

NASA Conference Publication 2146

**Aircraft Research
and Technology
for Future Fuels**

A Symposium held at
Lewis Research Center
Cleveland, Ohio
April 16-17, 1980

NASA

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FUTURE AVIATION FUELS OVERVIEW

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This initial session focuses on the outlook for aviation fuels through the turn of the century and beyond. This is certainly an ambitious topic considering the turbulence in the fuel supply industry during the 1970's and the uncertainties in future petroleum supplies, syncrude production, alternative energy sources, product demand, and Government regulation or intervention. However, the aviation community must address this topic if the continued health and growth of the air transportation industry is to be assured.

The general objectives of the NASA Lewis Alternative Aviation Fuels Research Program are to evaluate the potential characteristics of future jet aircraft fuels, to determine the effects of those fuels on engine and fuel system components, and to evolve component technology to use those fuels. The general structure of the program is illustrated in figure 1. The element labeled "identification of future fuels" encompasses activities to determine the range of probable properties of future fuels and to examine the effect of varying fuel properties on the fuel supply system. This element encompasses most of the activities in the program which are appropriate to this session. The activities directed toward identifying the effects of broadened-property fuels on aviation systems and evolving technology to use those fuels are separated into two elements, fuel system R&T and combustion R&T. Both of these R&T efforts rely on the "fuels and combustion fundamentals" activities for supporting research. The R&T and fundamentals elements will be described in subsequent sessions. The final element, consisting of systems analysis studies, is the culmination of the program. These will involve extensive economic and engineering trade-off studies to evaluate the effects of changing fuel properties on the overall fuel production and air transportation system.

A breakdown of the future fuels element, shown in figure 2, indicates four subelements or targets. The first of these is directed toward determining the range of probable properties of future fuels. Within this target an experimental in-house study is under way to investigate the effect of processing technique and severity on the characteristics of jet fuels produced from synthetic crudes. The in-house refinery studies have used a refinery model (ref. 1) assembled under a contract with Gordian Associates to study the effect of feedstock quality, refinery configuration, and product specifications on yield (ref. 2). An extension of this work will examine trends in aviation fuel refinery yields, cost, and energy consumption. A more extensive modeling activity has been under way at the University of California at Los Angeles for several years to generate projections of jet fuel supply and demand (ref. 3). This work will be described in a paper

later in this session. Eventually we plan to couple the refining and processing studies with studies of the effects of future fuels on aircraft and engine systems to identify trade-offs associated with changes in fuel properties.

The objective of the second target shown in figure 2 is to evolve improved correlations of fuel structure or composition with physical and chemical characteristics. The Colorado School of Mines is nearing completion of a research program to study correlations between organic nitrogen compounds and storage and thermal stability. This program as well as in-house studies in the area of thermal stability will be described in Session IV. With regard to physical properties, a research program was recently initiated at the Massachusetts Institute of Technology to derive improved correlations of freezing point and viscosity with fuel composition.

The third target in figure 2, analytical methods, consists of activities to identify and solve problems in characterizing broadened-property fuels. This work will also be described in a paper later in this session.

The final target involves the acquisition of test fuels which will be used throughout the various in-house and contracted fuels research projects. A workshop was held at the Lewis Research Center in 1977 to identify a referee fuel with broadened properties which could be used in test programs (ref. 4). This fuel, designated the experimental referee broadened-specification fuel or ERBS fuel has been procured and is described and characterized in reference 5. In addition, blending stock has been identified which can be blended with the ERBS fuel to produce a variation in hydrogen content with a minimal effect on other fuel properties.

The papers in this session cover a range of topics from current fuel trends to forecasts of future fuels and the utilization of shale-derived syncrudes. The presenters include representatives of nearly every major sector of the aviation fuel community, the fuel suppliers, the manufacturers, the airlines, and the Government. The material presented should not only identify the status and results of current activities, but also highlight areas where additional research is needed.

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AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS

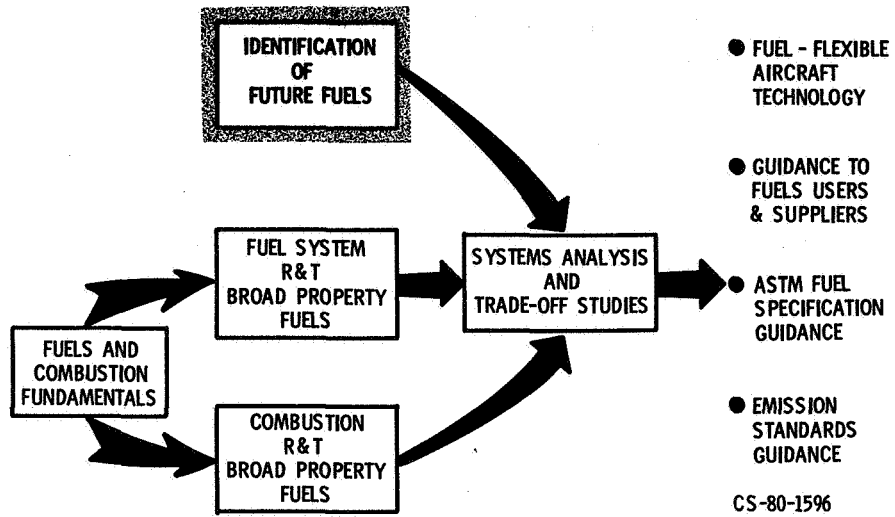


Figure 1

NASA LEWIS ACTIVITIES DIRECTED TOWARD IDENTIFICATION OF FUTURE AVIATION FUELS

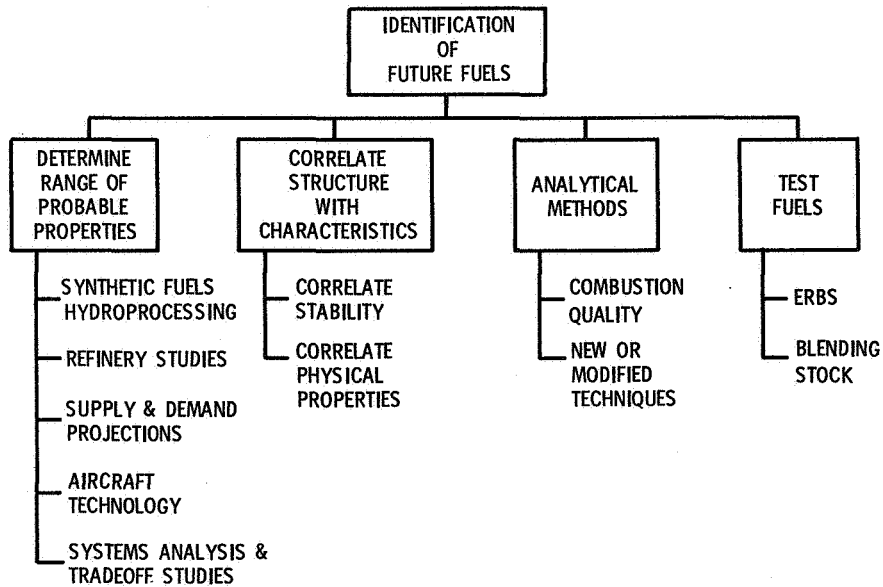


Figure 2

OUTLOOK FOR ALTERNATIVE ENERGY SOURCES

Michael E. Card
Acting Deputy Assistant Secretary
Department of Energy

President Carter has made the solution to our present energy problem the Nation's highest lasting priority. It really is the "moral equivalent of war," because without a steady flow of energy our country cannot survive. It will be a long war, lasting through this decade, through the 1990's, and into the next century. There will be no instant cures, no magic breakthroughs to save us at the last minute. There isn't going to be any sudden let-up in energy costs, no long drop in gas prices at the pump. And there won't be any guarantee against future energy shortages either. In fact, we can almost guarantee there will be energy shortages in the future. We just hope they won't be too serious or last too long. To win this long energy seige - this moral equivalent of war - we're going to have to become a nation committed to working together to conserve energy. Let's not duck that word - Conserve in the true sense doesn't mean going without. It means using our resources wisely, efficiently, with as little waste as possible.

We have to accept the reality of our energy problem: our dependence on foreign oil. The facts are clear:

- o Fact #1. Much of our imported oil comes from the most unstable part of the world. The Iranian revolution and the holding of U.S. hostages is only the latest trouble. In the last 30 years the Middle East has been the scene of half a dozen wars, a dozen revolutions, and nobody knows how many assassinations.
- o Fact #2. The oil output of the OPEC nations during the 1980's may stay at today's level, about 30 million barrels a day. But it may drop. Meanwhile, demand for oil is still growing, which pushes prices up. Between December 1978 and March 1980, a span of 15 months, the price of imported oil went from \$13 to \$32 a barrel. We spend about \$10 million every hour, every day of every week, for imported oil. That's about \$90 billion it will cost us this year, assuming prices don't go any higher.
- o Fact #3. Increases in non-OPEC oil production will not be enough to meet the increases in demand, in all likelihood.
- o Fact #4. Our own oil production, in spite of all the exploratory drilling we're doing, will probably fall about a million barrels a day by the mid 1980's. There are more than 2600 drilling rigs active in the U.S. today, more than at any time in the last 25 years. But the most optimistic outlook sees domestic oil production only staying level. We have 16 percent of the world's oil

production, but 29 percent of the world's oil consumption, and only 9 percent of the world's oil reserves.

It's a discouraging picture. After the 1973-74 oil embargo, our energy situation deteriorated. Even with some conservation and some reduction in demand, domestic energy consumption increased because both our population and the economy grew. But domestic energy production has been steady for a decade. Our big discovery of oil in Alaska has only meant that domestic production hasn't fallen yet.

It was not until last year that we reduced our oil imports, by about 2 percent. For the first time since 1975, total energy consumption decreased in 1979 - from 78.4 to 78.2 quads. Not much of a decrease, but a decrease nevertheless. Why so small a drop? Because we haven't yet really decided that we have to conserve - to do away with waste, to increase our efficiency, to use our energy resources wisely. Study after study - for example, the recent Harvard Business School Report "Energy Future" - shows that we still waste 30 to 40 percent of the energy we use. We throw it out like uneaten food. We let it escape through cracks under doors. We waste it out the tailpipes of untuned automobile engines.

We still depend on oil and gas for most of our energy. We use coal, our most plentiful resource, for only 19 percent of our energy. We use oil and gas for 70 percent, and 46 percent comes from oil. Nearly half of that, almost 20 percent of our total energy consumption, comes from imported oil. The net rate, last year, of imports was 7.7 million barrels a day, and 5.5 million of those imported barrels a day comes from OPEC nations. What are the costs of our dependence on foreign oil?

- o We have an inflation rate of over 13 percent, much of it due to the high cost of imported oil.
- o Our balance of trade last year was a \$31 billion deficit. That's more than our total exports for any year before 1966.
- o In 1971 we paid \$3.5 billion for foreign oil. This year, in 1980, the cost will reach \$90 billion - more than 20 times as much in one short decade.
- o Gasoline prices are up almost 300 percent since 1973. Home heating oil prices have nearly doubled since last winter.

Our first priority is to reduce oil imports. Last year the President pledged that our oil imports would never rise above 8.5 million barrels a day. He set the limit for 1979 at 8.2 million barrels and this January, in his State of the Union Address to Congress, he again set the limit at 8.2 million barrels a day for 1980. Our oil import goals are as follows:

- o To reduce imports by half by 1990.
- o To diversify our oil sources so we aren't so dependent on Middle East oil (2.1 million barrels a day of our OPEC oil comes from there).

For decades we built our economy as though energy costs didn't count, as though oil and gas were as cheap as dirt. They were, so now our houses, offices, factories, and automobiles are all designed to run on cheap oil and gas. Now we must change our wasteful energy habits and really begin to conserve, to use energy wisely. "We" means everyone. Conservation is not up to the Government or to Washington bureaucrats, or to industry. Conservation is up to everyone; it's up to you.

Industry has already demonstrated that productivity can increase at a much faster rate than energy consumption. Traditionally, energy consumption in this country has grown at about the same rate as the gross National product. That "lockstep" pattern has now been broken. From 1973 through 1979, while the GNP was increasing 16.5 percent, National energy consumption increased only 4.8 percent, and energy consumption by industry remained almost unchanged. This turnaround shows reduced energy consumption doesn't necessarily mean the end of growth. Interestingly, most of industry's energy savings up to now have been simply the result of improved "housekeeping" practices - of which there are many more still to be taken. Beyond these simple measures lie the capital improvement efforts - improvements that will make American industry inherently energy efficient.

Last November the President signed an appropriations act that provides \$2.208 billion to the Secretary of Energy to "expedite the domestic development and production of alternative fuels...at maximum levels at the earliest time practicable..." These funds were immediately available in several categories:

- o \$100 million per project development feasibility studies, to accelerate critical path efforts leading to commercial site development and plant construction.
- o \$100 million for cooperative agreements to support commercial scale development of alternative fuel facilities, targeted to projects in an advanced development stage.
- o \$1.5 billion for the purchase or production by way of purchase commitments or price guarantees of alternative fuels, to ease downside risks for alternative fuels that aren't likely to be price competitive in the near future.
- o \$500 million in loan guarantees, for technologies that should be economically viable once in production but face construction and start-up uncertainties.

These awards will be made for coal liquids, high-Btu gasification, low and medium-Btu gasification, oil shale, tar sands, unconventional gas, peat, biomass, and municipal and industrial waste.

Capitalizing these alternative fuel facilities at commercial scale is not easy, even with Government help. Banks are limited by law as to how much they can lend for individual projects, and even consortia of banks have their limit. Even the largest insurance companies cannot easily come up with all the money that will be needed over the next decade to get these alternative energy plants on line. To build a coal liquefaction plant, for example, the kind that has been built in South Africa, requires \$3 to \$5 billion. When the plant is on line it will produce some 50 000 barrels of synthetic oil a day. What can we expect from these alternative fuels? Our goal is some 1.5 to 2.5 million barrels a day by the mid 1980's.

Of concern to this symposium is the impact of the DOE alternative fuels program on aviation fuels. In the near term, now until 1985, there is unlikely to be any major change in the fuels used. In the midterm, 1985 to 2000, there will be limited transition to non-petroleum fuels based primarily on shale-oil-derived liquids and indirect coal liquefaction, depending on production levels. The President has established a goal for shale liquids production of 400 000 barrels a day by 1990, although some published estimates think 100 000 to 300 000 may be more likely. A recent study by Exxon for DOE rated shale oil liquids with the lowest cost rating, coal-derived liquids second and liquid hydrogen being the most expensive. Therefore, the future outlook for aircraft fuels is that for the near term, there possibly will be no major fuel changes, but minor specification changes may be possible if supplies decrease. In the midterm, a broad cut fuel may be used if current NASA development efforts are successful. As synfuel production levels increase beyond the 1990's there may be some mixtures of petroleum-based and synfuel products with the possibility of some shale distillate and indirect coal liquefaction products near the year 2000. Other than the NASA work on broadened-specification fuels, there is no isolated National research and development activity for aviation fuels.

In closing, there is an element of risk in any great venture, and energy policy is no exception. But the risks taken by private investors and corporations can be greater than the risks taken by the Government. The private sector has been too insistent on being presented with a sure thing before risking investment in energy projects. We in Government do not wish private investors to be reckless; merely responsive. Private investment and its concomitant risks will be absolutely essential to reducing dependence on imported oil. The greatest risk will lie in doing nothing at all. The Government for its part will provide the insurance that energy problems will not totally disrupt the country, that no one sector of society will suffer unduly or unfairly from energy shortages. That is what Government does best.

Domestically we must bring together the many factions that stand in the way of energy technology development in all forms. We must improve the siting process for construction of new energy facilities, so that each proposed

new facility, be it a pipeline, a nuclear plant, or a synfuel plant, does not fall to the onslaught of a vocal minority. We are a nation with a strong tradition for protecting the rights of minorities while respecting the will of the majority.

To be realistic however is not to be pessimistic or defeatist. America is not energy poor. In our coal deposits, unconventional gas and oil deposits, and most particularly in the innovative talents of our scientists and industrial entrepreneurs, we have all the wealth we need to achieve energy independence. So far we've lacked the will to develop our own vast energy resources. That's now changing. But we must guard against raising false hopes; we must discourage dreams of a scientific "breakthrough" that will spare us the trouble of developing a variety of new energy sources. After all, it took the United States 30 years to get into the hole we are in; it may take us that long to get out of it.

We are in danger. The whole free world is in danger. But over the years the energy crisis can also present us with unlimited opportunities - to strengthen our alliances, to improve our technologies, and to find alternative energy sources that will again restore us to energy independence. But we must prepare for the long haul. We must force a coalition that will last among all components of society - Government, industry, labor, the scientific community, and the general public. With that kind of a coalition, we can move confidently and smoothly through the transition from dependence on imported oil to diversified domestic sources.

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CURRENT JET FUEL TRENDS

Paul P. Campbell
United Airlines (Retired)

Relaxation of the limits in the widely used Standard Specification for Aviation Turbine Fuels ASTM D1655 for

- a) Maximum aromatics content from 20 to 25 percent and
- b) Minimum smoke point from 20 to 18

in 1976 and 1977 carried the proviso that the customer must be advised of supply of product within the relaxed range, i.e., over 20 percent aromatics or under 20 smoke point. This is frequently referred to as reportable fuel.

The amount of reportable fuel delivered to United Airlines gradually increased from a quarterly average of slightly over one percent total requirement for the year 1974 to a maximum of 17 percent in the third quarter 1978. At that time, the four quarter moving average reached a peak of slightly over 15 percent. Two thirds of this increase has taken place since the third quarter 1977 when Alaska North Slope crude shipments began to arrive at United States West Coast refineries. As this crude has fanned out across the country and fuel suppliers have developed improved refining techniques, the amount of reportable product was reduced to 7 percent in the first quarter 1979, the latest quarter for which data are available.

Information on United's fuel is drawn from a computerized data bank with input from fuel supplier refinery batch analysis reports. Refineries supplying United represent an estimated 60 to 70 percent of total United States commercial jet fuel production. Similar data are produced by IATA for fuel delivered to overseas carriers outside the United States. This information is developed for individual airports from data supplied by the various supplying oil companies. For 1977 and 1978, the amount of reportable fuel delivered to IATA carriers outside the United States fell in the same range as that experienced in the United States two to three years earlier. In 1979, it increased to between 7 and 8 percent, very close to the latest figure reported by United for domestic fuel.

Most reportable fuel is that with high aromatics content. While some fuel has both high aromatics content and low smoke point and some fuel has low smoke point only, such fuels represent less than 20 percent of the total amount reportable on the average. This has reached a high of 30 percent.

During the period under discussion (1974 - 1979) the average aromatics content for product for all refineries in the United data bank has increased from 16 percent to 17.5 percent. During most of this period, the aromatics content of fuel supplied to United has run somewhat below the average for all refineries. This situation has been reversed since 1977 as the effect of Alaska North Slope crude became more prominent. United's fuel is now running almost one percent higher in aromatics content than that from all refineries. This is believed to be the result of the very high proportion of United's fuel drawn from West Coast stations.

Despite the pronounced upward trend in aromatics content, during this five year period, the smoke point for all refineries has held steady between 22.5 and 23. This was also true for United's consumption until 1977 when it dropped to the range of 21.5 to 22.

It is evident that the arrival of Alaska North Slope crude in 1977 had a significant impact upon the aromatics content of jet fuel supply at West Coast points with less effect upon the entire United States domestic market. This increase in aromatics has not been accompanied by a corresponding reduction in burning quality as measured by smoke point. There has been a reduction of .6 smoke point on the average for United's fuel.

Looking at hydrogen content as a measure of burning quality, the all refinery average calculated hydrogen for 1978 was approximately 13.7 percent. The relationship between hydrogen content and aromatics content shows a slope of .043 percent reduction in hydrogen for one percent increase in aromatics. This would imply that the average hydrogen content of United's fuel has declined 0.1 percent between 1974 and 1979. Similar analysis for the hydrogen content - smoke point data indicates a smaller change. The slope here shows a .053 percent hydrogen reduction for a reduction of one smoke point. Thus the .6 reduction in smoke point between 1974 and 1979 would imply only a .03 reduction in hydrogen.

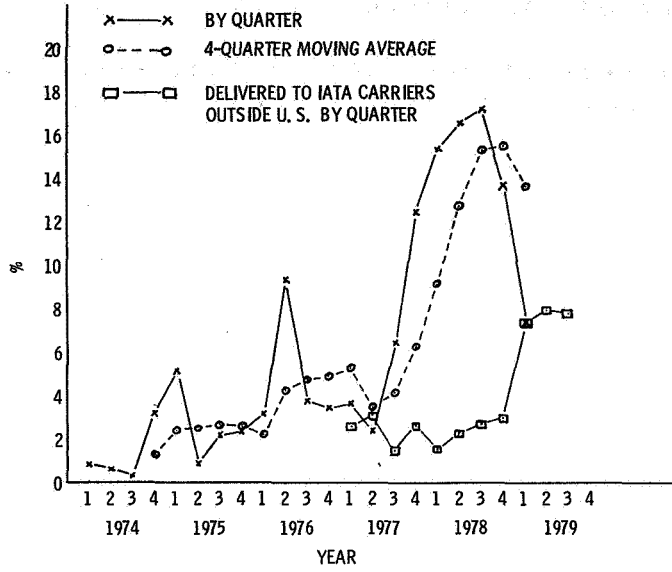
Certain trends in other specification parameters indicated by all the refinery data during the past three years include:

- Increase in average freezing point from -50°C (-58°F) to -47°C (-52°F).

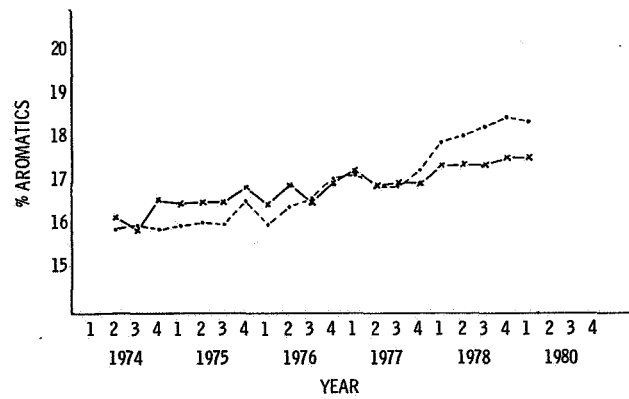
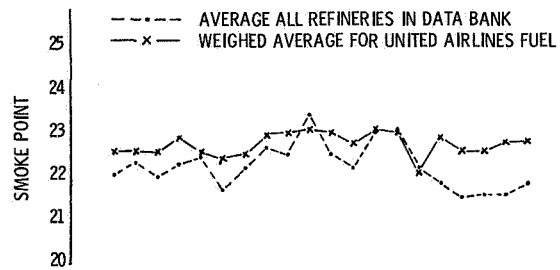
- Increase in average flashpoint from 48° C (118° F) to 52° C (126° F)
- Slight increase in density of .6 percent

Total sulfur content has been holding steady at .06 percent after a gradual increase from .04 percent over a period of several years.

REPORTABLE FUEL
DELIVERED TO UNITED AIRLINES



AVERAGE AROMATICS CONTENT AND SMOKE POINT



AVIATION FUELS OUTLOOK

Albert M. Momeny
Boeing Commercial Airplane Company

Passenger and cargo air traffic are expected to grow substantially in the next two decades. Even with an emphasis on fuel efficiency, the domestic demand for jet fuel is projected to increase from the current 5.2% of total refinery product output to as much as 10% of the total 1995 output. Options for satisfying this demand (Fig. 1) are being evaluated in current Boeing studies.

Approximately 15% of the U.S. refineries market commercial jet fuel (Jet A). In the long term, the product slate at these refineries is optimized for maximum profit. This typically means that there must be an available market for the entire line of products with emphasis on quality products such as jet fuel and gasoline. The market for each major product also must be reasonably secure. Refiners have indicated that a desirable market range for jet fuel is 15 to 25% of a refinery's product slate. Currently delivered Jet A has an average freezing point of -45°C and a 54°C flash point. These properties result in a typical refinery Jet A yield within the desirable market range as shown in Fig. 2. Refiners can maintain or even increase their Jet A market share by delivering Jet A with properties closer to the -40°C freezing point and 37.8°C flash point specification limits. Relaxing the freezing point and/or flash point requirements would result in a higher potential Jet A yield, as shown in Figs. 3 and 4. However, it is unlikely that the marketed yield would increase significantly; certainly not to the refinery jet fuel fraction yield required to satisfy Jet A requirements projected for 1995.

In some cases, the quantity of marketable jet fuel is limited by Jet A specification requirements, such as the 3% naphthalene maximum associated with smoke point. However, in most cases Jet A specification requirements do not restrict the quantity of jet fuel marketed by a refinery as indicated by the inspection data summary shown in Fig. 5. This situation is expected to exist for at least the balance of this century as shown for the selected property projections given in Figs. 6 and 7.

A promising direction towards increasing the jet fuel supply is to attract more refiners to the jet fuel market. There are many refiners currently not marketing jet fuel who have sufficient jet fuel potential to warrant the added distribution and quality control costs. Figures 8 and 9 show the jet fuel production capability of a major independent East Coast refinery currently not marketing Jet A. A yield of Jet A specification fuel of up to 20% is possible from this refinery. Fuel properties such as aromatic content, specific gravity, heat of combustion and smoke point fall within the existing specification limits for Jet A. Attracting new refiners to the jet fuel market will depend on economic incentives, ability to transport fuel, and projected market stability.

Synthetic fuels from shale or coal are the long term option for increasing the jet fuel supply. Oil shale and coal are the only two energy sources with large enough reserves to contribute to the nation's transportation energy need. There is a wide variety of options available for incorporating coal and oil shale into the energy supply system. Several of these, shown in Fig. 10, offer promise and were evaluated as a source for Jet A.

Many coal gasification processes have a liquid by-product that can be upgraded to a synthetic crude. This by-product liquid accounts for less than 10% of the plant product fuel output. The output of Jet A after refining would be less than 30% of this by-product liquid. Therefore, it is doubtful that by-product liquids from coal gasification processes can be significant sources of jet fuel.

Synthetic crudes from shale or coal liquid processes can be refined into finished products in a new refinery designed for the synthetic, or mixed with petroleum based crudes and refined in an existing refinery. The existing refinery may require some modification depending on the quantity of syncrude added to the feedstock and product mix requirements. Liquid products also can be obtained from coal by producing a synthesis gas and catalytically reforming the gas into a wide variety of finished products.

The syncrude from coal and shale and the finished product from coal processes allow a product slate that can be adjusted to product demand. The cost in both capital and energy increases with the severity of the processing required to satisfy a fixed product slate. It is possible to dedicate a synthetic fuel facility to the production of jet fuel with yields as high as 80% commercial plus military. However, it is not clear that the added expense could be justified by a commercial user or would be cost competitive in the long term.

Synthetic crudes from oil shale and coal can be processed to satisfy the Jet A specification as shown in Fig. 11. The desirability to produce jet fuel of a particular quality must be evaluated in terms of cost and energy efficiency of the total system including the aircraft.

The principal problem with oil from shale is its high nitrogen content. Fuels with a high nitrogen content tend to be unstable. Nitrogen also causes problems in refineries and it is expected that refinery requirements will dictate a nitrogen reduction that will be acceptable for aircraft.

Coal liquids from direct hydrogenation processes have a high aromatics, hence low hydrogen content. High aromatics cause increased combustor liner temperatures and a reduction in fuel energy. The acceptance of highly aromatic fuels in an aircraft would reduce fuel processing requirements and cost. However, aircraft fuel quantity requirements and maintenance would increase. Energy losses associated with the aircraft and ground system would be particularly severe if high aromatics were associated with high fuel freezing point. The energy saving from reduced fuel processing must be balanced against added airplane, refinery, storage and distribution system energy requirements as indicated in Fig. 12. The fuel produced using coal synthesis processes can satisfy Jet A requirements with little cost or energy loss penalty.

In the near term, the most likely commercial utilization of synthetic crudes will be as an additive to petroleum based crude feedstocks. This will allow an evolutionary development of shale and coal resources without requiring major modifications to the existing fuel refining and supply system.

A 20% shale syncrude mixed with crude oils and used as feedstock in refineries with access to the shale areas can easily handle syncrude quantities expected from production over the next two decades. The introduction of this syncrude into a Midwest refinery currently marketing jet fuel could cause a small drop in Jet A yield, as shown in Fig. 13. The nitrogen content of the jet fuel would be abnormally high and, if fuel thermal stability requirements could not be satisfied, the nitrogen might have to be removed. All other fuel properties could satisfy Jet A requirements.

Commercialization of coal liquid processes that produce a syncrude, such as donor solvent, is not expected until the late 1980's. Therefore, 10% coal liquids mixed with petroleum based crudes can account for coal syncrude production well into the next century. The introduction of this syncrude into a Gulf Coast refinery currently marketing jet fuel could cause a small drop in Jet A yield, as shown in Fig. 14. All other fuel properties could satisfy Jet A requirements.

In summary, Boeing studies to date have indicated that the most effective means to satisfy an increasing demand for jet fuel are: (1) Attract more refiners to the jet fuel market; (2) Encourage development of processes to convert oil shale and coal to transportation fuels. Furthermore, changing the Jet A specification would not significantly alter jet fuel availability.

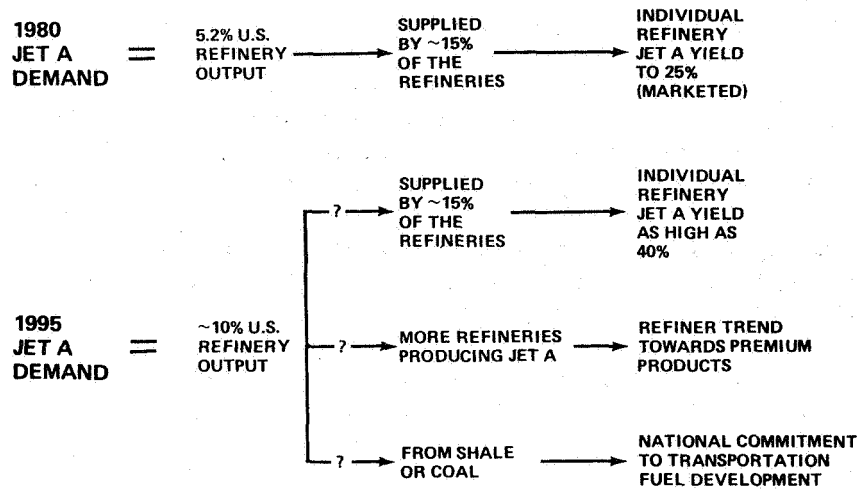


Figure 1. Jet A Supply Options

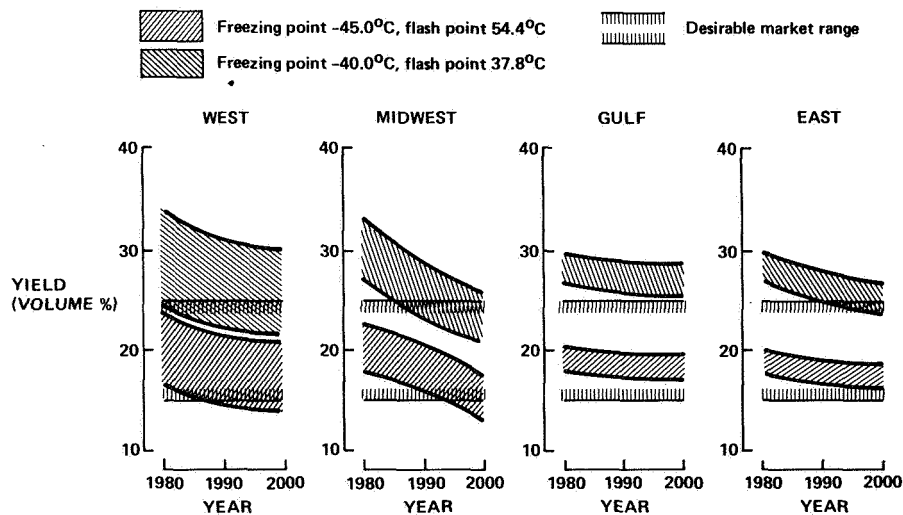


Figure 2. Refinery Jet Fuel Fraction—Yield

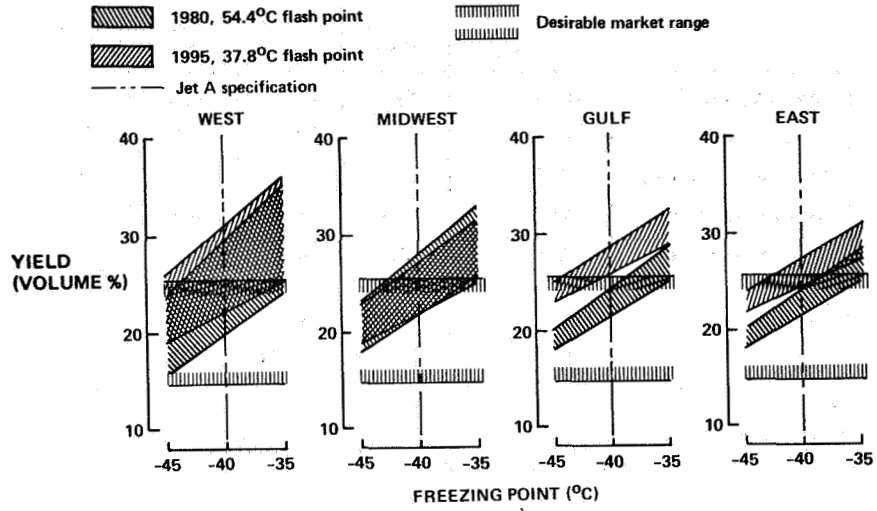


Figure 3. Jet Fuel Processing—Freezing Point Sensitivity

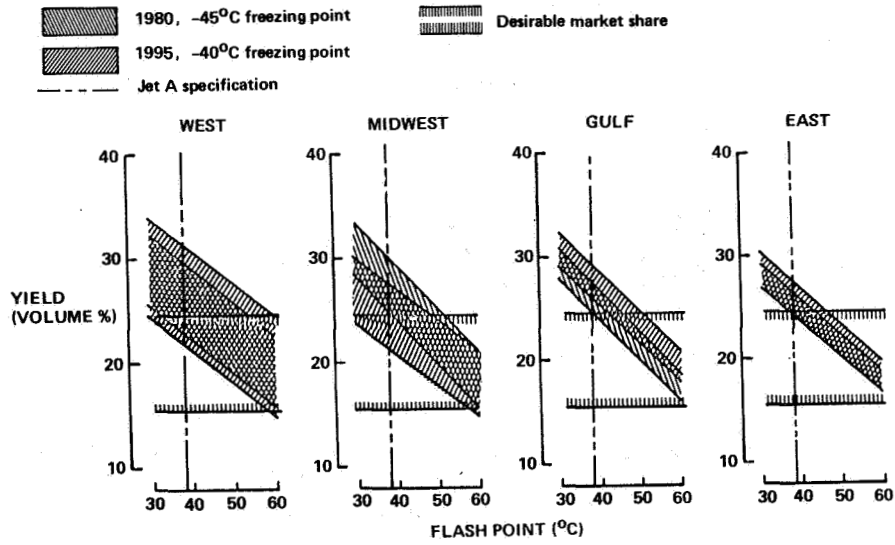


Figure 4. Jet Fuel Processing—Flash Point Sensitivity

	Jet A spec	Mean	Max	Min	At spec limit*
Freezing point (°C)	-40.0	-45.0	-40.0	-64.0	2
Flash point (°C)	37.8	54.4	64.4	37.8	1
Aromatics (volume %)	20/25	17.4	23.5	11.0	0
Smoke point (mm)**	20/18	22.7	28.0	18.7	1
Heat of combustion (MJ/kg)	42.8	43.2	44.0	43.0	0
Specific gravity	0.775/0.840	0.811	0.833	0.794	0
Sulfur	0.3	0.053	0.130	0.002	0

*Out of 60 samples

**Naphthalenes < 3 volume %

Figure 5. Jet A Inspection Data Limits—1978

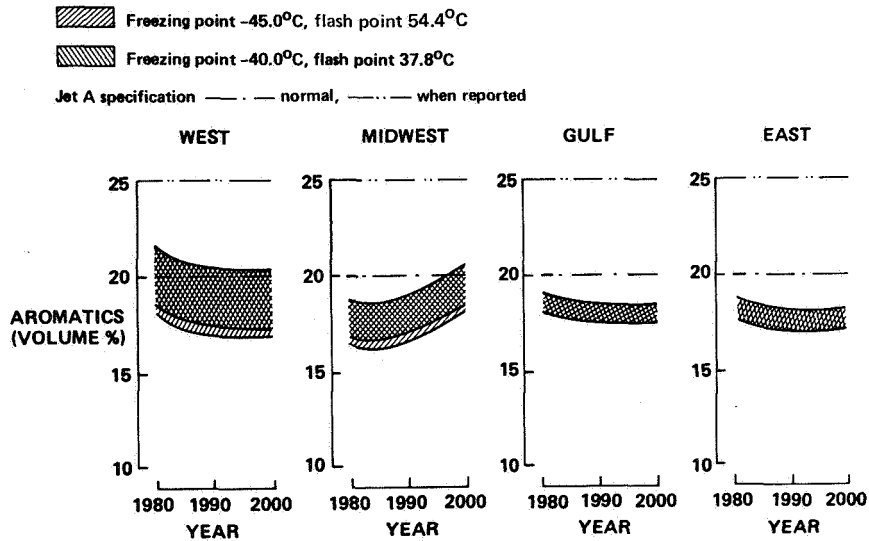


Figure 6. Refinery Jet Fuel Fraction—Aromatics

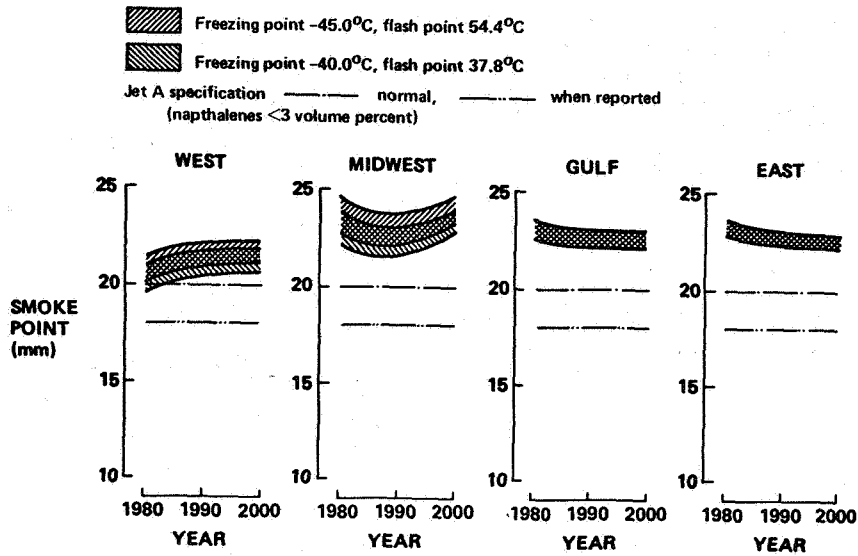


Figure 7. Refinery Jet Fuel Fraction—Smoke Point

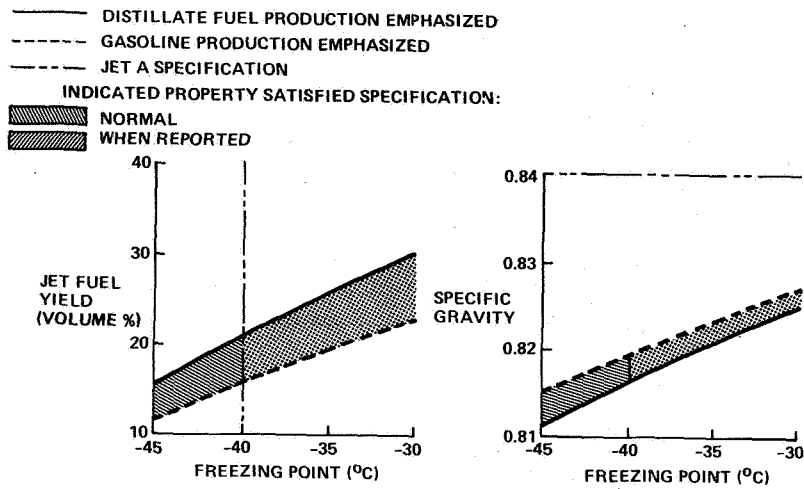


Figure 8. Jet Fuel Processing—Independent Refinery

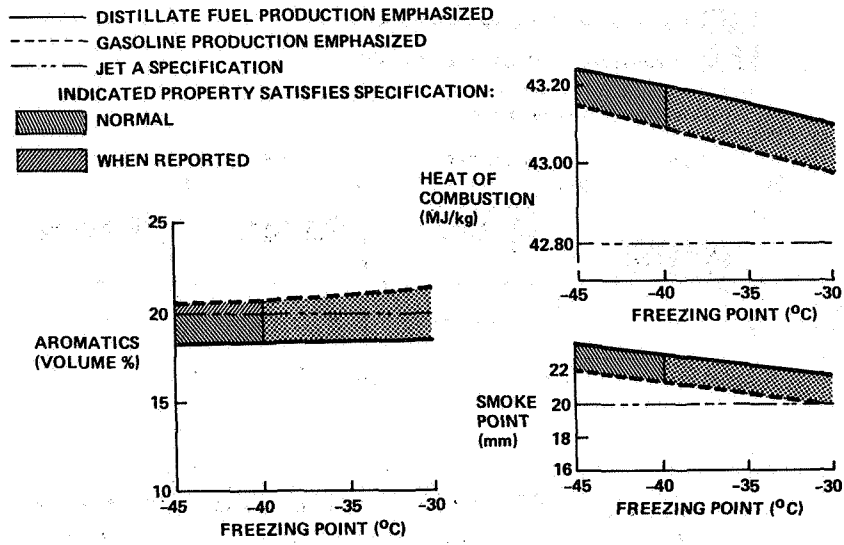


Figure 9. Jet Fuel Characteristics—Independent Refinery

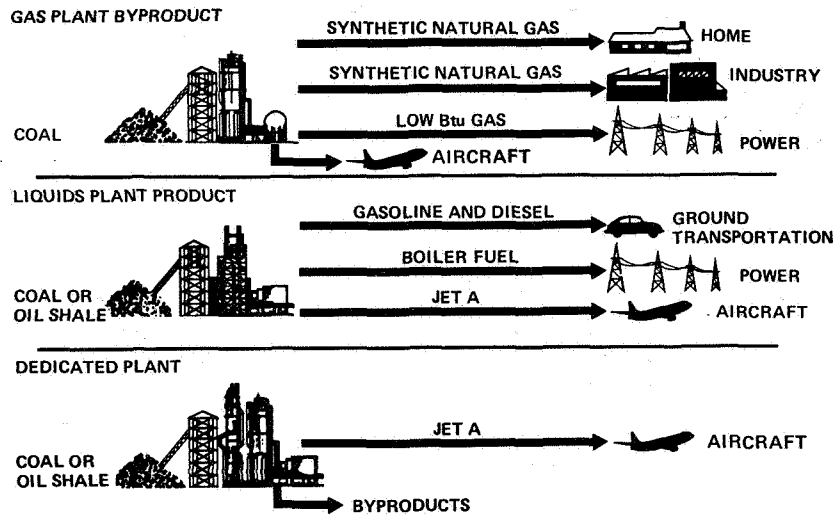
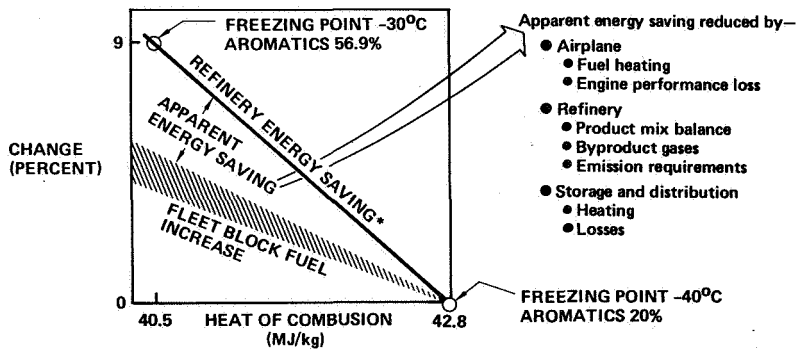


Figure 10. Synthetic Jet Fuel Production Options

Properties	Jet A selected specifications	Jet/coal hydrotreated	Jet/shale hydrotreated
Gravity (deg API at 16°C)	37 to 51	39	41
Freezing point (°C)	-40 maximum	-40	-40
Net heating value (MJ/kg)	42.8 minimum	43.0	43.0
Aromatics (volume %) If supplier notifies user	20 maximum 25 maximum	10.7	13.3
Smoke point (mm) If supplier notifies user	20 minimum 18 minimum	18	21
Flash point (°C)	37.8 minimum	41.1	40.6
Nitrogen (ppm)	—	33	205

Figure 11. Synthetic Jet Fuel Properties



*100% coal liquids; refinery hydrogen from coal

Figure 12. Refinery and Airplane Energy Sensitivity

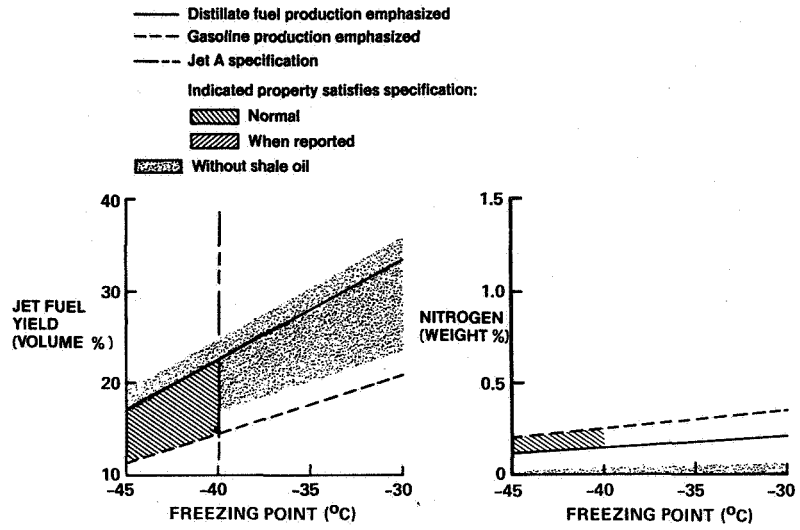


Figure 13. 20% Paraho Shale Oil Processing

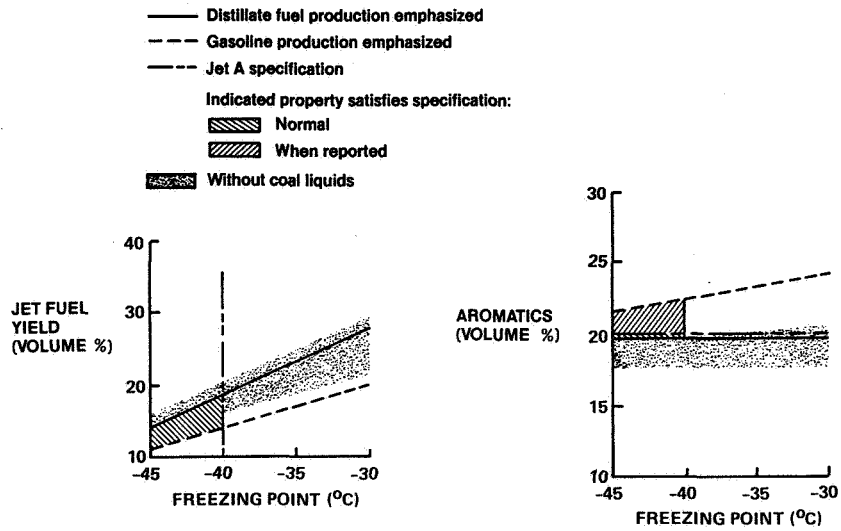


Figure 14. 10% Coal Liquids Processing

A METHODOLOGY FOR LONG-RANGE PREDICTION OF AIR TRANSPORTATION*

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ABSTRACT

The purpose of a research study reported in this paper was to provide a framework and methodology for long term projection of demand for aviation fuels. It required a close examination of some of the fundamental problems of predicting long run futures. The approach taken includes two basic components. The first was a new technique for establishing the socio-economic environment within which the future aviation industry is embedded. The concept utilized was a definition of an overall societal objective for the very long run future. Within a framework so defined, a set of scenarios by which the future will unfold are then written. These scenarios provide the determinants of the air transport industry operations and accordingly provide an assessment of future fuel requirements.

