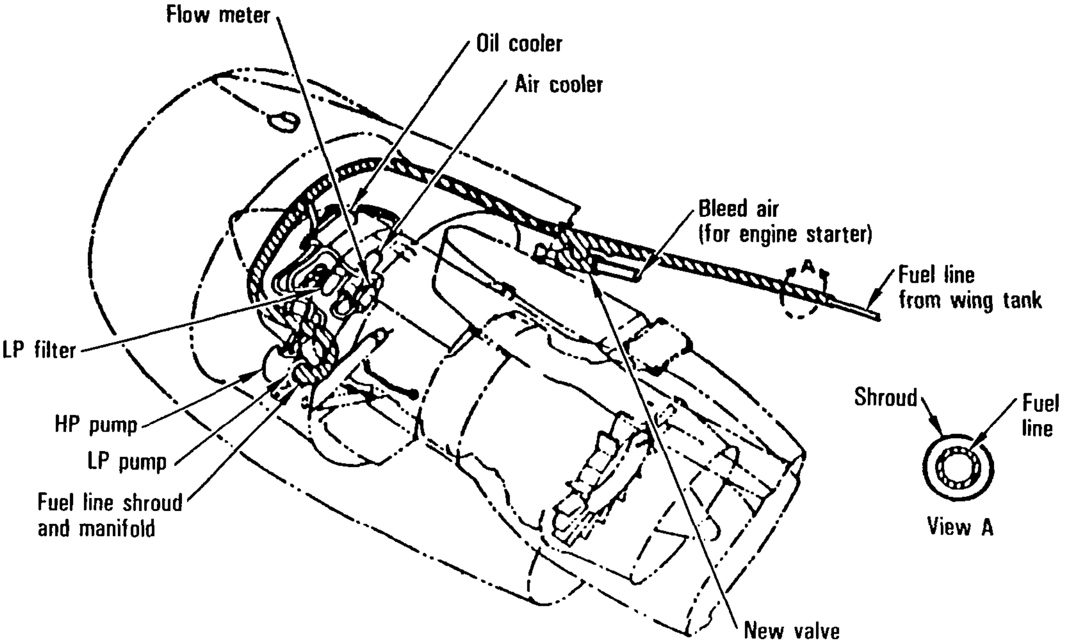


FIGURE 9

APU FUEL SYSTEM HEATING

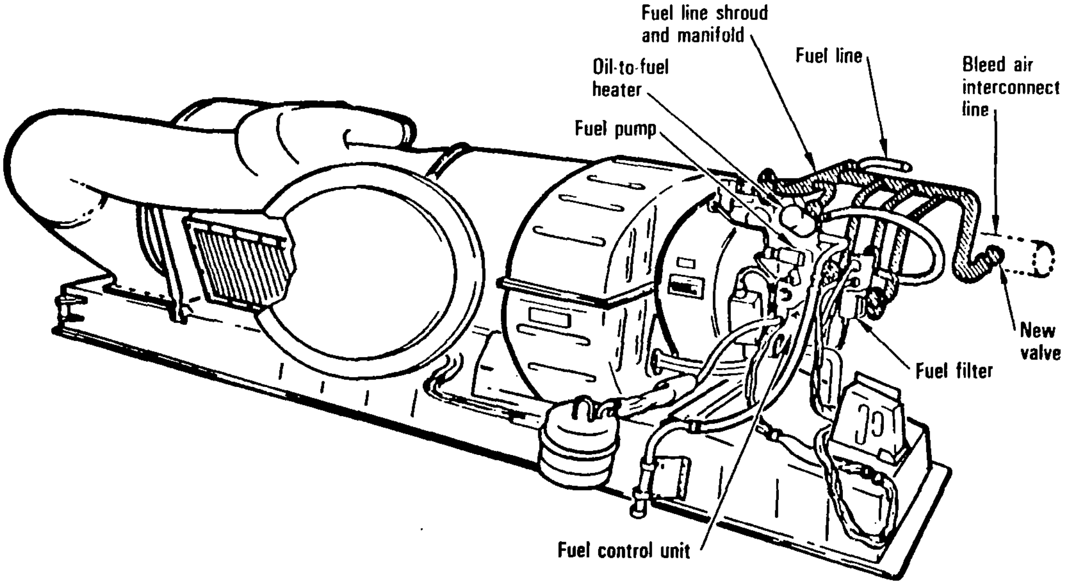


FIGURE 10

WEIGHTS AND ELECTRICAL POWER REQUIREMENTS FOR ENGINE FUEL SYSTEM HEATING

System	Insulation Weight		Fuel Tank Heater Weight		Fuel Tank Wiring Weight		Engine Fuel System Heating		Starter/Gen. Net Weight Added		Total		Electrical Power Required By Heaters Kilowatts	Additional Generator Capacity Required Kilowatts
	kg	(lb)	kg	(lb)	kg	(lb)	kg	(lb)	kg	(lb)	kg	(lb)		
I	0	0	59	(129)	46	(102)	61	(134)	470	(1036)	635	(1401)	270	270
II	646	(1425)	59	(129)	46	(102)	61	(134)	0	(0)	812	(1790)	87.3	0
III	779	(1717)	59	(129)	46	(102)	61	(134)	0	(0)	944	(2082)	74.8	0

FIGURE 11

FUEL SYSTEM TEMPERATURE PROFILES IN KEY SECTIONS OF FAN CASE

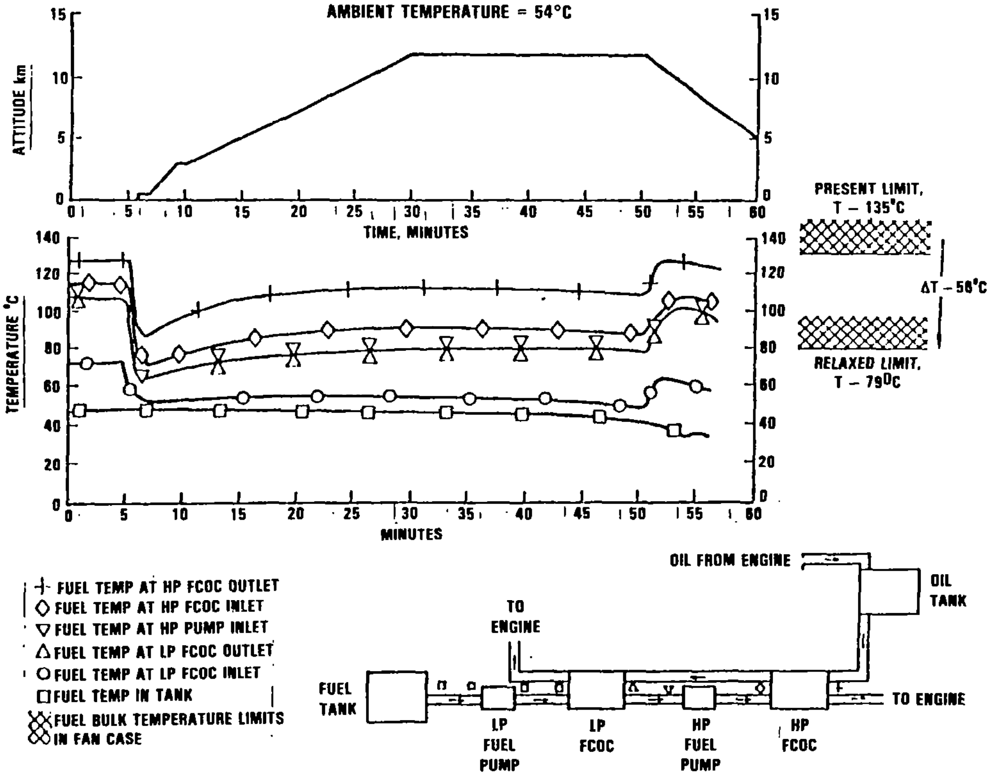


FIGURE 12

RECOMMENDED SYSTEM FOR LOW THERMAL STABILITY FUEL

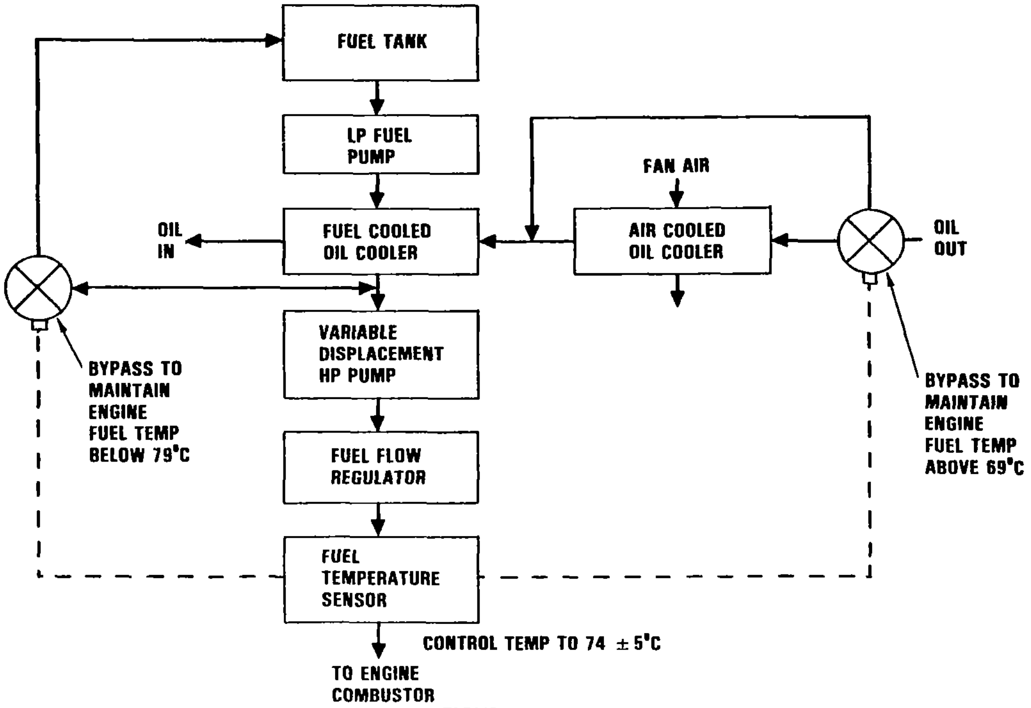


FIGURE 13

CANDIDATE FUEL SYSTEMS CONCEPT DESCRIPTIONS

	High Freeze Point Fuel		Low Thermal Stability Fuel
Candidate	Fuel Tank Modifications	Engine/APU Modifications	Engine/APU Modifications
A	o Electric foil heater on tank bottoms.	o Replace pneumatic starter with Sm/Co starter/generator. o Bleed air heating	o Oil heat rejection to air, consumed fuel and fuel tanks. o Variable displacement high pressure fuel pump. o Heat shielding of fuel injectors.
B	o Electric foil heater, o 3.175 mm (1/8in.) insulation on tank bottoms.	o Bleed air heating.	
C	o Electric foil heater, o 3.175 mm (1/8in.) insulation on tank bottoms, o 3.175 mm (1/8 in.) insulation on top of Tank 2 outboard.		