The second part was the modeling of the industry in terms of an abstracted set of variables to represent the overall industry performance on a macro scale. The model was validated by testing the desired output variables from the model with historical data over the past decades.

A METHODOLOGY FOR LONG RANGE PREDICTION OF AIR TRANSPORTATION

THE PURPOSE OF THIS PAPER is to report the results of a NASA sponsored research program for development of a methodology for projecting the long term requirements for future aviation fuels.

An integrated study of future aviation fuels requires consideration of a number of related areas. (See Fig. 1) The kind of fuel and the magnitude of future demand depends on the engine and airframe performance characteristics of future aircraft, the characteristics of the air transport system and the availability of future aviation fuels. As depicted in Figure I, the aircraft may be considered as a component of a larger system--air transportation--which in turn is a subset of the transportation system. Similarly,

availability, price, and technical characteristics of aviation fuel fit into the overall energy picture of the future. Finally a future transportation demand and energy requirements interact with and are impacted by many socio-economic variables.

1. THE PROBLEM OF LONG RANGE PREDICTION

The long lead times needed to develop and produce new engines and new aircraft types require some means for predicting very long term futures. Decisions which are made now must be based on future prospects of successful outcomes. However, we cannot know the future and out extrapolation of past trends as a means of forecasting the future inevitability will result in wide divergencies between predicted results and what really will come to be. Witness, for example, previous projections by well recognized authorities of airline transportation (Fig. 2). The extrapolations shown all reflect an exponentially increasing variance associated with futurity. It is indicative of the difficulty of the problems, that eight different projections made by the FAA, CAB, several airlines and several aircraft manufacturers all fell within the dashed lines of Fig. 2. Actual growth of air transport for that same short period of ten years, 1962 to 1976, fell outside the range of all of them. The question then is how can a methodology be developed for providing a view of the future needed for decision-making in the present in the face of an almost completely unknowable future.

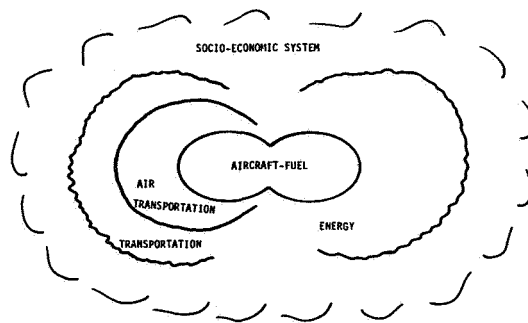


Fig. 1 Aviation Fuel and Its Related Areas

*Presented at the SAE International Air Transportation Meeting, Cincinnati, Ohio, May 20-22, 1980.

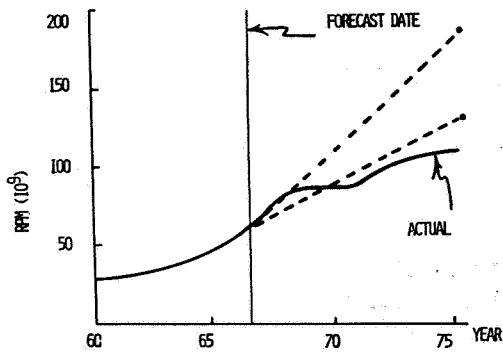


Fig. 2 Air Traffic Forecasts

The solution to this problem must be found by taking a new perspective of prediction from that of conventional forecasting. Our approach is to limit forecasts to those variables for which a very long experience and reasonably reliable record of success already exists, specifically, population and gross national product (GNP). Even for these major economic variables, an assumption must be made that there will not be some kind of major human catastrophe. One aspect of long range general economic projections that should be recognized is the difference between the variance of time and variance of result. It can reasonably be asserted that a certain economic future will come to be. However, the variance in the time such an occurrence is finally achieved can be quite sizeable. Furthermore, the distribution about the expected time certainly will not be linear in time. Probably log time will be a more meaningful measure. (1)*

It might be further noted that in keeping with time perception on a log scale, the actual time frame may not be important. If a given aspiration is achieved at all whether it takes 30 years or 50 years, may not be significant in making a present decision to launch and R&D program for a new engine.

The aspiration approach can be illustrated by reference to (Fig. 3). The horizon for forecasting the air transportation system is necessarily short because the divergence quickly exceeds useful decision making bounds. However, the aspiration bounds determined by a forecast of a much longer term horizon of the general economic environment are quite narrow. Thus as the future unfolds within the forecast time frame, special efforts will always become evident for redirecting action towards the long run aspiration. These action boundaries will tend to converge in contrast from the divergent forecast boundaries.

Given an economic environment that falls within reasonable bounds over the very long range, such as for example, fifty years, it becomes possible to describe the kind of future for which there would be generally accepted economic aspirations. The decisions

*Numbers in parentheses designate References at end of paper.

and actions required to achieve such aspirations then become definable. These aspirations must be defined broadly in consonance with a value system which generally and presently is considered to be representative of human welfare. Furthermore, the constraints on such aspirations can readily be determined by consideration of the physical limits on resources needed to satisfy the economic conditions which were forecast.

Of course it is readily recognized that the detailed characteristics of this long term future economy can vary widely. Also the way in which component systems such as the airline transportation system will be inter-related with the economy may evolve in any number of ways. Thus, writing scenarios also is a useful forecasting tool.

What will result is a somewhat fuzzy picture of the state of the particular system of interest in some long run future along with a precise measure of what that system is today. The aspiration of a desirable future, coupled with the scenario, together would provide a set of exogenous variables which are inputs as well as constraints on the actual system of concern, i.e. the transportation system.

We may describe the air transport future in terms of the set of endogenous variables which have been modeled to demonstrate the actual operation. By this procedure a reasonable prediction of the future air transportation system operation may be made.

It will be recognized and perhaps should be emphasized that there is a self fulfilling aspect of such a prediction. Nevertheless, in the face of an unknowable future the only reasonable starting point properly should be a broad statement of presently perceived long run future desires in order to identify the actions needed now to take a first step in the direction needed to reach the aspiration.

2. THE ASPIRATION FRAMEWORK

In a preliminary study (English, et al 1977), (2), a long term prediction of the air transport industry was based on 5 scenarios describing future developments of the U.S. economy. These five scenarios were essentially abstracted from four scenarios of the future depicted by the Hudson Institute plus one which we added. The Hudson Institute scenarios

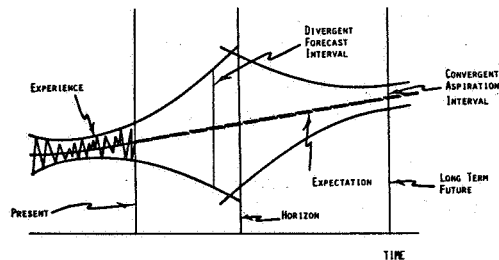


Fig. 3 Problem of Prediction

ranged from a very pessimistic future, (3), based on "A Limit to Growth," viewpoint, extension of the past U.S. experience at about the same rate of 3.4% as has been in existence, to a very optimistic growth rate. The intermediate Hudson Institute scenarios were essentially projections of GNP growth at different growth rates. In contrast, with the usual scenarios of some given steady growth, our fifth scenario was introduced in an attempt to consider effects of a serious dislocation of historical steady economic growth patterns. Such disruption was assumed to be due to a shortfall of energy supplies between now and 2000. However, in this scenario it was assumed that economic growth would be resumed following development of alternative energy supplies. This was termed the "Interrupted Growth Scenario." Such an interruption was also an implicit conclusion of the WAES, (4), an MIT study published independently and coincidentally with our report. However, an important difference between WAES study and our interrupted growth scenario is that it shows a gap between supply and demand. The study group acknowledged that such a gap could never occur. Either added supplies would have to develop from somewhere or demand, with attendant economic contraction, would decline. A big unknown which remained unresolved, was the degree to which GNP and energy may be coupled. A Harvard study by Stabaugh and Yurgin, (5), "Energy Future," 1979 contends that such a linkage is weak and that energy consumption without an attendant reduction in GNP. Nevertheless, this is moot and the interrupted growth scenario was considered when written in 1976, to be at least as likely as a moderate growth scenario.*

The introduction of the aspiration approach made it reasonable to encompass the future economic environment within the three scenarios of slow growth, interrupted growth and moderate growth. The extreme conditions of even more rapid growth as a most optimistic case and the "Limits to Growth," case as the most pessimistic case were not considered worth exploring in greater depth. Neither of these cases could result in important changes in NASA R&D policy. There would be no problem for the first extreme, and disaster in the second.

*Over three years has elapsed since the writing of the interrupted growth scenarios and in many ways the economy is showing signs of following that scenario. Current projections of various econometric models are indicating a recession in 1980 from which, while expecting recovery in 1981, the economy is not expected soon to exhibit any vigorous resurgence. Air transportation may have received a separate specific impulse as a result of deregulation in 1978. As a result the incipient decline in that industry may have been masked until now.

The essence of the median scenarios are summarized as follows:

- I. SOCIALLY CONSTRAINED GROWTH-2%
 - Decoupling of Energy/GNP Linkage
 - Conservation Option Emphasized
 - Major Changes in Life Styles
 - Economic Growth Below Historical Norms
 - Significant Change in Transportation Modes
- II. - UNINTERRUPTED GROWTH-3.4%
 - Historical Growth Pattern Continues in Future
 - No Major Changes in Economic Structure
 - Energy/GNP Ratio Declines Slowly
 - Air Transportation Continues to Grow Faster than GNP
 - Business as Usual
- III.- INTERRUPTED GROWTH
 - Major Restructuring of Energy Supply Systems
 - Energy Shortage with Strong GNP/Energy Dependence Drives Economy to Depression
 - Recovery in 10 to 15 Years will Require Major Supply Side Investments
 - Investments Require Higher Energy/GNP Ratios which can't be Realized
 - RESULT: Lower Living Standards.
 - Resumed Growth with Quite Different Component Growth Pattern

The UCLA work is continuing in order to refine a reasonable aspiration within these various economic futures, fifty years hence.

3. THE FUTURE AIR TRANSPORTATION TECHNOLOGY
 Because the prime objective of the study is to assess the level of total fuel demand, any improvements in overall fuel consumption will depend on possibility of improvement in operating efficiency. In turn, because of a changing mix of cost factors of airline operations, both travel demand and fuel demand will be affected by efficiency. Therefore, in order to establish aviation technology as an exogenous variable for the air transportation model, to be discussed in section 4,..., it was necessary to project possible technical changes in new aircraft and engines.

Improvements which may be expected to reduce fuel requirements per seat mile of capacity may be of two types:

- a) Basic technological improvements
- b) Operational induced design changes

The first of these will be due to such things as increased engine performance due to higher operating temperatures, improved airplane performance due to availability of better materials, structural concepts, active controls, boundary layer control and the like. In many cases the feasibility of design improvements are not dependent on break-throughs in new technology. The design principles may have been established long ago, but the economic justification for introducing them now derives from the changing ratio of fuel cost to other operating costs.

The second category will evolve from the response of operators to such things as the changing value systems of the traveling public. The trade-off between fare and such amenities as seat density, airplane size, speed and so forth, will lead to evolutionary changes in aircraft design.

Both of these kinds of changes take considerable time to effect changes in the characteristics of total fleet operations. Nevertheless, they must all be part of any prediction model for the long term air transport future.

4. THE AIR TRANSPORTATION MODEL

A model is an abstraction of reality. A fundamental difficulty in devising any model is to strike a proper balance between representing the system in too great detail on the one hand and oversimplifying on the other. The degree of complexity should be no greater than that needed to afford the desired precision of prediction of various measures of performance under given hypothesized inputs.

In the case of the long run future for air transport, in general, the significant inputs derive from the socio-economic environment. As pointed out above the relative description of the environment is obtained from a postulation of a long run socio-economic aspiration which is recognized as realizable. Given such an environment described in the broadest sense, the specific inputs into air transportation may then be determined by means of scenarios.

Thus, as depicted in Fig. 2 one can work from this somewhat cloudy picture of the environment to a more detailed depiction of the desired system--air transportation.

The justification for this indirect modeling must be that it affords an ability to forecast as well as a greater credibility of the forecast, as compared with a direct extrapolation of future air transportation from historical data. An important further justification is that the use of the model under a wide variety of changes in input variables, as well as of model parameters, will provide better insights into the underlying processes governing air transportation demand and hence of fuel requirements.

It should be noted that such an approach to modeling starts from a quite different perspective than that of an individual airline company. The airline company perspective necessarily is oriented towards a much shorter range viewpoint. It must be much more specific and detailed because company objectives are directed to the decision process of buying a particular aircraft type today.

In keeping with the overall industry view and the aspiration-scenario concept, a model was designed for predicting air transportation. The essence of the model and its relation with the environment is shown in Fig. 4. . . However, it is detailed for computerized application in Fig. 5. . .

The complete model includes submodels or input models which for the present are incomplete. Those shown in rectangular boxes in Fig. 5, are:

I. U.S. ENERGY MODEL to project supply, demand and price of the major energy types. A large energy model originally developed at Dartmouth College and known as Coal 2 was investigated and has promise for a direct coupling (6).

II. AVIATION FUEL MODEL to project aviation fuel specification, availability, and price of future aviation fuel. A representative refinery model, developed by Gordian Associates, was originally thought might be used. However, it requires some modification to be utilized. II TECHNOLOGICAL ADVANCEMENT IN NEW AIRCRAFT to project changes in engine and air frame developments. This is being investigated but probably will not be computerized. Direct assessments of technological changes may best be left as exogenous inputs.

IV. LOAD FACTOR AND UTILIZATION to provide an integral component of the air transportation model. Work is presently proceeding on this and should provide refinements for the operation of the model. Presently the load factor and utilization variables remain exogenous inputs specified in the scenarios.

The Model Core (7) what remains - depicted by the bubbles in Fig. 5, . . . constitutes the computerized model core. A basic premise was profit maximization--i.e. the differences between revenue and cost. Revenues depend on the variables of fare and demand. Costs are categorized as direct cost, indirect cost, and investment.

The air transport industry represented by the mutual interaction of the operators and the public response to the inputs from socio-economic environment. The major difference between this model and others used widely by the industry is its macro nature. Other models generally represent only segments of the industry for example, cargo, passengers, trunk lines, or local service lines. In such models demand for the particular sector is the only endogenous variable. Such variables as fare and investment are treated exogenously. Finally, the air transport system is treated dynamically with feedbacks within itself, as well as with the socio-economic environment.

The Digraph Approach a projective model is essentially an explicit expression of 'cause' and 'effect' relationship among a set

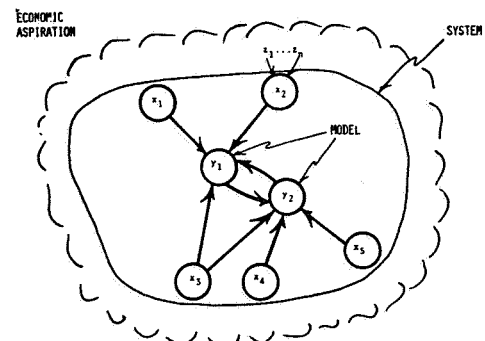


Fig. 4 System in Its Dynamic Environment

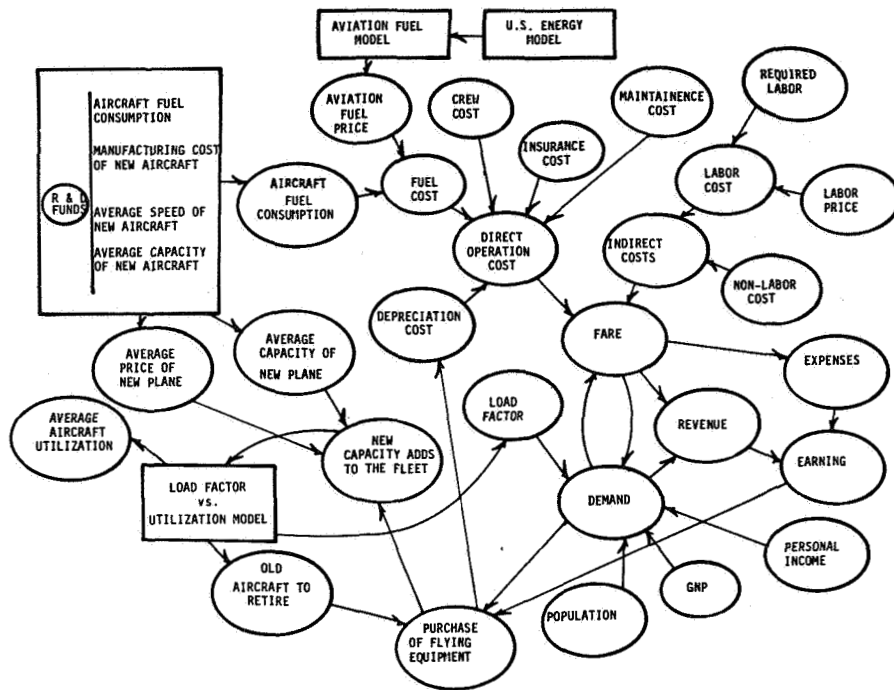


Fig. 5 A Conceptual Model of Aviation Industry

of variables. By knowing these cause/effect relationship and by assuming the future course in the change of causes, one can make projections of the system response. In constructing such a model, graph theory and in particular, digraph theory--the theory of directed graphs--have a natural appeal.

A digraph is a collection of nodes and arrows symbolize the relationship between variables. Construction of digraph models require identification of variables and determination of relationships among variables. The established relationships, then are represented by a cross-impact matrix. This is the essential element of a pulse process by which future values for endogenous variables of the system are projected (7,8). The choice of major variables of the air transportation system is based primarily on judgement aided by statistical analysis.

As an illustration and with reference to Figure 6,...each variable, may be a constant, a time variable, or a linear or non-linear function of one or more variables of the system. If it can be demonstrated that certain w 's are constants then they may be determined from reliable historical data. The structure of the model and the relationships between variables was found by examining a large number of hypo-

theses. These included appropriate time lag nodes.

Figures 7 and 8 show the results of the simulation. The values of endogenous variables of the system, demand, fare and investment are predicted. Each predicted point utilized the predicted value of that variable one period ago and not the historical data.

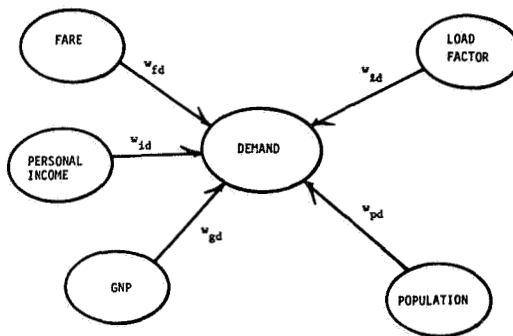


Fig. 6 Demand and Its Determinants

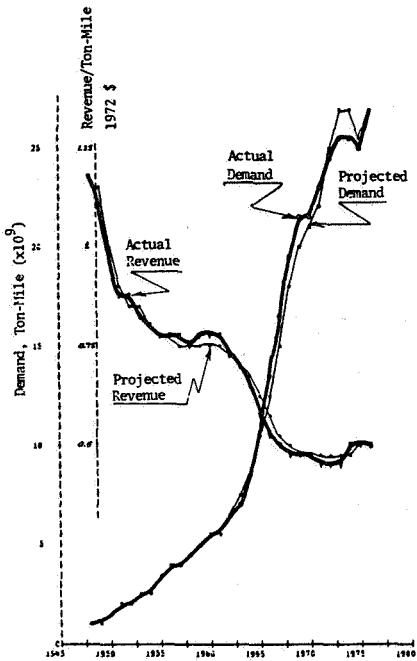


Fig. 7 Validation Test: Fare and Demand for Air Transportation

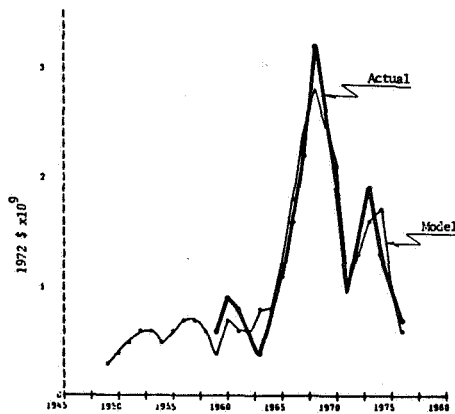


Fig. 8 Validation Test: Annual Purchase of Flying Equipment

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EFFECT OF REFINING VARIABLES ON THE PROPERTIES AND COMPOSITION OF JP-5

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Exxon Research and Engineering Company

Changes are taking place in the petroleum refining industry. New crude sources are being used, refineries are being modified and there are changes taking place in the demand for the various refined products such as jet fuel, diesel fuel, heating oil and gasoline. As a result of these and other events, subtle but significant changes may take place in the properties and composition of JP-5 as well as with its potential availability.

Recognizing these events, the U.S. Navy, Naval Air Propulsion Center in Trenton, New Jersey awarded a contract to Exxon Research and Engineering Company to study this area. The study entitled, "Effect of Refining Variables on the Properties and Composition of JP-5" was conducted under U.S. Navy Contract N00140-78-C-1491. The primary objective of the program was to identify potential future problem areas that could arise from changes in the composition, properties and potential availability of JP-5 produced in the near future.

The study employed a systems type approach, looking at the various processing trains used to make JP-5 in the U.S. and abroad, the types of crudes used with the different processing trains and the crude-processing interactions that might impact on the quality and potential availability of JP-5 produced in the near future. Analyses were made separately for the two major geographical regions (PADs) currently producing JP-5 for the U.S. Navy. Potential fuel problems concerning thermal stability, lubricity, low temperature flow, combustion, and the effect of the use of specific additives on fuel properties and performance were identified and discussed.

Estimates were made of the maximum theoretical yield of JP-5 that could be derived by distillation of typical foreign and domestic crudes that are used widely by PAD 5 and PAD 3 refineries, as well as from the blends of crudes that are currently in the U.S. Strategic Petroleum Reserve (SPR). These estimates were made using the Exxon Assay Stream Program, a computerized technique that can predict yields and a wide range of fuel properties for specified crudes and blends of crudes for given boundary conditions. Yields and properties were estimated for current specification JP-5 as well as for a range of conditions for relaxed freeze and/or flash points.

Several important findings and trends in crude quality and/or processing were identified in the program that could have important implications for the in-service performance of JP-5 produced in the near future. These include the following:

Crudes

- The average sulfur level of crudes being processed in the U.S. will continue

to increase significantly in the next decade. This is particularly true of PAD 5, the West Coast area.

- The use of Alaskan North Slope Crude is increasing greatly in PAD 5. This crude is relatively high in sulfur and aromatics compounds.
- Though used to a relatively small amount now, Mexican Isthmus Crude, a relatively high sulfur, high aromatics crude, should make a more significant contribution to the crudes used in PADs 3 and 5 in the next decade. The Strategic Petroleum Reserve contains a relatively large fraction of Mexican Isthmus Crude, thus making this crude potentially even more important in the future.
- As a result of the above, more severe processing may be required to make acceptable grade JP-5 in the future. Increased sulfur and/or aromatics content is a particular problem for PAD 5 refineries involved in making JP-5 for the Navy. Many of these refineries do not have hydroprocessing capability.

Refineries

- The refineries presently used to make JP-5 in the U.S. are located in PADs 3 and 5 only. About half of the PAD 5 refineries involved in JP-5 production are relatively small and have no middle distillate hydroprocessing capability. All four refineries making JP-5 in PAD 3 are large and have extensive hydroprocessing capability.
- Only about 20-25% of the available distillation capacity in PADs 3 and 5 is presently being utilized (contracted) to make JP-5 for the Navy, though most of the other refineries (not currently making JP-5) are utilized to manufacture middle distillates for other uses. The potential for expanding production is thus great if other refineries would participate.
- Foreign refineries making JP-5 are located in the Caribbean, Europe and the Far East. The fraction of foreign refinery capacity (refineries) that are involved in JP-5 production is about 5%. Thus, the potential for expansion of this refinery base for JP-5 production is even greater than the U.S.
- In FY-78, approximately 10^9 gals of JP-5 were made with U.S. refineries supplying about 77%, foreign refineries 23%. Exxon, Shell, and Mobil supply over 50%.
- Very little growth is projected in U.S. refinery capacity during the next 5 years, perhaps 5-8% over the (1980-85) five-year period. However, much more rapid growth is expected in the addition of hydroprocessing facilities. This is primarily a result of the need to adapt to higher sulfur, heavier crudes as indicated above.
- European refineries are installing several large fluid catalytic cracking and thermal cracking facilities in an attempt to provide more gasoline.

JP-5 Processing

- A wide range of processing routes are used to make JP-5 with many of the unit processes involved having the potential to affect the quality of the JP-5 produced. Unit processes employed include:

<u>Unit Process</u>	<u>Possible Side Effect Problems Resulting From Use</u>
Hydrocracking	Removal of natural antioxidants. Removal of compounds that could affect lubricity.
Hydrogenation	Removal of natural antioxidants. Removal of compounds that could affect lubricity.
Mild Hydrotreating	Same as above but to a much lower extent. Should not generally impair lubricity.
Caustic Washing	Disulfide formation, soap formation, aldehyde polymerization.
Merox Sweetening	Production of disulfides and polysulfides which can adversely affect thermal stability.
Doctor Sweetening	Same as above plus introduction to lead compounds.

- Small refineries employ more chemical processing in making JP-5 than large refineries and generally do not have hydroprocessing capability.
- Processing of JP-5 is not aimed at thermal stability per se but is targeted toward critical specifications, such as smoke point improvement and color improvement.
- Use of sweetening processes which convert mercaptans to disulfides are more deleterious to thermal stability than those which actually remove mercaptans from the fuel.
- Hydrocracking has the potential to greatly increase the yield of middle distillates.
- Major processing problems of small refiners include:
 - + Smoke Point - Particularly troublesome to small refiners that have limited aromatics removal capacity. (North Slope and many California crudes with high aromatics levels require aromatics removal capacity.)
 - + Freeze Point - A problem with some high paraffinic crudes. Usually handled by reducing upper end of distillate cut, cutting JP-5 yield.
 - + WSIM - Addition of corrosion inhibitors and anti-icing agents have caused problems with WSIM.

- Use of additives can greatly affect fuel properties/performance.
 - + Use of some anti-icing agents and/or corrosion inhibitors can downgrade the WSIM specification.
 - + Use of the anti-icing additive ethylene glycol monomethyl ether (EGME) degrades distillate Flash Point. However, di-ethylene glycol monomethyl ether (di-EGME) does not.

Crude Property/Availability Tradeoff

- Different crudes exhibit a wide variation in the maximum theoretical yield of JP-5 they can provide for current specification. Typical variations range from 7 to 19 volume % of crude.
- Use of current JP-5 anti-icing additive reduces the maximum theoretical yield from 5 to 15 volume % depending on the type of crude.
- Relaxation of JP-5 freeze and/or flash point specifications can yield significant increases in potential fuel availability. Freeze point relaxation gives a somewhat greater effect on increasing the maximum theoretical yield.

Trends in Middle Distillate Demand

- Increased demand for middle distillate fuels in the next decade, primarily due to increased use of diesel fuel (if automobiles are converted to diesels) will make distillate supplies for jet fuel, including JP-5, tighter.
- Increased demand for commercial jet fuel should also have a potentially adverse effect on supplies of distillate available for JP-5.
- Conversion technology such as hydrocracking, catalytic or thermal cracking plus hydrogenation of heavier stocks, may provide an attractive way of increasing middle distillate supplies. This approach could be even more useful if the projected decrease in gasoline demand can free heavier crude fractions for processing to middle distillates.

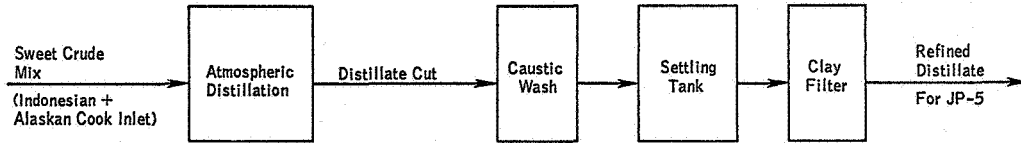
Other General Observations

- The use of additives such as anti-icing agents, antioxidants, corrosion inhibitors can have a dramatic effect on fuel properties and performance. Extreme care must be exercised when a new additive is put in the fuel or a change in additive concentration is made to solve a particular problem. Though it might act to mitigate one problem, it may intensify or promote another. A good example is the addition of a corrosion inhibitor to improve fuel lubricity problems. Such a change could have severe degradation effects on the WSIM specification, which in turn could cause other operational problems. The future trend will probably be toward more hydroprocessing because of rising aromatics and S levels so that there may be a need for additives to re-establish desirable properties that have been "processed" out of the fuel (e.g. lubricity).

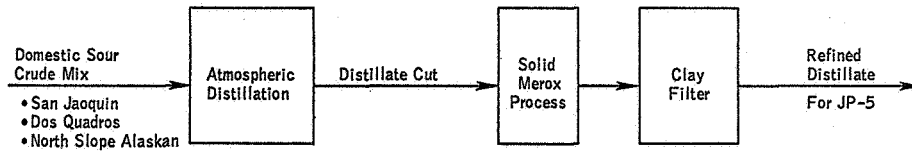
- As a result of the above, other alternative solutions to an operational problem which might involve modification of an inexpensive engine component or part may be preferable to changing additives or putting new additives in the fuel. This would be particularly the case if modification to the engine or other hardware component involved is restricted to a small fraction of the aircraft in service.
- JP-5, as well as other jet fuels, (except for specialty fuels such as JP-7, RP-1) are not processed with thermal stability as a specific objective but rather to meet the military specifications involved, which do not provide a good means of assessing thermal stability. The work conducted in this program provides much greater insight into the subtleties involved in the processing of JP-5 and how important each one of the unit processes involved in making the fuel is in producing fuel meeting current specifications.

TYPICAL PROCESSING SCHEMES EMPLOYED TO MAKE JP-5

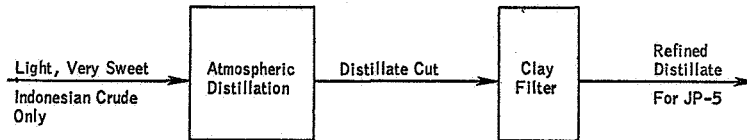
SMALL REFINERIES PAD 5



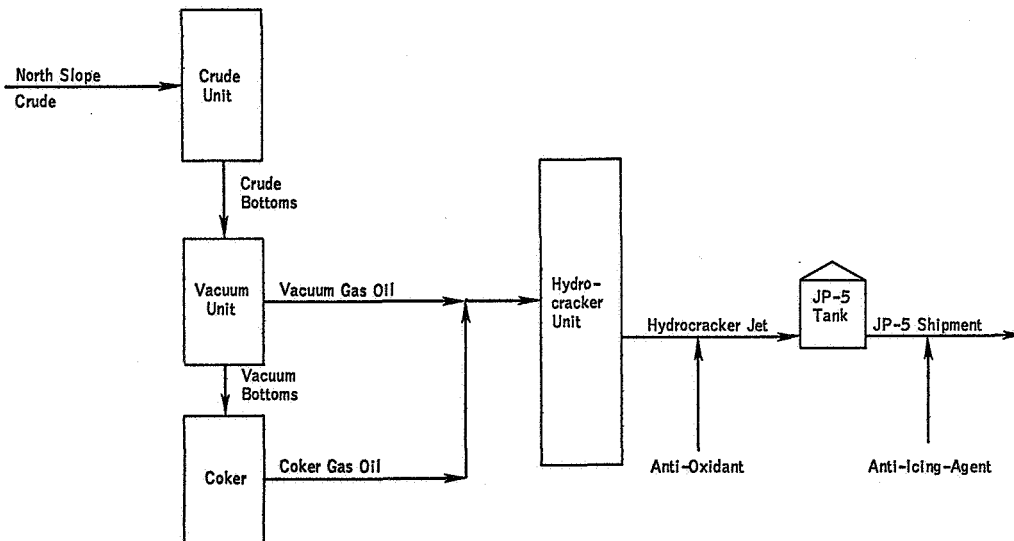
SMALL REFINERY V-B



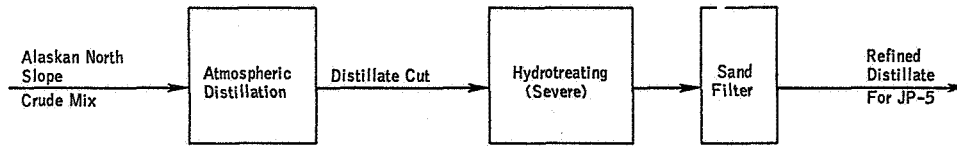
SMALL REFINERY V-C



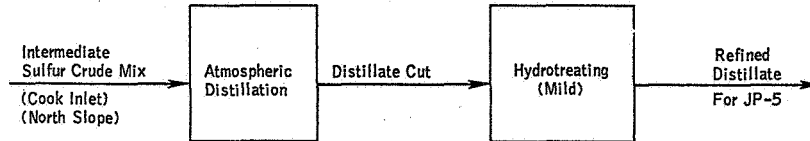
LARGE REFINERIES PAD 5



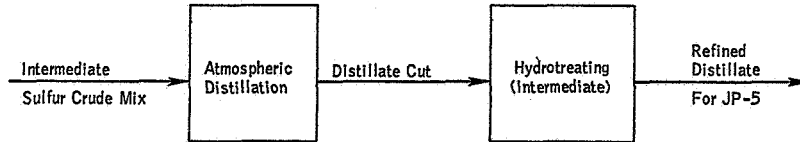
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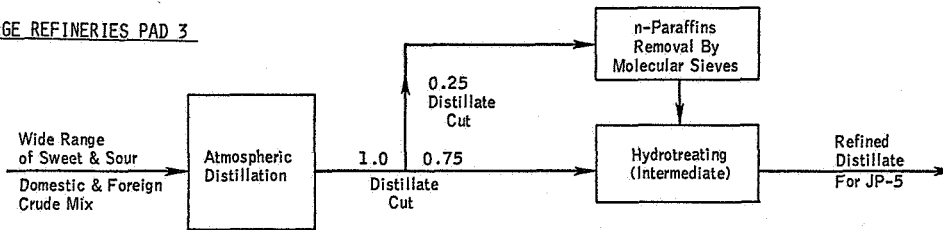
LARGE REFINERY V-E



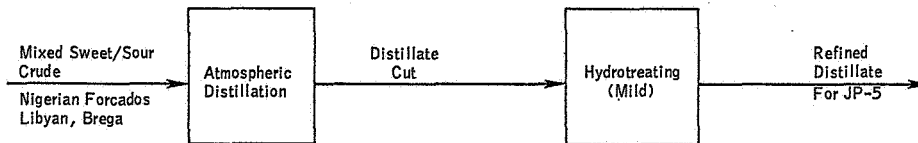
LARGE REFINERY V-F



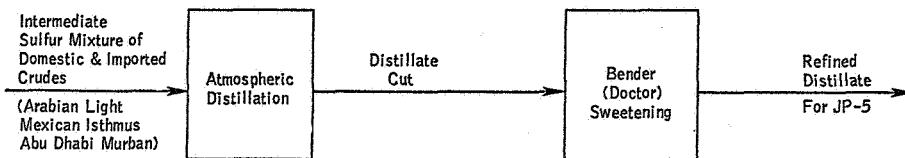
LARGE REFINERIES PAD 3



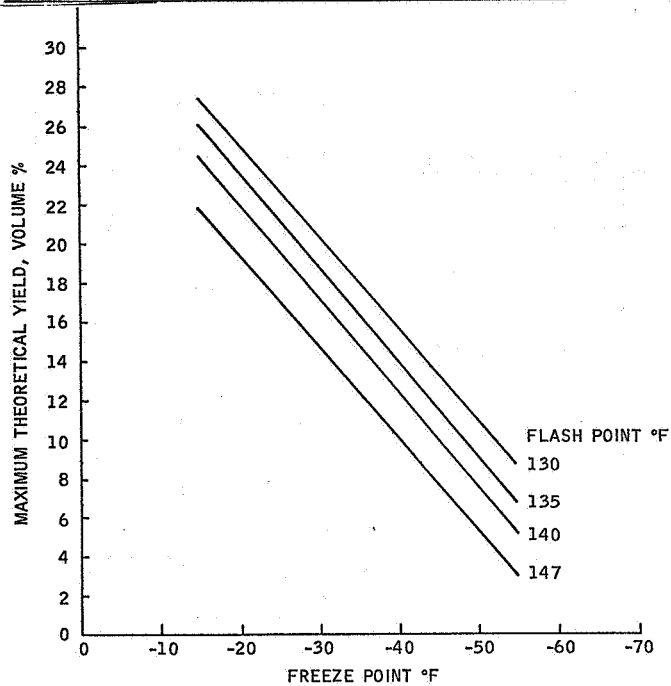
LARGE REFINERY III-B



LARGE REFINERY III-C



EFFECT OF RELAXATION OF FREEZE/FLASH POINT
ON MAXIMUM THEORETICAL YIELD - PARAMETRIC REPRESENTATION



JP-5 POTENTIAL AVAILABILITY

EFFECT OF RELAXATION OF FREEZE POINT

FREEZE POINT OF	MAXIMUM THEORETICAL YIELD(1)					
	CRUDE	A	B	C	D	E
-51 (CURRENT SPECIFICATION)		7.0	19.3	14.2	11.5	12.3
-45		9.9	23.9	17.4	14.4	15.5
% INCREASE OVER CURRENT SPECIFICATION		41%	24%	23%	25%	26%
-40		12.3	27.7	20.0	16.7	18.4
% INCREASE OVER CURRENT SPECIFICATION		76%	44%	41%	45%	50%
-30		17.1	35.3	25.3	21.4	23.9
% INCREASE OVER CURRENT SPECIFICATION		144%	83%	78%	86%	94%
YIELD/FREEZE POINT COEFFICIENT, VOL%/°F		0.48	0.73	0.52	0.47	0.52

(1) CRUDE DESCRIPTION:

- A MEDIUM GRAVITY, HIGH SULFUR MEXICAN CRUDE
- B LIGHT GRAVITY, LOW SULFUR, HIGH AROMATIC INDONESIA CRUDE
- C LIGHT GRAVITY, LOW SULFUR, LOW AROMATIC NIGERIAN CRUDE
- D HEAVY GRAVITY, HIGH SULFUR, HIGH AROMATIC ALASKAN CRUDE
- E LIGHT GRAVITY, LOW SULFUR, CALIFORNIA CRUDE

JP-5 POTENTIAL AVAILABILITY

EFFECT OF RELAXATION OF FLASH POINT

<u>FLASH POINT OF</u>	<u>CRUDE</u>	<u>MAXIMUM THEORETICAL YIELD(1)</u>				
		<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>
147		4.8	15.6	12.2	9.5	9.6
% DECREASE UNDER CURRENT SPECIFICATION		31%	19%	14%	17%	22%
140 (CURRENT SPECIFICATION)		7.0	19.3	14.2	11.5	12.3
135		8.5	21.8	16.0	13.0	14.4
% INCREASE OVER CURRENT SPECIFICATION		21%	13%	13%	13%	17%
130		10.4	24.5	17.7	14.4	16.3
% INCREASE OVER CURRENT SPECIFICATION		49%	27%	25%	25%	33%
YIELD/FLASH POINT COEFFICIENT, VOL%/°F		0.33	0.52	0.32	0.29	0.39

(1) CRUDE DESCRIPTION:

- A MEDIUM GRAVITY, HIGH SULFUR MEXICAN CRUDE
- B LIGHT GRAVITY, LOW SULFUR, HIGH AROMATIC INDONESIAN CRUDE
- C LIGHT GRAVITY, LOW SULFUR, LOW AROMATIC NIGERIAN CRUDE
- D HEAVY GRAVITY, HIGH SULFUR, HIGH AROMATIC ALASKAN CRUDE
- E LIGHT GRAVITY, LOW SULFUR, CALIFORNIA CRUDE

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FUEL/ENGINE/AIRFRAME TRADEOFF STUDY - PHASE I

A. T. Peacock
Douglas Aircraft Company

INTRODUCTION

The Douglas Aircraft Company received a contract from the Air Force to study the effects of broadening the specifications for JP-4 and JP-8 fuel on the performance and cost of all USAF aircraft presently using JP-4 as well as those expected to be introduced into the force structure by 1983. Phase I of this study was to determine analytically the effects of these specification changes on minimizing fuel cost and maximizing the fuel availability/flexibility without degrading performance, safety, and survivability/vulnerability.