Modifications Required by Other Fuel Property changes (No Performance Effects)

- o Aromatics - materials changes.
- o Viscosity - none required.
- o Lubricity - material changes.
- o Water Separation - none required.
- o *Electrical Conductivity* - antistatic additive may be added to fuel.
- o Flash Point/Vapor Pressure - none required.

FIGURE 14

COMPARISON OF CANDIDATES TO BASELINE AIRPLANE

ALL ENGINES OPERATING COLD DAY -9260 KILOMETERS (5000 N. MILES)

EFFECT OF OEW CHANGE

CANDIDATE	INCREASE IN EMPTY WEIGHT		Δ TOGW		Δ BLOCK FUEL	
	KG	(LB)	KG	(LB)	KG	(LB)
A	674	(1485)	1066	(2350)	340	(750)
B	850	(1875)	1349	(2975)	431	(950)
C	982	(2165)	1553	(3425)	494	(1090)

EFFECT OF SFC CHANGE

CANDIDATE	Δ% SFC DUE TO ADDITIONAL ENGINE FUEL CONSUMPTION	Δ TOGW		Δ BLOCK FUEL	
		KG	(LB)	KG	(LB)
A	.554	494	(1089)	480	(1060)
B	.196	175	(386)	155	(342)
C	.171	152	(335)	132	(293)

FIGURE 15

BASELINE AIRCRAFT PAYLOAD/RANGE – HOT DAY (ISA + 34°C)

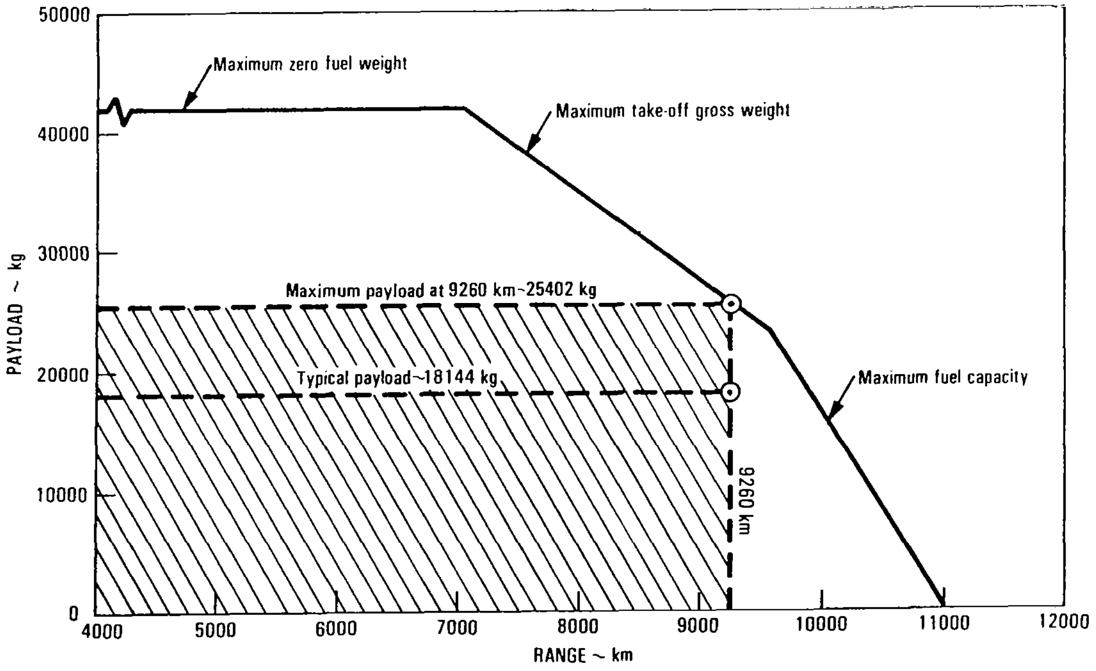


FIGURE 16

COST PREMISE

CONFIGURATION L-1011-500 BASED ON NEW PROGRAM PRODUCTION QUANTITY = 300

OPERATION

INTERNATIONAL	
STAGE LENGTH	9260 km (5000 n.mi.)
UTILIZATION	4718 BLOCK HOURS/YEAR
BLOCK TIME	11.2 BLOCK HOURS/TRIP
TRIPS PER YEAR	421
OPERATIONAL LIFE	16 YEARS
COST OF FUEL	$1.00/GALLON (INTERNATIONAL U.S. TRUNK - MAY 1982)
NON REVENUE FLYING	1.23 PERCENT

ECONOMICS

YEAR	1982
LABOR RATES	LOCKHEED (1982 DIRECT, OVERHEAD, G&A, OTHER)
PROFIT	10 PERCENT

MAINTENANCE

- STRUCTURAL INSPECTION REQUIRES STRIPPING AND REPLACING INSULATION AND HEATERS AT 20,000 HOURS (4 TIMES DURING LIFE) ON 8 PERCENT OF THE FLEET PLUS 10 PERCENT FOR MISCELLANEOUS CHECKS
- LIFE OF INSULATION AND HEATERS IS ASSUMED TO BE ONE HALF THE AIRCRAFT LIFE REQUIRING ONE STRIPPING AND REPLACEMENT FOR THE REMAINDER OF THE AIRCRAFT
- LABOR RATE $13.93/HOUR
- BURDEN FACTOR 3.13 (INTERNATIONAL)

FIGURE 17

INCREASE IN DIRECT OPERATING COST

(THOUSANDS OF 1982 DOLLARS)

		Candidate	
	A	B	C
ACQUISITION			
Full Scale Engineering Development (FSED)	9103	9103	9103
Procurement (300 Aircraft)	116162	161791	165111
(Heater Material Cost)*	(22848)	(22848)	(22848)
(Insulation Material Cost)*	(–)	(5242)	(6250)
Total Acquisition (300 Aircraft)	125265	170894	174214
DIRECT OPERATING COSTS			
Fuel	552960	394710	422510
Insurance	5569	7592	7739
Depreciation	112739	153804	156793
Maintenance	100361	260251	270173
Total DOC	771630	816360	857220
COST $/AC/YR			
Fuel Cost – $1.00/gal.	161	170	179
– $1.50/gal.	218	211	223
– $2.00/gal.	276	252	267

*Cost of heaters and insulation material in the aircraft is included in Procurement.

FIGURE 18

IMPACT OF FUEL COST ON DOC

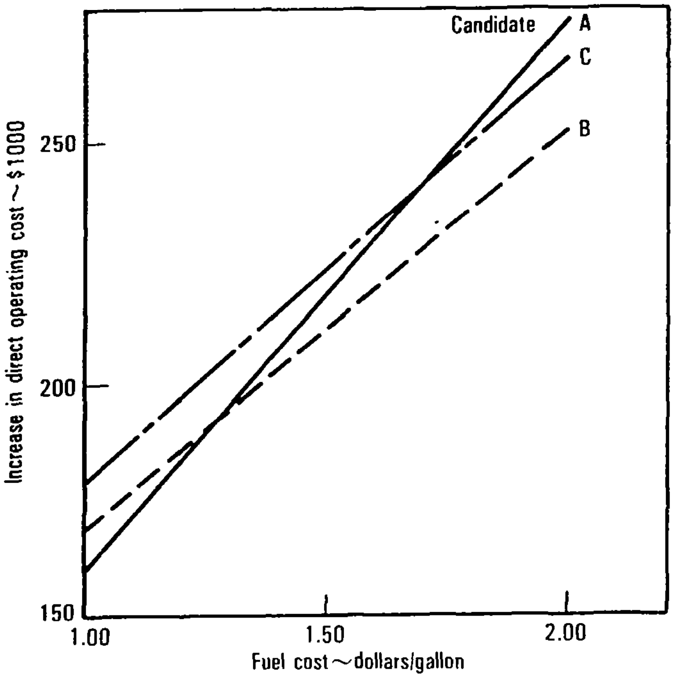


FIGURE 19

ECONOMIC IMPACT OF FUEL PROPERTIES ON TURBINE POWERED BUSINESS AIRCRAFT *

F.D. Powell
Simmonds Precision, ISD

The composition and properties of aviation fuels will change during the next decade as their sources change due to economic and political influences. The economic impact of these changes in the 1990 time-frame is considered.

Five potential fuels were selected, and their effects on the economics of operation of heavy jets, light jets, and turboprop aircraft were calculated. The fuel properties of principal economic importance are aromatic content, heat of combustion, and freezing temperature.

The results show that increasing aromatic content to 35% will cost the 1990 business fleet approximately 73 million (1982) dollars per annum, while decreasing the heat of combustion from the nominal 18574 to 18275 BTU/pound will cost 30 million. The effect of high freezing temperature (-29 °C) is less than 1 million per annum.

1. Introduction

The principal objective of this study is to estimate the economic impact on the turbine-powered business aviation fleet of potential changes in the composition and properties of aviation fuel. Secondary objectives include estimation of the sensitivity of costs to specific fuel properties, and an assessment of the directions in which further research should be directed.

The study was based on the published characteristics of typical and specific modern aircraft in three classes: heavy jet, light jet, and turboprop. Missions of these aircraft were simulated by computer methods for each aircraft for several range and payload combinations, and assumed atmospheric temperatures ranging from nominal to extremely cold. Five fuels were selected for comparison with the reference fuel, nominal Jet A. These fuels varied in aromatic content, heat of combustion, freezing temperature, density and several other properties of lesser importance. The extreme cold-day missions are outside the present operational envelopes of the aircraft.

---

* The work reported herein was conducted under Contract NAS3-22827, directed by Dr. C. Baker, NASA-Lewis Research Center.

This paper presents an overview of the data, the math-models, the data reduction and analysis procedure, and the results. The direct operating costs of the study fuels are compared with that of the reference fuel in the 1990 time-frame, and the anticipated fleet costs and fuel break-even costs are estimated.