The maximum variations to the property specifications to be considered were as shown in table I. Union Oil Company was chosen to study the property variation effects on fuels, Pratt & Whitney Aircraft Group studied the effects on engines, and McDonnell Douglas studied the effects on the airframe.

HIGHLIGHTS OF FUEL SUPPLY STUDY

Union Oil Company obtained twenty-four foreign and nine domestic crude assays which contained sufficient data to correlate freeze point and smoke point with initial boiling point and final boiling point. This data was examined to determine the effects on fuel availability, fuel costs, and hydrogen content (an important factor in engine life), when varying the fuel properties to the maximum amount shown in table I.

When comparing the change from theoretical yields of present specifications to proposed specifications, yields would increase as shown in table II. This large increase in JP-8 is due wholly to the extension of boiling limits in a narrow cut product that are made possible by an extension of the freeze point limits. Reasonable quantitative effects of fuel specification variations on military fuel prices could not be determined because of extreme market instability.

Seven selected crudes were analyzed for changes in hydrogen content which would result from the changes in specifications. Based on a similar weighting system as used for volume effects, the change in hydrogen content is predicted to be 0.3% lower (0.17 wt % H).

HIGHLIGHTS OF ENGINE STUDY

The overall objective of the engine manufacturer effort in Phase I was to assess the impact of broadened-specification fuels on the performance and

durability of gas turbine engines used in USAF aircraft. The various engine-related parameters addressed in this phase of the program included ignition characteristics, combustion efficiency, emissions, thermal loads, burner exit temperature distribution, erosion, and coking of the fuel system. The sensitivity of these parameters was discussed with regard to the proposed relaxations of current JP-4 and JP-8 fuel specifications shown in table I.

A fuel characterization study was performed to determine the effects of the proposed changes in JP-4 and JP-8 fuel specifications on fuel hydrogen content. Through the use of interproperty correlations, a change from current JP-4 and JP-8 fuel values of final boiling point and smoke point to the proposed specification limits is predicted to decrease current fuel values of hydrogen content by 0.25 (% by weight).

Thermal analyses were performed on combustor liner and turbine airfoil temperatures in two USAF engines: the J57-59W and the F100-PW-100. Increases in turbine airfoil temperatures were found to be negligible for both engines (figs. 1 and 2).

The Phase I effort concluded that there would be a small increase in maintenance costs due to a small decrease in combustor life. The study showed that the proposed relaxed specifications would have a negligible effect on visible smoke emissions. The broadened-property JP-4 and JP-8 fuels are expected to have no impact on engine performance, with the exception of ignition capability, relative to current JP-4 and JP-8 fuels. The higher viscosity and lower volatility of the broadened-property fuels may have an adverse effect on ignition capabilities when fuel and/or air temperatures are relatively low (cold-day ground starts and altitude ignition). The extent of this effect depends on both operating conditions and the particular engine employed and cannot be predicted because of a lack of pertinent data. However, the incremental effect of the broadened-property fuels on ignition capabilities relative to current JP-4 and JP-8 fuels is expected to be less than the incremental effect associated with the use of JP-5 relative to JP-4 fuel.

HIGHLIGHTS OF AIRFRAME STUDY

The main objective of the airframe manufacturer effort in Phase I was to determine the effect of broadened-specification fuels on aircraft fuel system performance. It was beyond the scope of this program to study all the airplanes in the Air Force inventory. "High fuel user" airplanes (fig. 3) were selected for this study. Together these aircraft consume 75% or more of the fuel used by the USAF.

The fuel systems and fuel management methods of each airplane were studied to evaluate the effect on the system performance of operating with tank fuel temperatures near the freeze point. The recovery temperature was used as a means of predicting minimum inflight fuel temperatures and the relationship with maximum allowable freeze points. It is recognized that

the use of MIL-STD-210B and the aircraft recovery temperatures is a fairly conservative approach; however, a less conservative approach could not be justified with the limited amount of data that is available on this subject.

Using the selected approach, with some consideration of flight conditions (figs. 4 and 5), it was determined that all the airplanes in the study could obtain tank fuel temperatures below the present maximum allowable freeze point of both JP-4 and JP-8. It was therefore concluded that the maximum allowable freeze point of JP-4 or JP-8 cannot be increased without degrading system performance and safety as critical conditions are approached.

CONCLUSIONS

Major conclusions from the fuel/engine/airframe tradeoff study were as follows:

1. An increased freeze point is questionable because of a data base problem.
2. There was no impact on engine performance, turbine durability, and coking.
3. There was a small maintenance cost increase as a result of a small combustor life decrease.
4. Using JP-4 as standard fuel will avoid the use of high-demand middle-distillate fuels and give producers flexibility.
5. Extensive use of JP-8 in the United States will increase middle-distillate demand and cause a slight increase in engine hot-section maintenance.
6. There is need for an accepted single flight model.
7. Present aircraft operations and systems are freeze-point sensitive.

RECOMMENDATIONS

Recommendations for USAF action and further study are as follows:

1. An experimental study of the effect of fuel properties on engines should be made, including carbon formation, deposition, and erosion; fuel thermal stability and coking in actual systems; and afterburner performance and durability.
2. An improved durability combustor liner design and development program (new design and retrofit) should be conducted.
3. The actual freeze point (not specification maximum) should be used for dispatch evaluations.
4. Aircraft systems and procedures for operations near the actual freezing point should be reviewed.
5. Tests should be conducted with special blend fuel at broadened-property limits.
6. Future aircraft studies should include airplane and systems design-cost trade-offs for higher freeze-point tolerance.

TABLE I
PROPOSED SPECIFICATION CHANGES

	<u>JP-4</u>	<u>JP-8</u>
FREEZE POINT, °F (°C)		
PRESENT SPECIFICATION, MAXIMUM	-72 (-58)	-58 (-50)
PROPOSED VARIATION	+14 (8)	+18 (10)
PROPOSED SPECIFICATION, MAXIMUM	-58 (-50)	-40 (-40)
FINAL BOILING POINT, °F (°C)		
PRESENT SPECIFICATION, MAXIMUM	518 (270)	572 (300)
PROPOSED VARIATION	+25 (14)	+25 (14)
PROPOSED SPECIFICATION, MAXIMUM	543 (284)	597 (314)
SMOKE POINT, mm		
PRESENT SPECIFICATION, MINIMUM		20 ^a
PROPOSED VARIATION		<u>-2</u>
PROPOSED SPECIFICATION, MINIMUM		18

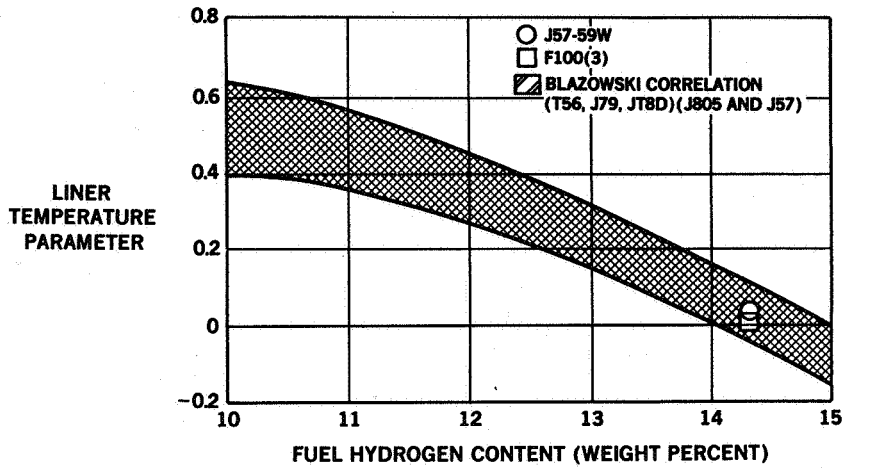
^a. MAXIMUM 3.0 VOLUME PERCENT NAPHTHALENES

TABLE II
EFFECT OF SPECIFICATION CHANGE ON YIELD

<u>FUEL TYPE</u>	<u>PERCENTAGE INCREASE</u>
JP-4	8.5-9.0
JP-8	41-62

FIGURE 1

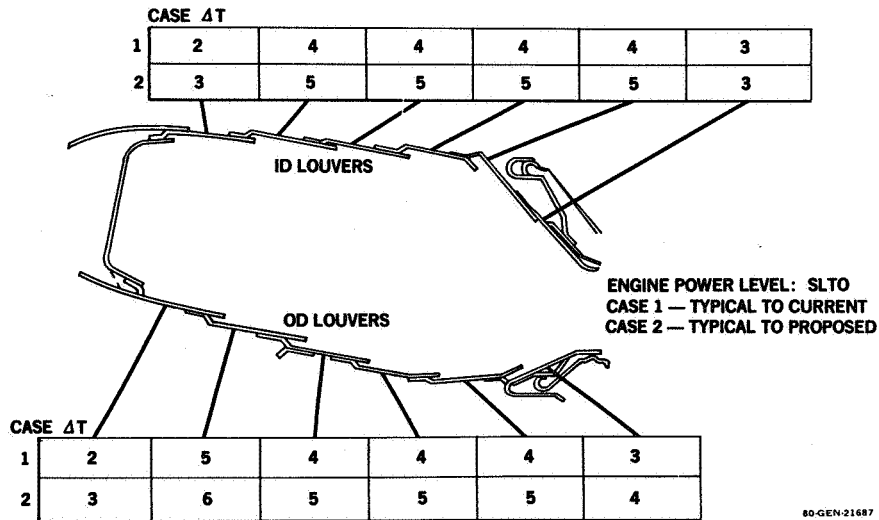
**J57 LINER TEMPERATURE PARAMETER AT CRUISE CONDITION
COMPARED WITH THE BLAZOWSKI CORRELATION**



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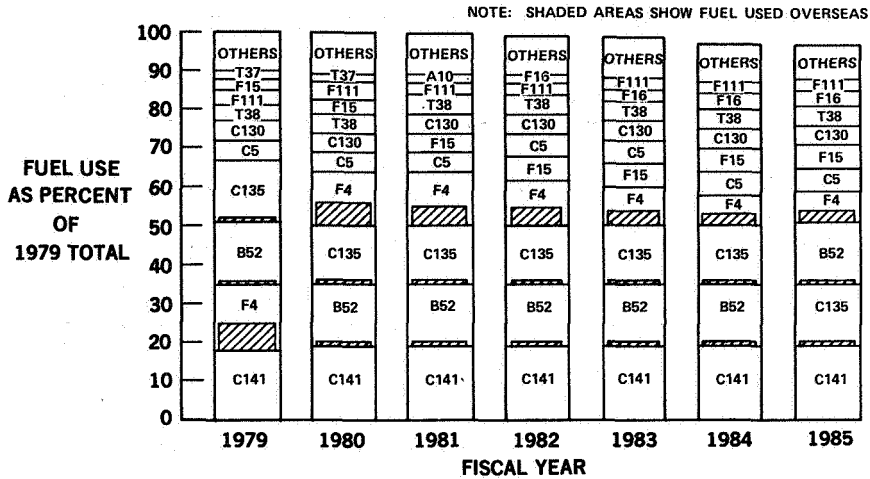
FIGURE 2

**EFFECT OF FUEL SPECIFICATION RELAXATIONS ON INCREASE
IN AVERAGE COMBUSTOR LINER TEMPERATURES**



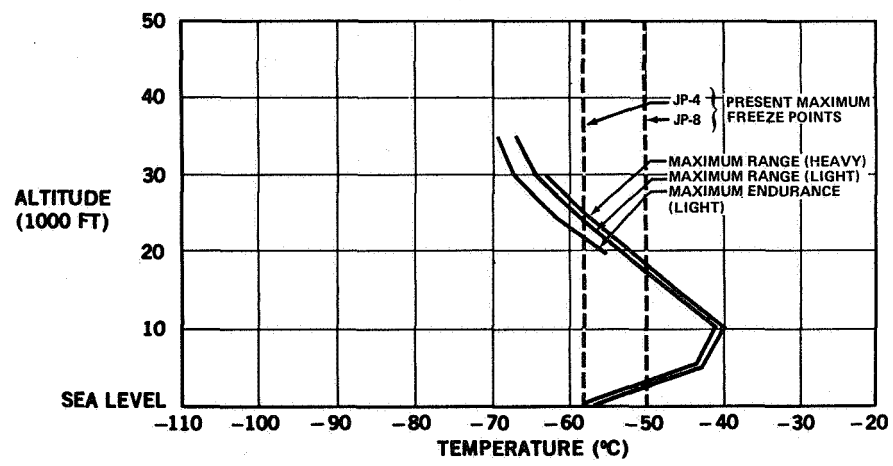
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FIGURE 3
PROJECTED FUEL USE



9-GEN-26683

FIGURE 4
C-130 ADIABATIC WALL TEMPERATURE



9-GEN-26649

FIGURE 5

ALLOWABLE FREEZE POINT INCREASE (°C)

NOTES:

1. OUTSIDE AIR TEMPERATURES FROM MIL-STD-210B, ONE DAY PER YEAR RISK MINIMUM TEMPERATURES
2. BASED ON ADIABATIC WALL TEMPERATURES

	<u>KC-10A</u>	<u>C-9</u>	<u>B-52</u>	<u>C-130</u>	<u>C-135</u>	<u>C-141</u>	<u>C-5</u>	<u>F-4</u>	<u>F-15</u>
JP-8									
MAXIMUM RANGE — HEAVY	0.5	-3.0	-5.0	-13.0	-4.0	-5.0	-3.5	4.5	1.5
MAXIMUM RANGE — LIGHT	-3.5	-6.5	-11.5	-16.5	-8.5	-9.5	-8.5	-0.5	-4.0
MAXIMUM ENDURANCE — LIGHT	-10.5	-14.5	-14.0	-19.5	-13.5	-18.5	-15.0	-7.5	-10.0
JP-4									
MAXIMUM RANGE — HEAVY	8.5	5.0	3.0	-5.0	4.0	3.0	4.5	12.5	9.5
MAXIMUM RANGE — LIGHT	4.5	1.5	-3.5	-8.5	-0.5	-1.5	-0.5	7.5	4.0
MAXIMUM ENDURANCE — LIGHT	-2.5	-6.5	-6.0	-11.5	-5.5	-10.5	-7.0	0.5	-2.0

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MILITARY JET FUEL FROM SHALE OIL

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Aero Propulsion Laboratory
Wright-Patterson Air Force Base

Military jet fuel accounts for 60% of the total fuel requirement of the Department of Defense (DOD) as shown in Table 1. Because of the need to obtain a secure domestic source for military fuel and because it is evident that the DOD must be in the position to utilize fuel produced from domestic non-petroleum sources, the Air Force has embarked on an Aviation Turbine Fuel Technology Program. As part of this Air Force Program "A Program Leading to Specification for Aviation Turbine Fuel Produced from Whole Crude Shale Oil" was initiated. Past studies have shown that oil from shale is the most promising alternate source of jet fuel. The oil shale industry is closer to commercialization than coal liquefaction and shale oil is more amenable to conversion into jet fuel than are coal liquids (Ref. 1, 2, 3). The shale oil program is investigating jet fuel qualities, yields and economics for novel processes capable of producing high yields of jet fuel. Shale derived fuel properties of special interest include boiling range, freeze point, combustion characteristics, and thermal and storage stability as affected by hydrocarbon type, and nitrogen and trace metal content. Contracts were awarded by the Air Force to three companies in January 1979 to carry out this 28 month, four phase program. Ashland Research and Development - Ashland Petroleum Co., Suntech Inc. - Sun Company, and UOP Process Division - UOP, Inc. have completed the preliminary process designs and economic evaluations constituting Phase I of this program. A brief description of the processes investigated and the preliminary results from Phase I follow.

The Ashland program is based upon a refining method called the "Extracta-cracking" process. This process is specifically designed for the conversion of nonconventional feedstocks into finished conventional products. A simple block diagram of this process is shown in Figure 1. Whole crude shale oil is converted by a combination of hydrotreating, extraction, and fluid cracking steps into a material suitable for finished fuel production. Final product treating steps are provided as necessary for the production of specification quality fuels. In general this process uses low pressure processing equipment and has relatively low hydrogen consumption for a process optimizing jet fuel.

The Suntech program is studying the technical feasibility of three different processing schemes. A base case was defined as a process in which the crude shale oil would be hydrotreated, washed with 80% sulfuric acid, and fractionated to yield straight run products. A second scheme, shown in Figure 2, involves treating with anhydrous hydrogen chloride in conjunction with hydrotreating and hydrocracking. A third scheme is similar to the HCl scheme, however, it utilizes a liquid extraction solvent. The solvent, N,N-dimethylformamide (DMF), was screened from several other candidates based on the selective removal of polyaromatics and nitrogen compounds. In general, the Suntech extraction processes offer flexibility in product slate with the capability to produce high yields of jet fuel and essentially eliminate residual fuel production.

The UOP program is studying variations of two basic flow schemes, one for JP-4 and one for JP-8. The UOP process is composed of hydrotreating and hydrocracking, utilizing a proprietary modified flow hydrocracking scheme. The UOP process for the production of JP-8 is shown in Figure 3. The only major difference between this scheme and the one to produce JP-4 is the addition of naphtha hydrotreating and platforming units for processing and gasoline fraction. Each of these two schemes was evaluated with three different product slates, one slate with the maximum jet fuel yield attainable and two slates with reduced jet fuel yields. The UOP scheme offers essentially proven operational technology to produce high yields of aviation turbine fuel from shale oil.

The shale oil crudes being studied in the Air Force program are Occidental modified in-situ retorted material and Paraho surface retorted material. These were selected primarily because of availability and because they are representative of a range of properties that could be expected in oil produced from western oil shale by various retorting methods.

The results that follow are from schemes maximizing JP-4 and JP-8 production. All information presented here was either directly extracted or derived from results presented by Ashland, Suntech, and UOP in Phase I reports submitted to the Air Force.

Yield and product information is presented in Tables 2 and 3. The product yield is based on the volume of all liquid feed material, including shale oil crude and fuel used for process heat and hydrogen production, divided into the volume of all liquid products.

It is anticipated that all product qualities will meet or exceed the current military specifications. However, the projected jet fuel qualities shown in Table 4 do show variance depending upon the processing method. It should be realized that for processes maximizing jet fuel some fuel properties will have to be pushed to the specification limit by definition. Experimental data on turbine fuel properties and on quality/yield/economic trade-offs will be generated later in these programs.

The overall economics are based on a nominal 100,000 barrel per day grass roots refinery located in the midwest adjacent to an existing refinery; some of the major economic bases are shown in Tables 5 and 6. The economic results in September 1978 dollars are shown in Tables 7 and 8 for JP-4 and JP-8 respectively. The bottom line product prices are all between 80 and 84¢/gallon at the refinery.

The economic results generated in Phase I are based on preliminary process designs. These process designs were developed without the data to be generated in bench and pilot plant scale tests which are scheduled to be accomplished in Phase II and III of the Ashlnad, Suntech and UOP programs. Data generated in Phases II and III will result in a better understanding of the yields, the properties, and the costs of jet fuel produced from whole crude shale oil. From this data, an updated overall economic evaluation will be accomplished in Phase IV of the programs.

Up to 1000 gallons of variable quality fuel samples will result from the Ashland and Suntech programs with less being generated in the UOP effort. A larger quantity of specification quality JP-4 is needed for a Fuel Mainburner/Turbine Effects program being carried out by General Electric and Pratt & Whitney as part of the Air Force Aviation Turbine Fuel Technology program. This test fuel was procured through the Suntech program with Hydrocarbon Research Inc. (HRI) participating as a subcontractor. A total of 11,300 gallons of specification quality JP-4 was produced by HRI from Geokinetics crude shale oil in a single stage severe hydrogenation process. The JP-4 yield from this process was 33%. The properties of the JP-4 and residual material produced are shown in Table 9. Also shown in Table 9 are the average properties of the JP-4 procured by the Air Force in 1978.

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TABLE 1
DOD FUEL PROCUREMENTS FY78
 220 MILLION BARRELS

<u>FUEL</u>	<u>% OF TOTAL</u>
JP-4	47%
JP-5	12%
OTHER JET FUELS	1%
DIESEL FUEL MARINE (DFM)	14%
RESIDUAL, DIESEL AND OTHER FUEL OILS	21%
GASOLINE	<u>5%</u>
TOTAL	100%

TABLE 2
YIELD DATA FOR PROCESSES MAXIMIZING JP-4

	ASHLAND	SUNTECH HCl EXTRACTION	UOP MAX JP-4	UOP JP-4/DFM
PRODUCT YIELD (VOL % OF FEED)	86.8	94.1	95.5	95.3
PRODUCT SLATE (VOL % OF PRODUCTS)				
JP-4	54.3	100.0	100.0	70.4
DFM/(DF-2)	(22.9)	---	---	29.6
BURNER FUEL	5.8	---	---	---
GASOLINE	17.0	---	---	---

TABLE 3
YIELD DATA FOR PROCESSES MAXIMIZING JP-8

	ASHLAND	SUNTECH	UOP	
		HCl EXTRACTION	MAX JP-8	JP-8/DFM
PRODUCT YIELD (VOL % OF FEED)	87.4	93.1	93.3	93.8
PRODUCT SLATE (VOL % OF PRODUCTS)				
JP-8	62.3	63.1	86.9	74.2
DFM	—	—	—	15.1
BURNER FUEL	5.7	—	—	—
GASOLINE	32.0	36.9	13.1	10.7

TABLE 4
PROJECTED QUALITIES OF SHALE OIL DERIVED JP-4

	MIL SPEC	ASHLAND	SUNTECH	UOP
GRAVITY (°API)	45-57	45	50.5	52.6
AROMATICS (VOL %)	25 MAX	25	11	6
FREEZING POINT (°F)	-72 MAX	-72	-75	-72
SMOKE POINT (MM)	20 MIN	20	> 20	35
SULFUR (PPM)	(4000)	< 1	< 5	< 1
NITROGEN (PPM)	NO SPEC	1	10	< 5
HYDROGEN (WT %)	13.6 MIN	13.6	14.0	14.5
RVP (PSI)	2-3	3	2.5	1.9

TABLE 5
ECONOMIC BASIS
CAPITAL RECOVERY

COST BASE:	SEPTEMBER 78
EQUITY FINANCING:	100%
RETURN ON INVESTMENT:	15% DISCOUNTED CASH FLOW AFTER TAXES
WORKING CAPITAL:	30 DAYS CRUDE INVENTORY AT \$16.00/BARREL 30 DAYS PRODUCT INVENTORY AT \$21.00/BARREL DEBT FINANCED AT 10% ANNUAL INTEREST RATE

TABLE 6
ECONOMIC BASIS
OPERATING COST

CRUDE SHALE OIL:	\$25.00 PER BARREL AT PLANT
FUEL:	EQUAL TO SHALE OIL CRUDE COST
PRODUCT VALUES:	FUELS EQUAL (\$21.00 FOR WORKING CAPITAL) BY-PRODUCTS - AMONIA - \$120/SHORT TON SULFUR - \$53/LONG TON

TABLE 7

ECONOMIC RESULTS FOR PROCESSES MAXIMIZING JP-4

	ASHLAND	SUNTECH	UOP	
		HCl EXTRACTION	MAX JP-4	JP-4/DFM
MANUFACTURING COSTS				
\$/BBL PRODUCT	5.33	8.55	8.69	7.84
ADJUSTED CRUDE COST				
\$/BBL PRODUCT	28.80	26.57	26.21	26.23
TOTAL COST				
\$/BBL PRODUCT	34.13	35.12	34.90	34.07
¢/GAL PRODUCT	81	84	83	81

TABLE 8

ECONOMIC RESULTS FOR PROCESSES MAXIMIZING JP-8

	ASHLAND	SUNTECH	UOP	
		HCl EXTRACTION	MAX JP-8	JP-8/DFM
MANUFACTURING COSTS				
\$/BBL PRODUCT)	5.20	8.55	8.39	7.56
ADJUSTED CRUDE COST				
\$/BBL PRODUCT)	28.60	26.85	26.80	26.65
TOTAL COST				
\$/BBL PRODUCT	33.80	35.40	35.19	34.21
¢/GAL PRODUCT	80	84	84	81

TABLE 9
PROPERTIES OF SUNTECH/HRI PRODUCTS

	1978 JP-4	HRI JP-4	HRI RESIDUAL
GRAVITY (°API)	53.9	50.2	37.4
AROMATICS (VOL%)	11.4	8.9	-
FREEZING POINT (°F)	-	-76	-
SULFUR (WT%)	0.04	< 0.01	< 0.01
NITROGEN (PPM)	-	< 1	4
HYDROGEN (WT%)	14.36	14.39	-
RVP (PSI)	2.6	2.5	-

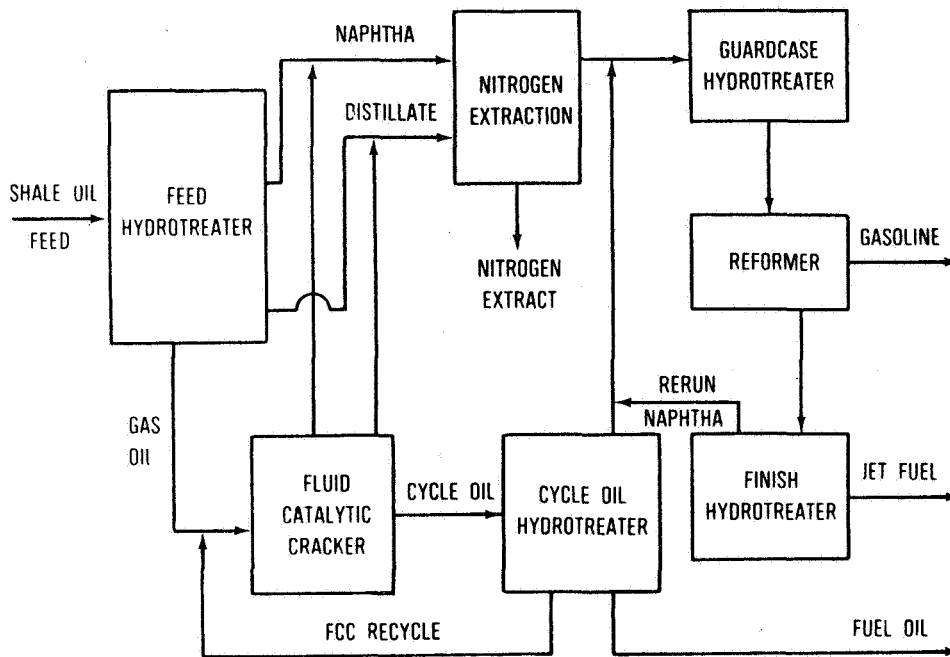


Figure 1. - Ashland Petroleum Co. - extract cracking process.

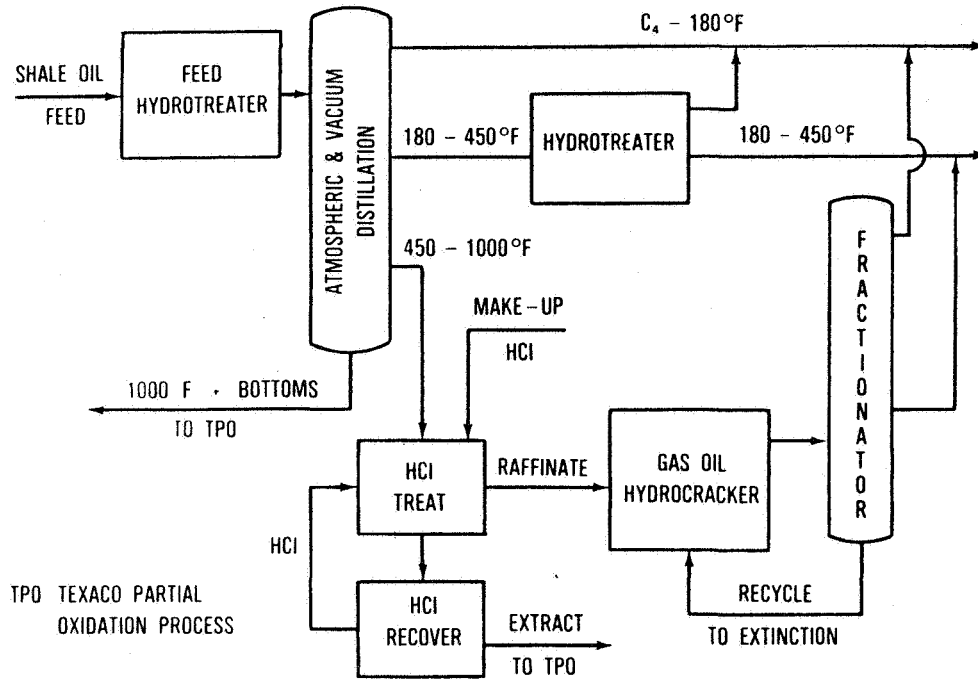


Figure 2. - Sun Technology - HCl extraction/max JP-4.

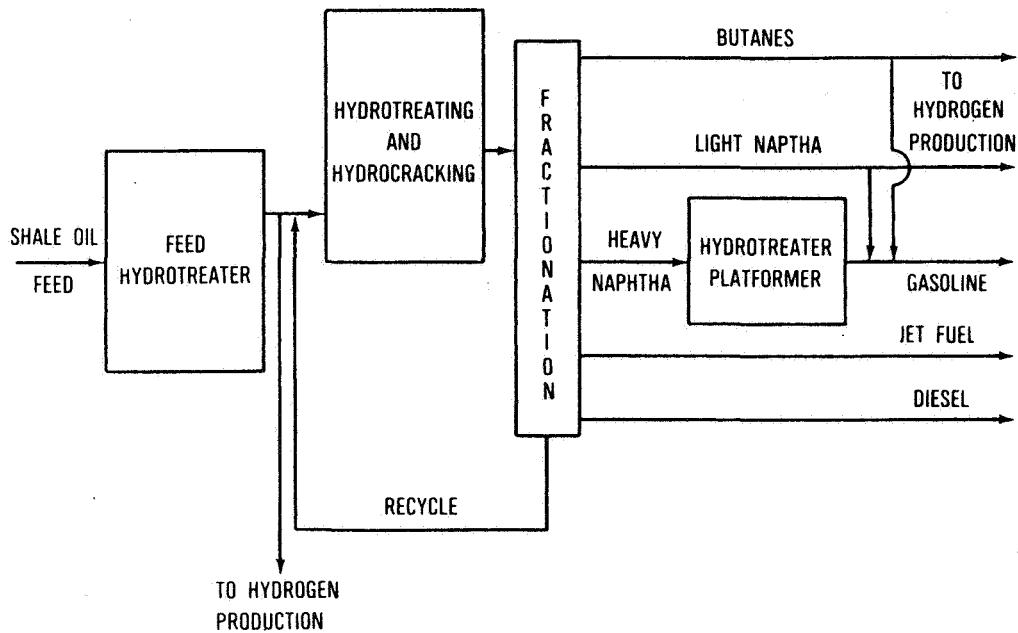


Figure 3. - UOP Process Division - modified flow hydrocracking JP-8.

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FUELS CHARACTERIZATION STUDIES

Gary T. Seng, Albert C. Antoine and Francisco J. Flores
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Lewis Research Center

The major thrust of the Lewis Research Center fuels characterization research effort is not only to characterize fuels derived from petroleum and nonpetroleum sources, but also to evaluate the use of current analytical techniques in the characterization of broadened-properties fuels. The research involves modifying these techniques or developing methods superior to those presently employed. Included in the latter category are liquid chromatography, gas chromatography, and nuclear magnetic resonance spectroscopy. Another important related area, synfuel hydroprocessing research, involves the use of an in-house hydroprocessing facility to study the effects of processing variables on the characteristics of fuels derived from syn-crudes and supplies samples for the analytical research program.

In comparison with a specification Jet A, the broadened-properties fuels exhibit characteristics that reflect some of the potential changes in future aircraft fuels. A number of these fuel property changes, listed in Table 1, could occur as a result of an increase in the amounts of cracked stock streams to be used in future jet fuel production or the introduction of syn-crudes into the refineries. A workshop was held at Lewis in 1977 to consider potential changes in jet fuel characteristics, particularly in the areas of combustion quality, freezing point, thermal stability and materials compatibility (ref. 1). A petroleum-derived broadened-properties fuel which was proposed at this workshop has been procured and characterized to serve as a referee fuel for analytical characterization and experimental combustor work (ref. 2). This experimental referee broadened-specification (ERBS) fuel is of major importance to the analytical methods development program. The ERBS fuel requirements and blend results are given in Table 2.

One specific area of fuels characterization that is presently receiving increased attention is hydrocarbon group-type analysis. Generally, group-type determinations on fuels distilling below 589 K (600° F) are performed by the fluorescent indicator adsorption method (FIA-ASTM D1319) (ref. 3). This method is time consuming, limited in its range of applicability, and subject to a number of errors. Recently, high-performance liquid chromatographic (HPLC) methods have been developed that improve all aspects of group-type analysis (refs. 4 to 7). A Lewis study that compared two HPLC techniques with the FIA method for a number of petroleum, shale, and coal-derived fuels indicated that significant differences did exist in the group-type results found, especially for the synfuels (ref. 7). Selected data from this study are presented in Table 3. These findings stressed the need for further research in this area. Currently, in-house HPLC group-type methods development is being approached from several directions, including aromatic fraction standards development and the elimination of standards through removal or partial removal of the alkene and aromatic fractions or through the use of

whole fuel refractive index values. More sensitive methods for alkene determinations using an ultraviolet-visible detector are also being pursued. Preliminary studies involving chemical removal of the alkene and aromatic fractions has yielded results that agree well with those found by the FIA method but demonstrate superior precision. This HPLC technique requires as little as ten minutes to complete. Research is continuing to further standardize this method, to improve the overall precision and accuracy of the results, and to extend the range of its applicability.

In addition to its use in qualitative and quantitative analyses of fuels, gas chromatography (GC) has been applied to the determination of a number of fuel physical properties (refs. 8 to 10). Some of the more successful GC physical property determinations for petroleum-derived fuels are the distillation curve (simulated distillation), heat of combustion, hydrogen content, API gravity, viscosity, flash point, and (to a lesser extent) freezing point. In a Lewis study that examined the feasibility of applying the GC relationships derived for petroleum fuels to synfuels, it was found that the simulated-distillation, heat-of-combustion, and hydrogen-content results were reasonably accurate but that the results of the other bulk fuel properties were not (ref. 10). Shale-derived fuels tended to yield results that were higher than the actual physical property value; coal-derived fuels yielded low results. Further investigations are warranted to develop GC physical property relationships that would be applicable to synfuels. Current research is aimed at developing a GC method for the determination of total synfuel nitrogen as well as the boiling-point distribution of the nitrogen-containing compounds in synfuels, by combining simulated distillation data and data obtained using a thermionic detector. Much of this effort has been devoted to the characterization of this detector due to the continued controversy concerning its stability and effective lifetime. The results of the study indicate that the simulated distillation-thermionic detector combination is a viable technique that has the potential of being developed into a routine method for future synfuel analysis.

Efforts to obtain detailed information on fuel composition by hydrogen and carbon-13 nuclear magnetic resonance spectroscopy (H and C-13 NMR) have been increasing in recent years due to the sizable amounts and types of data that can be obtained. A complete H and C-13 NMR sample analysis provides information on such important quantities as hydrogen to carbon ratios, relative amounts of each hydrocarbon group type, and, of particular importance, a detailed constituent breakdown (refs. 11 to 13). Lewis has initiated a grant with the University of Utah Research Institute to study petroleum and shale-oil-derived fuels primarily using C-13 NMR techniques. One objective is to correlate C-13 NMR data with fuel physical properties and combustor test results using Jet A and several broadened-properties fuels. A second is to examine the applicability of C-13 NMR to the determination of the composition of shale-oil crudes and products obtained from various stages of processing. The final objective is to employ C-13 NMR as a tool for monitoring fuel thermal degradation reactants and products of low thermal stability turbine fuels. To achieve the degree of detail required in the studies, samples are separated into as many as 16 to 20 fractions prior to

analysis. The combustor data are to be obtained from ongoing in-house and contract work; the processed shale oil samples are being obtained from the Ashland Oil Extractracracking Process through an Air Force Wright Aeronautical Laboratories contract.

A laboratory-scale hydroprocessing facility provides Lewis with the capability to generate a number of the samples required for analytical methods development as well as to perform limited studies on the synthesis and characterization of aviation turbine fuels derived from nonpetroleum sources. The facility is diagramed in Figure 1. A recent study was conducted to determine the characteristics of TOSCO II-derived fuels obtained under medium-severity hydroprocessing conditions and Paraho-derived fuels obtained under low-, medium-, and high-severity conditions. The fractions of whole shale oil boiling below 343^o C (650^o F) were hydroprocessed, and final distillations of each product were performed to obtain a fuel in the Jet A boiling range and a broadened-properties fuel with a final boiling point of 327^o C (620^o F). All products and final distillates were characterized in detail to identify those properties of the fuels that did not meet present specifications. A pictorial summary of the nitrogen results obtained for the Paraho crude oil and products is shown in Figure 2. It was determined that with the exception of the freezing point, which was high, a specification Jet A fuel can be produced from these syncrudes by the combination of high-severity hydroprocessing and distillation. The broadened-properties fuel produced from the same hydroprocessed product exhibited characteristics that were within the specifications set for the ERBS fuel in all cases except the freezing point and hydrogen content, which were both high.

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POTENTIAL JET FUEL CHARACTERISTICS

<u>CHARACTERISTIC</u>	<u>CURRENT JET A</u>	<u>FUTURE BROADENED- PROPERTIES FUELS</u>
<u>COMPOSITION:</u>		
AROMATICS, vol %	17-25	25-40
HYDROGEN, wt %	13.5-14.0	12-13.5
SULFUR, wt %	0.01-0.1	~0.3
NITROGEN, ppm	<10	50-2000
<u>VOLATILITY:</u>		
FLASH POINT, °C	38-66	38-66
BOILING RANGE, °C	171-277	171-343
<u>FLUIDITY:</u>		
FREEZING POINT, °C	-46 TO -40	-34 TO -18
VISCOSITY, cs AT -23° C	~5	~12
<u>HEAT OF COMBUSTION:</u>		
MJ/kg	42.80-43.26	41.87-42.80
<u>THERMAL STABILITY:</u>		
BREAKPOINT TEMP, °C	≥260	?

Table 1

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EXPERIMENTAL REFEREE BROADENED-SPECIFICATION (ERBS)

AVIATION TURBINE FUEL - REQUIREMENTS AND BLEND RESULTS

PROPERTY	REQUIREMENTS	BLEND RESULTS
COMPOSITION:		
HYDROGEN, wt %	12.8±0.2	12.86
AROMATICS, vol %	REPORT	35.0
SULFUR, MERCAPTAN, wt %	0.003 MAX	0.0005
SULFUR, TOTAL, wt %	0.3 MAX	0.085
NITROGEN, TOTAL, ppm	REPORT	54
NAPHTHALENES, vol %	REPORT	13.2
HYDROCARBON COMPOSITIONAL ANALYSIS	REPORT	
VOLATILITY:		
DISTILLATION TEMP, °C (°F)		
INITIAL BOILING POINT	REPORT	162 (324)
10 %	204 (400) MAX	188 (370)
50 %	REPORT	215 (419)
90 %	260 (500) MIN	279 (534)
FINAL BOILING POINT	REPORT	328 (622)
RESIDUE %	REPORT	1.2
LOSS, %	REPORT	0.3
FLASHPOINT, °C (°F)	38 (100) MIN	60 (140)
GRAVITY, API (15° C)	REPORT	37.1
GRAVITY, SPECIFIC (15/15° C)	REPORT	0.8381
FLUIDITY:		
FREEZING POINT, °C (°F)	-23 (-10) MAX	-29 (-20)
VISCOSITY, AT -23° C (-10° F), cSt	12, MAX	7.2
NET HEAT OF COMBUSTION, KJ/Kg (Btu/lb)	REPORT	42 427 (18 275)
THERMAL STABILITY:		
JFTOT, BREAKPOINT - TEMP, °C (°F) (TDR, 13; AND ΔP, 25 mm)	238 (460) MIN	255.5 (492)

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Table 2

COMPARISON OF AROMATICS DETERMINATION BY FIA AND HPLC METHODS

CRUDE SOURCE AND FUEL BOILING RANGE	FIA	MAXIMUM DEVIATION, % AROMATICS	HPLC METHOD 1		HPLC METHOD 2	
	AROMATICS, %		AROMATICS, %	DIFFERENCE (HPLC-FIA)	AROMATICS, %	DIFFERENCE (HPLC-FIA)
PETROLEUM 107°-262° C	21.2	0.4	17.6	-3.6	21.3	0.1
138°-258° C	17.4	0.3	13.4	-4.0	16.4	-1.0
SHALE 121°-288° C	15.7	2.5	21.3	5.6	20.8	5.1
COAL 121°-288° C	26.4	2.4	30.3	3.9	26.1	-0.3
COAL 121°-343° C	29.0	3.6	30.2	1.2	25.2	-3.8

*AVERAGE OF RESULTS FROM 3 LABORATORIES.

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Table 3

FUEL SYNTHESIS FACILITY

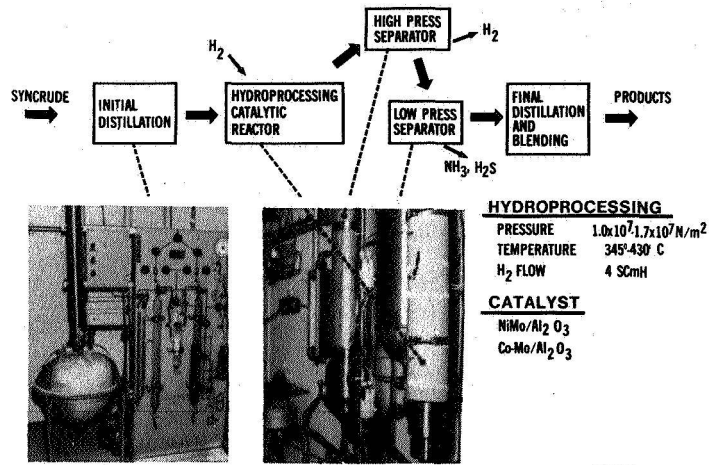


Figure 1

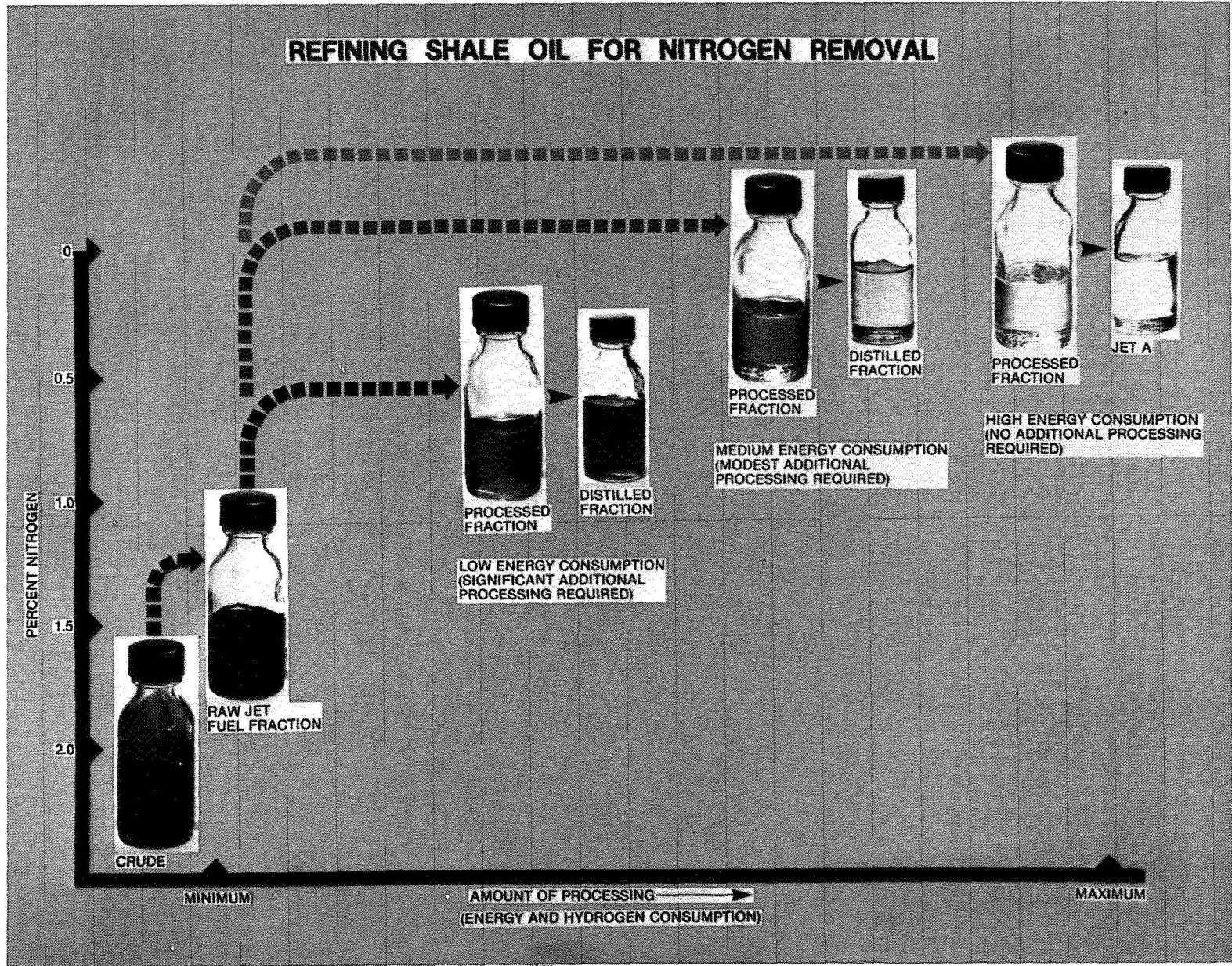


Figure 2

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COMBUSTION TECHNOLOGY OVERVIEW

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National Aeronautics and Space Administration
Lewis Research Center

The combustion of gas turbine fuels is the subject matter for the next two sessions. In the papers in this session combustor technology programs, as distinguished from combustion research of a more fundamental nature, are discussed, and the results of Government-funded contracts with engine manufacturers are described.

To evolve the combustor technology required for use of broadened-property fuels, several levels of combustor technology are being investigated. First, unmodified in-service combustors are being evaluated with broadened-property fuels. The intent of these investigations is to determine the extent to which fuel properties can be varied, to obtain a data base of combustion - fuel quality effects, and to determine the trade-offs associated with broadened-property fuels. Second, subcomponents of in-service combustors such as fuel injectors and liners, as well as air distributions and stoichiometry, are being altered to determine the extent to which fuel flexibility can be extended. Last, very advanced technology consisting of new combustor concepts is being evolved to optimize the fuel flexibility of gas turbine combustors.

The increasing concerns regarding the supply and quality of gas turbine fuels at present and for the future has served as the impetus for expanded research in many fuels and combustion areas. Department of Defense programs aimed at military aviation applications form a significant part of the material presented in this session. Specifically, two Air Force Wright Aeronautical Laboratory (AFWAL) programs are described by Thomas A. Jackson of AFWAL. These are the Fuel Character Effects on the J79 and F101 Engine Combustion Systems, a recently completed effort, and the Air Force Fuel Mainburner/Turbine Effects program, a major program currently in progress.

NASA Lewis programs aimed toward civil aviation applications include analytical evaluation of the effects of broadened-specification fuels on high-bypass turbofan engine combustors, which is described later in this overview; the Experimental Combustor Study program, a recently completed effort, which is described by John M. Kasper and Edward E. Ekstedt of the General Electric Co.; and the NASA Broadened-Specification Fuels Combustion Technology program, which is described in the papers by James S. Fear of NASA Lewis, Dr. Robert P. Lohmann of Pratt & Whitney, and Willard J. Dodds of General Electric Co.

A third area of fuels and combustion research, stationary-power gas turbines, is being pursued in the Department of Energy/NASA Low-NO_x Heavy-Fuel Combustor Concept program. This program consists of contracts with

five engine manufacturers and is aimed at evolving fuel-flexible, environmentally acceptable combustors capable of using heavy oil fuels and synfuels (non-petroleum-derived fuels) in utility and industrial applications. Although a presentation of this program is not included in this session, the program has been described in a recent ASME paper (ref. 1).

Before the NASA Lewis combustor technology programs were implemented, analytical studies were conducted under contracts with Pratt & Whitney Aircraft and the General Electric Co. These studies consisted of in-depth analyses of broadened-property fuel effects on the performance and emissions of current high-bypass-ratio, commercial aircraft engine combustors and future engine combustors of the Energy Efficient Engine (E³) type. These studies have been completed and the results published as NASA Contractor Reports (refs. 2 and 3).

Study results indicated that in conventional combustors the use of broadened-property fuels could have the following undesirable effects:

1. Liner temperatures could be higher because of increased flame radiation to combustor walls. Local liner temperatures could increase by as much as 40 kelvins. The higher temperatures could reduce liner fatigue life by 25 to 40 percent.

2. Attempts to reduce liner temperatures by providing increased coolant airflows could adversely affect combustor exit-temperature-distribution uniformity and thereby reduce turbine life.

3. Broadened-property fuels have poorer atomization characteristics, which would produce poorer, less-uniform fuel sprays and result in poorer ignition and altitude relight performance, deteriorated temperature distributions, increased smoke at high-power conditions, and higher emission levels of carbon monoxide and unburned hydrocarbons at low-power conditions.

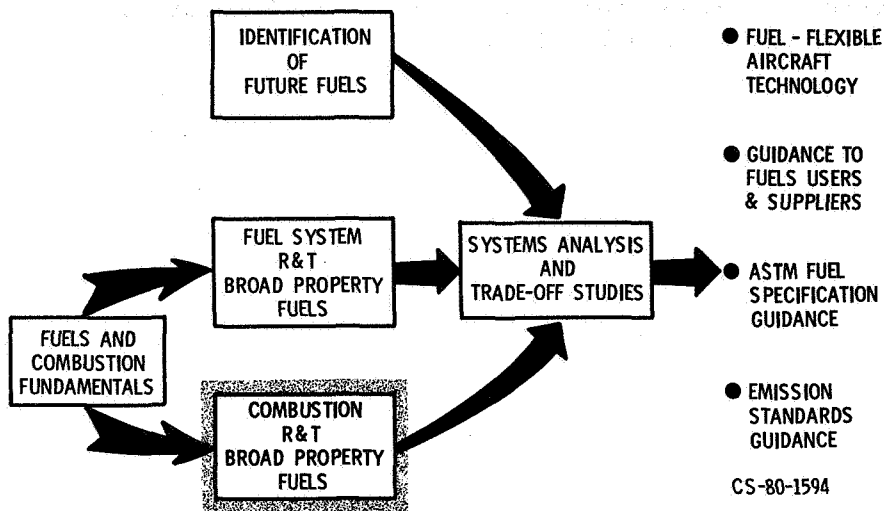
4. Maximum allowable fuel temperatures could be reduced by as much as 12 kelvins because of the poorer thermal stability of broadened-property fuels.

Study results also indicated that the effects of broadened-property fuels on combustors could be minimized by using multizone, lean-burning combustors. In these advanced combustor designs the combustion processes are more carefully controlled than in conventional combustors, and radiation levels to liners are minimized by burning at fuel-lean conditions during high-power operation. These indications have been substantiated in test rig and engine short-term evaluations where conventional combustors and multizone combustors were fueled with Jet A and broadened-property distillate fuels (refs. 4, 5, and 6).

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AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS

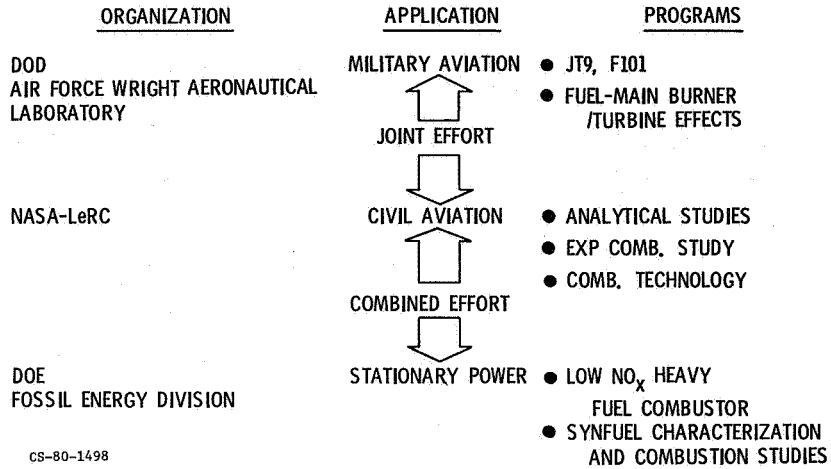


FUELS/COMBUSTION TECHNOLOGY PROGRAMS

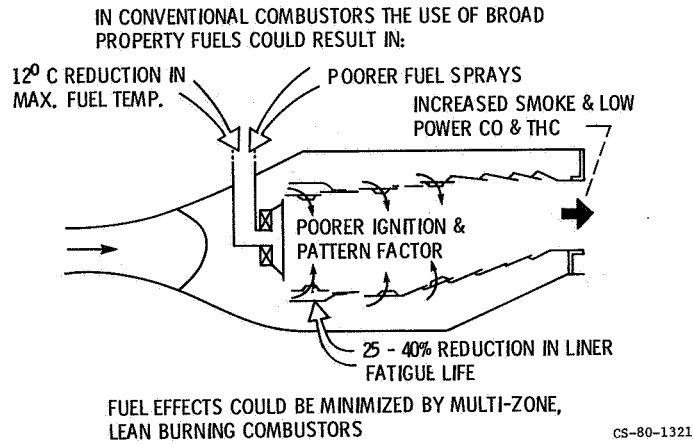
COMBUSTORS/ENGINES	OBJECTIVE	EMPHASIS
IN-SERVICE	ASSESS FUEL FLEXIBILITY DATA BASE TRADEOFFS	EXAMINE PERFORMANCE WITH BROAD PROPERTY FUELS
IN-SERVICE	EXTEND FUEL FLEXIBILITY	SUBCOMPONENT IMPROVEMENT
NEW CONCEPTS	OPTIMIZE FUEL FLEXIBILITY CAPABILITIES	EVOLVE ADVANCED COMBUSTION TECHNOLOGY

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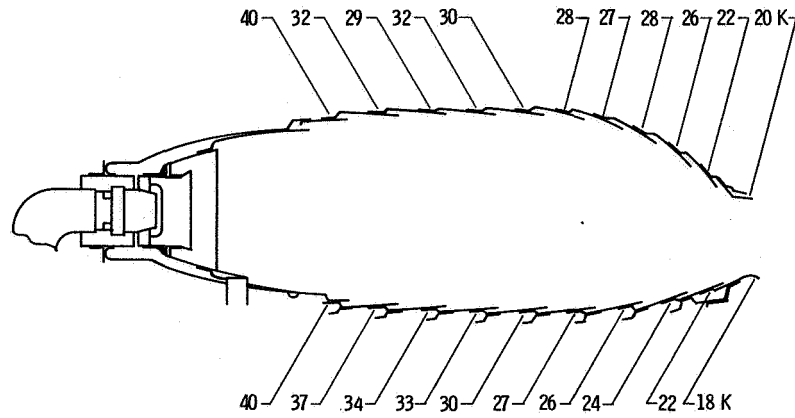
GAS TURBINE FUELS/COMBUSTION RESEARCH



ANALYTICAL STUDY RESULTS

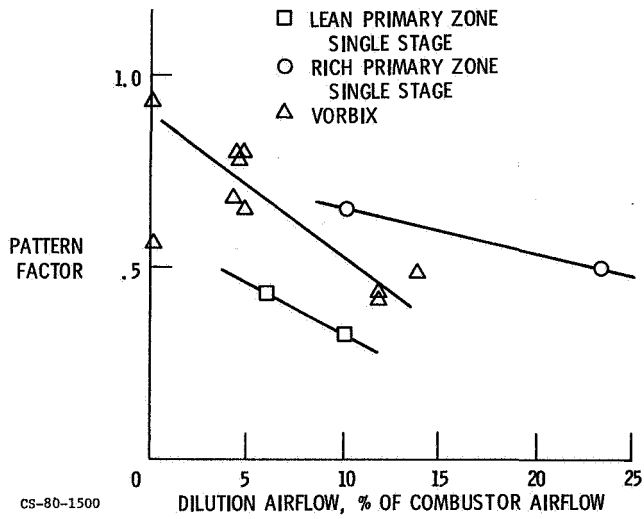


INCREASE IN LINER TEMPERATURES WITH ERBS FUEL



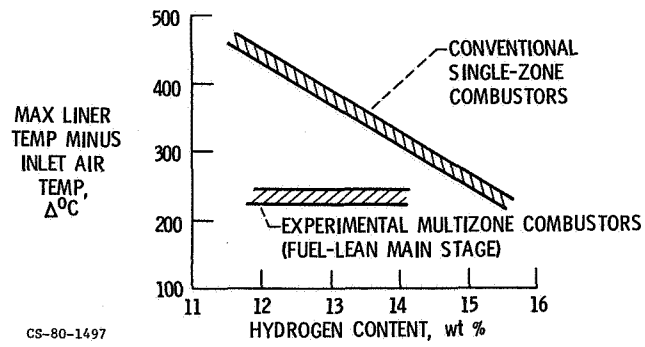
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EFFECT OF DILUTION AIR QUANTITY ON COMBUSTOR PATTERN FACTOR



CS-80-1500

EFFECT OF HYDROGEN CONTENT OF FUEL ON LINER TEMPERATURE



CS-80-1497

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EXPERIMENTAL COMBUSTOR STUDY PROGRAM

John M. Kasper and Edward E. Ekstedt
General Electric Company

The objective of this recently completed program was to evaluate the use of advanced combustor concepts as a means of accommodating possible future broad-specification fuels.

The combustor evaluations consisted of sector combustor tests, using a three-swirl cup sector CF6-50 test rig. The tests were conducted with a non-vitiated air supply and an on-line exhaust gas analysis system, as well as other normally used combustion testing control systems, instrumentation and data acquisition equipment.

The various combustor configurations were evaluated at true cruise and simulated takeoff (P_3 reduced from 2.96 MPa to 1.59 MPa) conditions for the CF6-50 cycle. In each test, the combustors were evaluated with three fuels:

- o Jet A - 14% Hydrogen by weight
- o ERBS - 13% Hydrogen by weight
- o Special Blend - 12% Hydrogen by weight

The program included one test of a current production CF6-50 combustor configuration, Figure 1, to serve as a baseline for comparison, one test each of three advanced combustor concepts and a parametric test of the most promising of the three advanced concepts.

The three advanced double annular combustor concepts, which are also illustrated in Figure 1, consisted of (1) a concept employing high pressure drop fuel nozzles for improved atomization, (2) a concept with premixing tubes in the main stage, and (3) a concept with the pilot stage on the inside and the main stage on the outside, which is the reverse of the other two concepts. This last concept was intended to reduce the main stage length and, therefore, its residence time and NO_x emissions levels, and to provide an improved exit radial temperature profile. Double annular combustors, with the pilot on the outside, have shown tendencies in previous tests to have inboard-peaked temperature profiles.

The baseline CF6-50 burner was tested first. The baseline test showed that smoke and CO levels for sector tests would be somewhat higher than for full annular tests because of leakage in the rig; however, trends with operating conditions were as expected. Other test data would not be affected. The baseline burner showed some sensitivity to fuel hydrogen content with regard to smoke, NO_x (takeoff), and liner temperatures.

Of the four burners tested, Concept 2 had the lowest NO_x levels, a very clean dome with virtually no carbon deposits, lower smoke levels than the baseline combustor, very low dome temperatures and no combustion instability at any operating condition. Liner temperatures were low except for a region on the inner liner downstream of the premixing tubes. This liner temperature problem would be relatively easy to remedy by the use of hole pattern adjustments and preferential cooling. Therefore these high temperatures were not considered a major problem.

Concept 1 produced low smoke levels and showed little sensitivity to fuel hydrogen content with regard to smoke levels and metal temperatures. NO_x levels were lower than CF6-50 levels but higher than Concept 2 levels. These levels were higher than expected for this design based on previous tests of similar designs in the Experimental Clean Combustor Program. It is suspected that these results were due to the loss of some nichrome patches on dilution holes, which adversely affected combustor airflow distribution. The liners were made from CF6-50 combustors.

Concept 3 produced the lowest smoke levels and demonstrated that the radial temperature profile could be inverted by reversing the pilot and main stage domes in a double annular combustor. The NO_x levels were between those measured for the other two concepts. However, this combustor encountered combustion resonance and dome flame stability problems at some operating conditions. It is believed that during a portion of the test the flame was not seated in the pilot dome as evidenced by very low metal temperatures. It is likely that the observed resonance and dome instability were influenced by leakage between the three-cup sector and the test rig side walls. Because of combustion stability problems, this combustor yielded high CO and some liner temperature data which are not believed representative of this concept's potential, and this data is omitted in the following figures. It is believed that a complete set of representative data was obtained for Jet A fuel.

Concept 2 demonstrated the potential of a premixed-prevaporized design in achieving low NO_x levels and clean liners and domes. The Concept 1 test showed that high ΔP fuel nozzles gave no significant improvement over the low ΔP fuel nozzles tested earlier in similar combustor designs. Data from the Concept 3 test was considered not representative of the concept's potential because of combustion stability and resonance problems. Thus Concept 2 was chosen for the parametric test. Although no refinement or development tests to resolve problems were conducted on these advanced designs, they all appear to have potential for use with fuels with broadened specifications. Dome temperatures for all of the three advanced designs were extremely low and showed essentially no effect of fuel type whereas for the baseline combustor, dome temperatures were higher with reduced fuel hydrogen content. These results are illustrated in Figure 2.

Liner temperatures also tended to exhibit reduced sensitivity to fuel hydrogen content for the advanced designs. Figure 3 shows trends of liner temperature as a function of fuel hydrogen content relative to temperatures measured using Jet A fuel. As is shown, the lowest temperatures were not obtained with the premixed system (Concept 2). Previous experience with double

annular combustors, including a premixed system (NASA/GE Experimental Clean Combustor Program), would lead one to expect less sensitivity for a premixed system than for a double annular combustor. It is theorized, therefore, that the fuel-air mixture at the premixing tube exit was not as uniform as possible and that this lack of uniformity influenced the liner temperature results.

Carbon deposits in the dome regions were also significantly reduced with the advanced domes. Figure 4 shows the baseline combustor post-test dome conditions. A light coating of soot is evident on a large portion of the dome surface and some buildup occurred on the swirl cup venturi trailing edges. All three of the advanced designs had relatively little carbon on the pilot dome surfaces. Concepts 1 and 3 had some carbon on the main stage dome surfaces. Concept 2, with the premixed main stage, had virtually no carbon on the dome as shown by Figure 5. It should be noted that all of the advanced designs had prototype fuel nozzles that had a bluff region between the fuel nozzle and swirl cup. These bluff regions, which would be eliminated in product engine designs, had carbon deposits.

Smoke data exhibited the expected trend toward generally increased smoke with reduced hydrogen content. Concept 2, with the premixing dome, had higher smoke levels than the other two advanced designs. This finding is also believed to be the result of less than uniform fuel-air mixtures at the exit of the premixing duct. Concept 3 had the lowest smoke levels measured; Concept 1 also had low smoke levels and showed the least sensitivity to fuel type. Figure 6 presents some of the smoke data correlations for the four combustor configurations at simulated takeoff conditions.

Only general trends for radial exit temperature profiles are obtainable in sector combustor tests. However, it appears that Concept 3 with the inverted main to pilot stage shifted the profile in the desired direction. For Concept 1 with the main stage on the inboard side, the profile was peaked at approximately 30% of the radial exit height (peaked inboard). For Concept 3 with the main stage on the outboard side, the profile was peaked at approximately 60% of the exit height.

All of the advanced designs appear to have the potential for low NO_x levels. The increased ΔP nozzles used in Concept 1 did not provide reduced NO_x relative to earlier full annular tests of double annular combustors (NASA/GE Experimental Clean Combustor Program) although these results were clouded by the liner hardware problems previously mentioned. Concept 3 provided slightly lower NO_x levels than Concept 1, apparently due to its reduced main stage residence time. Concept 2, the premixed main stage design, had the lowest NO_x levels and the least NO_x sensitivity to fuel hydrogen content, as shown in Figure 7.

The advanced concepts all had higher CO levels than the baseline combustor. This is as expected, based on previous tests, and is attributed to the lean dome operation of these designs. At idle conditions the advanced designs would all have very low CO levels since only the pilot stages would be in operation. Fuel hydrogen content was not found to have a strong effect on CO emissions as shown in Figure 8.

Concluding Remarks

All of the advanced concepts show promise for reduced sensitivity to fuel hydrogen content. Some hardware problems were encountered, but these problems could be quickly resolved if refinement tests were conducted.

The design with the premixing main stage was selected for the parametric test because of its low NO_x emissions level, carbon free dome and very low dome temperatures which were essentially independent of fuel type. The other advanced designs also had low dome temperatures. The premixing dome design liner temperatures exhibited less sensitivity to fuel type than did the baseline combustor, although more sensitivity than observed for Concept 1. The inner liner hot spot and the observed smoke results for the premixing design suggest that the fuel-air mixture was not as uniform as desired. Additional work with premixing dome designs is recommended.

The Concept 3 double annular combustor with the two domes reversed indicated an improved exit temperature profile. One possible alternative design would be Concept 3 with a premixing dome.

Test Combustor Configurations

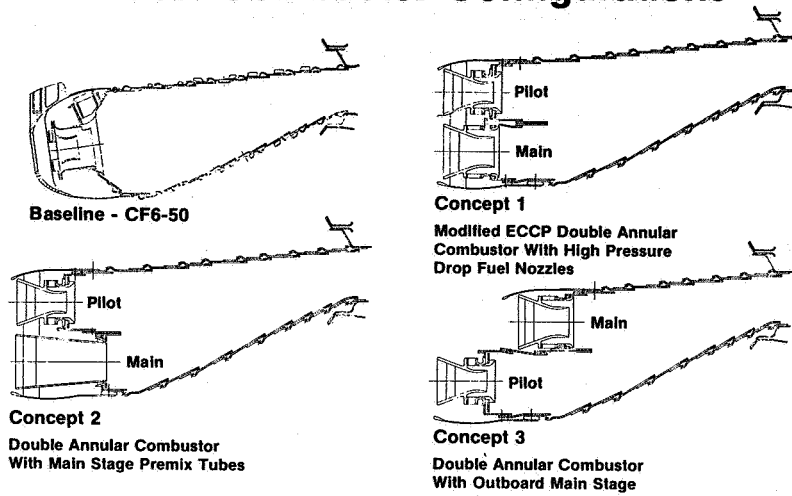


FIGURE 1

Local Dome Temperature Vs Fuel Hydrogen Content

True Cruise Conditions, $f = .021$. T/C Between Main Cup Centerlines

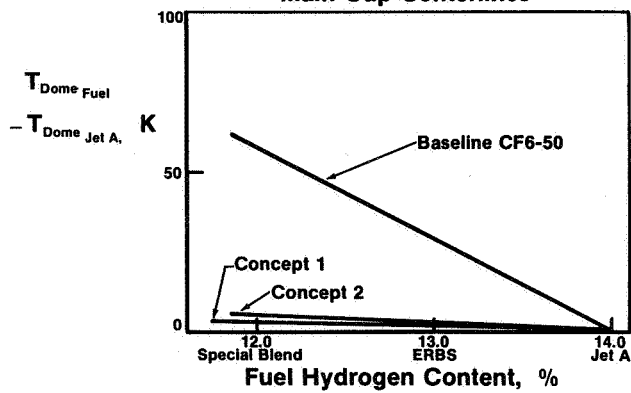


FIGURE 2

Local Liner Temperature Vs Fuel Hydrogen Content

True Cruise Conditions, $f = .021$

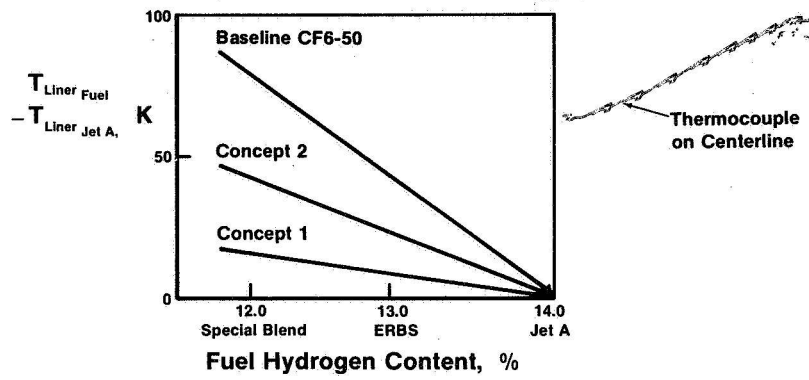


FIGURE 3

Baseline
CF6-50
Dome
After
Screening
Test

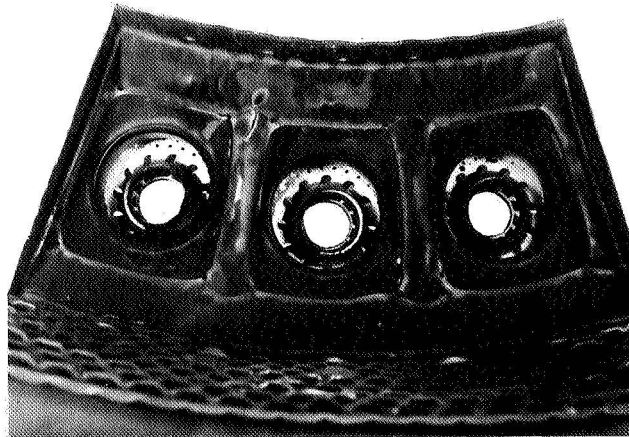


FIGURE 4

**Concept 2
Dome
After
Parametric
Test**

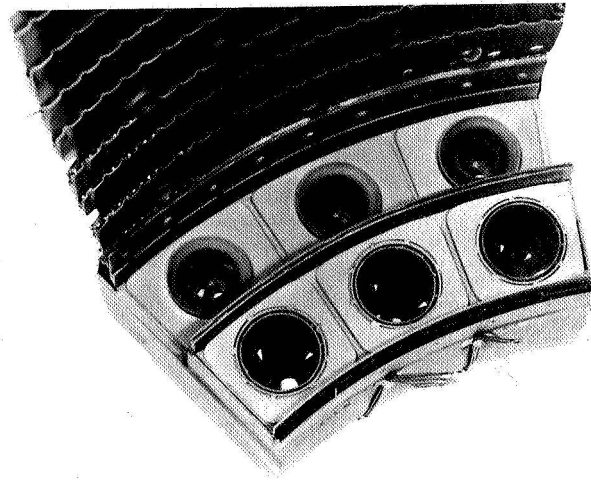


FIGURE 5

**SAE Smoke Number Vs
Fuel Hydrogen Content**

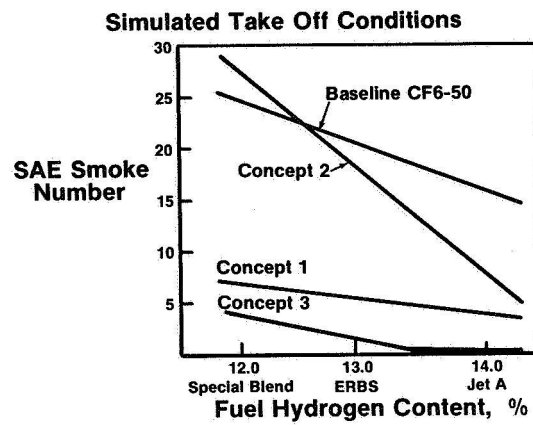


FIGURE 6

NO_x Emission Index Vs Fuel Hydrogen Content

True Cruise Conditions, $f = .016$.

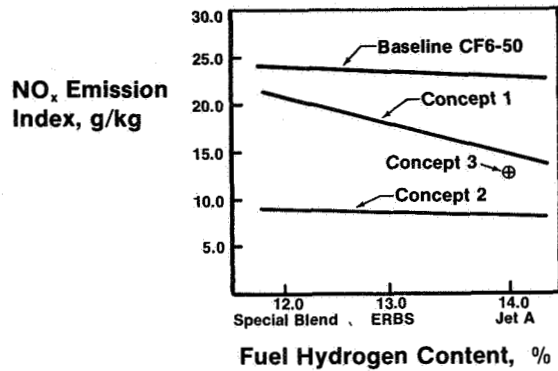


FIGURE 7

CO Emission Index vs Fuel Hydrogen Content

True Cruise Conditions, $f = .016$

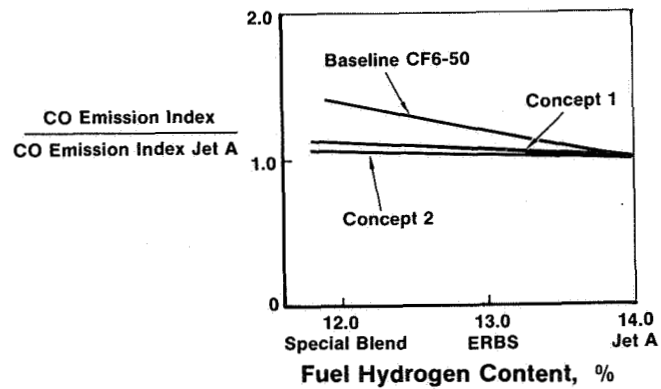


FIGURE 8

FUEL CHARACTER EFFECTS ON THE J79 AND F101 ENGINE COMBUSTION SYSTEMS

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Between 1977 and 1978 time period four contractual efforts were initiated to evaluate the effects of select fuel property variations on several major engine classifications. The engines that would be most widely used by the Air Force through the next decade were divided into three categories: low pressure ratio, cannular combustion system; high pressure ratio, annular combustion system; and high pressure ratio, cannular system. The fourth program involved an advanced combustion system.

The first two categories were represented by the J79 and the F101 gas turbine engines, respectively. The third category was represented by the TF41 engine. This system will, however, not be discussed as the evaluation is not finished. The contracts to evaluate fuel effects in the J79 and F101 systems were awarded at about the same time to the same company, General Electric. Both programs were cofunded by the Aero Propulsion Laboratory and the Air Force Engineering Services Center. The efforts were timed to run concurrently. Thus, test fuels used on the program were identical.

All testing within both efforts was conducted on component rigs. The test rigs and the test points were established to evaluate the effects of fuel properties on the static performance, the ignition and stability limitations, the carboning and fuel nozzle fouling tendencies, and the durability of each combustion system. Static performance was measured at four operating conditions: idle, cruise, takeoff, and dash. Partial scaling of inlet air pressure and mass flow was necessary for the J79 dash condition and the F101 takeoff and dash conditions. Ignition properties were evaluated at standard and cold day ground conditions as well as at several points of the altitude windmilling/relight requirement map. Stability was evaluated by determining the fuel lean blowout point and the pressure blowout point at several operating points. Carboning and fuel nozzle fouling tests were conducted in special rigs, operated at special conditions, selected to accelerate these phenomena. In addition, hardware life predictions were made of the combustor liner (based on metal temperature measurements) and of the turbine (based on radial temperature profile and pattern factor measurements).

Thirteen refined and blended fuels were used in these programs. These fuels exhibited significant variations in hydrogen content (12.0 to 14.5 weight percent), aromatic type (monocyclic or bicyclic), initial boiling point (285 to 393 K by gas chromatograph), final boiling point (532 to 679 K also by gas chromatograph), and viscosity (0.83 to 3.25 mm²/s at 300 K).

The results varied between the two programs. Trends were very similar but the degree of fuel sensitivity was not constant. For both systems the dominant fuel property during high pressure operation was found to be fuel hydrogen content. For the J79 this fuel property strongly affected smoke, carbon deposition, liner temperature (and, therefore, liner life), and flame radiation and moderately affected NO_x emissions. For the F101 system hydrogen content strongly affected smoke emissions, liner temperature (and life), and NO_x emissions.

For operation at low pressure test points the fuel volatility and viscosity became the dominant fuel properties for both systems. The cold day ground starting and altitude relight capabilities of the systems were degraded with reduced volatility and increased viscosity. Typically, the 10% recovery temperatures of the fuels' distillation behavior were used as a measure of fuel volatility. Viscosity was introduced into the correlations through the relative Sauter Mean Diameter (SMD), a parameter characterizing the fuel spray. These values were calculated for each test fuel at each condition of interest and referenced to the SMD of JP-4. The F101 was more sensitive than the J79 to variations in these parameters.

The F101 fuel divider valve indicated a sensitivity to the fuel thermal stability in an accelerated cycle test involving two fuels of widely different thermal stability properties. The tests were not conclusive but did indicate a correlation of laboratory measured fuel thermal stability and the cycles to a discrete degradation in the operation of the F101 fuel divider valve, arbitrarily chosen to be a 10% increase in flow hysteresis at a fuel pressure drop of 1.24 MPa. Related testing of the J79 fuel nozzle indicated no apparent fuel sensitivity over the range tested. This was expected since the J79 fuel nozzle passages are not as critically dimensioned as those of the F101.

Aromatic type and final boiling point do not significantly affect combustion data.

Correlations of other fuel properties with these and other performance parameters were examined. The above relationships, however, were the most dominant. Details of the J79 and F101 fuel effects programs can be found in AFAPL-TR-79-2015 and AFAPL-TR-79-2018, respectively.

Test Fuel Chemical and Physical Properties.

Fuel No.	Fuel Components		Hydrogen Content H Weight %	Heating Value (net) MJ/kg	Density		Viscosity		Surface Tension		Vapor Pressure	
	Base Fuel	Blending Agents			$\rho_{300 K}$ kg/m ³	$\rho_{300 K} \times 10^{-3}$ g/cm ³	$\nu_{300 K}$ mm ² /s	$\nu_{300 K} [(\nu + 0.7)]$ [in τ]	$\sigma_{300 K}$ mN/m	$\sigma_{300 K} \times 10^3$ dyne/cm	$P_{300 K}$ kPa	$P_{300 K} [(\nu + 0.7)]$ [in τ]
1	JP-4	-	14.5	43.603	752.7	7.935	0.924	4.112	23.27	10.01	12.04	9.80
2	JP-8	-	14.0	43.210	799.5	7.363	1.849	4.009	25.85	9.53	2.15	6.19
3	JP-8	Gulf Mineral Seal Oil	13.9	43.189	801.2	7.330	2.071	3.995	25.92	9.78	1.97	5.84
4	JP-8	2040 Solvent	12.0	41.947	852.3	7.455	1.809	4.170	27.62	8.24	1.16	7.78
5	JP-8	Xylene Bottoms	13.0	42.724	813.4	7.525	1.428	4.051	26.38	9.50	1.48	10.86
6	JP-8	Xylene Bottoms	12.0	42.129	827.6	7.775	1.160	4.111	26.66	9.47	1.33	10.77
7	JP-8	2040	13.0	42.556	825.2	7.437	1.804	4.103	26.42	6.20	1.38	7.48
8	JP-4	2040	12.0	42.203	829.7	7.832	1.141	4.179	25.22	7.31	7.38	11.60
9	JP-4	2040	13.0	42.629	796.3	7.758	1.028	4.144	23.75	6.94	8.61	11.41
10	JP-4	Xylene	12.0	42.196	808.0	8.150	0.830	4.237	25.21	7.97	6.17	11.31
11	JP-4	Xylene	13.0	42.682	786.5	8.072	0.835	4.328	24.20	5.40	9.06	10.47
12	JP-4	Xylene & GMSO	14.0	43.366	769.6	7.813	1.057	4.027	23.45	7.20	10.25	10.57
13	2-D	-	13.1	42.691	837.2	7.041	3.245	4.315	27.35	6.35	1.59	6.43
Test Method			D3701 (NMR)	D240 (Bomb)	Dilatometer		D445		Capillary Rise		Micro-vapor Pressure Apparatus	

TEST CONDITIONS/APPARATUS

CONDITION	APPARATUS	
	J79	F101
Performance		
• Idle		
• Cruise	{ Hi Pressure	{ Hi Pressure
• Takeoff	{ Single Can Rig	{ Full Annular Rig
• Dash		
Pattern Factor	{ Hi Pressure	{ Atmospheric
Relight/Stability	{ Single Can Rig	{ Full Annular Rig
• Standard Day Ign	{ Hi Pressure	{ Atmospheric
• Idle Stability	{ Single Can Rig	{ Full Annular Rig
• Cold Day Grd Ign	{ Lo Pressure	{ Lo Pressure
• Altitude Ign/Stability	{ Single Can Rig	{ 54° Sector Rig
Carbon Deposition	{ Hi Pressure	{ Hi Pressure
	{ Single Can Rig	{ Single Cup Rig
Fuel Nozzle Fouling	{ Fuel Nozzle Rig	{ Short Term/Long Term
		{ Fuel Metering Valve Rig

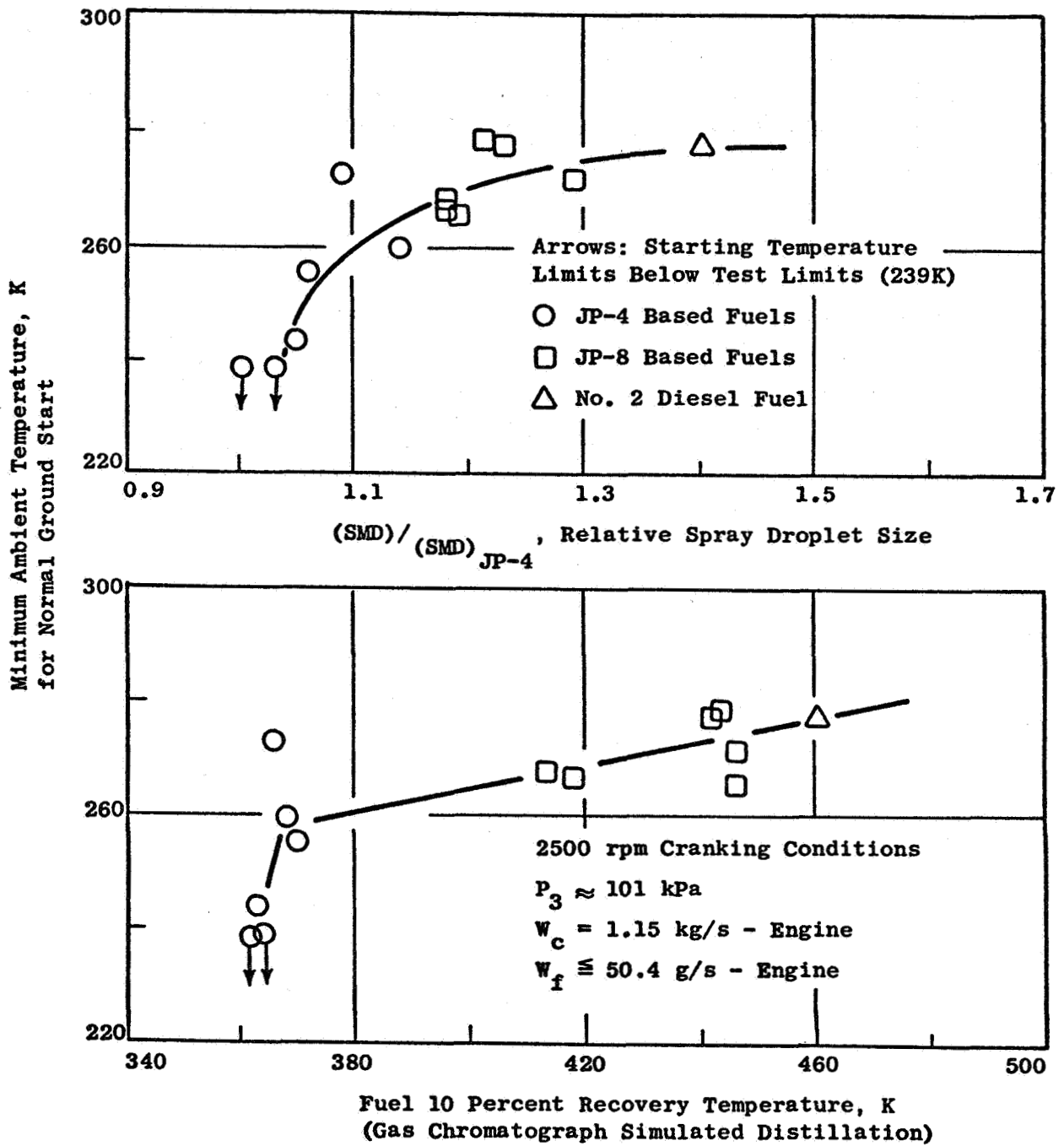


Figure 1 . Effect of Fuel Atomization and Volatility on Cold Day Ground Starting Capability.