2. Data, Flight Profile Model, and Analysis Procedure

2.1 Data

The data which define the aircraft, their direct operating costs, and the atmosphere are presented in Figure 1. Aircraft data were taken from the pilot's operations manuals for the three specific aircraft, which were defined to be representative of the three classes. Table 1A presents data of mission lengths and frequencies based on surveys of the fleet. Only the heavy jet data were provided [6]; it was assumed that the light jet data were similar to those for the heavy jet since the ranges for the two aircraft are quite similar. The ranges for the turboprop were assumed, based on scaling by ranges of the two classes. Table 1B presents the pertinent range, fuel and payload data for the various missions used in this study. For each aircraft class, the two longer-range missions were simulated for a median temperature day, (assumed to be the ISA), a 2% probable-cold day, and a 0.3% probable-cold day, to enable examining the problems of freezing of fuel in the wing tanks. The 2% and 0.3% atmospheric profiles were determined by linear interpolation of the atmosphere-temperature data [1] shown in Figure 1. The aircraft operational properties required for the simulation were estimated by interpolation or extrapolation, as required, from data in the pilot's operational manuals; extrapolation was required for the cold-day simulations. The shorter range missions were selected to enable linear interpolation for trip distance as a function of trip-frequency, and thus to determine the average trip properties.

Table 2 presents estimates of the population [2], [3], of the three aircraft classes, and of the annual number of missions and flight miles per class and per vehicle, [4], [5]. Unfortunately, one of the sources lumps all fixed wing aircraft, while the other lumps all jets, but segregates turboprops. It was necessary to assume the number of missions per year to be equal for the heavy and light jets in order to produce the heavy and light jet segregation required in this study.

Table 3 presents the significant properties of the reference and study fuels, [7-13]. The aromatic content and heat of combustion have direct and significant effects on the operating costs. The freezing temperature has a relatively small direct effect on cost; other parameters in this table are used in the fuel freezing analysis, or have other operational implications.

2.2 Flight Profile Model

Figure 2 shows the principal elements of the mathematical model used in computation of the flight profile. This model uses input data from the operational handbook, the defined mission profile, and atmospheric environment. During climb, altitude increments of 1000' are assumed and the increments of range, fuel-burn, and time are computed at each increment of altitude in accordance with the handbook's speed/altitude profile recommendation. When cruise altitude is reached the computation interval is changed to 25 nautical miles; this is a compromise between computational economy and precision.

The temperature of the fuel in the wing tanks is important as fuel can easily freeze in these shallow tanks. The effects of freezing temperature are therefore part of this study. It was determined that long-range cold-weather operation would be grossly impaired for the fuels with higher freezing temperature and it was therefore concluded that fuel heating would be required in order to enable economic comparisons. Heat was therefore added, as shown in Figure 2, to keep each fuel at 1.67°C above its freezing temperature. At the end of the flight, the computer profile printout presents the flight duration, fuel burn, and added heat requirement. This enables computation of the economic impact of the various fuel properties.

2.3 Analysis Procedure

This section outlines the procedure for converting the trajectory data to relative costs for each aircraft mission, and how the mission data are combined to yield cost data for the average mission for each class. Weighting of the costs for the average mission by the composition of the business fleet enables estimation and projection of the relative direct operating costs of the anticipated 1990 fleet.

The analysis procedure has two phases: estimation of the incremental costs for each aircraft and mission, and combination of these mission data to yield average missions, class, and fleet results. The aircraft and mission cost analyses are discussed below. The significant cost drivers, aromatic content, heat of combustion, and fuel freezing temperature, are considered separately. It is assumed that all fuels have the same cost.

Figure 3 shows the procedure for analysis of the incremental cost of aromatic content for the specific mission:

Heavy jet; 2700 NM mission; Fuel load, 6695kg; payload, 680kg;
Atmosphere; 0.3% probable cold day.

The judgement of the engine manufacturer was that all fuels should be flown at the same speed/altitude profile, therefore the flight duration of 6.055 hours is the same for the two fuels, Jet A, and Spec-Limit Jet A, with aromatic contents of 17.5% and 20% respectively. Entering the curve, relative loss of life as a function of aromatic content, at the lower-left corner of this figure, the aromatic content of 20% shows a 6% loss of engine hot-section life [14] due to the increased flame radiation temperature associated with increased aromatic content. The hot-section overhaul cost is approximately 45% of the total overhaul cost of the engine. The product, (0.06))(0.45) = 0.027, shows that the operating cost is increased by 2.7% of the engine operating cost of $200 per flight hour, or 0.027 (200) = $ 5.40 per flight hour. As the flight duration is 6.055 hours, the cost increment is $32.70. The data on engine hot-section overhaul costs are based on conversations with engine manufacturers.

Figure 4 shows, again in a block-diagram form, the procedure for determining the relative costs of varying heat of combustion in the same mission. The initial fuel load is compared to the fuel-burn for the two fuels to determine the reserve fuel. As a reserve is essential, an increment of the study fuel is required so that the energy reserves of the study and reference fuels are equal This increment of 19.50kg is added to the excess burn of the study fuel of 51.36kg. The excess consumption is therefore 70.86kg. In order to land with 70.86kg more of the #2 fuel than it did, the aircraft must take off with 79.36kg more fuel, as some of the extra fuel loaded must be burned in order to carry the remainder; this is the tankering factor used in Figure 4. Fuel consumption ($\dot{W}$) is a function of weight (W). The model $\dot{W}=-a(\exp(bW))$ was assumed, and the parameters a and b were determined from the data at the beginning and end of cruise. It was then easily determined that this model fits the trajectory data very well throughout cruise. Solution of the differential equation shows that the fuel mass at the end of cruise, WT, is related to the fuel mass at the beginning of cruise, WO, by the relationship

$$\exp(-b(WT)) = abt + \exp(-b(WO))$$

where t, the duration of cruise, is available from the flight profile data. The rate of change of initial weight per unit final weight is now found to be $\partial WO/\partial WT = \dot{W}O/\dot{W}T$. Tankering was assumed to be restricted to cruise; this tends slightly to underestimate the effect. The relative cost is then determined by multiplying the required excess initial fuel weight by the cost of fuel, assumed to be approximately 57 cents per kilogram to determine the relative cost of fuel, $ 45.40, for the mission.

The cost of the heater plus heat is now considered; see Fig. 5. The weight of the heater required to keep the wing tank fuel temperature at 1.67 degrees C above its freezing temperature was determined. As most of the weight of the heater is due to the required pipes, pumps, and brackets, and relatively little is due to the heat exchanger, the weight is relatively insensitive to the fuel freezing temperature. The weight of the heater required for each study fuel was compared to the heater required for the reference fuel, if any. The difference was multiplied by the factor (Direct Operating Cost/Dry Weight) to generate the relative cost. In this computation, direct operating cost is the total cost of time plus the cost of fuel. The heater is assumed to be heated by burning fuel at 40% efficiency; the cost of heat is therefore the cost of the fuel burned for this purpose. This cost is very small. In this analysis it was assumed that the aircraft must be able to complete every assigned mission. The weight of the heater for the aircraft is thus determined for all missions by the long-range 0.3% probable cold day mission, which imposes the most severe requirements on the heater. Reference to Figure 1 shows that the cruise altitude atmospheric temperature difference between a 0.3% and a 2% probable cold day is small enough that it is not reasonable to reject the extreme cold day missions.

The second phase of data reduction is now considered.

Each of the two longer-range missions was simulated for a variety of probable-cold days, whose results were weighted-averaged to yield average relative costs for each of these two missions. These two longer-range average missions were used together with the mid-range and short-range nominal-temperature missions, defined in Table 1B, to enable linear interpolation and extrapolation of costs in each of the trip-range/trip-frequency sections shown in Table 1A. Probability (frequency) weighting of these various relative costs enables calculating the average mission, the average total cost of the reference fuel, and the relative costs of the several study fuels in the average mission. Finally, multiplication of the costs for each vehicle in the three classes by the annual number of missions and then by the population of each class yields the annual costs for each each vehicle and for the class. Summation then yields the costs for the fleet.

3. Results

Table 4 presents the total costs of the reference fuel and the relative costs of the study fuels in the statistically average trip, i.e., the average costs or relative costs statistically averaged over all the various missions. These costs are for a single vehicle in each class in 1982 dollars. Some comments are appropriate.

Fuel #5, "Reduced Flash", has lower aromatic content, higher heat of combustion, and lower freezing temperature than the reference fuel; it costs less to operate with this fuel. The relative costs are therefore all negative.

Fuels #2 and 3 differ only in their freezing temperatures. They are quite similar to the reference fuels and their relative costs are consequently small and similar. Fuels 4 and 6 differ sharply in all properties from the reference fuel; their relative costs reflect these differences. Fuel #6 is similar to the ERBS (Experimental Referree Broadened Specification) fuel, but with a higher aromatic content.

The product of the costs per average mission per vehicle, in Table 4, and the annual number of missions per vehicle, Table 2, enables calculating the annual relative costs of the various fuels per vehicle in 1980 and in 1990. These results appear in the top part of Tables 5, in 1982 dollars. Multiplication of the costs in Table 4 by the number of missions in each class enables calculation of the annual costs to the fleet class in 1980 and 1990. These fleet class annual costs appear in the lower part of Tables 5, in millions of 1982 dollars.

The total (relative) costs of the several classes are combined to form the estimated costs of the business turbine powered fleet. This result is shown in the upper part of Table 6, in millions of 1982 dollars. In the bottom row of Table 6 are presented the break-even costs of the study fuels: fuel #6 must cost only 92.1% of the reference fuel cost to yield the same total fleet cost in 1990.

The data of Table 6 may be analyzed to demonstrate the relative costs of the various properties of the study fuels. The results of this analysis appear in Figure 6. Increases of aromatic content strongly increase relative cost while decreases even more strongly decrease it. Changes of heat of combustion linearly affect the relative cost. The effect is of moderate strength, as the range of heats of combustion is relatively small; all the study fuels are quite energetic. As remarked above, the relative cost impact of fuel freezing temperature is very small; the operational problems of a fuel heater are probably of much greater importance than the direct cost impact.

4. Conclusions and Recommendations

Increasing aromatic content and decreasing heat of combustion are the two principal cost drivers for the 1990 business turbine powered fleet. Research in engine design and materials may prove useful in enabling future aircraft engines to tolerate the problems associated with increased aromatic content. Fuel freezing temperature is not a significant cost element; the flight safety and operational aspects of a fuel heater may be more important. Development of fuel freezing-point depressants, or additives which prevent fuel-fractionization and crystallization, are suggested.