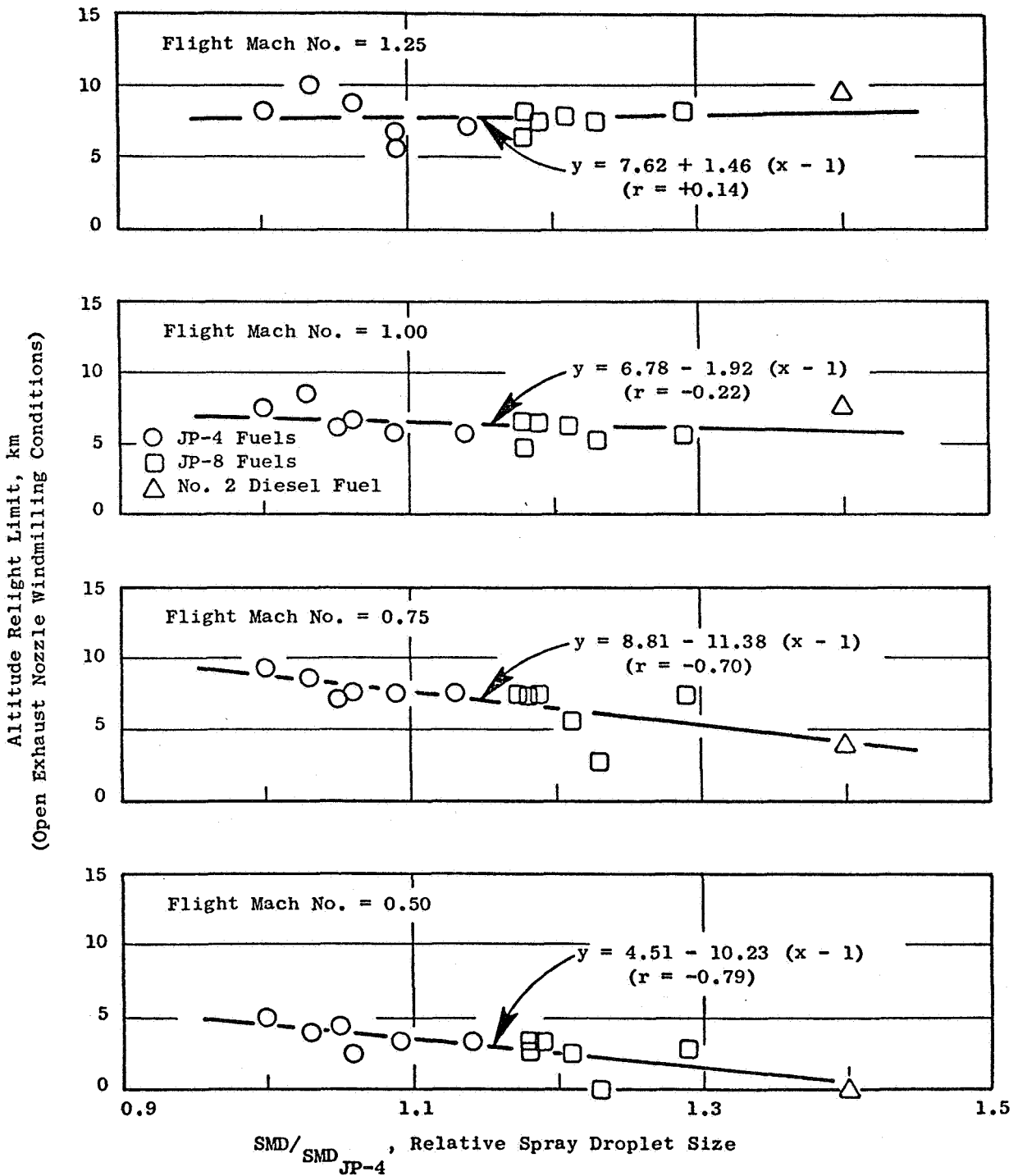


Figure 2 . Effect of Fuel Atomization on Altitude Relight Limits (Open Exhaust Nozzle Windmilling Conditions).

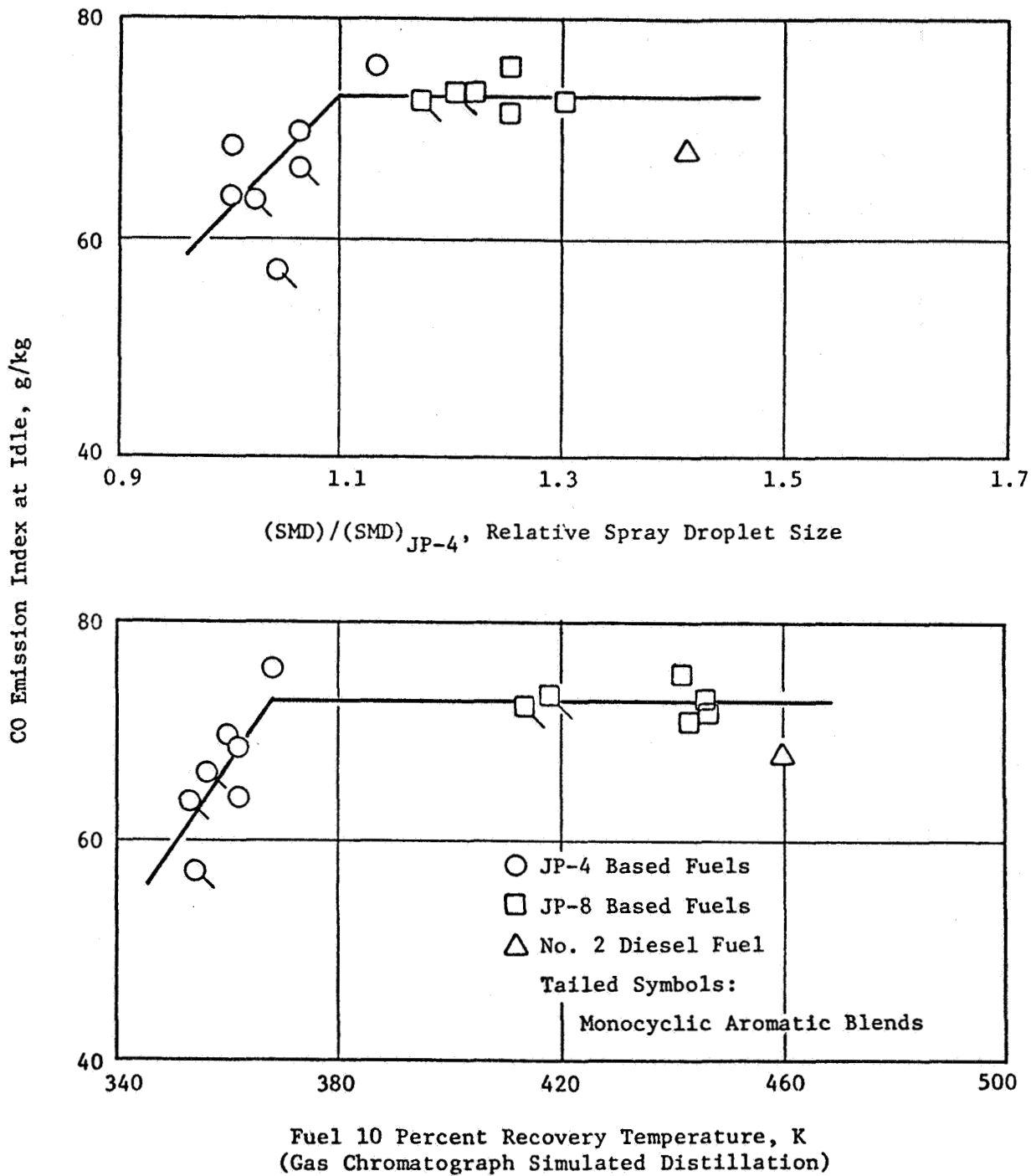


Figure 3 . Effect of Fuel Atomization and Volatility on Idle CO Emission Levels.

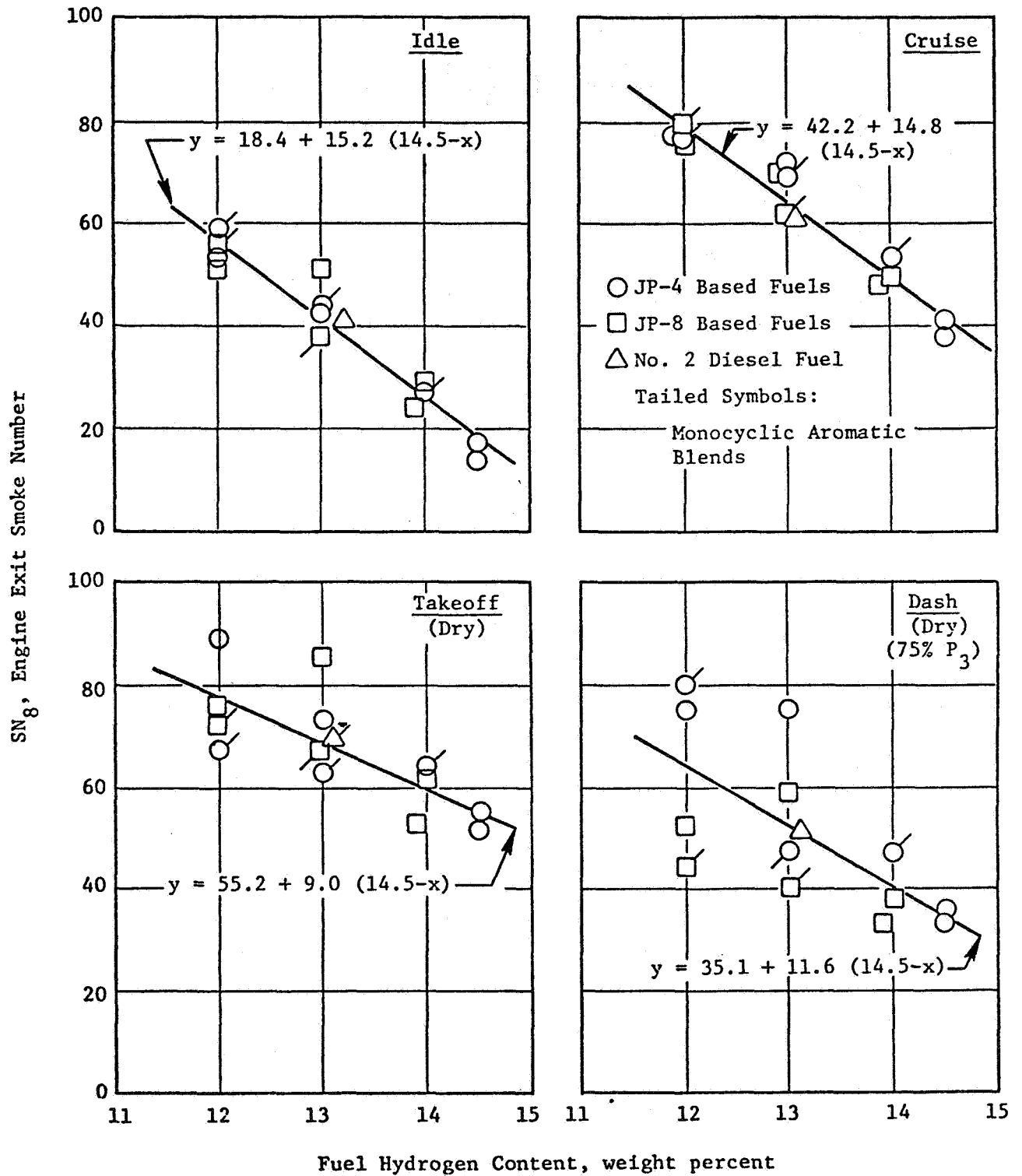


Figure 4 . Effect of Fuel Hydrogen Content on Smoke Emission Levels.

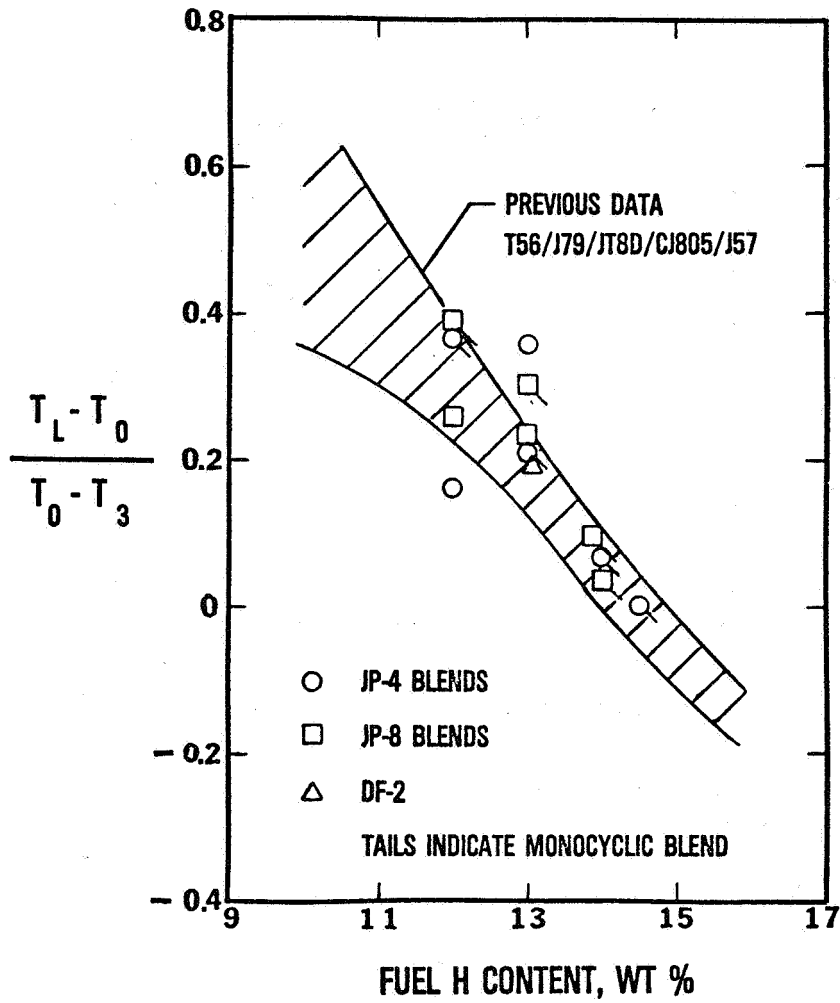


Figure 5. Effect of Fuel Hydrogen Content on Liner Temperature Parameter at Cruise Operating Conditions.

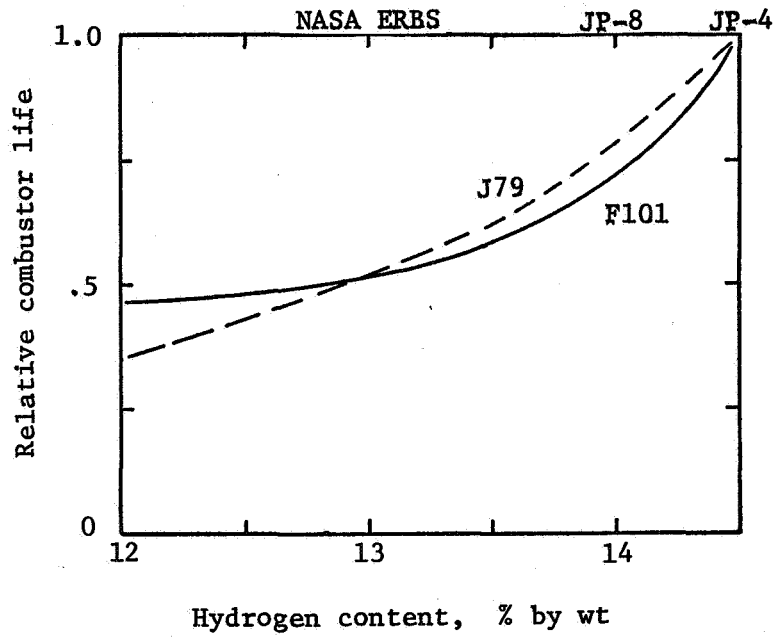


Figure 6. Effect of fuel hydrogen content on combustor durability.

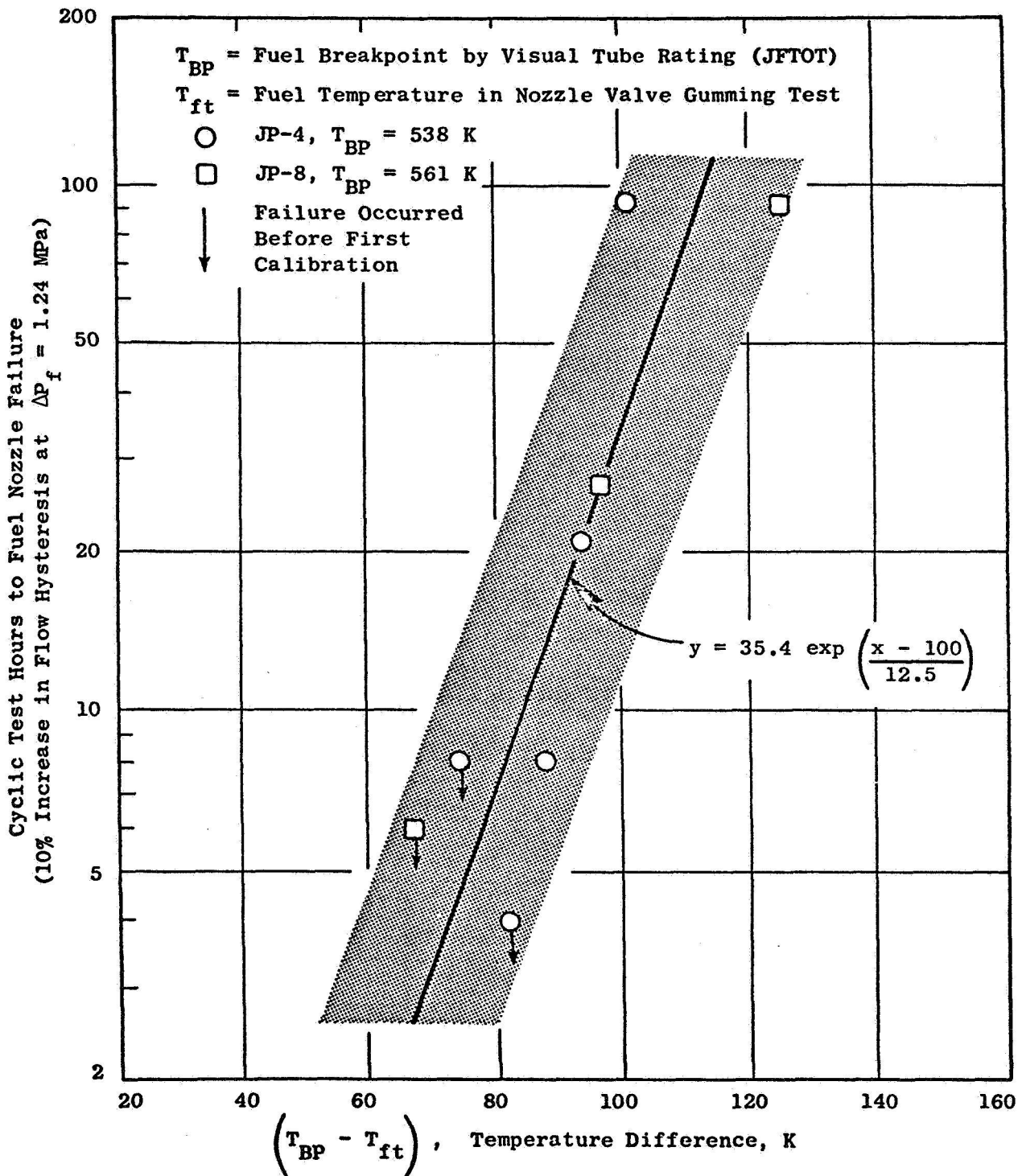


Figure 7. Effect of Fuel Temperature and Type on Fuel Nozzle Valve Life.

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NASA BROADENED-SPECIFICATION FUELS COMBUSTION TECHNOLOGY PROGRAM

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The NASA Broadened-Specification Fuels Combustion Technology program is being conducted (1) to evolve and demonstrate the technology required to enable current and next-generation high-thrust, high-bypass-ratio turbofan engines to use fuels with broadened properties and (2) to verify the evolved technology in full-scale engine tests.

Two contractors are participating in this program. The General Electric Co., using their CF6-80 engine as a baseline design, and the Pratt & Whitney Aircraft Group of the United Technologies Corp., using their JT9D-7 engine. Present planning is that parallel programs will be conducted with the two contractors through the planned three separately contracted phases:

Phase I, combustor concept screening - A series of sector-rig tests to determine the best configurations for further evaluation, based on their ability to use fuels with broadened properties while meeting exhaust emissions and performance goals and having suitable durability characteristics. Phase I is approximately an 18-month effort.

Phase II, combustor optimization testing - A series of sector-rig or full-annular rig tests of the best designs from phase I to establish the required overall combustion system emissions, performance, and durability characteristics and engine adaptability. Emphasis will be placed on interaction of the combustion system with other engine components. This phase is projected to take 16 months.

Phase III, engine verification testing - Steady-state and transient testing of the best combustion system (or systems) of phase II as part of a complete engine. Phase III is projected to take 16 months.

Phase I is scheduled for completion in early 1981, phase II in mid-1982, and phase III in late 1983.

In designing combustion systems for their respective programs, the contractors were required to observe certain constraints:

(1) The program fuels to be used are Jet A and three broadened-properties fuels. One is a reference fuel, called the experimental referee broadened-specification (ERBS) fuel, with a hydrogen content of 12.8 percent by weight. (In comparison Jet A's hydrogen content is 13.5 to 14 percent.) Combustion system designs were to be based on using the reference broadened-properties fuel. The other two fuels are blends of the reference fuel and a blending stock that reduces the 12.8 percent hydrogen content of the reference fuel to 12.3 and

11.8 percent, respectively. These two fuels are being used so that trends in the effects of the progressive lowering of fuel hydrogen content and the corresponding raising of aromatics content can be examined.

(2) Of the three combustion system concepts to be designed by each contractor, one was to involve relatively minor modifications to the production combustion system of the baseline engine. This is to allow modification of in-service engines so that they can use broadened-properties fuels while meeting appropriate emissions requirements and maintaining the performance and durability characteristics of the production combustion system. The other two concepts were to be advanced designs for use in future engines.

Two methods are used to counteract the effects of increased aromatics on liner life:

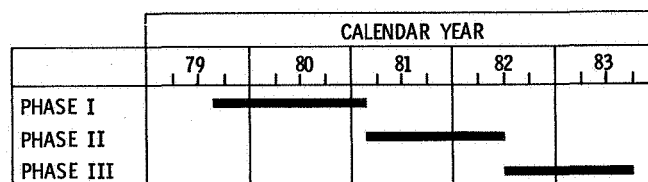
- (1) Reducing the radiation effect by optimizing stoichiometry through staged combustion and variable geometry
- (2) Offsetting the radiation effect by improving liner cooling effectiveness and using thermal barrier coatings

Among the problems to be expected in the use of broadened-properties fuels, and which are addressed in this program, are

- (1) Higher aromatics content, causing
 - (a) Increased flame luminosity, which results in increased radiative heat transfer to combustion liners and shorter liner life
 - (b) Increased engine visible smoke output
 - (c) Increased carbon deposition on fuel nozzles and combustor liners
- (2) Lower volatility and higher viscosity, causing
 - (a) More difficult cold start and altitude relight
 - (b) Greater difficulty in achieving satisfactory emissions levels at low-power conditions
- (3) Reduced thermal stability, causing
 - (a) Fuel system deposits
 - (b) Fuel injector plugging

Final design of the combustion systems has been completed. Phase I is now in the fabrication stage, with testing to begin in approximately 2 months.

ANTICIPATED PROGRAM SCHEDULE



CS-80-1279

COMPARISON OF JET A AND BROAD-PROPERTIES TEST FUELS

FUEL PROPERTY	JET A	BROAD-PROPERTIES TEST FUELS		
		TEST FUEL 1 (REFERENCE)	TEST FUEL 2	TEST FUEL 3
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

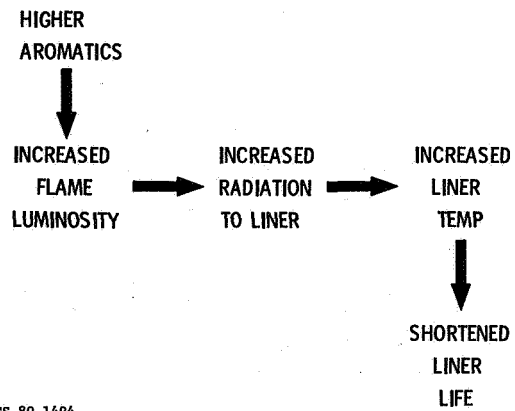
CS-80-1495

COMBUSTION SYSTEM CONCEPTS

	<u>TYPE OF DESIGN</u>	<u>APPLICATION</u>
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

EFFECT OF INCREASED AROMATICS ON LINER LIFE



CS-80-1494

AIR FORCE FUEL MAINBURNER/TURBINE EFFECTS PROGRAMS

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In 1979 a multiyear program was initiated within the Air Force entitled "The Aviation Turbine Fuel Technology Program" (ATFTP). The objective of this effort is to provide for the necessary test validation of a jet fuel which will result in adequate fuel availability and lower aircraft system life cycle cost than for the current Air Force standard jet fuel, JP-4. One of the first evaluations to be conducted within this program is the determination of fuel property effects on aircraft gas turbine engine mainburners and turbines. This program is discussed herein.

The objective of the Fuel Mainburner/Turbine Effects Program is to quantify the relationships between select fuel properties and the performance, maintainability, reliability, and durability of mainburner and turbine components of current Air Force aircraft gas turbine engines. This effort differs from preceding combustor/fuel effects programs in two ways. First, the transient performance of these systems is to be evaluated in addition to static performance. Second, fuel effects on turbine materials are extended beyond measurements of the combustor's exhaust gas temperature profile to actual oxidation/erosion studies.

Six engines have been selected as desirable test candidates. These engines are the J79, J85, J57, TF30, TF39, and F100. These engines represent two major combustor configurations (cannular and annular), a wide range of system pressure ratios, several types of mission cycles (fighter, trainer, bomber, and transport), a difference of approximately 25 years from the introduction of the oldest to the newest system, and the design philosophies of the two major suppliers of military aircraft gas turbine engines.

Two awards were made under this program. General Electric (GE) Company was awarded a contract to evaluate fuel effects in the J79, J85, and TF39 systems. The principal investigator at GE is Mr. C. C. Gleason. A contract was established with Pratt and Whitney (PW) Aircraft to evaluate fuel effects in the J57 and F100 engines (the TF30 was dropped from consideration for cost reasons). The principal investigator at PW is Mr. J. R. Herrin. Both efforts are entirely supported by funds under the ATFTP.

Fuel selection for each program has been, in general, the responsibility of the contractors. Two fuels, a petroleum derived JP-4 and an oil shale derived JP-4, are exceptions to this. The petroleum JP-4 is to be used as a baseline in all tests. The shale JP-4 is to be used in nearly all tests (high consumption engine tests are not included) as part of an Air Force Shale Oil Acceptance Program. Up to four other test fuels are to be selected by each contractor for any given test (the fuels can be different from one test to another). Government approval of all test fuels and the specific tests in which they are used is required in both programs.

The GE program is a mix of component rig and full engine tests. The bulk of the data will be obtained in the component tests. Static performance, ignition and stability limitations, carboning and fuel nozzle fouling tendencies, turbine material oxidation and erosion properties, and hardware durability will be assessed through testing of heavily instrumented rigs. The engine tests will then be run to validate some of the rig work and to document fuel effects on the radiant heat load on the turbine stators and fuel effects on the transient operation of each engine (accels and decels). Data generated during engine tests will consist of combustor liner temperatures, turbine stator temperatures, and smoke and gaseous emissions measurements.

The PW program consists of component rig tests, exclusively. The scope of this effort is similar to the GE test rig work except that there is no fuel nozzle fouling test requirement on the PW effort. Transient testing in the PW program will consist of a series of rapid changes in fuel flow while holding constant airflow in the rig. Overshoots and undershoots of the engine fuel-air ratio, experienced when changing power points, will be simulated as will the rate of change of fuel-air ratio.

In both programs fuel properties will be correlated with combustion system performance parameters. In addition life predictions will be made for combustor and turbine hardware. These predictions will be based on a typical mission for each system, measured metal temperatures and temperature gradients, and oxidation/corrosion effects (if any).

Both programs will conclude the test phase of their efforts in the fourth quarter of fiscal year 1980. Contracts will be concluded in the second quarter of fiscal year 1981 with final reports issued shortly thereafter.

AF ENGINE INVENTORY (NEAR FUTURE)

ENGINE	MANUFACTURER	NO. PROJECTED	ACC. % OF PROJECTED TOTAL
J57	P-W	6122	23.8
J79	GE	3218	36.3
J85	GE	2743	47.0
T56	ALLISON	2538	56.9
F100	P-W	2108	65.1
TF33	P-W	2025	73.0
J69	TELEDYNE	1480	78.8
TF34	GE	1466	84.5
F101	GE	960	88.2
TF30	P-W	797	91.3
TF41	ALLISON	293	92.4
TF39	GE	275	93.5

TEST FUELS (GE)

Fuel Blend No. (1)	Component (s)	Estimated Fuel Properties				
		% H ₂	Real Dist., K		Viscosity mm ² /s @ 300K	JFTOT Breakpoint, K
			IBP	FBP		
1	Conventional JP-4	14.5	340	525	0.9	535
2	Conventional JP-8	14.0	445	550	1.8	575
8	JP-4/Solvent	12.0	340	545	1.1	535
9	JP-4/Solvent	13.0	340	545	1.0	535
13	Conventional No. 2 Diesel	13.1	445	615	3.2	503
14	No. 2 Diesel/Solvent	12.0	445	615	3.0	503
15	Shale-Derived JP-4	-	-	-	-	-

(1) Blend numbers 1-13 common to previous USAF/GE programs.

FUEL MAINBURNER/TURBINE EFFECTS TEST SCOPE (GE)

TEST VEHICLE	COMBUSTOR DOME AND LINER TEMPERATURE	SMOKE AND GASEOUS EMISSIONS	COMBUSTOR EXIT TEMP DISTRIBUTION	COMBUSTOR STABILITY AT IDLE	COLD DAY GROUND START	ALTITUDE RELIGHT AND STABILITY	FUEL NOZZLE PLUGGING	CARBON DEPOSITION	TRANSIENT RESPONSE	TURBINE MATERIAL EROSION	TURBINE STATOR HEAT LOAD	FUELS TO BE TESTED
J79 SINGLE COMBUSTOR HIGH PRESSURE RIG	X	X						X				3
J85 FULL ANNULAR COMBUSTOR HIGH/LOW PRESSURE RIG	X	X	X	X	X	X		X				6
TF39 FULL ANNULAR COMBUSTOR ATMOSPHERIC-PRESSURE RIG			X	X								3
TF39 360° SECTOR COMBUSTOR HIGH PRESSURE RIG	X	X						X				6
TF39 60° SECTOR COMBUSTOR LOW PRESSURE RIG					X	X						6
J79/J85/TF39 FUEL NOZZLE FOULING RIG							X					2
J79/J85/TF39 TURBINE MATERIAL EROSION RIG									X			1
J73 ENGINE	X	X						X			X	2
J85 ENGINE	X	X					X	X			X	6
TF39 ENGINE	X	X					X	X			X	2

PW IGNITION TEST FUELS

Test Fuel No.	JP4	JP4-S	1	2	3	4
Viscosity CS at 60°F	0.8		2.5-3.0	0.8-1.0	1.0-1.5	0.8-1.0
Initial Boiling Pt. °F	140		140	140	340	140
20% Recovery Temperature	230		230	320	370	230
Hydrogen Content	14.		13.8	13.8	13.8	12.5

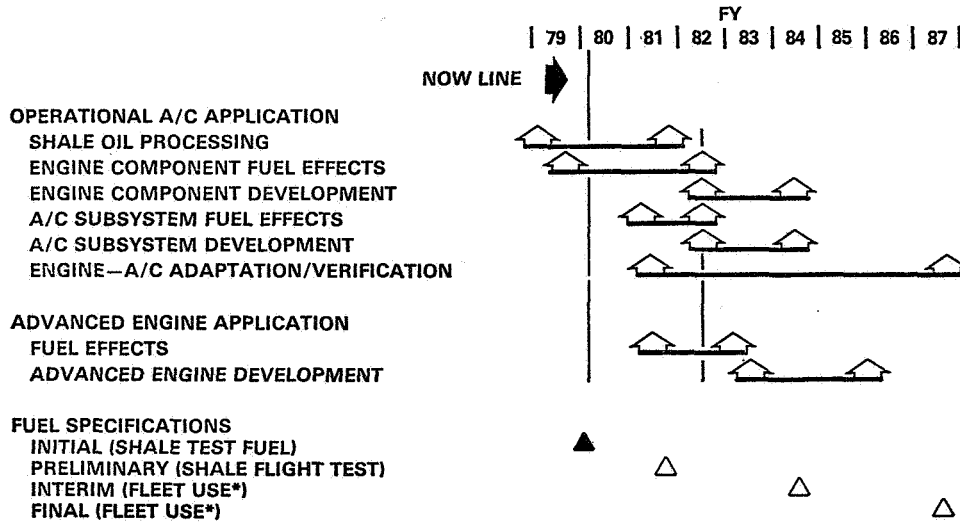
DURABILITY TEST FUELS

Test Fuel No.	JP4	JP4-S	5	6	7	8
Viscosity, CS 60°F	0.8		2.2-2.4	1.6-1.8	2.6-2.8	2.4-2.6
Initial Boiling Pt. °F	140		330	140	360	330
20% Recovery Temperature	230		360	230	400	360
End Point (°F)	474		480	630	630	630
Hydrogen Content	14		13.8	13.0	12.0	12.0
Aromatic Type			Single-Ring		Double-Ring	

FUEL MAINBURNER/TURBINE EFFECTS TEST SCOPE (P&W)

TEST VEHICLE	COMBUSTOR DOME AND LINER TEMPERATURES	SMOKE AND GASEOUS EMISSIONS	COMBUSTOR EXIT TEMP DISTRIBUTION	COMBUSTOR STABILITY AND ALTITUDE RELIGHT	STANDARD AND COLD DAY GROUND START	CARBON DEPOSITION	TRANSIENT RESPONSE	TURBINE MATERIAL EROSION
J57 (TF33) SINGLE CAN HI PRESSURE RIG	6	6	6			3	6	
J57 (TF33) MULTIPLE CAN FULL ANN/LO PRESS RIG				6	6			
F100 90° SECTOR RIG	6	6	6	6	6	3	6	2
Lo PRESS TURBINE RIG								2

AVIATION TURBINE FUEL TECHNOLOGY



*MULTI SOURCES

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THE BROADENED-SPECIFICATION FUELS COMBUSTION TECHNOLOGY
PROGRAM AT PRATT & WHITNEY AIRCRAFT

Robert P. Lohmann
Commercial Products Division
Pratt & Whitney Aircraft Group

Under Phase I of the Broadened-Specification Fuels Combustion Technology Program, Pratt and Whitney Aircraft will be conducting combustor tests to evaluate the impact of the use of broadened-specification fuels on combustor design. Particular emphasis will be placed on establishing the viability of various combustor modifications to permit the use of broadened-specification fuels while meeting exhaust emissions and performance specifications and maintaining acceptable combustor operational and durability characteristics.

The reference engine for this program is the JT9D-7F shown in figure 1. Three different combustor concepts will be evaluated under the program. The simplest concept, the basic single-stage combustor, will consist of the current production model and an advanced version of the combustor in the JT9D-7F engine. These combustor configurations are shown in figures 2 and 3. The second concept is the advanced Vorbix combustor shown in figure 4. This concept, currently being established under the National Aeronautics and Space Administration/Pratt & Whitney Aircraft Energy Efficient Engine Program, incorporates several improvements over the configurations evolved under the Experimental Clean Combustor program. The most advanced concept is a variable geometry single-stage combustor with a simplex fuel injection system. Figure 5 shows a conceptual definition of a variable geometry combustor designed for modulation of the primary-dilution zone airflow split. Under Phase I of the program, this concept will be evaluated in a series of fixed geometry configurations with the intent of introducing variable combustor components in Phase II.

The combustor evaluation tests will involve assessment of various design modifications on the operating capability of each of the combustor concepts with Experimental Referee Broadened-Specification Fuel (ERBS). The modifications that will be evaluated include perturbations of the combustor airflow schedules to alter local stoichiometry and residence time histories, revisions to the fuel injectors, and variations in liner cooling including the use of thermal barrier coatings and/or advanced cooling concepts.

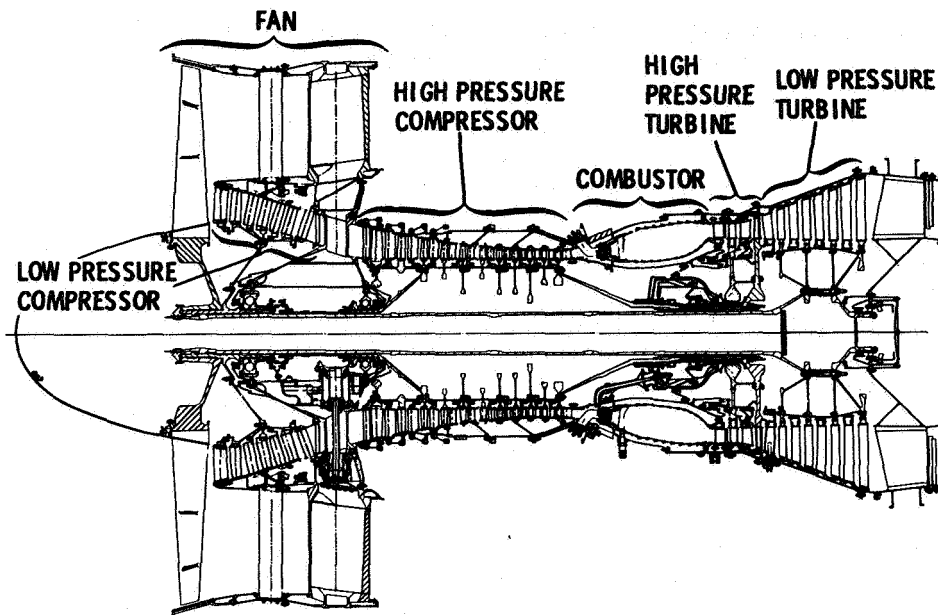


FIGURE 1 The JT9D-7F Reference Engine

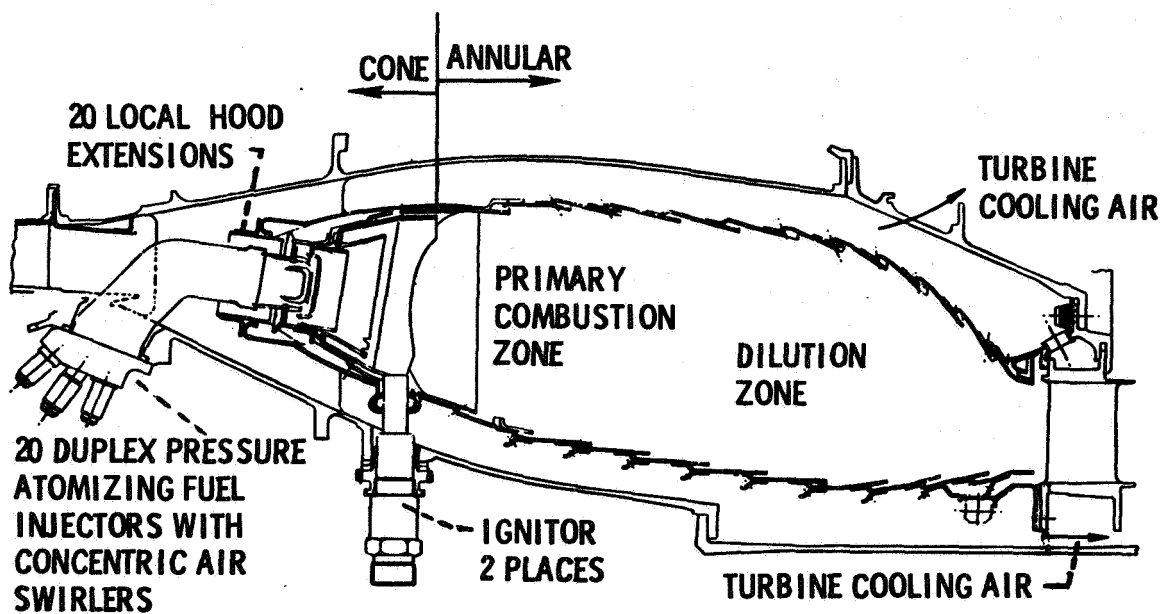


FIGURE 2 Current Production Configuration of the JT9D-7F Single Stage Combustor

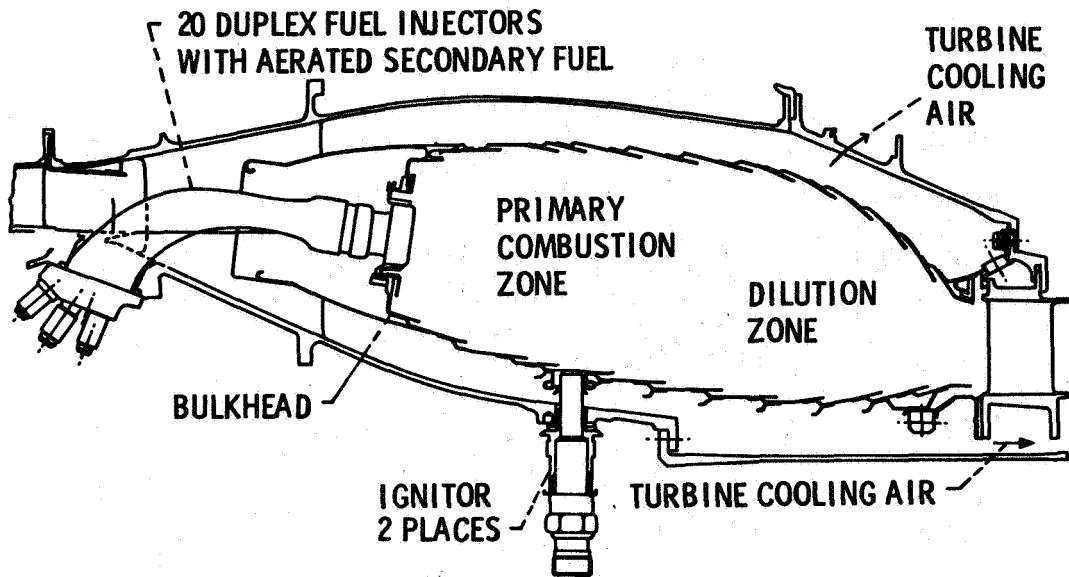


FIGURE 3 Advanced Single Stage Combustor

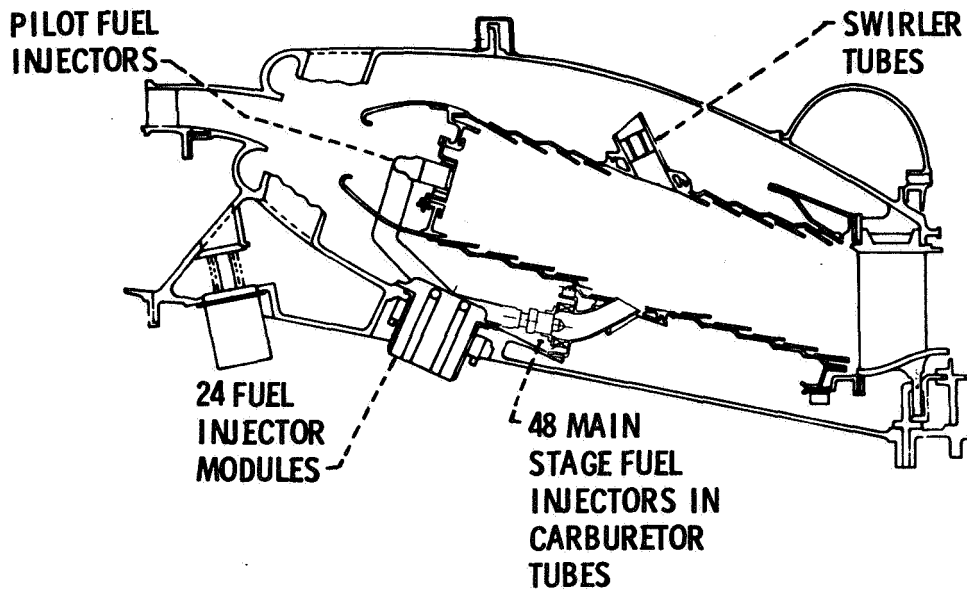


FIGURE 4 Advanced Vorbix Combustor Concept

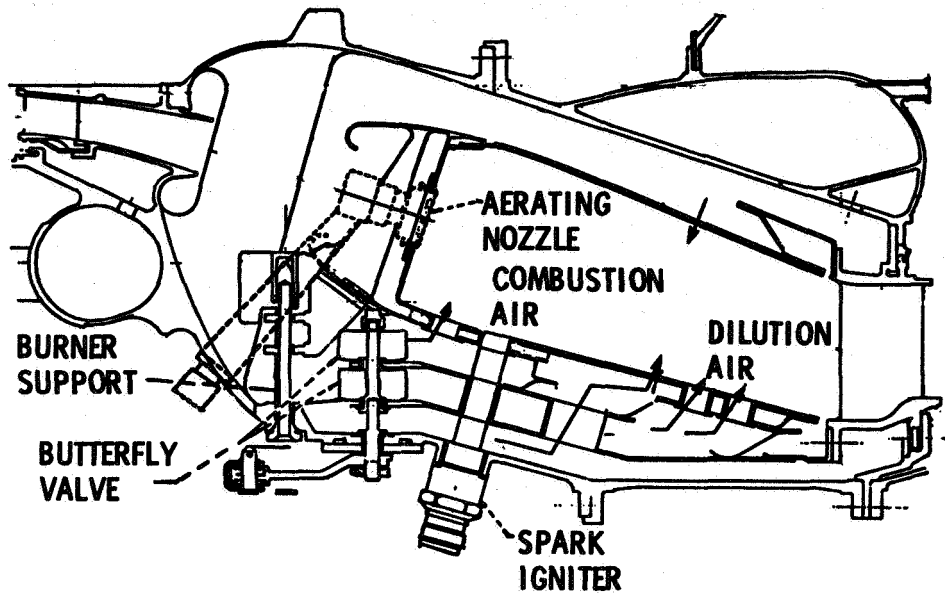


FIGURE 5 Variable Geometry Combustor Concept

NASA/GENERAL ELECTRIC BROAD-SPECIFICATION FUELS

COMBUSTION TECHNOLOGY PROGRAM - PHASE I

Willard J. Dodds
General Electric
Aircraft Engine Group

The use of broad-specification fuels in aircraft turbine engine combustion systems presents several design problems. In general, levels of exhaust pollutant emissions increase and the combustor performance and durability requirements become more difficult to meet as the fuel specifications are relaxed. Fuel hydrogen content will be lower than in presently used fuels, causing increased visible smoke output, increased carbon deposition on fuel nozzles and combustor liners, increased NO_x emissions, and increased flame luminosity, resulting in increased radiant heat transfer and shorter life. Fuel volatility will be lower and viscosity will be higher than in presently used fuels. This will result in more difficult cold start and altitude relight and greater difficulty in achieving satisfactory emissions levels at low power conditions. Thermal stability may be poorer than in presently used fuels, causing fuel system deposits and fuel injector plugging.