5. References

1. "Military Standard: Climatic Extremes for Military Equipment", MIL-STD-210B, 15 December, 1973

2. "Turbine-Powered Business Aircraft", & "Turbofan/Turbojet Aircraft", and "Turboprop Aircraft", "Aviation Week and Space Technology", March 9, 1981

3. "Aircraft Forecast, Military and Civil", Forecast Associates, Ridgefield, Conn., November, '82

4. FAA Report No. FAA-MS-79-7, "General Aviation Pilot and Aircraft Survey", S. J. Pinciaro, December, 1979

5. National Business Aircraft Association, Inc., "Management Aids", Vol. XII, No. 3, May, 1983

6. M. Becker, private communication

7. Barnett, H. G., and Hibbard, R. R., "Properties of Aircraft Fuels", NACA Technical Note TN 3276, 1956

8. Longwell, J. P., "Alternative Aircraft Fuels", NASA Technical Memorandum TM-73836, 1978

9. Smith, M., "Aviation Fuels", G. T. Foulis & Co., 1970

10. Maxwell, J. B., "Data Book on Hydrocarbons", 2nd Edition, D. Van Nostrand, 1968

11. Prok, G. M., and Seng, G. T., "Initial Characterization of an Experimental Referee Broadened Specification (ERBS) Aviation Turbine Fuel", NASA Technical Memorandum TM-81440, 1980

12. Shelton, E. M., "Aviation Turbine Fuels", 1978, BETC/PPS-79-2, Bartlesville Energy Technology Center, Department of Energy, Bartlesville, Oklahoma, 1979

13. Shelton, E. M., "Aviation Turbine Fuels", 1980 DOE/BETC/PPS-81/2, Bartlesville Energy Technology Center, U.S. Dept. of Energy, Bartlesville, Oklahoma, 1981

14. Grobman, J., and Reck, G. M., "The Impact of Fuels on Aircraft Technology Through the Year 2000", NASA Technical Memorandum 81492, 1980

AIRCRAFT CLASS	AIRCRAFT CHARACTERISTICS		COST PER FLIGHT HOUR, EXCLUDING FUEL	
HEAVY JET	WEIGHT WING AREA RANGE	17600KG 47M^2 3510NM	ENGINE OTHER TOTAL	\$200 \$213 \$413
LIGHT JET	WEIGHT WING AREA RANGE	8300KG 24M^2 2900NM	ENGINE OTHER TOTAL	\$ 84 \$167 \$251
TURBO-PROP	WEIGHT WING AREA RANGE	4700KG 28M^2 2000NM	ENGINE OTHER TOTAL	\$ 52 \$ 80 \$132

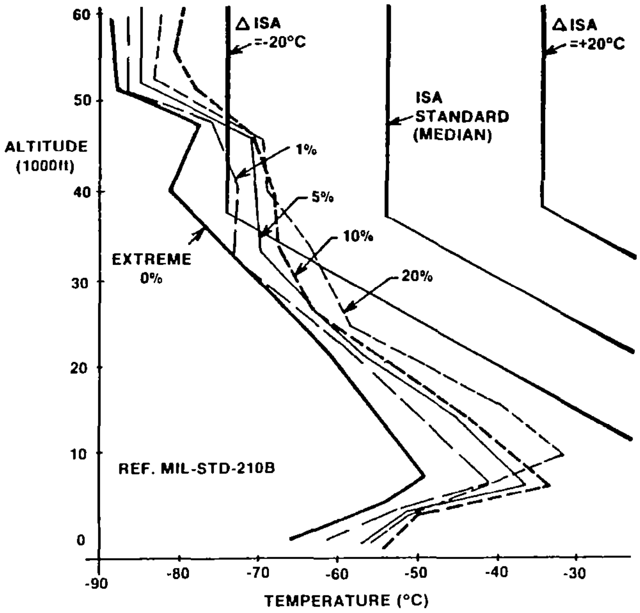


FIGURE 1
AIRCRAFT, DIRECT OPERATING COSTS & ATMOSPHERE

TABLE 1A
DATA: FLEET CLASS MISSION LENGTHS & FREQUENCY

FREQUENCY, PERCENT		5	10	15	20	20	20	10
MISSION LENGTHS, NAUT. MILES	HEAVY JET LIGHT JET	0-250	250-500	500-750	750-1,000	1,000-1,500	1,500-2,000	2,000+
	TURBO PROP	0-200	200-400	400-600	600-800	800-1,000	1,000-1,200	1,200+

TABLE 1B
STUDY MISSIONS

HEAVY JET	DIST. PAY LOAD FUEL	400NM 1340KG 1590KG	900NM 1340 2720	2000NM 1340 5590	2700 680 6650
LIGHT JET	DIST. PAY LOAD FUEL	400NM 1250KG 820KG	900 1250 1410	1500 1250 2530	2500 400 3370
TURBO PROP	DIST. PAY LOAD FUEL	300NM 620KG 450KG	800 620 1310		1600 620 1310

TABLE 2

AIRCRAFT CLASS & FLEET STATISTICS CLASS & FLEET POPULATION & MISSIONS

TIME-FRAME	CLASS	NO. IN CLASS	ANNUAL NO. OF MISSIONS	ANNUAL NO. OF MISSIONS PER VEHICLE	MILLIONS OF FLIGHT MILES PER ANNUM
1980	HEAVY JET	1,433	135,889	95	156
	LIGHT JET	2,790	264,808	95	304
	TURBO PROP	5,014	417,949	83	326
	FLEET	9,237	818,646	—	786
1990	HEAVY JET	2,907	301,394	104	346
	LIGHT JET	6,448	586,237	91	673
	TURBO PROP	13,731	925,641	67	722
	FLEET	23,086	1,813,272	—	1,741

TABLE 3

DATA: FUELS

ECONOMIC EFFECTS

WING-TANK FREEZING EFFECTS

FUEL #	FUEL "NAME"	PERCENT AROMATICS	HEAT OF COMBUSTION BTU/#	FREEZE POINT, /FLASH POINT °C	DENSITY #/FT^3	SPECIFIC HEAT $\frac{BTU}{\#}$/°R @ 60°F	ABS. VISCOSITY $\frac{\#/FT}{MIN}$ @ 60°F	TRUE VAPOR PRESSURE PSI, @ 100°F
1	REFERENCE JET A	17.5	18574	-44/55	50.70	0.463	0.0655	0.208
2	SPEC.-LIMIT JET A	20.0	18400	-40/37.8	52.39	0.452	0.0947	0.407
3	"HIGH FREEZE POINT"	20.0	18400	-35/60	52.39	0.452	0.0998	0.090
4	"HIGH AROMATIC"	30.0	18275	-31.7/57.8	52.39	0.425	0.0998	0.116
5	REDUCED FLASH	16.0	18620	-55/30	49.89	0.465	0.0612	1.02
6	SPECIAL	35.0	18275	-28.9/60	52.39	0.420	0.0812	0.100

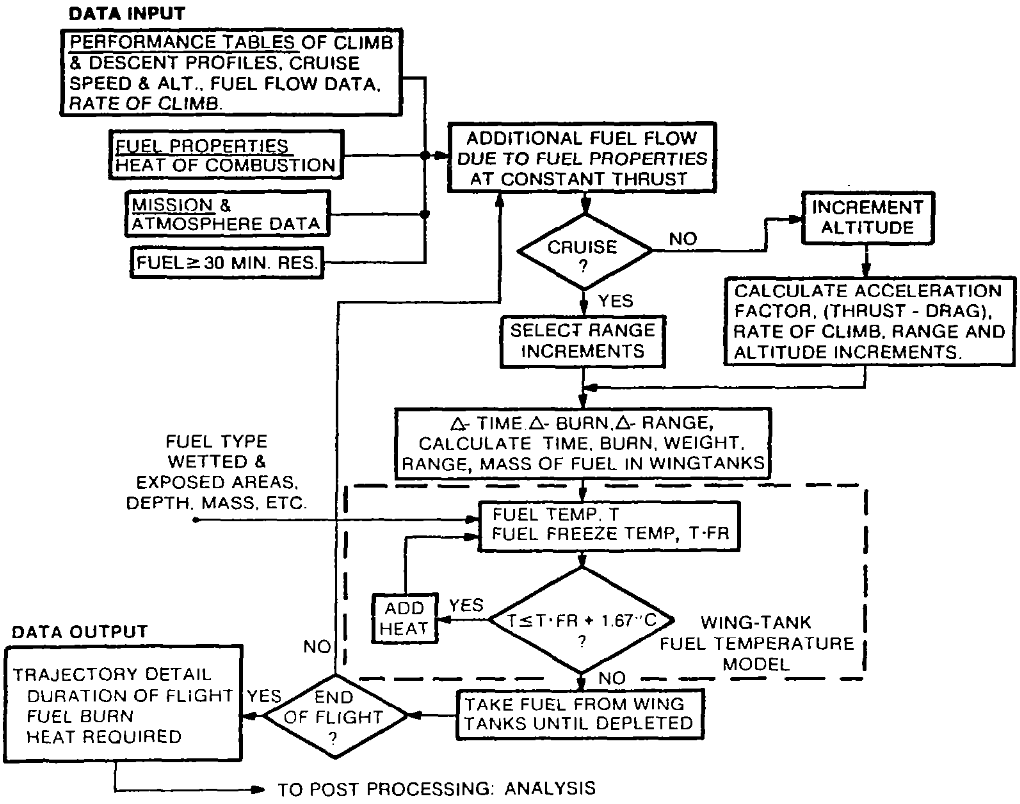


FIGURE 2
MATH MODEL – FLIGHT-PROFILE SIMULATOR

#	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT WEIGHT, KG	RELATIVE COST OF TIME
1	REFERENCE FUEL - 17.5% AROMAT	6.055	4597	0.00	0.00	
2	JET-A SPEC. LIM. 20.0% AROMAT.	6.055	4648	8.84	0.10	$32.70

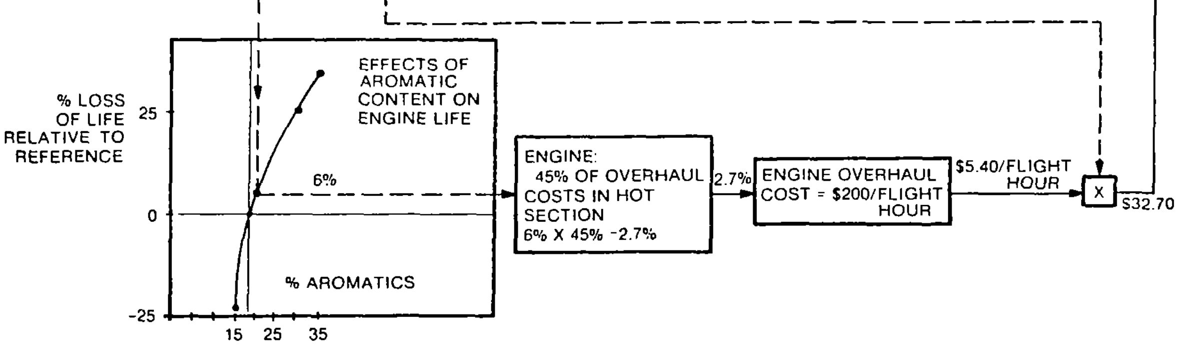
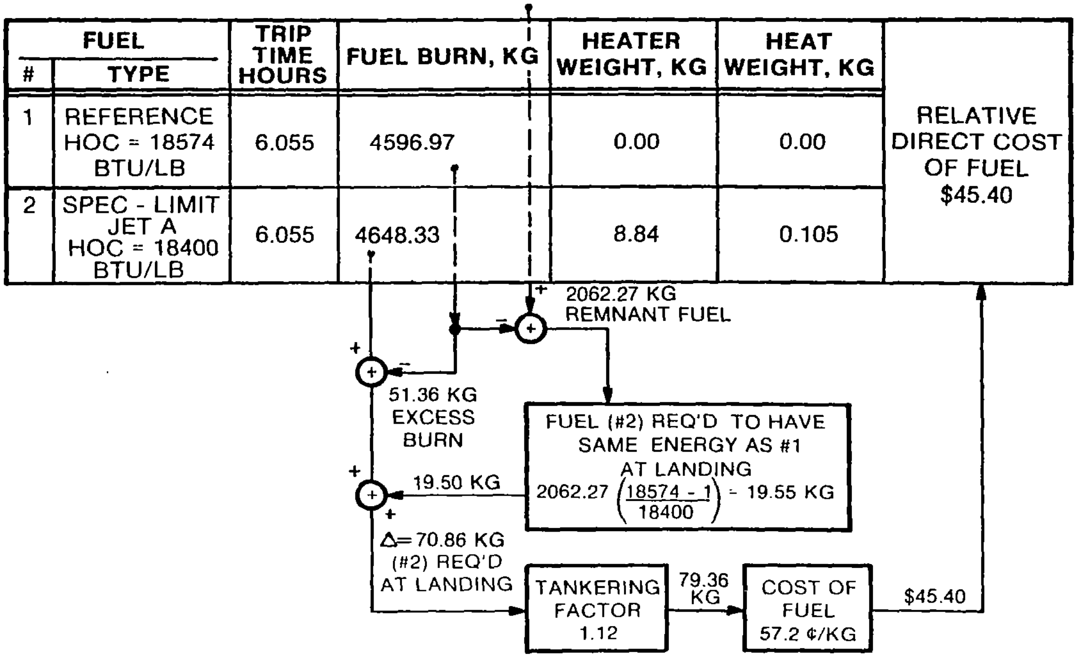


FIGURE 3

RELATIVE COST OF AROMATIC CONTENT
HEAVY JET, 2700NM MISSION, 0.3% PROBABLE — COLD DAY.

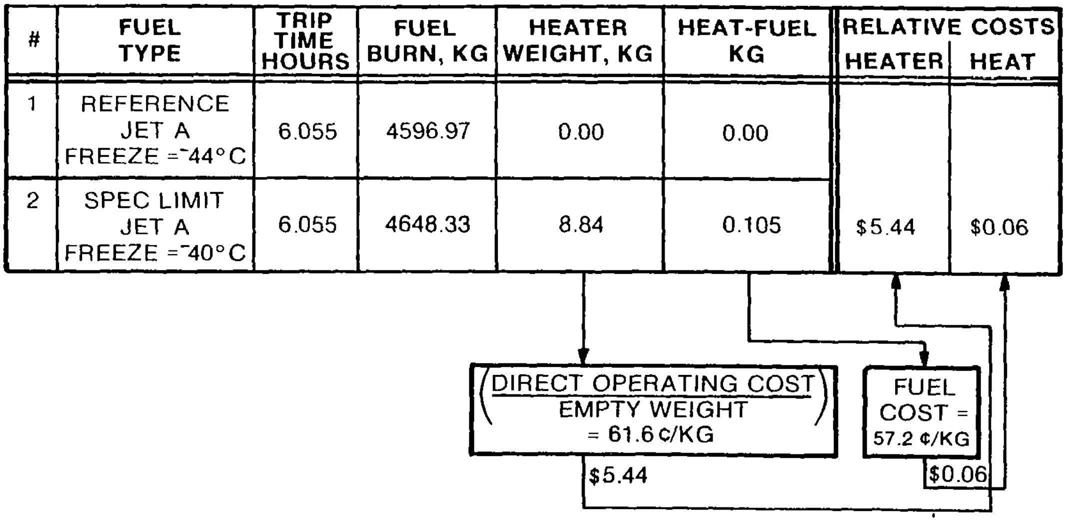
HEAVY JET, 2700 NM MISSION, 0.3% PROBABLE - COLD DAY,
FUEL LOAD 6659.1 KG



FUEL #	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT WEIGHT, KG	
1	REFERENCE HOC = 18574 BTU/LB	6.055	4596.97	0.00	0.00	RELATIVE DIRECT COST OF FUEL $45.40
2	SPEC - LIMIT JET A HOC = 18400 BTU/LB	6.055	4648.33	8.84	0.105	

FIGURE 4
RELATIVE COST OF HEAT OF COMBUSTION

HEAVY JET, 2700 NM TRIP, 0.3% COLD DAY



#	FUEL TYPE	TRIP TIME HOURS	FUEL BURN, KG	HEATER WEIGHT, KG	HEAT-FUEL KG	RELATIVE COSTS HEATER	RELATIVE COSTS HEAT
1	REFERENCE JET A FREEZE = −44°C	6.055	4596.97	0.00	0.00		
2	SPEC LIMIT JET A FREEZE = −40°C	6.055	4648.33	8.84	0.105	$5.44	$0.06

FIGURE 5
RELATIVE COST OF FREEZING TEMPERATURE

TABLE 4
COST PER AVERAGE MISSION

CLASS & AVERAGE TRIP DISTANCE	TOTAL COSTS	RELATIVE COST OF STUDY FUELS				
	1. REFERENCE	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
	% AROM = 17.5 HOC = 18574 TF = -44°C	% AROM = 20.0 HOC = 18400 TF = -40°C	% AROM = 20.0 HOC = 18400 TF = -35°C	% AROM = 30.0 HOC = 18275 TF = -31.7°C	% AROM = 16.0 HOC = 18620 TF = -55°C	% AROM = 35.0 HOC = 18275 TF = -28.9°C
HEAVY JET 1230NM	T:$ 1168.26	15 27	15 27	66.23	-58.59	89.18
	F:$ 1540 35	20.62	20 62	35.68	-5.39	35 68
	H:$ 0 00	2 64	2 67	2.70	0.00	2.73
	Σ:$ 2708.61	38 53	38 56	104.61	-63.98	127 59
LIGHT JET 1170NM	714.67	6 47	6.47	30 54	-24.79	37.73
	847 01	10 72	10.72	18.37	-3.18	18.37
	3.13	0 01	0.03	0.07	-3.13	0.09
	1564.81	17.20	17.22	48.98	-31.10	56.19
TURBO PROP 816NM	418.58	4.44	4.44	19.28	-17.07	25.95
	353 84	5 34	5.34	9.25	-1.42	9.25
	2.53	0 01	0.09	0.08	-0.06	0.11
	774.95	9.79	9.87	28 61	-18.55	35.31

T: (RELATIVE) COST OF TIME
F: (RELATIVE) COST OF FUEL
H: (RELATIVE) COST OF HEATER & HEAT
Σ: (RELATIVE) TOTAL COST

TABLE 5A
TOTAL COST OF REFERENCE FUEL AND RELATIVE COSTS OF STUDY FUELS FOR AIRCRAFT CLASS, PER VEHICLE AND PER FLEET CLASS.
(1982 DOLLARS)

FUELS AND PROPERTIES	TOTAL COSTS	RELATIVE COST OF STUDY FUELS				
	1. REFERENCE	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
	% AROM = 17.5 HOC = 18574 TF = -44°C	% AROM = 20.0 HOC = 18400 TF = -40°C	% AROM = 20.0 HOC = 18400 TF = -35°C	% AROM = 30.0 HOC = 18275 TF = -31.7°C	% AROM = 16.0 HOC = 18620 TF = -55°C	% AROM = 35.0 HOC = 18275 TF = -28.9°C
ANNUAL COSTS PER VEHICLE IN 1980	T:$ 110,984	1451	1451	6292	-5566	8472
	F:$ 146,069	1959	1959	3390	-512	3390
	H:$ 0	250	253	256	0	259
	Σ:$ 257,053	3660	3663	9938	-6078	12121
AND 1990 IN 1982 DOLLARS	121,499	1580	1580	6888	-6093	9275
	160,196	2144	2144	3711	-561	3711
	0	274	277	281	0	284
	281,695	3998	4001	10880	-6654	13270
ANNUAL COSTS IN THE FLEET CLASS IN 1980	158 75	2 08	2.08	9.00	-7.96	12.12
	209.32	2.80	2.80	4 85	-0.73	4.85
	0.00	0.36	0.36	0.37	0	0.37
	368.07	5.24	5.24	14.22	-8.69	17.34
AND 1990 IN MILLIONS OF 1982 DOLLARS	352.11	4.60	4.60	19.96	-17.66	26.88
	464.25	6.21	6.21	10.75	-1.62	10.75
	0.00	0.80	0.80	0.81	0	0.82
	816.36	11.61	11.61	31.52	-19.28	38.45

FLEET CLASS:
HEAVY JET

T: (RELATIVE) COST OF TIME
F: (RELATIVE) COST OF FUEL
H: (RELATIVE) COST OF HEATER & HEAT
Σ: (RELATIVE) TOTAL COST

TABLE 5B

TOTAL COST OF REFERENCE FUEL AND RELATIVE COSTS OF STUDY FUELS FOR AIRCRAFT CLASS, PER VEHICLE IN DOLLARS AND PER FLEET SEGMENT IN MILLIONS OF DOLLARS. (1982 DOLLARS)