Design approaches to counteract the effects of decreased fuel hydrogen content include the use of short combustors with improved liner cooling techniques. Improved combustor dome and swirler designs eliminate carbon deposition and improve primary zone mixing, thereby decreasing smoke formation and flame luminosity and minimizing repetitive hot streaks which can reduce liner life. In advanced designs, smoke, NO_x and flame luminosity can all be reduced by providing for lean combustion at high power operating conditions. Effects of increased viscosity and reduced volatility can be reduced by the use of improved dome, fuel injector and swirler designs to improve fuel atomization and mixing at lightoff and low power operating conditions, and by providing low velocities and near-stoichiometric mixtures in the combustor primary zone at low power operating conditions. Fuel thermal stability effects can be reduced by reducing fuel manifold temperatures and by using more effective thermal insulation in fuel system components.

In Phase I of the NASA/General Electric Broad-Specification Fuels Technology program, three different combustor design concepts will be evaluated for their ability to use broad-specification fuels while meeting several specific emissions, performance, and durability goals. These combustor concepts cover a range from those having limited complexity and relatively low technical risk to those having high potential for achieving all of the program goals at the expense of increased technical risk.

The concept with the least complexity is the basic CF6-80 combustor. This advanced single-annular combustor is a direct derivative of the successful CF6-50 combustor design. Compared to the CF6-50 design, the CF6-80 combustor

length has been reduced by 8 cm, counterrotating dome swirlers are used rather than the corotating design, and the liner film cooling slots are a newly developed rolled-ring design that features improved film cooling effectiveness and maximum resistance to film slot closure.

The second concept is a parallel-staged double-annular design similar to that used in the NASA/GE Experimental Clean Combustor and E³ programs. At lightoff and low power operating conditions, all of the fuel is burned in the pilot stage, which is designed to provide low velocity, near-stoichiometric primary combustion. At high power conditions, both the pilot and main stages are fueled, but most of the fuel is injected into the main stage dome. This dome is designed to provide lean combustion and short residence times to reduce NO_x and smoke formation, thereby reducing flame luminosity effects.

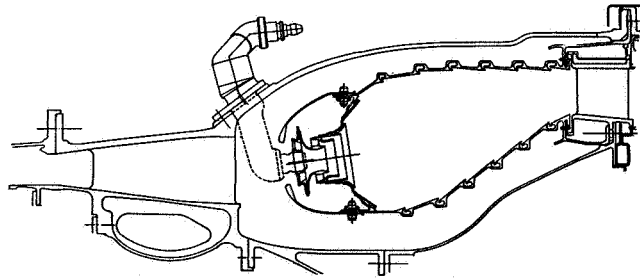
The third concept is an advanced, short single-annular combustor which employs variable geometry swirlers to provide optimum flow rates and stoichiometries in the dome region at the various operating conditions. At lightoff and low power conditions, the swirlers are closed down to reduce the combustor velocity to provide near-stoichiometric primary zone mixtures. At high power conditions, the swirlers are opened to provide lean, high velocity combustion.

The combustor test program will consist of screening tests of a baseline configuration and approximately five modifications of each combustor concept. About six additional refinement tests will then be conducted to improve the performance of selected combustor configurations and to more completely document combustor operating characteristics and fuel properties effects. All testing will be conducted using a full-scale CF6-80 sector test rig which is designed to operate at the full sea-level-takeoff pressure and temperature conditions of the CF6-80 engine.

Combustor Design Considerations

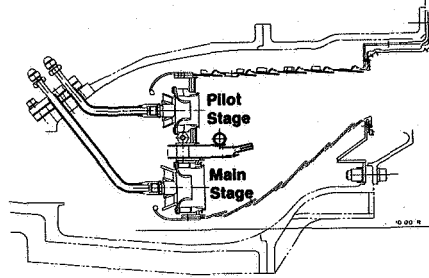
<u>Fuel Property Change</u>	<u>Problems</u>	<u>Approach</u>
<ul style="list-style-type: none"> • Reduced Hydrogen Content/Higher Aromatics 	<ul style="list-style-type: none"> • Increased Flame Luminosity (Increased Liner Temperatures) • Increased Smoke • Increased NOx • Increased Carboning 	<ul style="list-style-type: none"> • Lean-Well Mixed Combustion at High Power • Short Combustor-Reduced Liner Cooling Requirements
<ul style="list-style-type: none"> • Increased Viscosity/Reduced Volatility 	<ul style="list-style-type: none"> • Increased Ground Start/Relight Difficulty • Increased Low Power Emissions (CO & HC) 	<ul style="list-style-type: none"> • Improved Dome/Swirlers Designs • Rich-Low Velocity Combustion at Low Power • Improved Dome/Swirlers Designs
<ul style="list-style-type: none"> • Reduced Thermal Stability 	<ul style="list-style-type: none"> • Fuel Valve & Nozzle Fouling 	<ul style="list-style-type: none"> • Increase Fuel System Insulation

Baseline CF6-80 Combustor



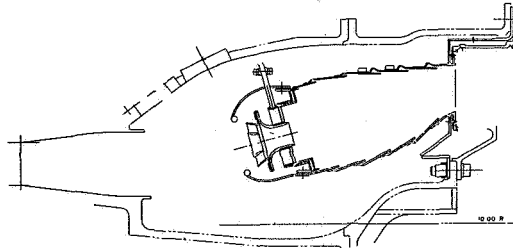
- Short Single Annular Combustor Design
- Counterrotating Dome Swirlers
- Advanced Liner Cooling Slot Design
- Short Prediffuser

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 E³ 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

Combustor Design Parameters

	Baseline <u>CF6-80</u>	Double <u>Annular</u>		Variable <u>Geometry</u>
		<u>Pilot</u>	<u>Main</u>	
Low Power (Idle)				
Dome Reference Velocity, m/s	8.3	6.6	—	5.7
Dome Swirler Equivalence Ratio	0.73	1.1	—	1.0
High Power (Takeoff)				
Dome Reference Velocity, m/s	11.3	9.0	28.6	19.3
Dome Overall Equivalence Ratio	0.88	0.63	0.63	0.60
Combustor Length, cm	27.7	22.1	22.1	20.8

Planned Test Program

- Scope:**
- Screening Tests on Six Configurations of Each Concept (18 Tests Total). 60 Percent of Engine Pressure.
 - Refinement Tests on Two Most Promising Concepts (6 Tests Total). Some Tests at Full Engine Pressure.

Test

Vehicle: CF6-80 High Pressure (Up to 3.5 MPa) Five Cup (60-Degree) Sector Combustor Test Rig.

Test

Facility: Test Cell A3 — Evendale.

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FUELS RESEARCH - COMBUSTION EFFECTS OVERVIEW

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National Aeronautics and Space Administration
Lewis Research Center

Fuels combustion research is conducted (1) to isolate and identify those physical and chemical properties of fuels that affect aviation gas-turbine combustion; (2) to determine combustion sensitivity to variations in particular fuel properties; and (3) to identify advanced combustion concepts and subcomponents that could lessen the effect of using broadened-property fuels.

Fuels combustion research needs have been identified through various analytical and experimental assessments of the effect of broadened-property fuels on gas-turbine combustors. Activities to address those needs may fall into three categories: fundamentals, combustion concepts, and long-term fuel effects.

Combustion fundamentals encompasses analytical and experimental efforts where unrestricted approaches to simulating combustors are pursued in an attempt to discern broad general results. Five thrusts are identified: (1) chemical kinetics, wherein experiments and analyses are performed to identify rate-controlling mechanisms; (2) soot formation and oxidation, wherein mechanisms of soot formation and subsequent burnout are identified; (3) flame radiation, in which radiant heat flux to combustor liners is measured and soot concentration profiles are obtained from spectral radiant intensities; (4) thermodynamic properties, wherein analyses and subsequent computer programs are developed to provide data required for using broadened-property fuels; and (5) partial oxidation, in which techniques such as catalytic reaction are used to partially oxidize the fuel so as to reduce soot-forming tendencies.

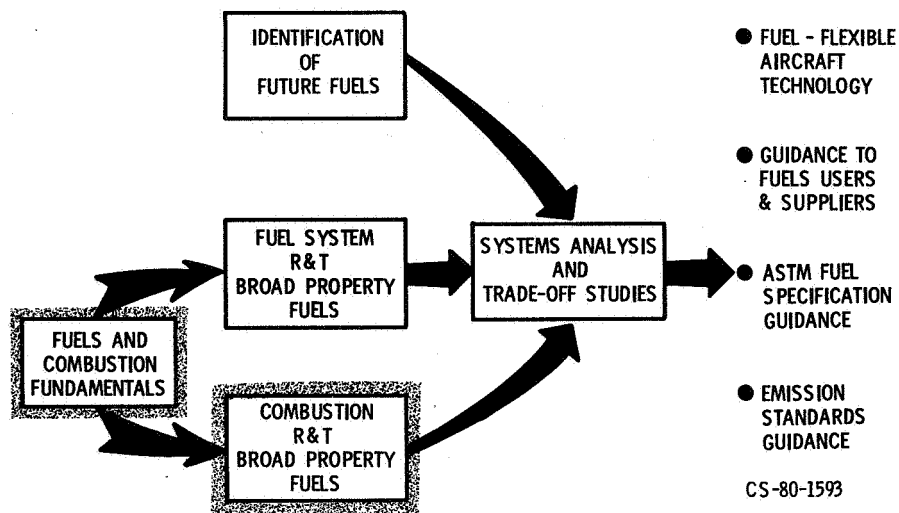
In the second category, combustion concepts, programs are directed toward evolving advanced technology aimed at optimizing combustion performance with broadened-property fuels. Five thrusts are identified: (1) performance studies of unmodified, inservice combustors to define potential problems and to provide a baseline of broadened-property-fuel effects; (2) burning zone studies, in which several advanced combustion concepts are evaluated with alternative fuels; (3) fuel injection studies, in which the spatial and size distributions of fuel sprays are evaluated with broadened-property fuels for several types of fuel injectors; (4) liner concepts, in which advanced liner coatings, advanced designs, and redistributed cooling-air flows are studied; and (5) fuels safety studies, in which the characteristics of fuel systems and combustor performance are studied with special fuels designed to reduce fires during a crash.

The last category is long-term fuel effects. These activities, which will be started once the best approaches to using broadened-property fuels are identified, are concerned primarily with durability evaluations modeled to accelerate long-term cyclic effects.

Three of the six papers in this session are concerned with combustion fundamentals. They present analytical and experimental studies of fuel property effects on soot formation and oxidation. Dr. Ruth of Exxon Research and Engineering Co. reviews a multiyear effort, funded by DOE, that examines fuel property effects on soot formation in strongly backmixed combustion. Professor Prado of the Massachusetts Institute of Technology reviews recent work of the Chemical Engineering Department on soot formation and burnout in flames. Dr. Moses of Southwest Research Institute reviews a recently completed effort, funded by NASA, that examined molecular structure effects on soot formation in combustors.

The remaining three session papers focus on a variety of combustion concepts. Professor Skifstad of Purdue University reviews the progress of a NASA-funded grant aimed at identifying fuel property effects on the spray characteristics of various classes of fuel injectors. Mr. Schmidt of the NASA Lewis Aircraft Safety Office reviews an FAA - NASA-funded study with Pratt & Whitney Aircraft Group on the compatibility of an antimisting fuel with fuel system and combustor operation. Finally, Mr. Humenik of the NASA Lewis Fuels Branch reviews some in-house studies on the sensitivities of tubular combustors to broadened-property fuels and summarizes the results of flame-tube tests.

AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS



ATOMIZATION OF BROAD SPECIFICATION AIRCRAFT FUELS

J.G. Skifstad and A.H. Lefebvre
Purdue University

The atomization properties of any liquid fuel for potential use in aircraft gas turbine engines are widely recognized to be of prime importance. These properties are important because the ignition and subsequent combustion behavior of the fuel-spray/air mixture are strongly affected by the nature of the fuel spray preparation and distribution. For example, the mean size of the droplets in the spray (e.g., Sauter mean diameter, SMD), the distribution of droplet sizes present at any local position in the spray, the local fuel/air mixture ratio, the fraction of fuel vaporized, and other factors, related to the airflow/spray dynamics, for instance, may be expected to be largely established by the liquid injection devices and the arrangements for the airflow in the primary region of the combustion chamber. Clearly, the fuel properties which affect atomization behavior (viscosity, surface tension and density) will be less favorable for the broad specification fuels under consideration here, as compared with those for conventional fuels. To be sure, other operational factors such as thermal stability, storage and transport considerations, pumping behavior, and so on, must also be considered. But the fuel must ultimately be well-atomized in the engine over a suitable range of operating conditions to be at all acceptable as a fuel for aircraft gas turbines. Those conditions necessarily include extremes, such as altitude relight and cold start conditions, as well as normal operating conditions for the engine.

Fuel injectors for specific gas turbine engines are designed to atomize the fuel and to distribute the fuel in the primary air flow over a range of engine operating conditions from idle to full power. These injectors employ one or more of several characteristic types of injection schemes, such as simplex, duplex, air-assist, and airblast, for instance. They vary in their reliance on one or more of the basic mechanisms utilized to effect breakup of the liquid into fine droplets, and in the nature of the control of the processes to enable operation over a sufficiently wide range of fuel flow rates. The technology involved in the development of such injectors remains virtually an empirical art. Nonetheless, there have been some investigations of a sufficiently detailed character to anticipate the trends in the atomization produced by certain types of injectors likely to be employed for the more viscous fuels of interest.

Of the numerous correlations available describing the dependence of the SMD of the spray droplets on the liquid properties, the operating conditions of the atomizer and the properties of the environment, typical relations for simplex (swirl) atomizers and airblast atomizers indicate the SMD increases with increasing viscosity and surface tension, and weakly increases with liquid density. There is evidence the SMD for the swirl atomizer is not significantly dependent on the liquid surface tension. Experimental curves for an airblast atomizer illustrating the variation of SMD with liquid

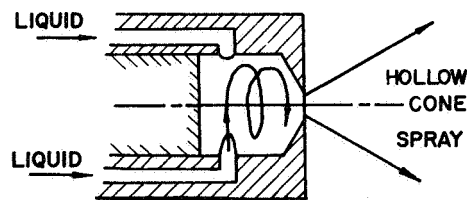
viscosity, surface tension, and density show that increases in each of those fuel properties result in larger spray droplet sizes. Variations of the SMD with ambient pressure or temperature are also illustrated, showing that increases in ambient pressure and decreases in temperature yield smaller drop sizes. The experimental curves are taken from investigations on airblast atomizers conducted by one of the authors (AHL) and his former colleagues at Cranfield University. The importance of these particular results here lies in the fact that airblast atomizers appear to offer the greatest promise for fine atomization of the heavier fuels. The results shown do not exhibit the complete picture, however, insofar as operation over a range of conditions is required and there are other factors involved, such as the fuel penetration and distribution in the airflow within a particular combustion chamber. Complete data for fuels of interest are simply not available.

A research program at Purdue (NSG 3258, NASA Lewis Research Center) is to explore the atomization behavior of representative fuel injectors with fuels simulating the properties of those falling under the broad specification fuel classification. These fuels will be sprayed into nitrogen atmospheres at ambient pressures up to about 20 atm and at ambient gas temperatures up to 1000 °K. The gas flow and distribution conditions are to be chosen merely to avoid recirculation of spray droplets in the flowfield within the pressure vessel and otherwise are to be made to have minimal effect on the spray dynamics. Measurements of the spray properties (local measurements of the droplet size distribution at points in the near field of the injector) are to be made with an imaging-type spray analyzer donated to Purdue by the Parker-Hannifin Corporation. This device is capable of individual droplet size measurements from 8 microns to 512 microns. It is an automated system coupled with a PDP 11V03 computer installation.

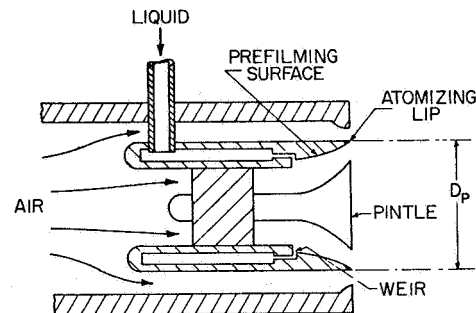
Given the results of these investigations, it should be apparent what tradeoffs are likely to be involved in utilizing each of the characteristic types of fuel injectors for the range of fuels of interest and over the range of ambient parameters of interest. These tradeoffs will involve all of the spray properties measured, including droplet size distribution data, spatial variations of that distribution, and the spatial distribution of the spray droplet density. The extent and nature of atomization properties of the broad specification fuels should then be apparent for each type of injector and the more promising attributes of injectors for specific aircraft gas turbine applications using these fuels might then be identified and incorporated in new designs.

	SPECIFIC GRAVITY	KINEMATIC VISCOSITY (M ² /S)	SURFACE TENSION (N/M)
AVIATION KEROSENE	0.79	1.6×10^{-6}	24×10^{-3}
DIESEL FUELS	0.83	6×10^{-6}	26×10^{-3}
GAS OILS	0.87	30×10^{-6}	29×10^{-3}
MARINE ENGINE FUELS	0.94	400×10^{-6}	30×10^{-3}

FIGURE 1. REPRESENTATIVE LIQUID PROPERTIES FOR PETROLEUM FUELS (293 °K)



(A) SIMPLEX SWIRL ATOMIZER



(B) AIRBLAST ATOMIZER

FIGURE 2. ATOMIZER CONFIGURATIONS

INSTABILITIES

- CAPILLARY WAVES
- SHEAR DRIVEN WAVES
- VORTEX INSTABILITIES
- ACOUSTIC INSTABILITIES
- TURBULENCE

LIQUID PHASE GEOMETRY

- JETS
- SHEETS
- FILMS
- DROPLETS
- LIGAMENTS

FREE BOUNDARY INTERACTIONS

- GAS PHASE SHEAR
- ACOUSTIC FIELDS, PULSES
- LIQUID/SOLID SEPARATION
- CAVITATION PHENOMENA
- THERMAL PHENOMENA

ENERGY CONSIDERATIONS

- EQUILIBRIUM ENERGY REQ'D LOW
- RATES OF DEFORMATION ARE NECESSARILY HIGH
- THERMAL LIMITATIONS OF FUELS

FIGURE 3. ATOMIZATION PHYSICS

$$\text{SMD} = K \cdot (\text{FN}) \cdot \mu_L^{0.2} \quad \text{SMALL NOZZLES}$$
$$\text{FN} = W_L / \sqrt{\Delta P_L}$$

(A) SIMPLEX SWIRL ATOMIZERS (SIMMONS)

$$\text{SMD} = 0.073 \left(\frac{\sigma_L}{\rho_A U^2} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} D_P^{0.4} \left(1 + \frac{W_L}{W_A} \right) + 0.015 \left(\frac{\mu_L^2 D_P}{\sigma_L \rho_L} \right)^{0.5} \left(1 + \frac{W_L}{W_A} \right)$$

(B) AIRBLAST ATOMIZERS (LEFEBVRE)

FIGURE 4. SMD CORRELATIONS

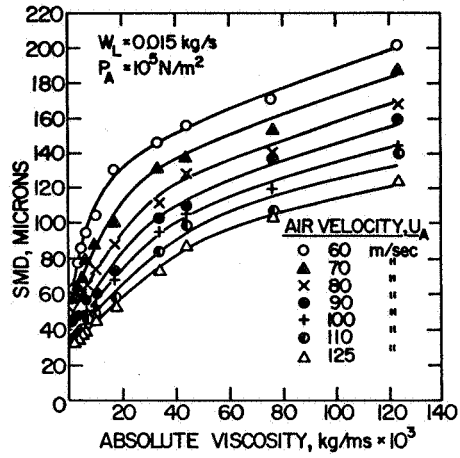


FIGURE 5. EFFECT OF LIQUID VISCOSITY ON DROP SIZE FOR A PRE-FILMING AIRBLAST ATOMIZER (RIZKALLA AND LEFEBVRE)

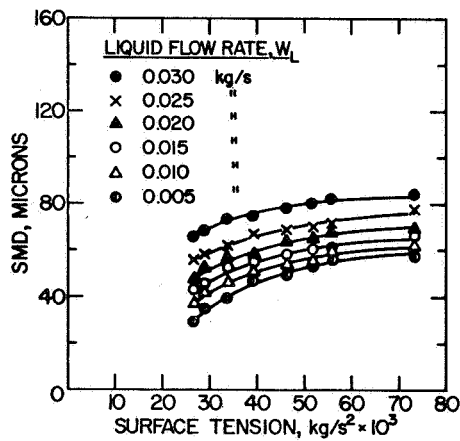


FIGURE 6. EFFECT OF SURFACE TENSION ON DROP SIZE FOR A PRE-FILMING AIRBLAST ATOMIZER (RIZKALLA AND LEFEBVRE)

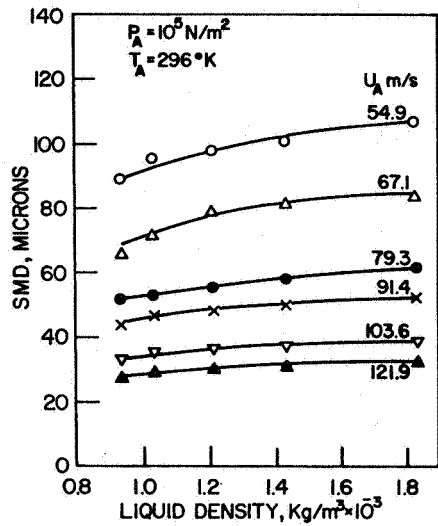


FIGURE 7. EFFECT OF LIQUID DENSITY ON DROP SIZE FOR A PRE-FILMING AIRBLAST ATOMIZER (RIZK AND LEFEBVRE)

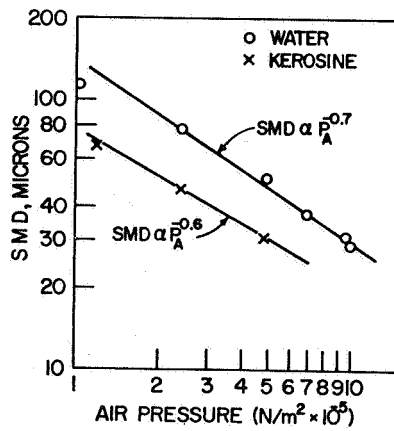


FIGURE 8. EFFECT OF AMBIENT AIR PRESSURE ON DROP SIZE FOR AN AIRBLAST ATOMIZER (RIZKALLA AND LEFEBVRE)

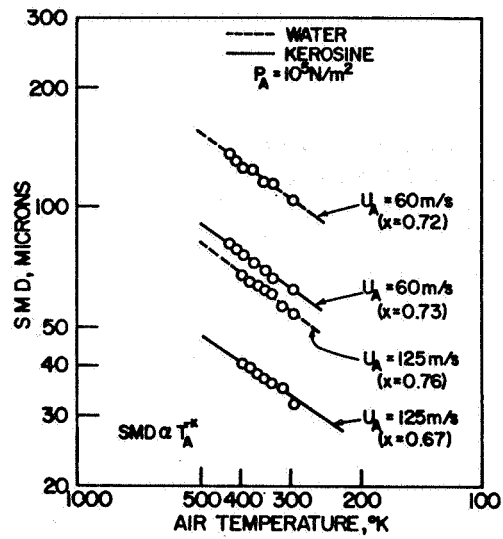


FIGURE 9. EFFECT OF AMBIENT AIR TEMPERATURE ON DROP SIZE FOR AN AIRBLAST ATOMIZER (RIZKALLA AND LEFEBVRE)

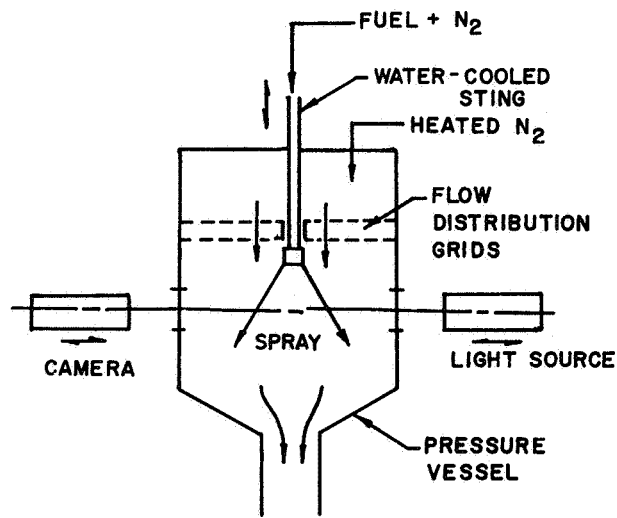


FIGURE 10. EXPERIMENTAL APPARATUS

CAMERA/LIGHT SOURCE
AND INJECTOR ARE
TRAVERSED UNDER
COMPUTER CONTROL

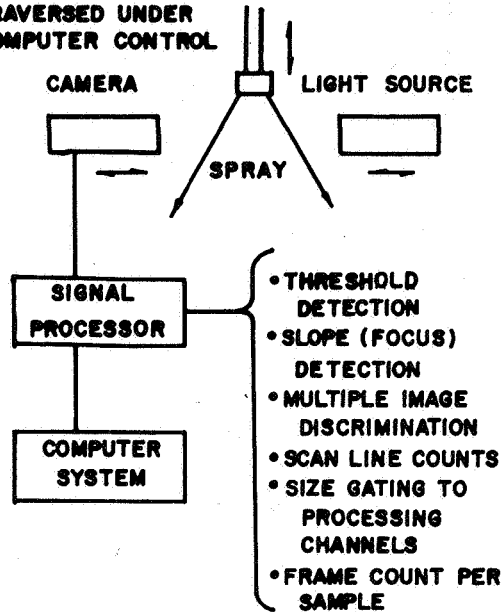


FIGURE II. PARKER - HANNIFIN SPRAY DROPLET ANALYZER

ANTIMISTING KEROSENE

Harold W. Schmidt
National Aeronautics and Space Administration
Lewis Research Center

Antimisting kerosene (AMK) is a kerosene-fraction jet fuel containing an additive that reduces the flammability of the fuel in an aircraft crash circumstance. AMK additives, when dissolved in Jet A fuel in concentrations in the range of 0.3 percent, have been demonstrated to inhibit ignition and flame propagation of the released fuel in simulated crash tests. The AMK fuel resists misting and atomization from wind shear and impact forces and instead tends to agglomerate into globules. This agglomeration significantly reduces ignitability and flame propagation.

Several AMK additives have been developed and evaluated for their potential to reduce post-crash fires. The antimisting additive (FM-9), selected for more comprehensive testing in this program, was developed by the Imperial Chemical Industries and the Royal Aircraft Establishment of the United Kingdom and is being evaluated for crash-fire resistance by the U.S. FAA in an agreement with the United Kingdom.

The NASA has agreed to conduct propulsion system tests for the FAA. The purposes of the tests are to evaluate the effects of the additive on engine operation, to identify operating problems, to assess the adaptability of existing engines to AMK, and to determine the potential viability of this fuel for use in present and future fan-jet engines. The Pratt & Whitney Aircraft Group has been contracted to perform the experimental test program on the JT8-D engine and fuel system components.

This additive, FM-9, which creates the high shear resistance desirable in the crash circumstance, results in non-Newtonian flow characteristics that cause some undesirable behavior in the engine fuel system. For example, figure 1(a) shows the typical atomization of Jet A fuel in a standard JT8-D nozzle at ignition flow rates. Figure 1(b) shows the behavior of undegraded AMK in the same nozzle. However, in actual conditions, the AMK would be partially degraded from being pumped through the fuel control system. Similarly, figure 2 shows the effect of the nozzle design on undegraded AMK. Figure 2(a) is for the standard nozzle, and figures 2(b) and (c) are for nozzles with successively increased atomization capabilities built into their designs. Figure 3(a) shows the change of viscosity of AMK fuel as a function of shear exposure time in a blender. Changes in viscosity of this magnitude are significantly higher than changes due to temperature (fig. 3(b)) and are in addition to the temperature influence on viscosity.

The very high-molecular-weight polymeric additive tends to clog small flow passages, screens, filters, and close-tolerance clearances in the fuel controller. AMK fuel exhibits the greatest shear resistance and crash-fire resistance

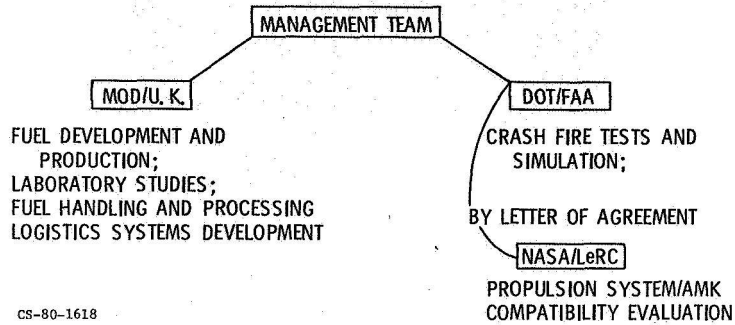
right after mixing and before any exposure to shear, such as pumping and flow through pipes, fittings, filters, or other components. Successive exposure to any of these shear forces tends to break the polymeric molecules and thereby reduce the average molecular weight and the subsequent shear resistance. Continuation of such degradation causes the AMK to revert back toward the original properties of the base fuel.

This characteristic provides the possibility of using AMK in existing engines by assuring a level of degradation required for acceptable performance for each critical component. In anticipation of this possible requirement, the United Kingdom is developing a fuel degrader that could be incorporated into the fuel system. The practicality of the various ways to accommodate AMK fuel in existing engines will be evaluated in this program. If it is determined that retrofit modification of the fuel feed system would be required to accommodate AMK fuel in existing engines, the extent of such modification requirements will be identified and evaluated. This will determine the course of follow-on experimental work on AMK fuel.

Antimisting kerosene is being considered as a jet fuel because 15 percent of the total fatalities in aircraft accidents result from postcrash fire. Significant postcrash fires do not occur in accidents caused by fuel depletion. Simulated crash tests with AMK fuels have demonstrated the potential reduction in postcrash fire. Further development effort would be warranted if the fuel can be used in turbofan jet engines without extensive modification. Of several additives tested, FM-9, developed by ICI and the RAE of Great Britain, was selected for further evaluation.

AMK PROGRAM ORGANIZATION

- ORGANIZATIONAL COMPOSITION - BY MEMORANDUM OF UNDERSTANDING BETWEEN THE MINISTRY OF DEFENSE, U.S. AND DOT/FAA, U.S.
- MANAGEMENT TEAM - MINISTRY OF DEFENSE (MOD) AND DOT/FAA
- PROJECT RESPONSIBILITY -



CS-80-1618

TYPICAL ATOMIZATION OF JET A FUEL USING JT8-D STANDARD NOZZLE AT IGNITION FLOW RATES $T_F = 17^{\circ} C$

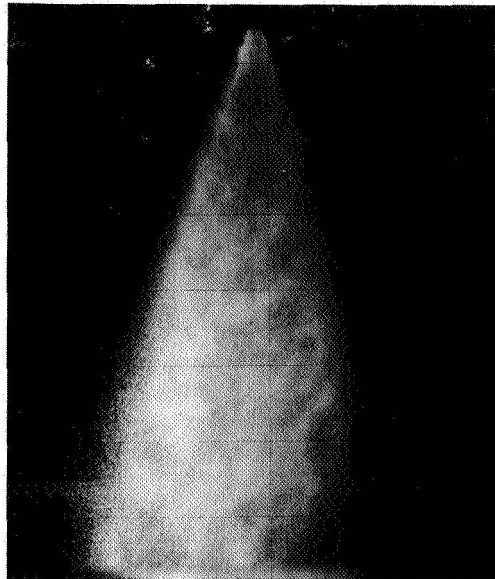


Figure 1(a)

TYPICAL ATOMIZATION OF UNDEGRADED AMK IN
JT8-D STANDARD NOZZLE AT IGNITION FLOW RATES

$T_F = 13^{\circ} \text{C}$

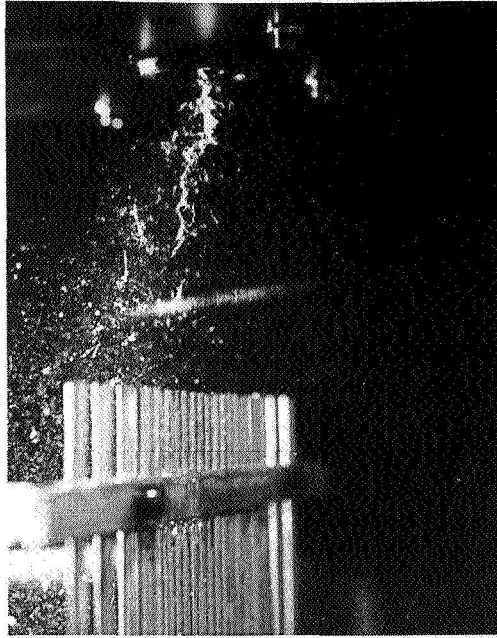


Figure 1(b)

TYPICAL ATOMIZATION OF UNDEGRADED AMK IN
JT8-D STANDARD NOZZLE AT CRUISE FLOW RATES

$T_F = 14^{\circ} \text{C}$

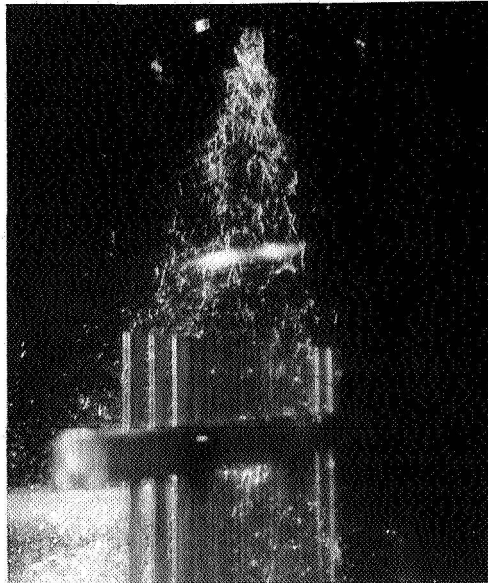


Figure 2(a)

TYPICAL ATOMIZATION OF UNDEGRADED AMK IN
JT8-D LOW EMISSION NOZZLE AT CRUISE FLOW RATES
 $T_F = 16^{\circ} \text{C}$



Figure 2(b)

TYPICAL ATOMIZATION OF UNDEGRADED AMK IN
AIR BOOST NOZZLE AT CRUISE FLOW RATES
 $T_F = 7^{\circ} \text{C}$

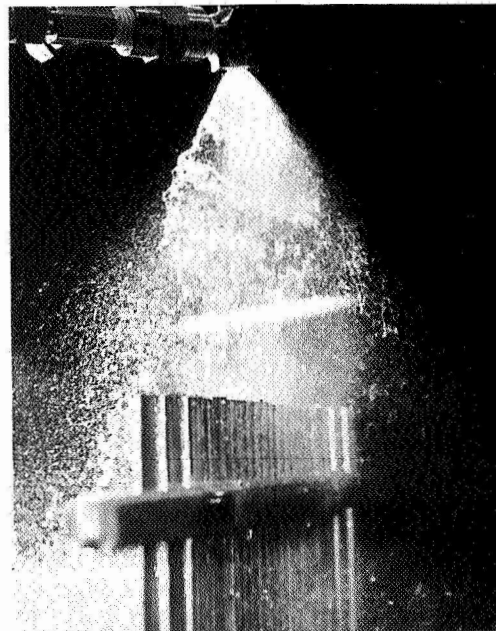
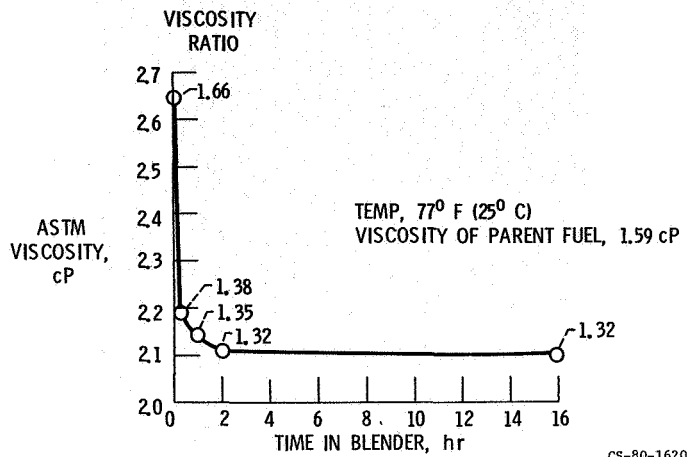


Figure 2(c)

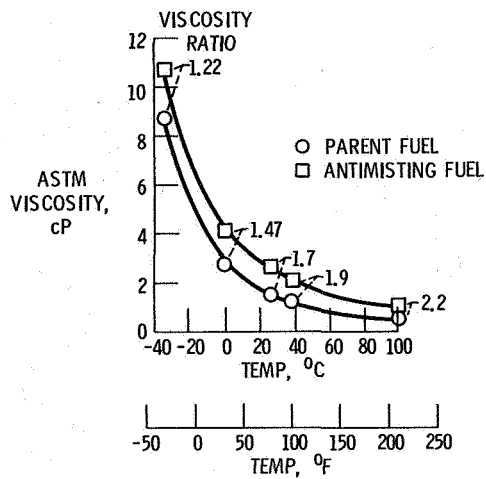
VISCOSITY CHARACTERISTICS OF AMK
CHANGE IN VISCOSITY WITH TIME IN BLENDER



CS-80-1620

Figure 3(a)

VISCOSITY CHARACTERISTICS OF AMK
EFFECT OF TEMPERATURE ON VISCOSITY



CS-80-1619

Figure 3(b)

SOOT FORMATION AND BURNOUT IN FLAMES

G. Prado, J.D. Bittner, K. Neoh, and J.B. Howard
Massachusetts Institute of Technology

Foreseeable trends in fossil fuel availability indicate that the aromatic content of future fuels will be significantly higher than present levels. There are substantial economic and public health incentives to pursue the clean and efficient use of such highly aromatic fuels, especially as their strong sooting tendency is well known. For example, the Experimental Referee Broad Specification (ERBS) fuel, proposed by NASA as representative of a near-term alternate fuel for aircraft contains 29.6% of aromatics, as compared to 17.3% in Jet A aviation turbine kerosene.