FUELS AND PROPERTIES	TOTAL COSTS	RELATIVE COST OF STUDY FUELS				
	1. REFERENCE	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
	% AROM = 17.5 HOC = 18574 TF = -44°C	% AROM = 20.0 HOC = 18400 TF = -40°C	% AROM = 20.0 HOC = 18400 TF = -35°C	% AROM = 30.0 HOC = 18275 TF = -31.7°C	% AROM = 16.0 HOC = 18620 TF = -55°C	% AROM = 35.0 HOC = 18275 TF = -28.9°C
ANNUAL COSTS PER VEHICLE IN 1980	T:$ 67831	614	614	2661	-2353	3581
	F:$ 80392	1017	1017	1781	-302	1781
	H:$ 297	1	3	7	-297	9
	Σ:$ 148520	1632	1634	4449	-2952	5371
AND 1990 IN 1982 DOLLARS	66976	588	588	2549	-2254	3430
	77008	974	974	1706	-289	1706
	285	1	3	6	-285	8
	142269	1563	1565	4261	-2828	5144
ANNUAL COSTS IN THE FLEET CLASS IN 1980	189 25	1 71	1.71	7 43	-6.56	10.00
	224 30	2.84	2 84	4 97	-0.84	4 97
	0 83	0 00	0.01	0.02	-0 83	0 02
	414 38	4 55	4 56	12 42	-8 23	14 99
AND 1990 IN MILLIONS OF 1982 DOLLARS	418 97	3.79	3.79	16 44	-14 53	22 12
	496 55	6 28	6 28	11 00	-1 86	11 00
	1 83	0 01	0 02	0.04	-1 83	0 05
	917 35	10.08	10.09	27.48	-18 22	33 17

FLEET CLASS:
LIGHT JET

T: (RELATIVE) COST OF TIME
F: (RELATIVE) COST OF FUEL
H: (RELATIVE) COST OF HEATER & HEAT
Σ: (RELATIVE) TOTAL COST

TABLE 5C

TOTAL COSTS OF REFERENCE FUEL AND RELATIVE COSTS OF STUDY FUELS FOR AIRCRAFT CLASS, PER VEHICLE IN DOLLARS AND PER FLEET SEGMENT IN MILLIONS OF DOLLARS (1982 DOLLARS)

FUELS AND PROPERTIES	TOTAL COSTS	RELATIVE COST OF STUDY FUELS				
	1. REFERENCE	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
	% AROM = 17.5 HOC = 18574 TF = -44°C	% AROM = 20.0 HOC = 18400 TF = -40°C	% AROM = 20.0 HOC = 18400 TF = -35°C	% AROM = 30.0 HOC = 18275 TF = -31.7°C	% AROM = 16.0 HOC = 18620 TF = -55°C	% AROM = 35.0 HOC = 18275 TF = -28.9°C
ANNUAL COSTS PER VEHICLE IN 1980	T:$ 34891	370	370	1607	-1423	2163
	F:$ 29495	445	445	771	-118	771
	H:$ 211	1	8	7	-5	9
	Σ:$ 64597	816	823	2385	-1546	2943
AND 1990 IN 1982 DOLLARS	28218	299	299	1300	-1151	1749
	23853	360	360	624	-96	624
	171	1	6	5	-4	7
	42242	660	665	1929	-1251	2380
ANNUAL COSTS IN THE FLEET CLASS IN 1980	174.95	1.86	1.86	8.06	-7.13	10 85
	147.89	2.23	2.23	3.87	-0.59	3.87
	1.06	0 00	0 04	0 03	-0 03	0 05
	323.90	4 09	4.13	11.96	-7.75	14.77
AND 1990 IN MILLIONS OF 1982 DOLLARS	387.45	4.11	4.11	17.85	-15 80	24.02
	327 53	4.94	4.94	8.56	-1 31	8 56
	2 34	0 01	0 08	0 07	-0 06	0.10
	717 32	9 06	9.13	26 48	-17.17	32 68

FLEET CLASS:
TURBO PROP

T: (RELATIVE) COST OF TIME
F: (RELATIVE) COST OF FUEL
H: (RELATIVE) COST OF HEATER & HEAT
Σ: (RELATIVE) TOTAL COST

TABLE 6

TOTAL FLEET COST OF REFERENCE FUEL AND TOTAL FLEET RELATIVE COSTS OF STUDY FUELS IN 1980 AND 1990 IN MILLIONS OF 1982 DOLLARS, AND BREAKDOWN COSTS.

FUELS AND PROPERTIES	TOTAL COSTS	RELATIVE COST OF STUDY FUELS				
	1. REFERENCE	2. SPEC LIMIT	3. HI-FREEZE	4. HI-AROM	5. REDUCED FLASH	6. SPECIAL
	% AROM = 17.5 HOC = 18574 TF = -44°C	% AROM = 20.0 HOC = 18400 TF = -40°C	% AROM = 20.0 HOC = 18400 TF = -35°C	% AROM = 30.0 HOC = 18275 TF = -31.7°C	% AROM = 16.0 HOC = 18620 TF = -55°C	% AROM = 35.0 HOC = 18275 TF = -28.9°C
1980	T: $ 523 F: $ 582 H: $ 2 Σ: $ 1107	5.65 7.87 0.36 13.88	5.65 7.87 0.39 13.91	24.48 13.69 0.42 38.59	-21.65 -2.16 -0.86 -24.67	32.97 13.69 0.44 47.10
1990	1159 1288 4 2451	12.50 17.43 0.82 30.75	12.50 17.43 0.90 30.83	54.25 30.31 0.92 85.48	-47.99 -4.79 -1.89 -54.67	73.02 30.31 0.97 104.30
STUDY FUELS BREAKEVEN COSTS, 1990, AS A PERCENT OF THE REFERENCE FUEL	100.0	97.6	97.6	93.5	104.3	92.1

T: (RELATIVE) COST OF TIME
F: (RELATIVE) COST OF FUEL
H: (RELATIVE) COST OF HEATER & HEAT
Σ: (RELATIVE) TOTAL COST

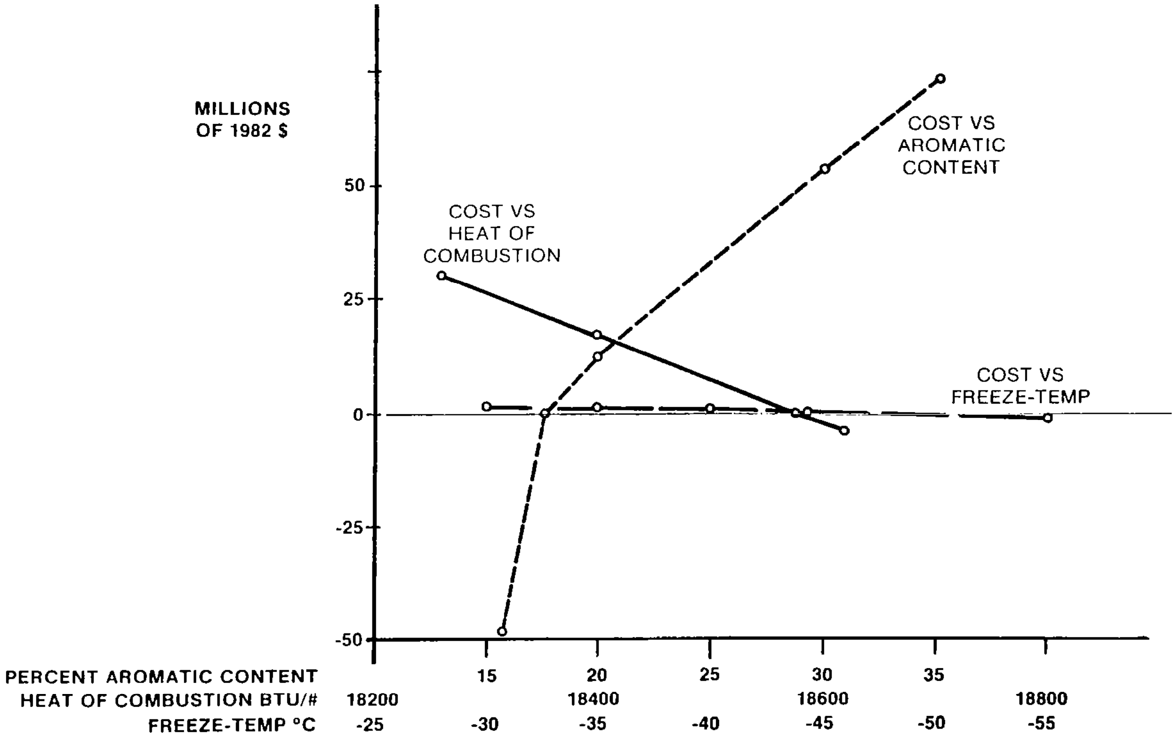


FIGURE 6

ANNUAL RELATIVE COSTS TO BUSINESS FLEET OF VARIOUS FUEL PROPERTIES IN 1990.

FUEL PROPERTY EFFECTS ON NAVY AIRCRAFT FUEL SYSTEMS

C.A. Moses
Southwest Research Institute

The U.S. Navy is experiencing pressures to modify the JP5 fuel specification because of the growing shortage of high-quality crude oils from which kerosene can be simply distilled and the increased costs of refining lesser-quality crude oils to meet the current specifications. These changes in refining techniques can yield a finished fuel that, in general, could have somewhat different physical and chemical properties than virgin distillate. The pending introduction of synfuels derived from shale oil, perhaps tar sands and even coal liquids, implies even greater changes in fuel properties. The Navy is therefore faced with the problem of ensuring compatibility of its aircraft with fuels that may be different than the fuels for which the equipment was designed and qualified. Requalification of all of the engines and airframe fuel systems would be prohibitively expensive. A program is therefore underway to develop a methodology to qualify future fuels by using bench-scale and component testing to minimize the full-scale engine/airframe testing otherwise required to ensure compatibility.

A related problem is the temporary use of non-specification fuels in an emergency to alleviate fuel shortages. In both cases, it is important to understand how fuel properties affect hardware performance, durability, and reliability. In this case, though, the information is necessary to know how best to use the off-spec fuel and what the potential impact will be for a relatively small number of flights.

Fuel related problems can be categorized into two areas: combustion and non-combustion problems. Combustion problems would include soot formation and ignition/altitude relight. This presentation is concerned with the non-combustion problems of:

- materials compatibility,
- thermal stability, and
- lubricity

The discussion is basically a summary of the current efforts at SwRI to support the aforementioned development of the Navy's Alternate Test Procedure (ATP) to qualify future Navy aircraft fuels.

Materials Compatibility

Jet fuels have traditionally been composed of saturates and aromatic hydrocarbons. The aromatics act as solvents to some kinds of elastomeric materials, especially nitrile rubbers, e.g., Buna N. One of the limits on JP5 production in some areas is the aromatic content, currently controlled to less than 25 percent. Figure 1 reproduces some data from Navy and Air Force studies of several years ago that suggests that the higher molecular weight aromatics found in JP5 have less solvent activity than those found in JP4 and the jet reference fuel which is 30% toluene/70% iso-octane. Thus there may be an opportunity for relaxing the aromatic limit without sacrificing compatibility. Another concern is that if fuel chemistry is changing, are aromatics the only constituents that need to be controlled? The preliminary data in Figure 2 addresses both questions. Fuel blends with increasing JP5-type aromatic concentration are seen to produce less volume swell than an equivalent aromatic concentration in the reference fuel. Furthermore, blends with naphthenes, decalin, tetralin, and naphthalenes do not deviate significantly from the correlation line of aromatic blends. Similar results are found with tensile strength and elongation. Other elastomers, sealants, and adhesives are also being tested.

Lubricity

Hydrotreating is used by refineries to eliminate sulfur and reduce the aromatic content of fuels. In doing so, it removes those compounds in the fuel which contribute to the lubricity of the fuel. While there are lubricity additives available, some users are reluctant to use them; also they tend to disappear during shipping and storage. There have already been some flight problems in both the military and civilian sectors, and with the tendency to hydrotreat increasing, there may be more problems.

There are no controls on fuel lubricity. The two tests which are being actively developed are the ball-on-cylinder machine (BOCM or BOCLE) and the Lucas dwell tester. Neither has been related to fuel pump lubricity requirements. The SwRI effort has been to try to relate the BOCM results to actual wear or distress in gear-type fuel pumps. Figure 3 compares gear distress after 100 hours of operation at the flow rates and pressure for maximum power of that engine; the gears in the upper photograph were run on a fuel with good lubricity (BOCM wear scar = 0.4 mm) while a low lubricity fuel was used in the lower one (BOCM wear scar = 0.6 mm). The upper photograph shows no distress at all; in fact, the original horizontal grinding marks are still evident. In the lower picture, considerable "scuffing" occurred as evidenced by the vertical lines that are visible. Between the vertical scuff lines and the horizontal grinding marks is an area of "wear." Figure 4 presents a correlation between the degree of "scuff" present at the BOCM rating of the fuel. This is the first known attempt at relating fuel lubricity to pump distress, and indicates that the BOCM method does measure lubricity in an appropriate manner. Other work remains since not all pumps would have the same lubricity requirement; also it is important to know whether the BOCM appreciates additives in the same way that pumps do.

Thermal Stability

The above problems are considered important for specification fuels. Thermal stability should be adequately controlled except when off-spec fuels might be used in emergencies. The major impact area is considered to be in the atomizer where deposits can plug small orifices or cause flow divider valves to stick. This in turn would alter fuel flow rates to different atomizers thus degrading the exhaust temperature pattern factor and reducing the life of the turbine blades.

Thermal stability is controlled by the JFTOT procedure; however, this is a pass/fail test and gives no quantitative information which can be related to fouling life of hardware. Recently procedures have been developed to determine a so-called "break-point temperature" using successive JFTOT runs at various temperatures to detemine the temperature which produces a deposit rating. Hot fuel nozzle fouling tests are being conducted under subcontract to General Electric to supplement earlier work by the Air Force in this area. By the end of the program, data will have been generated on at least a dozen different atomizers including simplex and duplex pressure atomizers and air-blast atomizers. Figure 5 presents a typical relationship between a parameter involving the breakpoint temperature and the operating temperature of the fuel with the relative fouling life of the primary and secondary orifices as well as the flow divider valve. As would be expected, when the breakpoint temperature approaches the operating temperature, the deposition rates increase and life is reduced. A data base such as this can be used to determine the impact of using a fuel of low thermal stability.

Summary

These problem areas are considered the most important non-combustion problems with future aircraft fuels. While this data is being generated for application to JP5 and Navy aircraft, these problems are considered universal to all aviation systems. The severity and the solutions may vary according to fuel type, however.

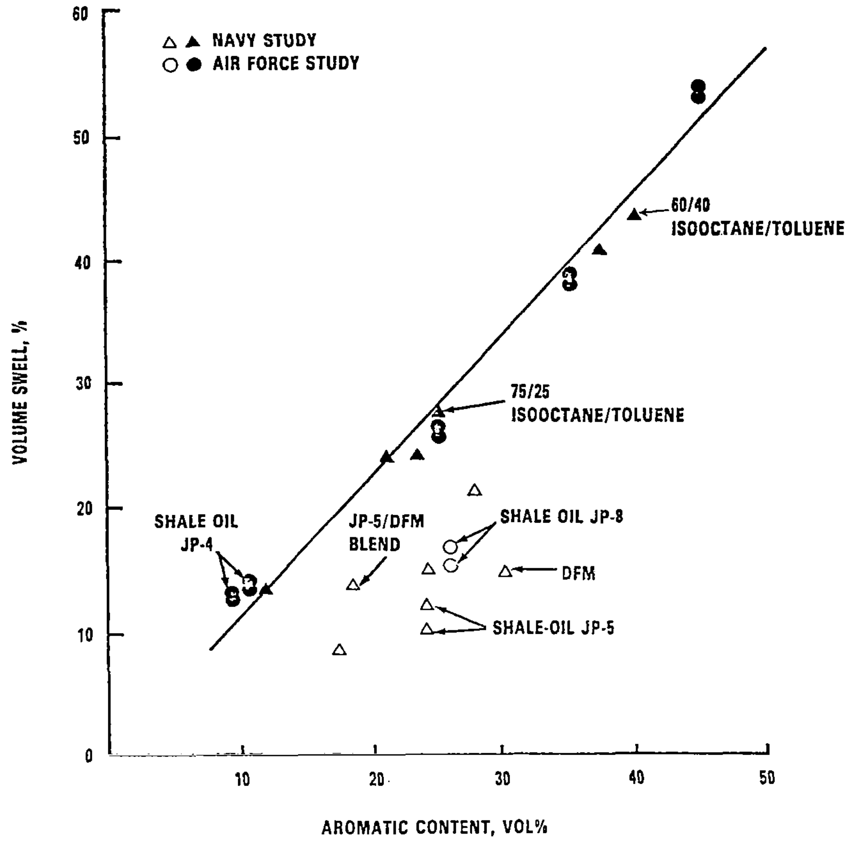


FIGURE 1. EFFECT OF AROMATIC CONTENT ON VOLUME SWELL OF BUNA-N

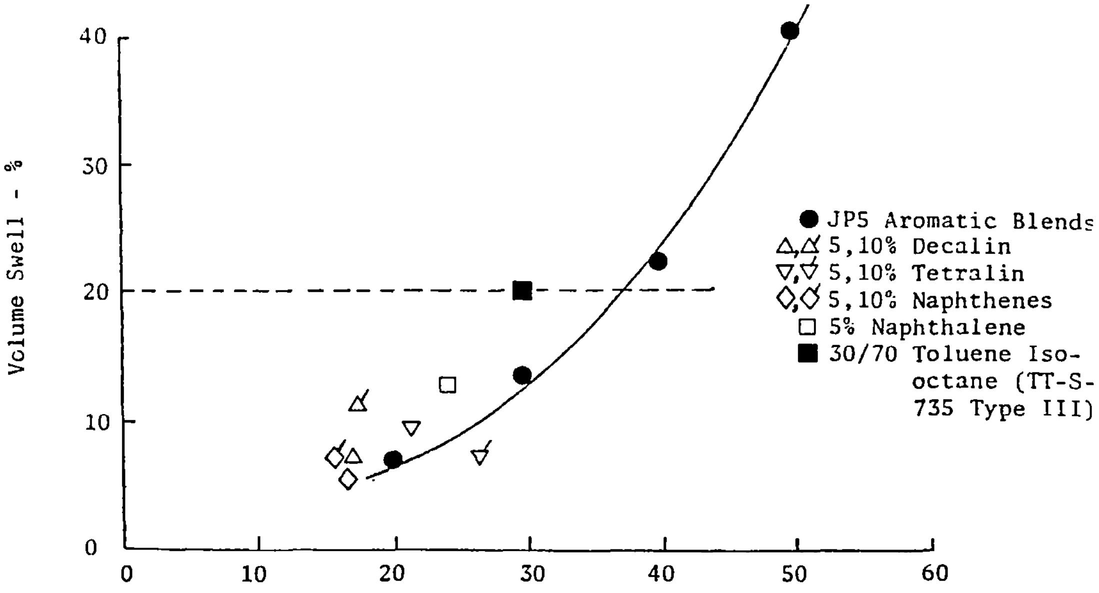
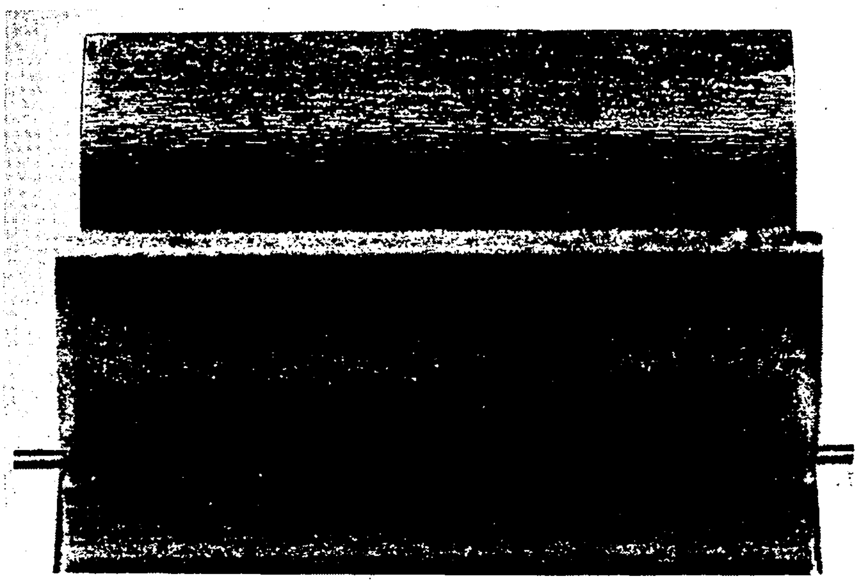
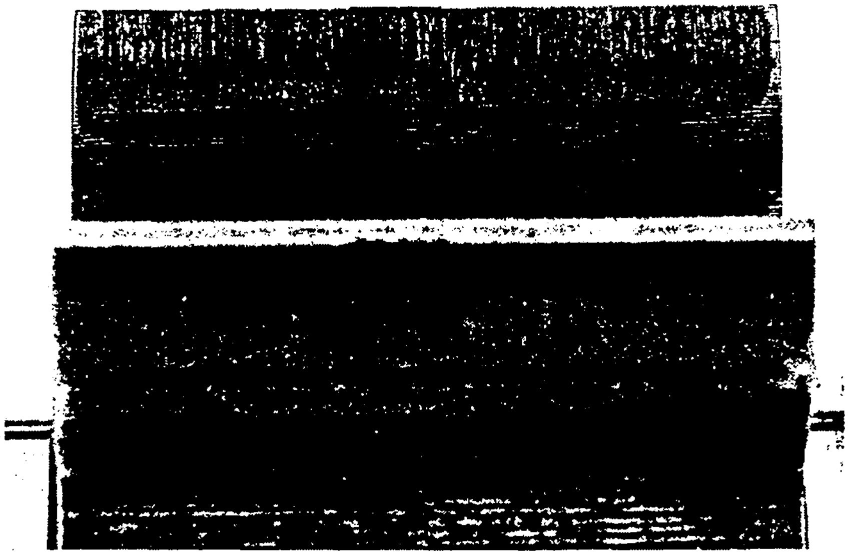