The amount of soot formed when burning a benzene/hexane mixture in a turbulent combustor simulating gas turbine engines illustrates the expected effect of increasing the aromatic fraction (Fig. 1). Soot concentration profiles in the same combustor for kerosene fuel are shown on Fig. 2. Modeling these profiles requires the understanding of complex processes such as the chemistry of formation of soot precursors, the nucleation, growth and subsequent burnout of soot particles, and the effect of mixing intensity on the previous steps. The presentation will focus on recent results from experiments designed to shed light on these different processes.

While the strong sooting tendencies of aromatic hydrocarbons are well known, the underlying mechanism of this behavior is not established. Some experimental evidence suggests that the intact aromatic ring and not fragmentation products is responsible for the propensity of aromatic hydrocarbons to form soot. Accordingly, destruction of the ring during combustion might offer a route for the reduction of soot formation from aromatic fuels. To investigate these mechanisms, the structure of a near sooting, low pressure (20 torrs) benzene-oxygen-argon flame has been studied using a mass spectrometer coupled with a molecular beam sampling system¹. Some results in terms of mole fraction of molecular and radical species are shown in Figs. 3 to 6, and will be discussed in more details. They suggest that soot precursors are high molecular mass polyaromatic molecules. The process may start by addition of vinyl-acetylene to phenyl radical to form naphthalene (Table I). A benzyl-type radical is formed by methyl radical substitution at the α -position in naphthalene (Table II) and subsequent abstraction of a methyl hydrogen. The product of C_2H_2 addition to this benzyl-type radical can be rapidly stabilized by cyclization to form a six-membered ring through an internal aromatic substitution reaction. Such a mechanism will explain the strong sooting tendencies of methyl-substituted aromatics under a variety of conditions.

The nature of soot nuclei is not well established. A possibility is that the large polyaromatic molecules undergo coagulation, and once formed, the particles provide a surface on which gas phase material can deposit. Recent results² derived from laser-light scattering and absorption study of soot

formation in premixed and diffusion laminar flames reveal two regimes of soot particle growth. For soot volume fraction smaller than about 10^{-7} , the growing particles maintain an approximately spherical shape. At larger soot volume fraction, chain forming collisions occur, simultaneously with some surface growth. In both regimes, the particle number density is described by the free molecular collision theory, the final number of agglomerates being always close to $10^{10}/\text{cm}^3$ (Fig. 7).

In most practical combustors, soot burnout occurs at the end of the process, reducing the amount of soot released in the environment (Fig. 2). An ongoing program³ at M.I.T. is addressing the following questions 1) relative importance of the various oxidants O_2 , OH , O , CO_2 , and H_2O in soot oxidation, 2) effect of oxidation on the internal structure of the soot particles, 3) burnout characteristics of soot from premixed flames and from fuel pyrolysis, 4) effect of temperature-time history of soot formation on soot burnout. Results at this stage indicate that the specific burnout rates based on the external surface area of the particles are larger than predicted by the classical Nagle and Strickland-Constable formula. The N_2 BET surface area of soot increases considerably more during burnout than can be accounted for by the decrease of particle diameter, indicating opening of porosity. Under some conditions, a breakup of soot agglomerates appears to occur during the post-combustion.

Finally, in turbulent combustors⁴, the mixing characteristics of fuel and air can affect considerably the amount of soot produced and released in the atmosphere (Fig. 2 and 8). For some conditions (Fig. 8) the soot emission levels are in reverse order of maximum soot concentration, stressing the importance of burnout.

REFERENCES

1. Bittner, J.D.: Ph.D. Thesis, M.I.T. (in preparation)
2. Prado, G. et al: Submitted for Presentation at the 18th Symposium (International) on Combustion, Waterloo (Canada)
3. Neoh, K.: Ph.D. Thesis, M.I.T. (in preparation)
4. Prado, G. et al: 16th Symposium (International) on Combustion, p.649 (1977)

TABLE I: PHENYL RADICAL & VINYLACETYLENE

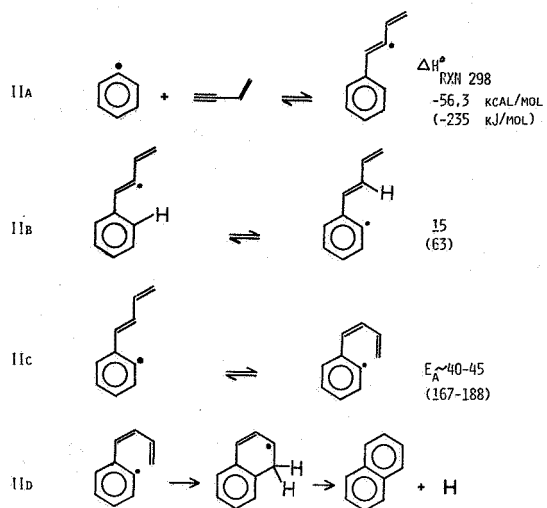
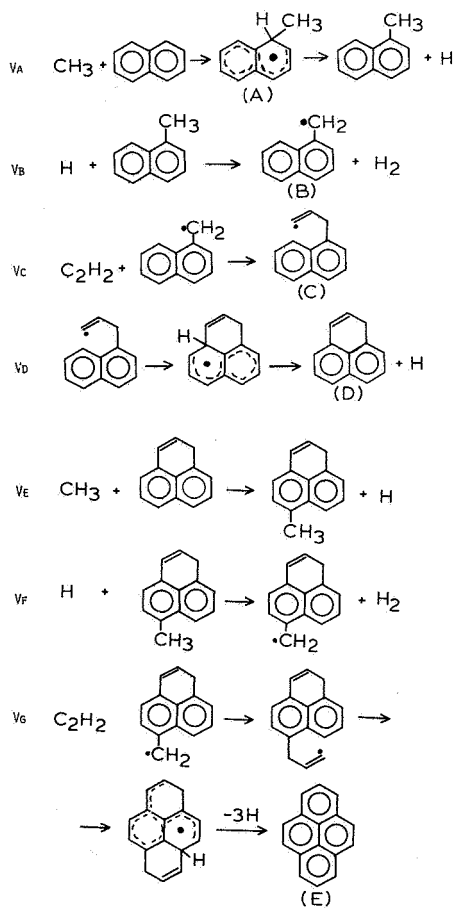


TABLE II: METHYL SUBSTITUTION



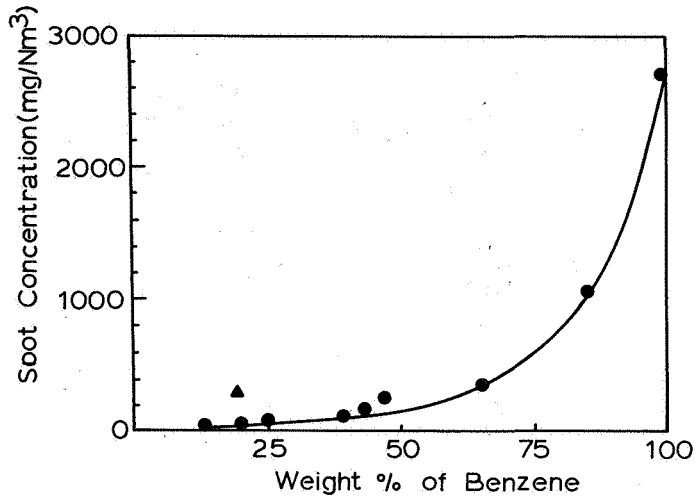


FIG. 1 INFLUENCE OF FUEL AROMATIC CONTENT ON SOOT CONCENTRATION TURBULENT COMBUSTOR. FUEL EQUIVALENCE RATIO = 1.0. ATOMIZING AIR PRESSURE = 184kPa. COLD GAS VELOCITY = 2.67 m/sec. (●) MIXTURE HEPTANE-BENZENE. (▲) KEROSENE

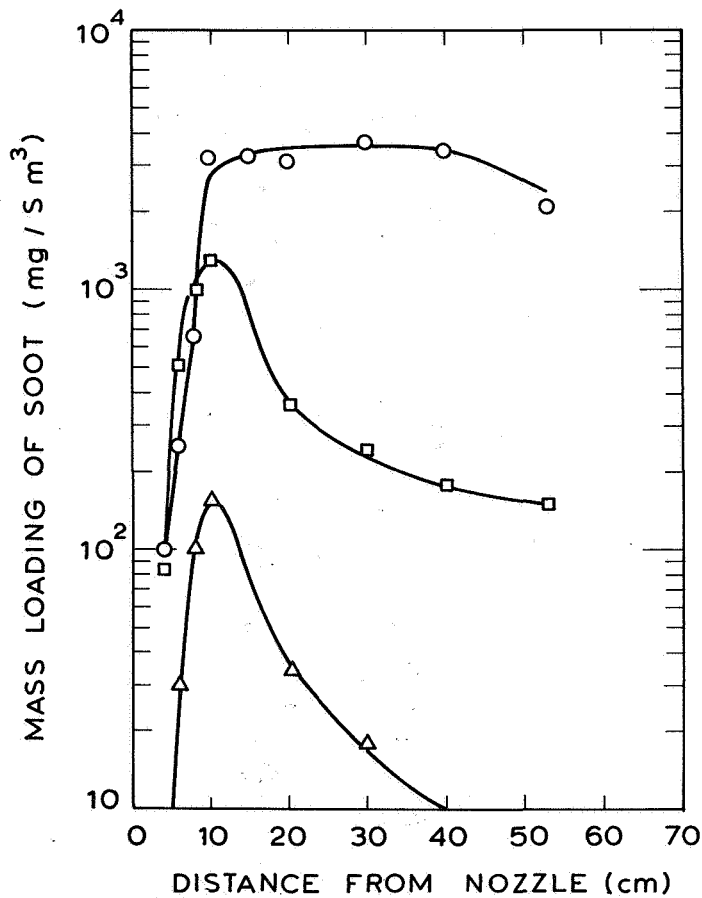


FIG. 2 INFLUENCE OF ATOMIZING-AIR PRESSURE ON AXIAL SOOT CONCENTRATION KEROSENE/AIR. FUEL EQUIVALENCE RATIO = 1.0. COLD GAS VELOCITY = 0.96m/sec. ATOMIZING-AIR PRESSURE = (○) 184kPa, (□) 205kPa, (▲) 239kPa.

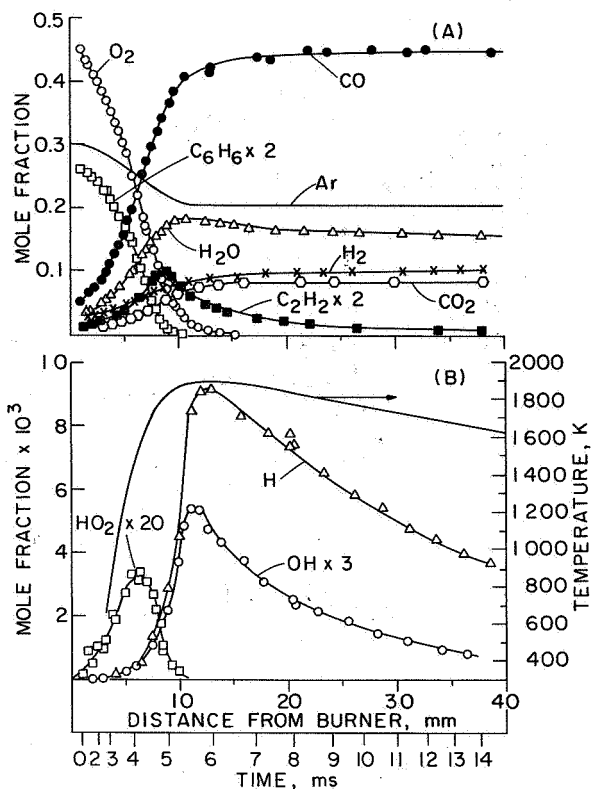


FIG. 3 MOLE FRACTION AND TEMPERATURE VS DISTANCE FROM BURNER IN A NEAR SOOTING ($\phi = 1.8$) BENZENE (13.5m%) OXYGEN (56.5m%) ARGON (30.0m%) FLAME. COLD GAS VELOCITY = 0.5m/sec. PRESSURE = 2.67kPa (20TORR). (A) MAJOR STABLE SPECIES. (B) H, OH, HO₂ AND TEMPERATURE

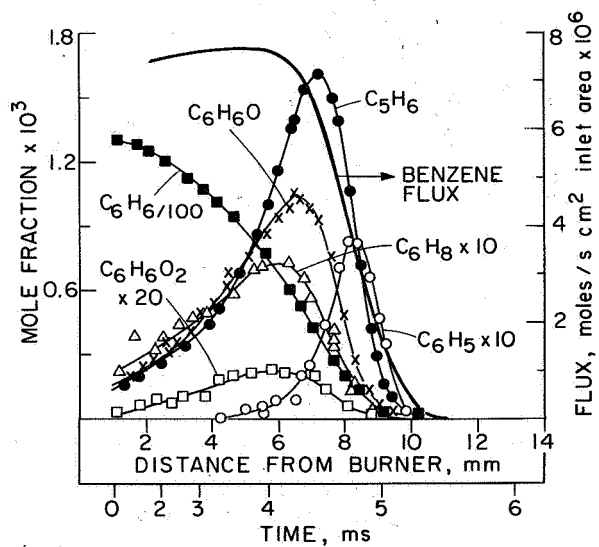


FIG. 4 FLUX AND MOLE FRACTION OF BENZENE AND MOLE FRACTIONS OF SPECIES OF POSSIBLE IMPORTANCE IN BENZENE DECOMPOSITION VS DISTANCE FROM BURNER IN A NEAR SOOTING ($\phi = 1.8$) BENZENE (13.5m%) OXYGEN (56.5m%) ARGON (30.0m%) FLAME. COLD GAS VELOCITY = 0.5m/sec. PRESSURE = 2.67kPa (20TORR)

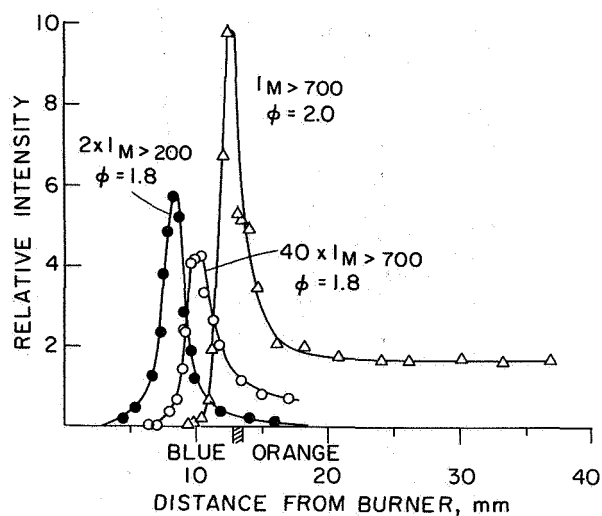


FIG. 5 RELATIVE INTENSITIES OF SIGNALS FROM HIGH MASS MODE OPERATION VS DISTANCE FROM BURNER. BENZENE-OXYGEN-ARGON FLAME. PRESSURE = 2.67kPa (20 TORR), COLD GAS VELOCITY = 0.5m/sec.

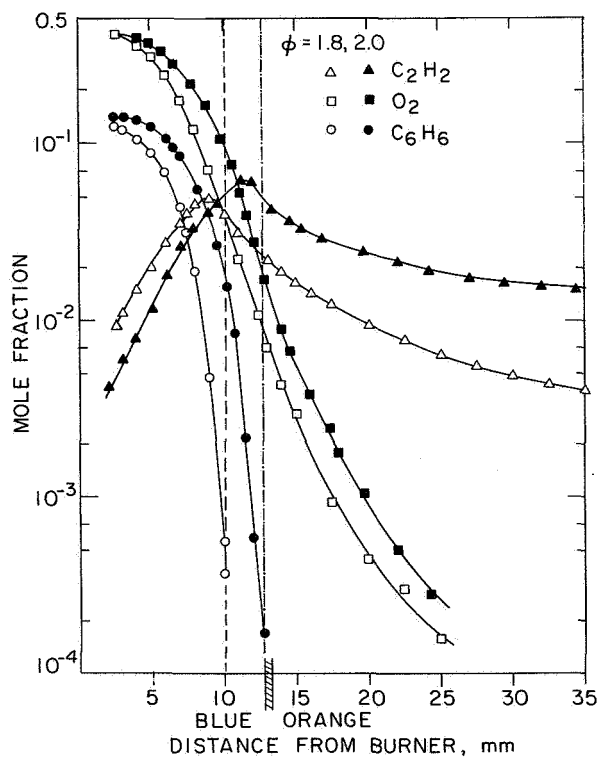


FIG. 6 MOLE FRACTION OF C_2H_2 , O_2 , and C_6H_6 VS DISTANCE FROM BURNER FOR NEAR SOOTING ($\phi = 1.8$, OPEN SYMBOLS) AND SOOTING ($\phi = 2.0$, SHADED SYMBOLS) FLAMES. BENZENE-OXYGEN-ARGON FLAME. PRESSURE = 2.67kPa (20 TORR). COLD GAS VELOCITY = 0.5m/sec.

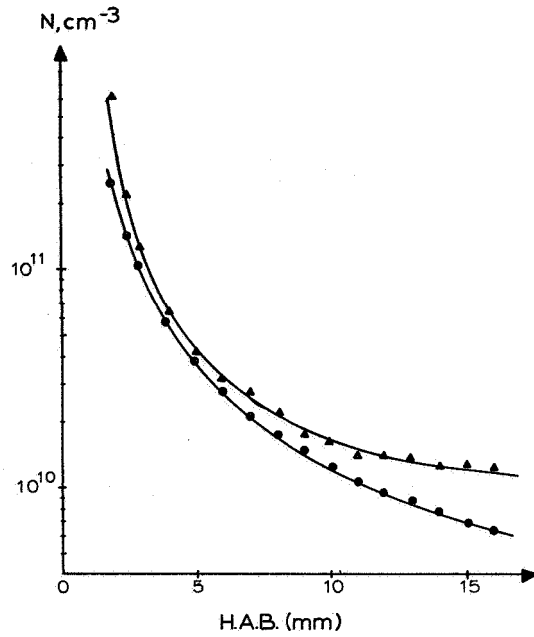


FIG. 7 EXPERIMENTAL (Δ) AND COMPUTED (\bullet) NUMBER DENSITY OF PARTICLES (N, cm^{-3}), PROPANE/OXYGEN FLAME. FUEL EQUIVALENCE RATIO = 2.5. ATMOSPHERIC PRESSURE. COLD GAS VELOCITY = 5.50cm/sec.

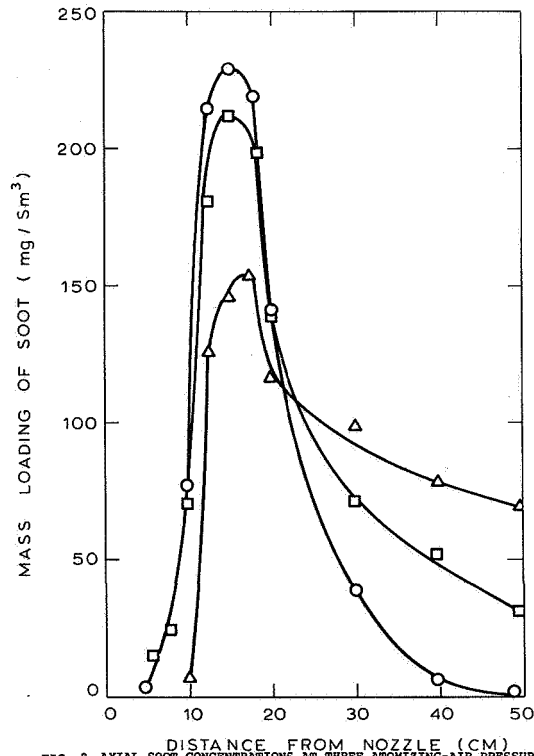


FIG. 8 AXIAL SOOT CONCENTRATIONS AT THREE ATOMIZING-AIR PRESSURE KEROSENE/AIR- FUEL EQUIVALENCE RATIO = 1.0. COLD GAS VELOCITY = 2.67m/sec. ATOMIZING-AIR PRESSURE = (O)184kPa, (□) 205kPa, (Δ)239kPa.

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FUEL PROPERTY EFFECTS IN STIRRED COMBUSTORS

L. A. Ruth and W. S. Blazowski
Exxon Research and Engineering Company

A multi-year effort, funded by the Department of Energy, is being conducted to (a) provide an improved understanding of the effect of fuel properties, such as H and N content, on combustion characteristics and (b) develop analytical models and correlations to predict fuel effects and to assist engine designers in the future development of fuel-flexible systems. The data gathering part of this program, which is the subject of this paper, is being performed by Exxon Research. Analytical modeling is being performed concurrently by Science Applications, Inc.

Our experimental program has focused, thus far, on soot formation in strongly backmixed combustion. Experiments were performed using the jet-stirred combustor (JSC). This device provides a combustion volume in which temperature and combustion are uniform. It simulates the recirculating characteristics of the gas turbine primary zone; it is in this zone where mixture conditions are sufficiently rich to produce soot. Hence, the JSC allows study of soot formation in an aerodynamic situation relevant to gas turbines.

Fuel-rich combustion and soot formation behavior of a number of pure hydrocarbons were investigated. We found that the hydrocarbons tested could be grouped into three categories on the basis of their soot formation characteristics:

<u>Category I</u>	<u>Category II</u>	<u>Category III</u>
(Like ethylene)	(Like toluene)	(Unlike ethylene or toluene)
Hexane	Xylene (o, m, or p)	1-Methyl-naphthalene
Cyclo-hexane	Cumene	
n-Octane	Tetralin	
iso-Octane	Dicyclopentadiene	
1-Octene		
Cyclo-oxtane		
Decalin		

Category I hydrocarbons produced large amounts of exhaust hydrocarbons without sooting. Category II produced measureable soot above the incipient soot limit, defined as the leanest equivalence ratio at which soot was observed. It was at the incipient soot limit, which was about 1.4, that we first detected significant concentrations of exhaust hydrocarbons for Category II fuels. Furthermore, for these fuels, the amount of soot produced as equivalence ratio was increased beyond the incipient soot limit was similar. How-

ever, 1-methyl-naphthalene was significantly different in this respect, producing much higher soot quantities than the second category and having an even lower incipient soot limit. Consequently, this double-ring aromatic represents a third category of soot-forming hydrocarbon.

Blends of iso-octane and toluene were also tested to determine the behavior of a two-component mixture of Category I and II hydrocarbons. Mixtures of 50 or more percent toluene sooted, while a 25-percent toluene blend did not. For mixtures which did soot, increases in the toluene content resulted in increased soot production at all equivalence ratios. It was also determined that, with less toluene in the blend, the concentration of hydrocarbons at the incipient limit tended to increase. These results indicate a combination of Category I and II behaviors, and imply that a combination of the analytical descriptions for iso-octane and toluene might be a reasonable approach for the prediction of sooting characteristics of such fuel blends.

The iso-octane/toluene soot production data was also examined to evaluate the effect of fuel hydrogen content, a parameter often reported as useful in correlating sooting characteristics. At constant equivalence ratios of 1.6 and 1.8, a good correlation implying a linear relationship was obtained. Actual gas turbine combustor testing has also found an approximately linear relationship between fuel hydrogen content and soot production; thus, our results indicate a similarity between sooting in the well-characterized JSC and that in an actual combustor.

Many mechanistic models for soot production have been proposed. A simplified model (following Graham) suggests that aromatic hydrocarbons can produce soot via two mechanisms: (a) condensation of the aromatic rings into a graphite-like structure or (b) breakup to small hydrocarbon fragments which then polymerize to form larger, hydrogen deficient, molecules which eventually nucleate and produce soot. Based on his experiments, Graham concluded that the condensation route is much faster than the fragmentation/polymerization route. Further, since aliphatics can soot via fragmentation/polymerization only, aliphatics should produce much less soot than aromatics.

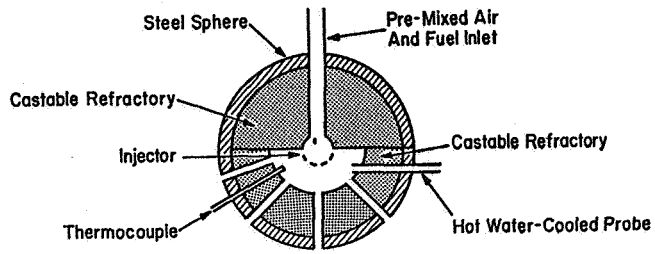
Our present results are consistent with this model. We observed that soot formation with aromatics (Category II) commences with the initial presence of hydrocarbons in the exhaust. If it is assumed that these breakthrough hydrocarbons maintain their aromatic character, this observation reflects the fast kinetics of the ring-building or condensation reactions. Further, the results for 2-methyl-naphthalene indicate that a double-ring aromatic provides the most rapid soot formation of the hydrocarbons studied. On the other hand, the aliphatic hydrocarbons produced large concentrations of exhaust hydrocarbons without soot formation. This observation is consistent with the slow process of polymerization of small hydrocarbon fragments.

The following conclusions were drawn from this multi-year experimental study:

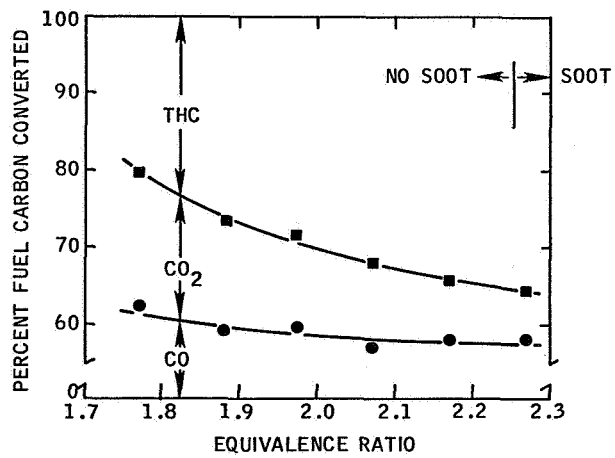
1. C_2H_4 and $C_6H_5CH_3$ are distinctly different.
2. Total hydrocarbons are the key factor in consideration of soot limit and production.
3. Other hydrocarbons are like C_2H_4 or like $C_6H_5CH_3$.
4. Fuel blend testing indicates a combination of behaviors.
5. Results are consistent with simple soot formation mechanisms.
6. There is encouragement for quasi-global characterization.

Future experimental work should characterize exhaust hydrocarbons in a variable-pressure stirred reactor; investigate unmixedness/droplet effects; include continuous flow system studies on soot formation, soot oxidation, and FBN chemistry; investigate turbulence/unmixedness coupling; and include small-scale combustor tests.

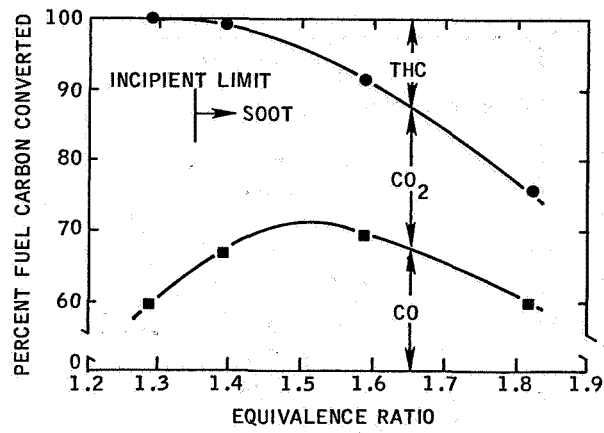
Finally, it should be noted that the results reported here were obtained in a very well-mixed system with vapor fuel. In real systems, liquid droplets will be present which will complicate the situation with turbulence/unmixedness/mass transfer effects. Further experiments in this program will consider the inhomogeneity present during spray combustion.



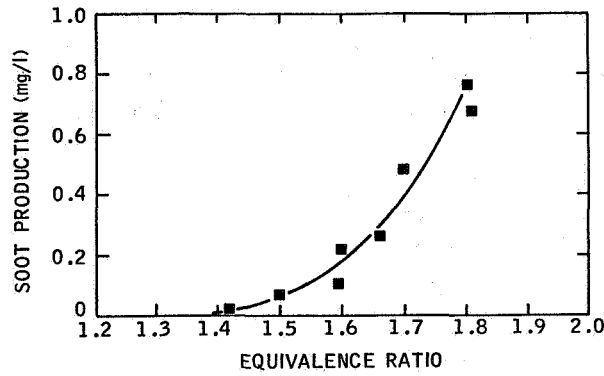
JET-STIRRED COMBUSTOR



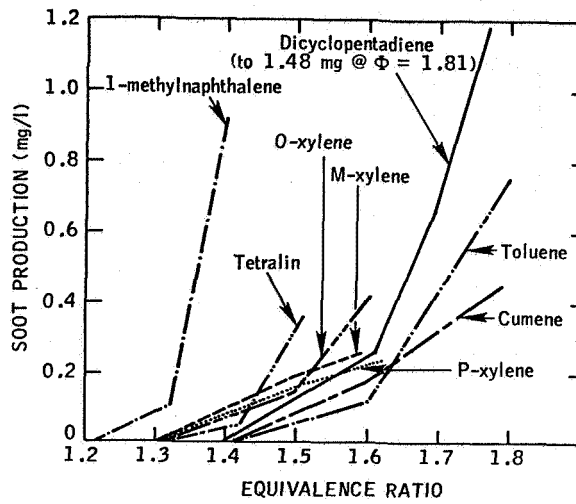
PERCENTAGE OF FUEL CARBON CONVERTED TO EXHAUST PRODUCTS-ETHYLENE/AIR COMBUSTION



PERCENTAGE OF FUEL CARBON CONVERTED TO EXHAUST PRODUCTS-TOLUENE/AIR COMBUSTION



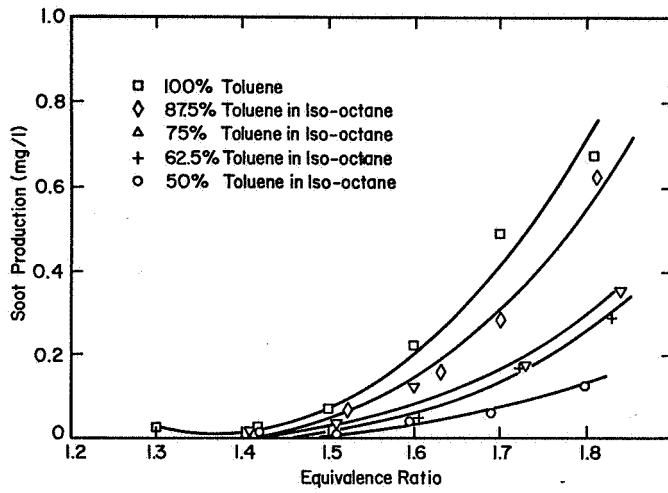
SOOT PRODUCTION vs. EQUIVALENCE RATIO FOR TOLUENE/AIR COMBUSTION



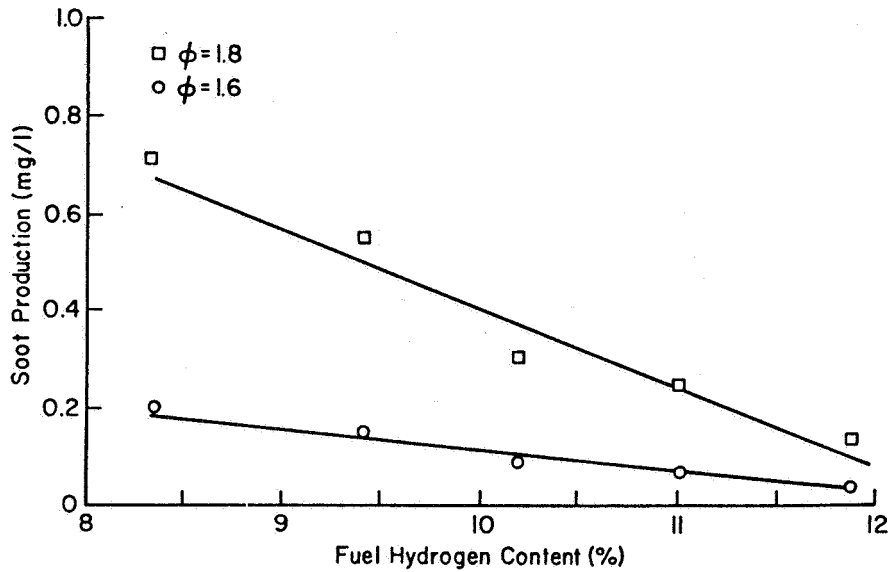
SOOT PRODUCTION vs. EQUIVALENCE RATIO FOR COMBUSTION OF VARIOUS PURE HYDROCARBONS

SOOTING CHARACTERISTICS OF PURE FUELS

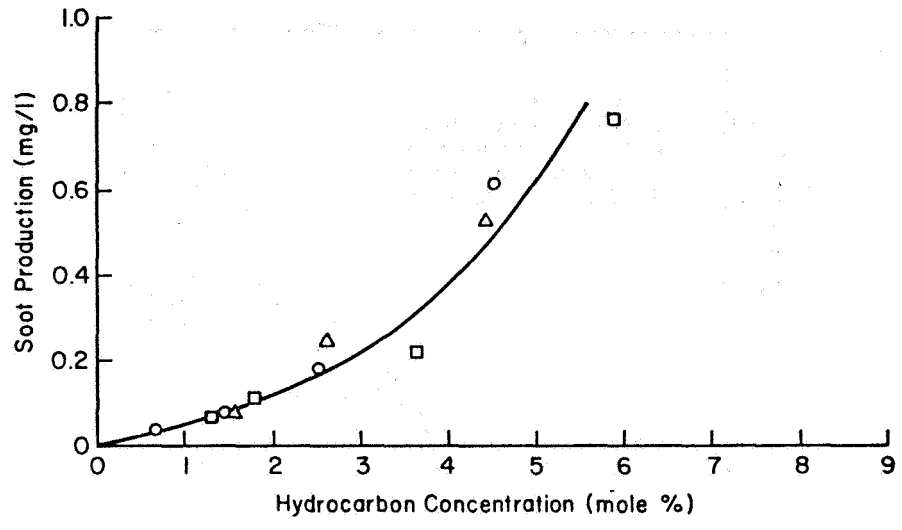
<u>CATEGORY I</u>	<u>CATEGORY II</u>	<u>CATEGORY III</u>
ETHYLENE	TOLUENE	1-METHYL-NAPHTHALENE
HEXANE	O-XYLENE	
CYCLOHEXANE	M-XYLENE	
N-OCTANE	P-XYLENE	
ISO-OCTANE	CUMENE	
1-OCTENE	TETRALIN	
CYCLO-OCTANE	DICYCLOPENTADIENE	
DECALIN		



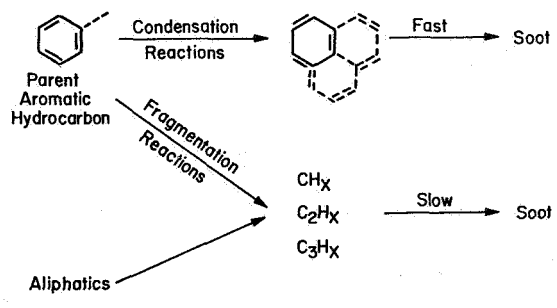
SOOT PRODUCTION vs. EQUIVALENCE RATIO FOR TOLUENE/ISO-OCTANE BLENDS



SOOT PRODUCTION vs. FUEL HYDROGEN CONTENT FOR TOLUENE ISO-OCTANE BLENDS



SOOT PRODUCTION VS. EXHAUST HYDROCARBONS CONCENTRATION FOR TOLUENE AIR COMBUSTION



SIMPLIFIED SOOT FORMATION MECHANISM (GRAHAM)

EFFECT OF FUEL MOLECULAR STRUCTURE ON SOOT FORMATION

IN GAS TURBINE COMBUSTION*

D. W. Naegeli and C. A. Moses
Southwest Research Institute

A number of studies have shown that for gas turbine combustors hydrogen content is a stronger correlating parameter for flame radiation than the more traditional properties of aromatic content or smoke point, especially when the fuels contain significant concentration of hydrocarbons other than paraffins and alkyl-benzenes. The authors have shown that for light and middle distillate fuels viscosity and end point do not affect the correlation, leading to the conclusion that soot formation is primarily due to gas phase reactions rather than liquid phase pyrolysis. Some perturbations in the data suggest, however, that there are secondary effects due to hydrocarbon structure.

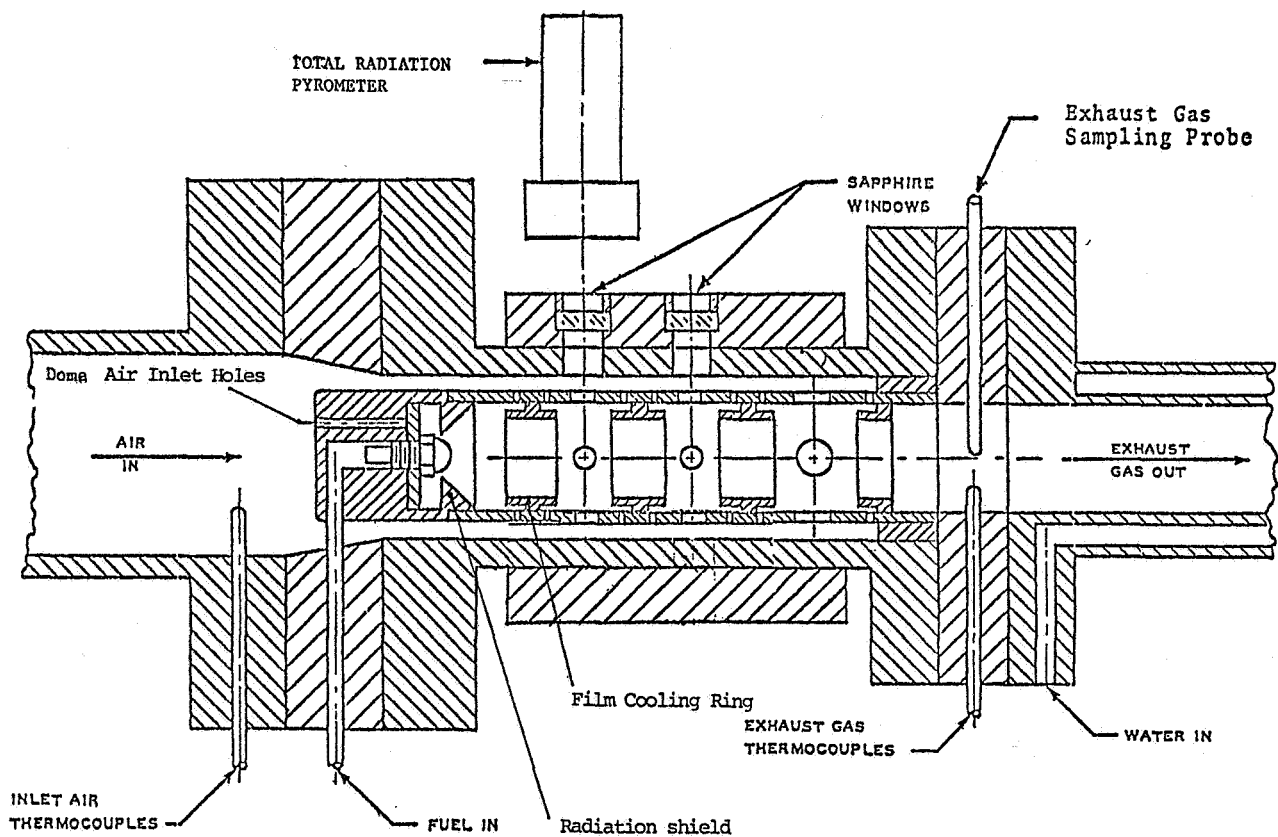
The purpose of this study is to indicate under what conditions and to what extent fuel variations at the same hydrogen content will affect soot formation in a gas turbine combustor. Six fuels were burned in a research combustor over a matrix of about 50 test conditions with test conditions ranging over 500-1800 kPa (5-18 atm) pressure and 500-1000 K burner inlet temperature; fuel-air ratios were varied from 0.008-0.024. Flame radiation measurements were made through a sapphire window toward the end of the primary zone. The hydrogen content of the six test fuels ranged from 12.80 to 12.88%. Five fuels emphasized different hydrocarbon types: aromatics (mono-, di-, and tri-cyclic), naphthenes (decalin) and partially hydrogenated aromatics (tetralin); the sixth fuel emphasized final boiling point.

Because of the large number of operating conditions, the data presentation has been simplified by first normalizing the flame radiation to that of a low aromatic Jet-A fuel at the same operating condition. This showed a consistent trend among the fuels that those with the unsaturated polycyclic ring compounds produced higher flame radiation. The results for each fuel were then averaged over all the operating conditions to produce a "radiation-index-R" for each fuel. Correlations were then made between this index and various fuel properties. The correlation with the smoke points of the fuels was surprisingly good, $r^2 = 0.94$; while aromatic content and total aromatic-ring carbon were poor correlating parameters, $r^2 = 0.49$ and 0.64 respectively; and obviously hydrogen content would not be good since all fuels had essentially the same hydrogen content.

*This work was supported by the Fuels Technology Branch of NASA Lewis Research Center, Cleveland, Ohio.

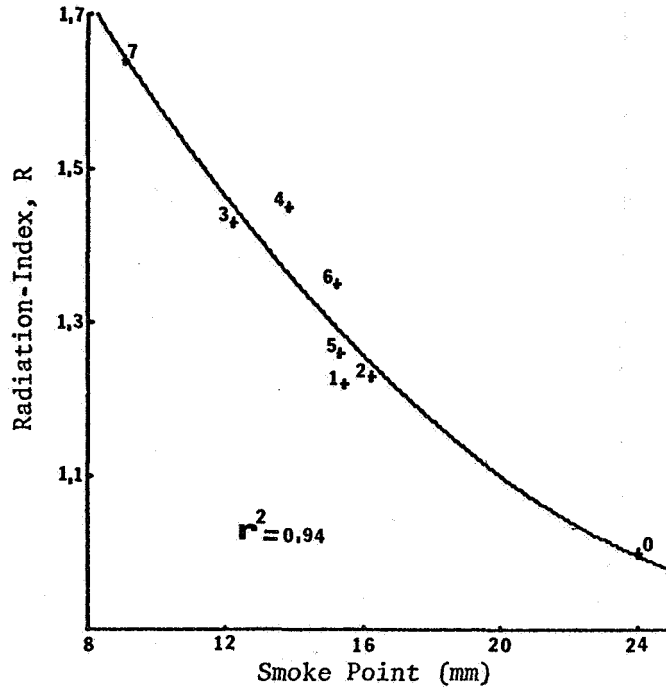
Fuels 1 and 2 with alkyl-benzenes and decalin had essentially the same flame radiation, confirming a hydrogen correlation in agreement with earlier work. The fuels with naphthalenes, tetralin, and anthracene produced higher radiation levels. For the fuels with naphthalenes and anthracene this increase in radiation above the hydrogen correlation, ΔR , correlated well with the percent of carbon that was tied up in the polycyclic aromatic rings. The fuel with tetralin produced radiation somewhere in between that of naphthalene and decalin, which is not surprising since its structure contains one saturated and one unsaturated ring.