FIGURE 2. EFFECT OF JP5 AROMATIC CONTENT ON LOW-NITRILE BUNA-N



Good Lubricity



Low Lubricity

FIGURE 3. COMPARISON OF FUEL PUMP GEARS OPERATED ON DIFFERENT LUBRICITY FUELS

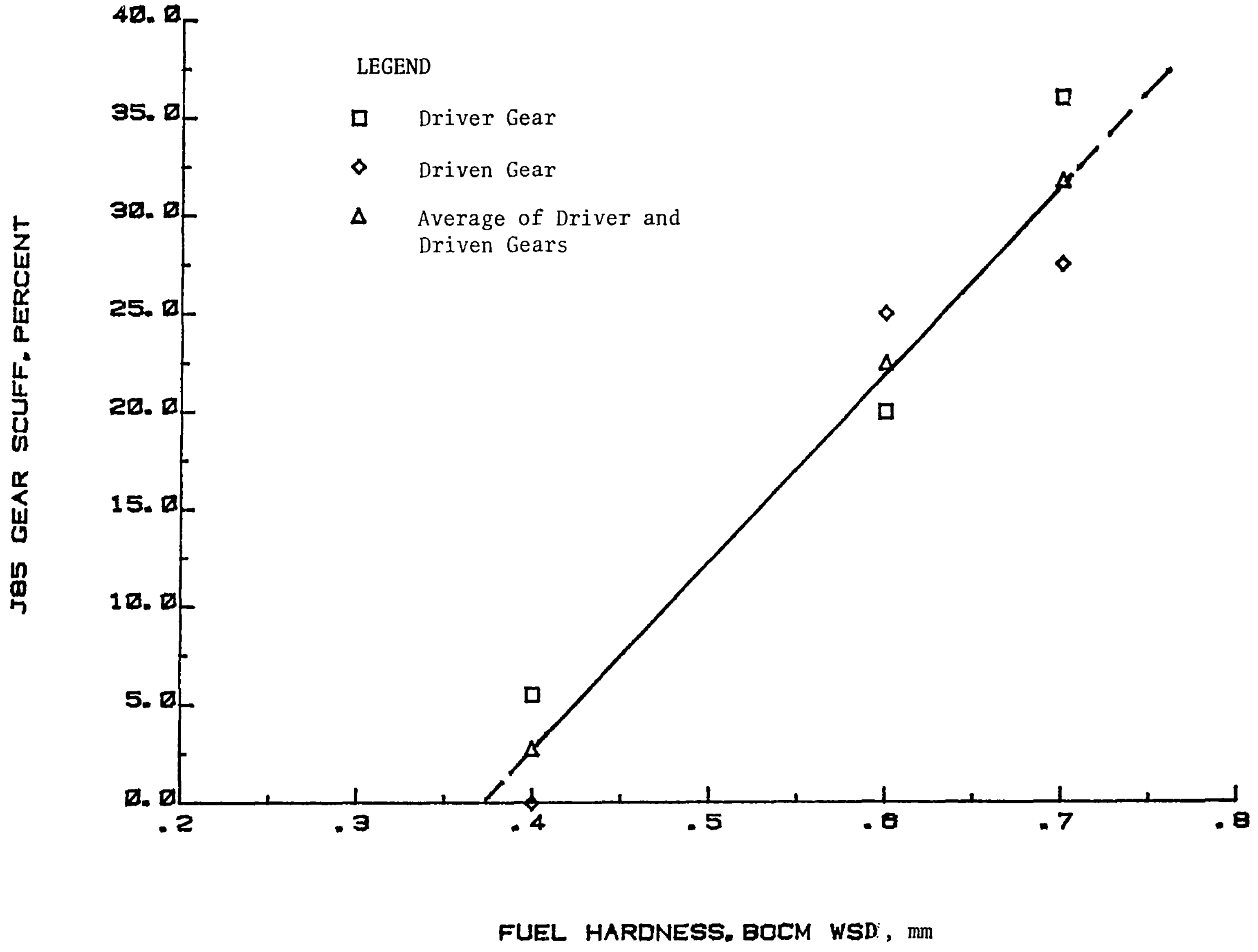


FIGURE 4. EFFECT OF FUEL HARDNESS ON J85 FUEL PUMP GEAR SCUFFING

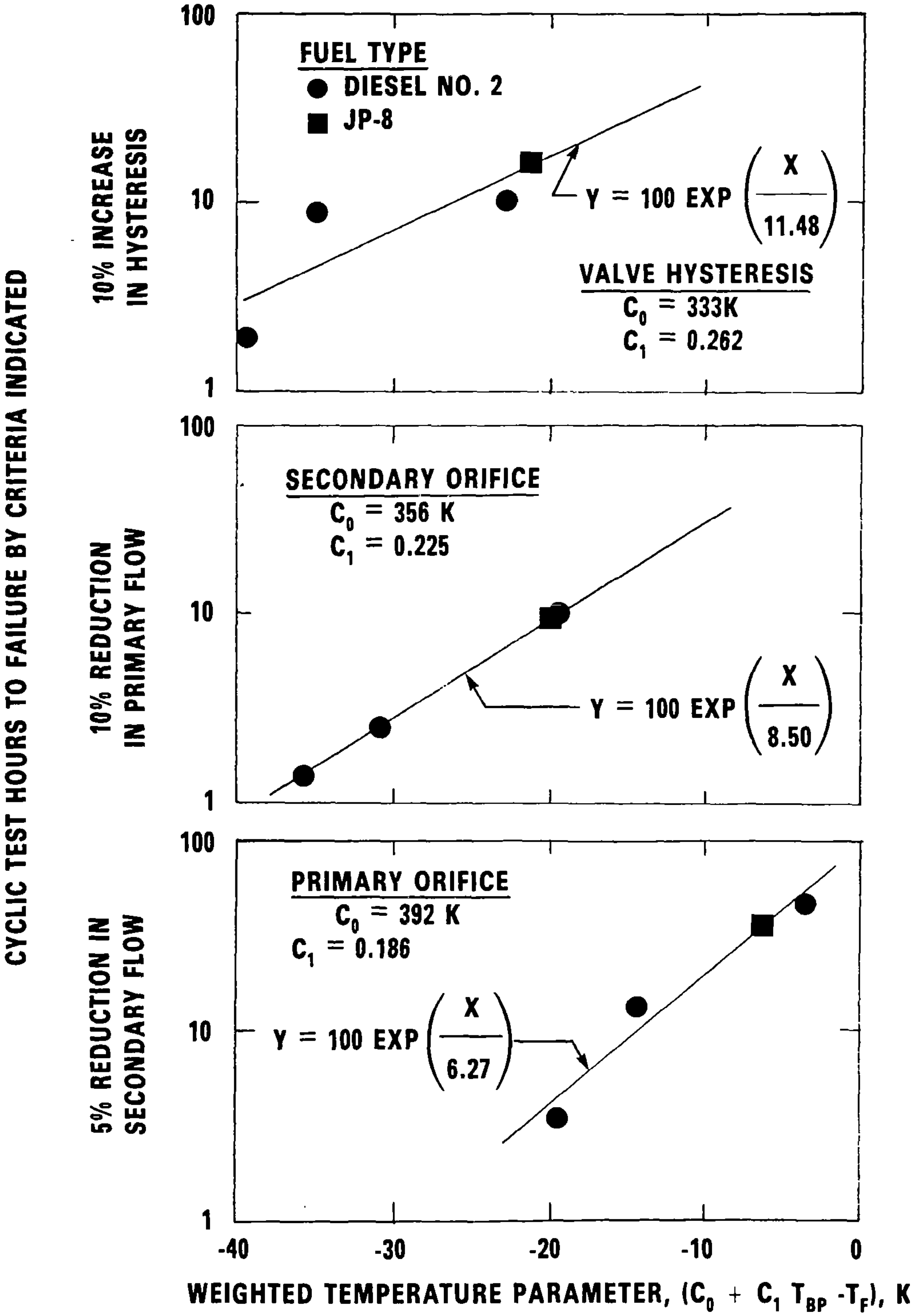


FIGURE 5. CORRELATION OF J79-17A FUEL NOZZLE FOULING TEST RESULTS

CHALLENGES FOR FUTURE FUELS RESEARCH AND TECHNOLOGY

Rick Rudey, Moderator, NASA Lewis Research Center
Don Bahr, General Electric Company
Don Dix, Department of Defense
Dick Linn, American Airlines
Jack Longwell, MTI
Howard Skavdahl, Boeing

Oral presentations only.

1. Report No. NASA CP-2307	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

Assessment of Alternative Aircraft Fuels

5. Report Date
April 1984

6. Performing Organization Code
945-05-31

7. Author(s)

8. Performing Organization Report No.
E-1878

10. Work Unit No.

9. Performing Organization Name and Address

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Conference Publication

12. Sponsoring Agency Name and Address

National Aeronautics and Space Administration
Washington, D.C. 20546

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The purpose of this symposium, at the Lewis Research Center on November 2-3, 1983, was to review the expected availability and quality of future aviation turbine fuels including recent technical results, and a status review of DOD and NASA sponsored fuels research projects. Technical presentations were made by representatives from industry, the Air Force, and NASA. The topics covered included the possible characteristics of future fuels, the effects of changing fuel characteristics on the performance and durability of jet aircraft components and systems, and the prospects for evolving suitable technology to produce and use future fuels.

17. Key Words (Suggested by Author(s))

Aircraft fuels
Combustion chambers
Refining
Shale oil
Freezing point
Thermal stability
Combustion products

18. Distribution Statement

Unclassified - unlimited
STAR Category 07

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of pages**	**22. Price***
Unclassified	Unclassified	195	A09

*For sale by the National Technical Information Service, Springfield, Virginia 22161