The presence of about 20% polycyclic ring carbon is equivalent to a reduction in hydrogen content of a little over 1%. The sensitivity of flame radiation to the polycyclic aromatic contribution decreased as burner inlet pressure and as fuel/air ratio increased; inlet air temperature had no apparent effect.

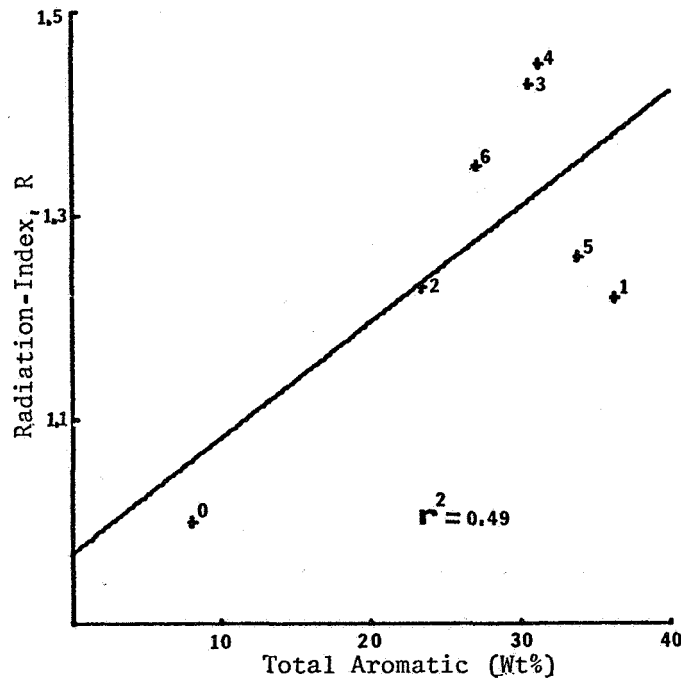


PHILLIPS 2 - INCH COMBUSTOR

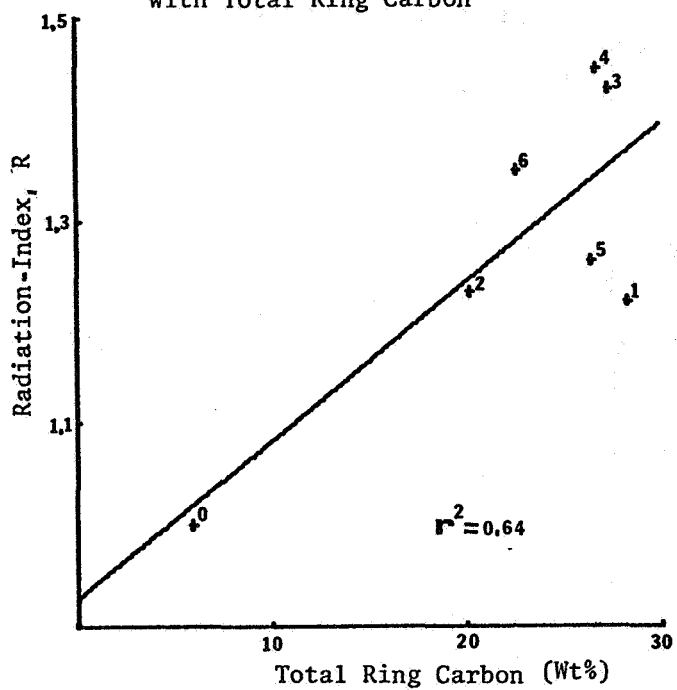
Correlation of Radiation Index with Smoke Point



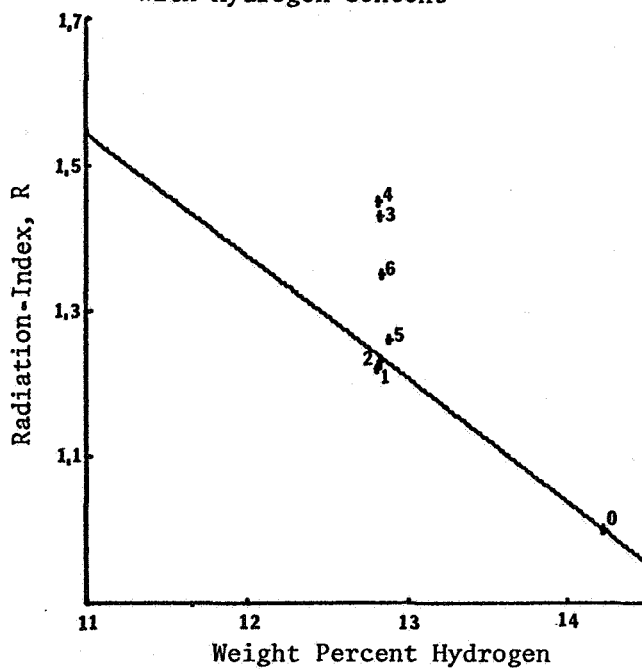
Correlation of Radiation-Index with Total Aromatics



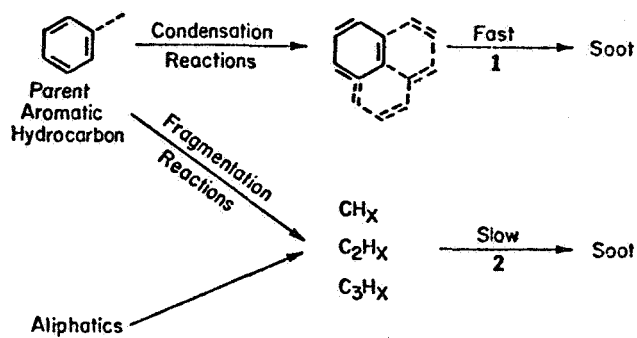
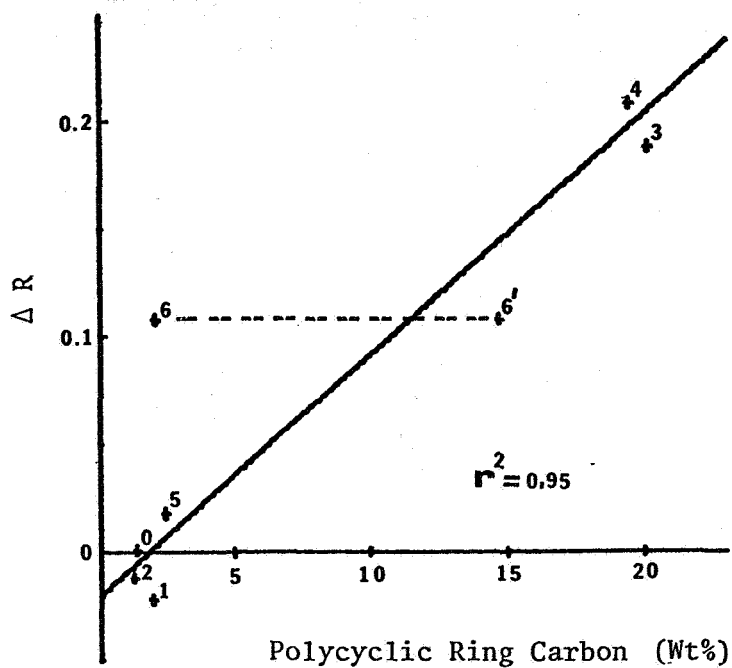
Correlation of Radiation-Index with Total Ring Carbon



Correlation of Radiation-Index With Hydrogen Content



Correlation of the Deviation (ΔR) in Radiation-Index From Hydrogen-Content-Correlation With Polycyclic Ring Carbon



- TYPICAL SYNCRUDE AROMATICS

alkyl-naphthalenes



tetralins



- TYPICAL PETROLEUM AROMATICS

alkyl-benzenes



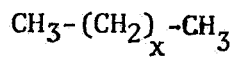
- TYPICAL SYNCRUDE SATURATES

naphthenes

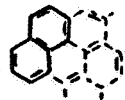


- TYPICAL PETROLEUM SATURATES

paraffins

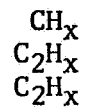


Condensation
Reactions



Fast
1 → Soot

Fragmentation
Reactions



Slow
2 → Soot

PRELIMINARY STUDIES OF COMBUSTOR SENSITIVITY
TO ALTERNATIVE FUELS

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National Aeronautics and Space Administration
Lewis Research Center

The Lewis Research Center has several in-house research programs under way to study combustion problems associated with using alternative fuels for ground power and aeropropulsion applications. The programs, which currently include individual combustor tests of tubular combustion chambers and basic flame-tube studies, will eventually include testing of rectangular sections designed to simulate large annular combustor test conditions. These programs are intended to study the effects of using alternative fuels with reduced hydrogen content, increased aromatic content, and a broad variation in fuel property characteristics. Data of special interest include flame radiation characteristics in the various combustor zones, the corresponding increase in liner temperature from increased radiant heat flux, the effect of fuel-bound nitrogen on oxides of nitrogen (NO_x) emissions, and the overall total effect of fuel variations on exhaust emissions. These data are applicable to aeropropulsion broadened-property fuels technology programs and joint NASA/Department of Energy stationary-power gas turbine programs. The in-house fuels combustion programs are described in table I. The NASA facilities used for these programs are a moderate-flow facility for high-pressure studies of tubular and simulated annular combustor sections and a limited-flow facility for basic low-pressure, flame-tube experiments.

The tubular combustor experiments were conducted with several test fuels in order to study basic alternative fuel effects by comparing the combustor sensitivity with fuel variations and with configuration modifications. A schematic of the tubular combustor test section is shown in figure 1. The test combustors were stock commercial aircraft units designated as models A and B and were obtained in 1974 and 1978, respectively. These models differed slightly in primary-zone stoichiometry and in provisions for liner cooling. The variation in average liner temperatures with increase in fuel-air ratio is shown in figure 2; the variation in SAE smoke numbers with increase in fuel-air ratio is shown in figure 3.

Data from these tubular combustor experiments have demonstrated the following characteristics:

- (1) Average liner temperatures rise substantially with increases in fuel-air ratio.
- (2) Combustor design modifications can significantly reduce average liner temperatures.
- (3) The increase in average liner temperature due to reduced fuel hydrogen content appears to be independent of the combustor design modification.

(4) An apparent design trade-off produced a decrease in average liner temperature while causing an increase in smoke emission.

Supplemental performance data for tubular combustor model A are contained in reference 1.

Flame radiation studies were conducted with tubular combustor model B. The assembly of the combustor housing with provisions for monitoring radiant heat flux is shown in figures 4 and 5. The variation of radiant heat flux with increase in combustor pressure is shown in figure 6.

Data from tubular combustor flame radiation studies have demonstrated the following characteristics:

- (1) Radiant heat flux increases with rising combustor pressure and with reductions in fuel hydrogen content.
- (2) The differential increase in radiant heat flux with combustor pressure diminishes with rising combustor pressure.
- (3) Average liner temperatures are relatively insensitive to increases in combustor pressure.
- (4) The differential increase in average liner temperature with reductions in fuel hydrogen content diminishes with rising combustor pressure.

Supplemental spectral flame radiation data obtained with tubular combustor model B are contained in reference 2.

Studies of the conversion of fuel-bound nitrogen to NO_x emissions were conducted with a basic two-stage flame-tube combustor test section. A schematic of the test facility used for low-pressure flame-tube experiments is shown in figure 7. Gaseous propane mixed with toluene and/or pyridine was used to get various nitrogen concentrations and hydrogen-carbon ratios. The variation of percent conversion of fuel-bound nitrogen with increase in primary equivalence ratio is shown in figure 8.

Data from the flame-tube experiments have demonstrated the following characteristics:

- (1) Rich-lean two-stage combustion is successful in reducing the conversion of fuel-bound nitrogen to NO_x .
- (2) Optimum primary equivalence ratios are roughly 1.4 to 1.7 for fuels ranging from 9 to 18.3 percent hydrogen content.
- (3) The optimum secondary equivalence ratio is about 0.5.

Supplemental data and more detailed discussion of the results from the flame-tube experiments are contained in reference 3.

REFERENCES

1. Butze, Helmut F.; and Humenik, Francis M.: Parametric Performance of a Turbojet Engine Combustor Using Jet A and a Diesel Fuel. NASA TM-79089, 1979.
2. Claus, Russell W.: Spectral Flame Radiance from a Tubular Can Combustor. NASA TP-1722, 1980.
3. Schultz, Donald F.; and Wolfbrandt, Gary: Flame Tube Parametric Studies for Control of Fuel Bound Nitrogen Using Rich-Lean Two-Stage Combustion. DOE/NASA/2593-80/15; NASA TM-81472, Apr. 1980.

TABLE I. - LEWIS IN-HOUSE PROGRAMS TO STUDY COMBUSTION PROBLEMS ASSOCIATED WITH USE OF ALTERNATIVE FUELS

PROGRAM TITLE	COMBUSTOR TYPES	FUELS (% H)
COMBUSTOR EXPERIMENTS WITH ALTERNATIVE FUELS	TUBULAR CONVENTIONAL ADVANCED SUB-COMPONENTS ANNULAR SECTION	JET A (13, 9) TEST FUELS (11,0-15,3)
FLAME RADIATION STUDY	SAME AS ABOVE	JET A (13, 9) TEST FUEL (12, 9)
GAS TURBINE STATIONARY POWER COMBUSTION-(CRT) (NASA/DOE)	TWO-STAGE FLAME TUBE	SRC II (8, 8, 11, 6) PROPANE-TOLUENE-PYRIDINE (9, 0, 11,3, 13,6, 15,7)
	TUBULAR	NO. 2 DIESEL (13,5) NO. 4 HEATING OIL (11,9)

CS-80-1555

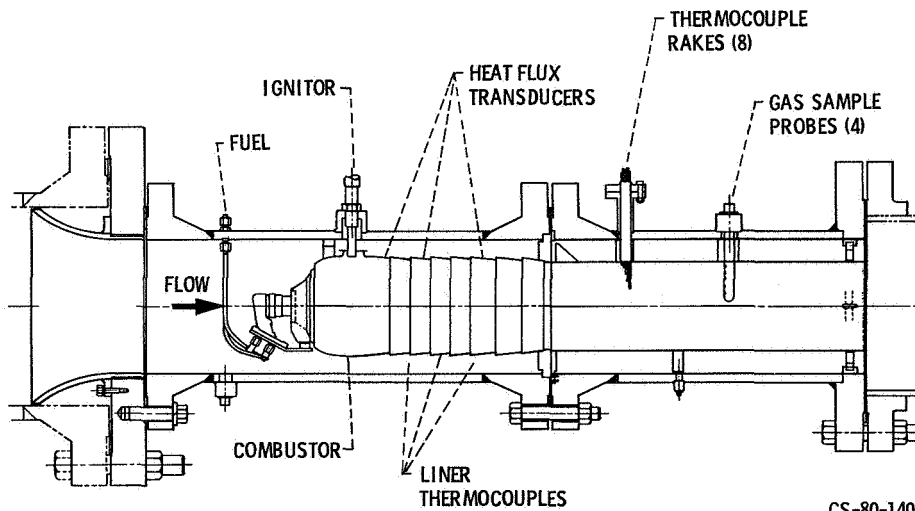
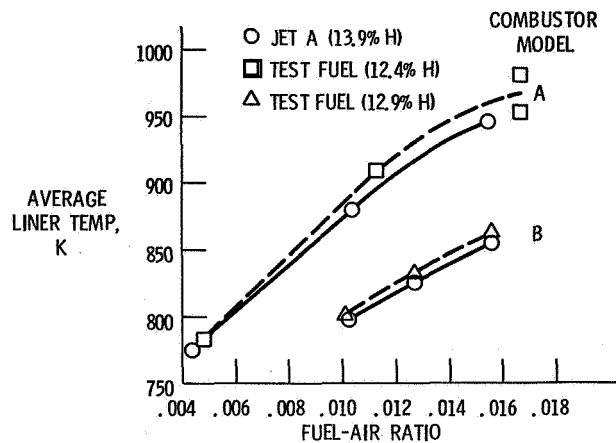
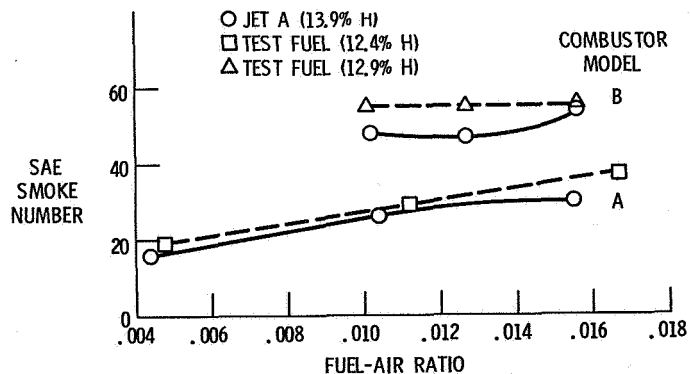


Figure 1. - Schematic of tubular combustor installation. Nominal flow capabilities of test facility: in let pressure, 25 atm; in let air temperature, 870 K; in let airflow rate, 10 kg/sec.



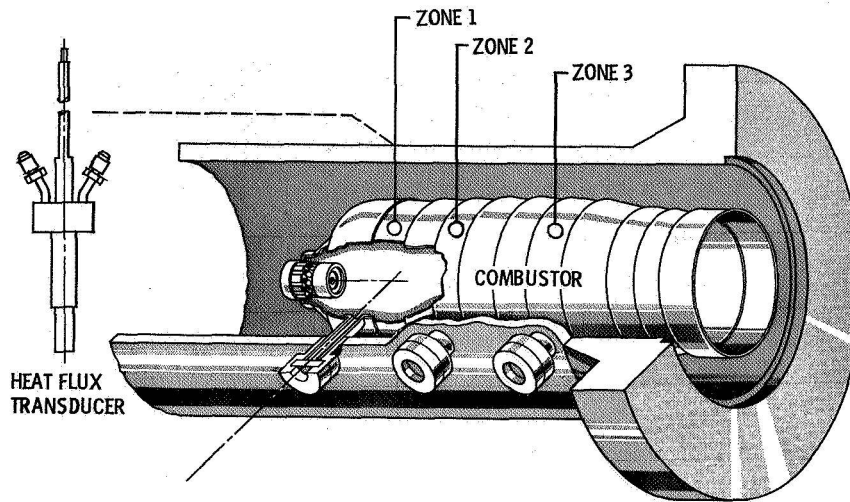
CS-80-1554

Figure 2. - Variation of average liner temperatures with fuel-air ratio for tubular combustor models A and B using Jet A and using test fuels with reduced hydrogen content. Nominal test conditions: inlet air temperature, 700 K; inlet air pressure, 170 N/cm²; reference velocity, 15.1 m/sec.



CS-80-1552

Figure 3. - Variation of SAE smoke number with fuel-air ratio for tubular combustor models A and B using Jet A and using test fuels with reduced hydrogen content. Nominal test conditions: inlet air temperature, 700 K; inlet air pressure, 170 N/cm²; and reference velocity, 15.1 m/sec.



CS-80-1403

Figure 4. - Assembly of tubular combustor for flame radiation studies. Radiant heat flux transducers installed in zones 1, 2, and 3 were thermopile type with water cooling and nitrogen purge.

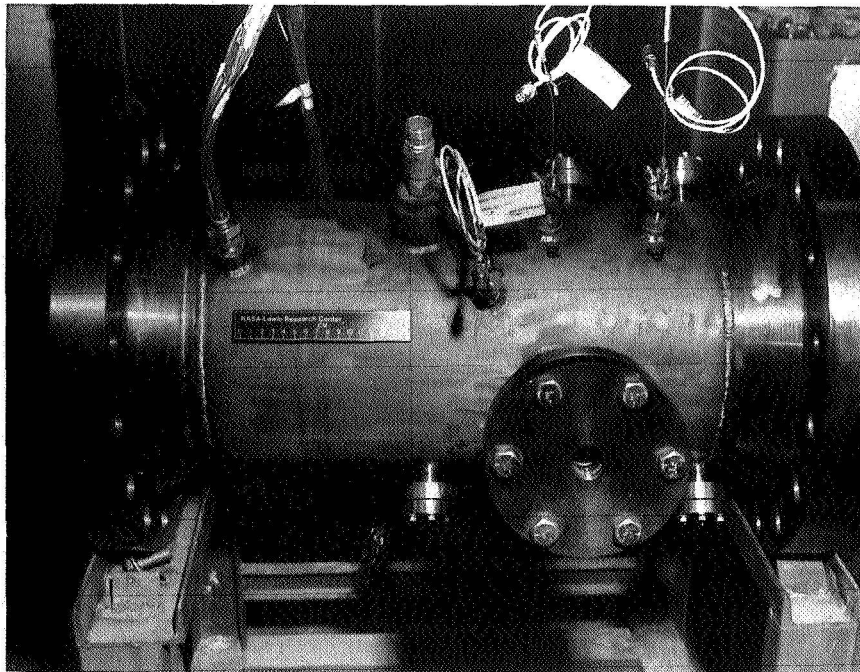
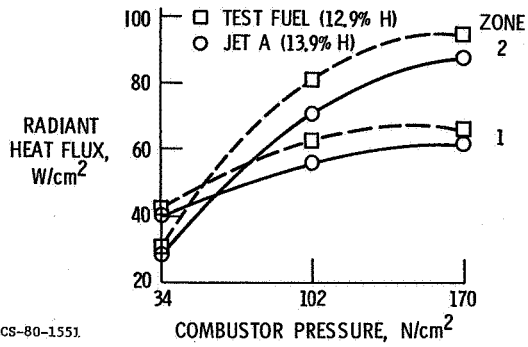


Figure 5. - Installation of radiant heat flux transducers.

CS-80-1556



CS-80-1551

Figure 6. - Variation of radiant heat flux with increase in combustor pressure. Nominal test conditions; inlet air temperature, 700 K; fuel-air ratio, 0.0155; and reference velocity, 15.1 m/sec.

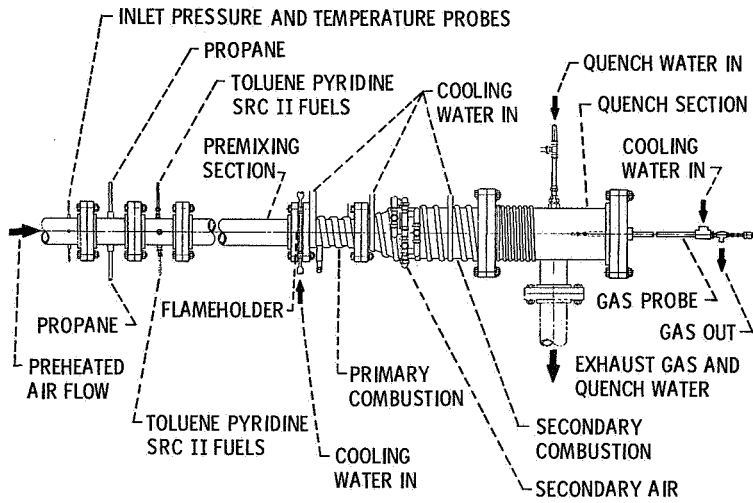
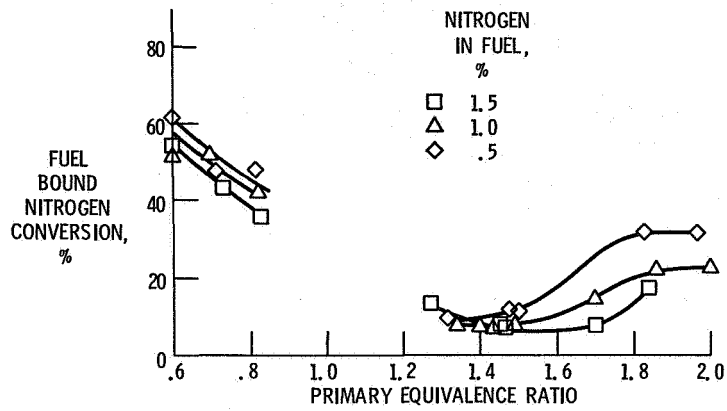


Figure 7. - Schematic of two-stage flame-tube test section. Nominal test facility capabilities; inlet pressure, 6 atm; inlet air temperature, 700 K; and inlet airflow rate, 1.4 kg/sec.



CS-80-1553

Figure 8. - Variation of conversion of fuel-bound nitrogen with increase in primary equivalence ratio. Nominal test conditions: inlet air temperature, 672 K; inlet pressure, 48 N/cm². Secondary equivalence ratio was optimized at about 0.5. Test fuel was a mixture of propane, toluene, and pyridine to get 9.0 percent fuel hydrogen content and 0.5, 1.0, and 1.5 percent nitrogen in the fuel.

FUELS RESEARCH - FUEL THERMAL STABILITY OVERVIEW

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National Aeronautics and Space Administration
Lewis Research Center

It has become apparent that the world supply of petroleum crude is a limited resource and that alternative fuels or crude supplies must be examined as a means of ensuring an adequate supply of aviation fuel for the next 50 years or more. Several changes that may be expected include refinery processing of higher boiling-point crude fractions to increase the yield of mid-distillate fuels, relaxing current jet fuel specifications to increase yield, and incorporating alternative crude sources such as shale oil or coal oil into refinery feedstocks. These approaches are not necessarily mutually exclusive and, in fact, would likely be used in combination to alleviate fuel availability problems.

One potentially detrimental effect that must be considered in any of these approaches concerns the chemical instability of the jet fuel product. The term instability refers to chemical alteration or degradation of the fuel that may occur as a result of thermal stress (thermal instability) or during long-term storage (storage instability). The problem manifests itself as sediment in storage tanks or filters, fouling of heat-exchanger surfaces, or undesirable deposits in fuel manifolds or combustor spray nozzles.

Thermal instability was first identified as a problem in aviation turbine engines in the 1950's, but the development of the SST in the 1960's focused much more attention on it. In the SST, the fuel serves as a heat sink for the wing surfaces, which are aerodynamically heated, and as a result the fuel is susceptible to thermal degradation.

In subsonic aircraft, aerodynamic heating is not a problem and fuel tank temperatures are much lower than those in supersonic aircraft. However, in the subsonic aircraft fuel system, high fuel temperatures are encountered in the lubricating-oil heat exchanger (where the fuel is used to cool the engine lubricant) and in the combustor fuel manifold and nozzles. Thermal instability can result in deposits fouling heat-exchanger surfaces, which can decrease heat transfer, and in deposits in spray nozzles causing nonuniformities in spray patterns, which could reduce hot-section-component durability. The current trend toward higher cycle-pressure-ratio engines with higher combustor inlet temperatures tends to aggravate stability problems, as do more sophisticated fuel injection systems with closer spray-nozzle tolerances and multiple injectors with lower pilot-fuel flow rates.

Much information has been obtained on the nature of the chemical processes associated with thermal instability. It is generally agreed that autoxidation, from oxygen in the fuel, is the primary mechanism in initiating deposit formation. The course of the reaction can be followed by moni-

toring the concentration of intermediates, such as the hydroperoxides. The chemistry of the reactions involved is usually free radical, and therefore any constituent that tends to form free radicals easily will probably be instrumental in degrading the fuel out of proportion to its concentration. Heterocompounds containing nitrogen, sulfur, or oxygen and trace metals, particularly copper, have been shown to be detrimental to stability. Although some aspects of the degradation process are understood, much information is still lacking. For example, beyond elemental analyses, little is known regarding the actual structure of the deposit. Also, the specific influence of the many possible nitrogen-containing compounds, singly or in combination, has only begun to be determined.

Shale and coal syncrudes are typically higher in one or more of the elements likely to promote deposition, and fuels derived from these feedstocks will probably exhibit degraded thermal stability without additional refinery processing. Future fuels derived from petroleum with potentially broadened properties may contain higher concentrations of olefins and aromatics, which can also degrade stability characteristics. Many of these factors will be significant in the use of broadened-property or synthetic fuels.

Several test methods have been developed for characterizing jet fuel thermal stability. Two test procedures currently in use for specifying aviation turbine fuels are the ASTM-CRC Fuel Coker and the Jet Fuel Thermal Oxidation Tester (JFTOT). Both of these methods pass the test fuel over a heated tube and then through a filter that traps any degradation products formed during the test. A qualitative assessment of the thermal stability of the fuel is provided by the extent of filter plugging as indicated by measuring the pressure drop across the test filter and by a visual evaluation of the amount of deposit on the heated tube. The simple pass-or-fail criterion provided by these tests is adequate for the present generation of relatively stable fuels, but a more quantitative measure of stability may be desirable in the future as fuels that may not have uniformly high quality become more common.

The objectives of NASA's thermal stability research are to determine the thermal stability characteristics of potential future fuels, to identify and examine the effects of these characteristics on aircraft fuel systems, and to evolve advanced fuel system technology and design guidelines for future fuels with lower thermal stability. Thermal stability considerations may affect fuel availability, total fuel-related systems cost, overall system energy consumption, engine performance and durability, and environmental considerations.

On November 1 and 2, 1978, Lewis hosted a workshop on jet fuel thermal stability in order to present a forum for discussing the various aspects of the thermal instability problem and to identify critical areas for focusing future efforts (ref. 1). Some of the conclusions of this workshop were as follows:

1. New laboratory techniques are not required, but improvements in existing test methods are needed.

2. End-use performance is not well correlated with laboratory test devices.
3. Trends in engine design indicate a more severe problem in the future.
4. There is a need for balance between concerns for thermal stability and emission controls, energy efficiency, durability, and cost.

The workshop also recommended the following areas for future work:

1. Perform more detailed characterization of deposits.
2. Examine effects of fuel composition.
3. Perform additional studies on the effects of metal surfaces, dissolved metals, additives, and interactions.
4. Obtain parametric data by using a generalized test apparatus that could relate laboratory screening tests to actual performance.
5. Study storage and aging effects.
6. Develop standard sampling and handling techniques.
7. Establish referee fuels.
8. Determine importance of non-free-radical reactions.
9. Conduct survey to determine stability at delivery point.

The first five recommendations for future work are presently being actively pursued under NASA sponsorship. A contractual effort on the chemistry of fuel deposits and precursors is presently in the planning stages. The results of two contracted activities are given in two papers, the first by Dr. Alexander Vranos of UTRC, on an experimental study of thermal stability, and the second by Dr. Stephen R. Daniel of the Colorado School of Mines, on the effects of nitrogen compounds on stability. In addition, Mr. C. J. Nowack of the Naval Air Propulsion Center will bring us up to date on part of the Navy's activities.

A number of research projects are being conducted here at Lewis. Mr. Edgar L. Wong is studying the chemistry of fuel thermal deposits by using a modified JFTOT and pure compounds. Dr. Albert C. Antoine is examining the effects of nitrogen compounds on thermal stability by doping jet fuels. Under the characterization of fuel thermal stability are two related efforts. The first is a parametric study over a wide range of conditions using a test facility capable of determining the effect of many variables. Besides evaluating future fuels this apparatus will (1) aid in relating laboratory-scale tests to full-scale experience, (2) help in determining the potential of accelerated testing, and (3) provide data on the mechanisms underlying the deposition process. The second part of the characterization effort is aimed at developing and improving techniques for examining the products of degradation so as to learn as much as possible from every sample and every test.

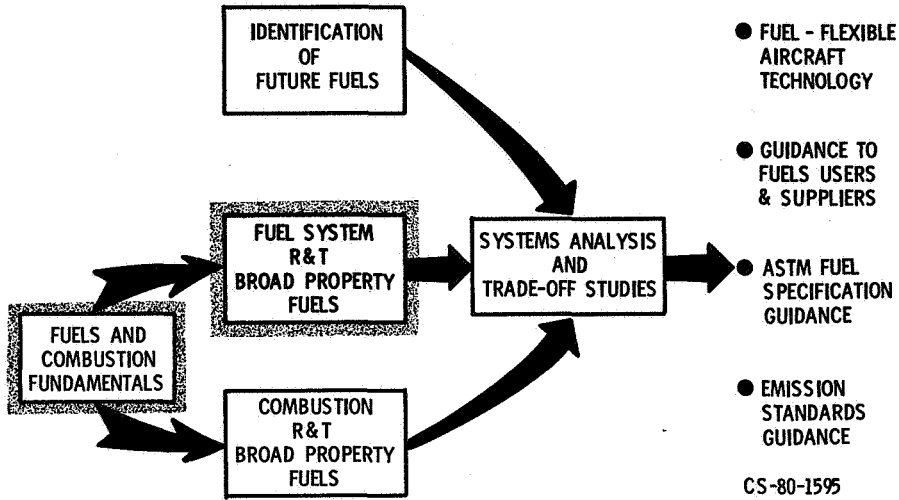
As a part of these efforts a special test section was designed and built for use with the standard JFTOT. In this apparatus deposits are formed on a flat specimen rather than on a tube. With this geometry a number of analytical tools can be used for deposit analyses. This apparatus will be used for making samples to aid in developing diagnostic techniques and also as a screening device for the parametric test facility.

Because of a crowded schedule there was not sufficient time at the symposium to present the work of all the organizations involved in thermal stability research. In addition to those organizations represented here, there is a considerable body of work being supported by the Naval Research Laboratory, the Air Force Aero Propulsion Laboratory, the Army Fuels and Lubricants Research Laboratory, and the DOE Bartlesville Energy Technology Center.

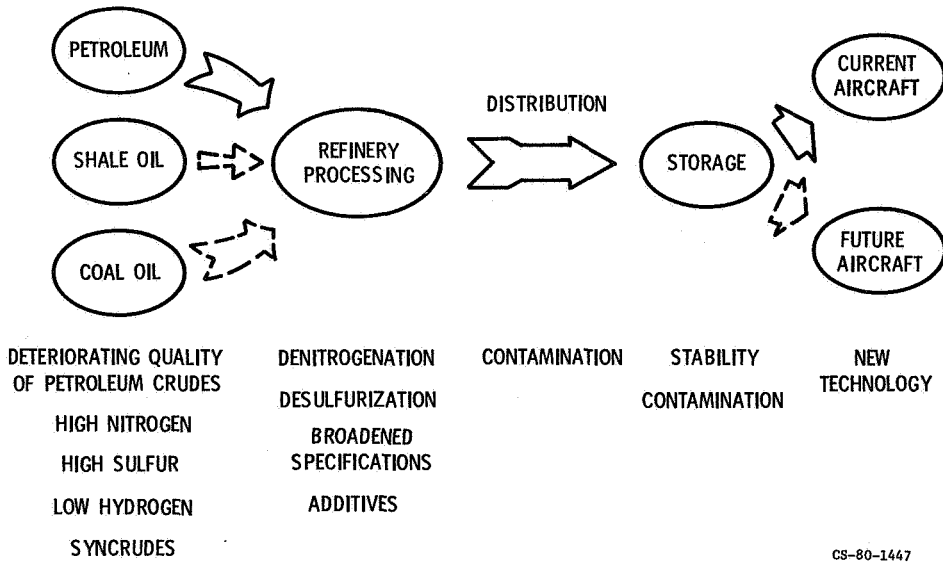
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1. Taylor, William F., ed.: Jet Fuel Thermal Stability. NASA TM-79231, 1979.

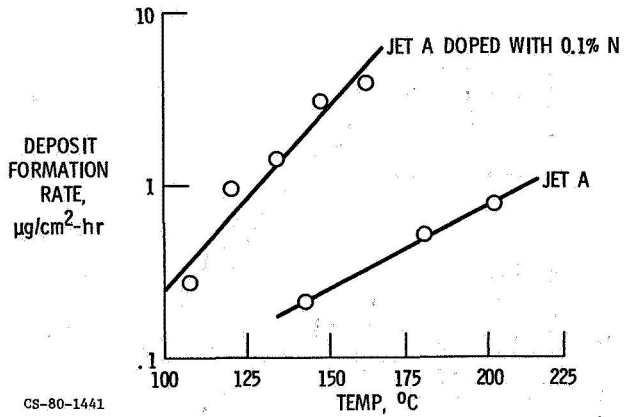
AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS



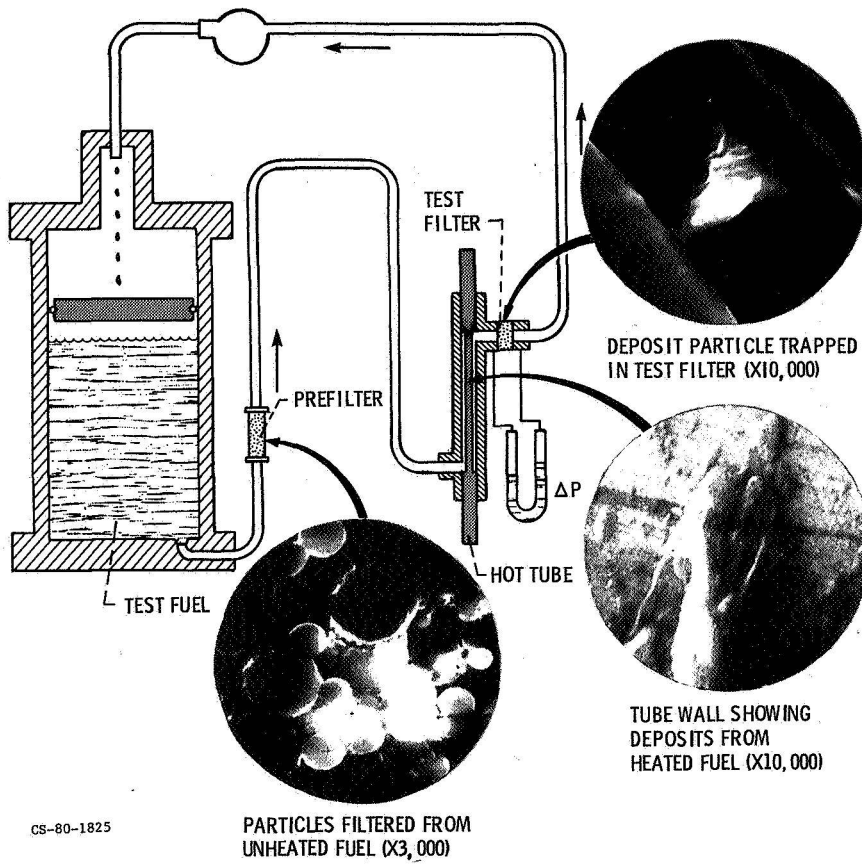
THERMAL STABILITY CONSIDERATIONS



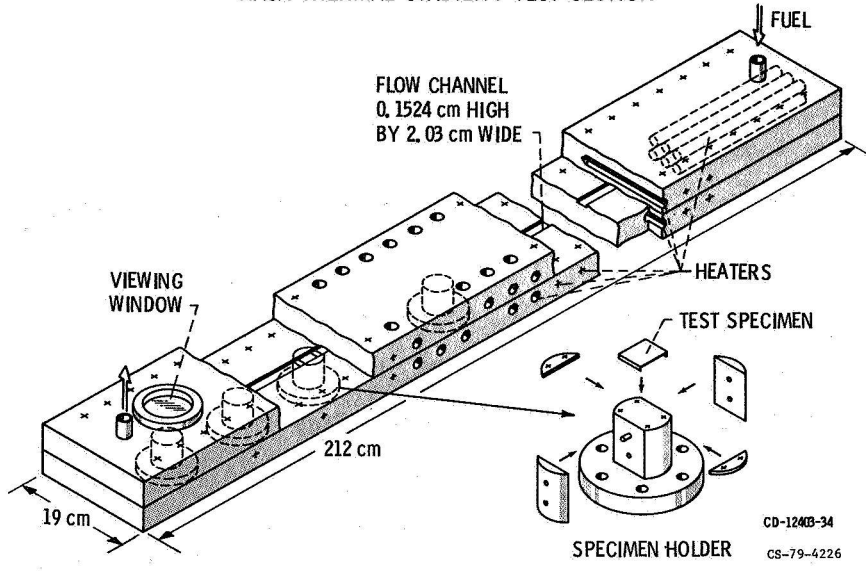
EFFECT OF FUEL NITROGEN CONTENT ON THERMAL STABILITY



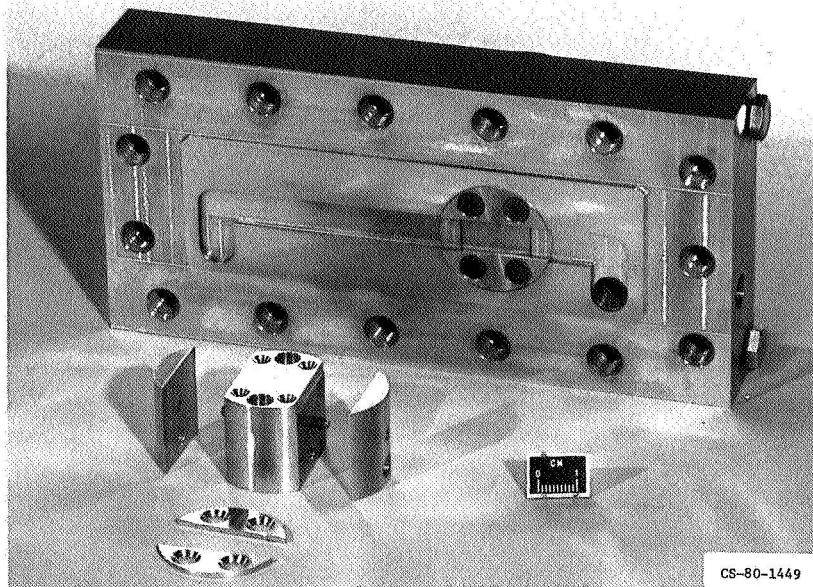
JET FUEL THERMAL OXIDATION TESTER (JFTOT) SCHEMATIC



NASA THERMAL STABILITY TEST SECTION



FLAT SAMPLE HOLDER FOR JFTOT



SOME ANALYTICAL TECHNIQUES FOR THERMAL STABILITY TESTS

TECHNIQUE	INFORMATION TO BE OBTAINED
GAS CHROMATOGRAPHY/ LIQUID CHROMATOGRAPHY	FUEL COMPOSITION, PRIOR TO AND FOLLOWING TEST
POLAROGRAPHIC SENSOR	MONITOR TOTAL DISSOLVED O ₂ IN FUEL
MICROBALANCE	WEIGHT OF DEPOSITS AND PARTICULATES
SCANNING ELECTRON MICROSCOPY	MORPHOLOGY OF DEPOSIT AND PARTICULATES
ATOMIC SPECTROSCOPY ELEMENTAL ANALYSIS	TRACE METALS IN FUEL COMPOSITION OF DEPOSITS AND PARTICULATES
ELECTRON SPECTROSCOPY FOR CHEMICAL ANALYSIS (ESCA)	COMPOSITION AND STRUCTURE OF DEPOSITS AND PARTICULATES
FOURIER TRANSFORM INFRARED (FT-IR)	STRUCTURE OF DEPOSITS AND PARTICULATES
PHOTOACOUSTIC SPECTROSCOPY (PAS)	DEPOSIT STRUCTURE, THERMAL DIFFUSIVITY, THICKNESS
WET METHODS (TITRATION)	MONITOR HYDROPEROXIDE FORMATION IN FUEL

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

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United Technologies Research Center

INTRODUCTION

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

TEST APPARATUS

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

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

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

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

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

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

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

RESULTS

Experiments with Jet A Fuel

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

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

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

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

No. 2 Oil Tests

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

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

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

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TABLE I
FUEL PROPERTIES

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

*Temporary waiver to 2.20

TABLE II
TEST VARIABLES

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

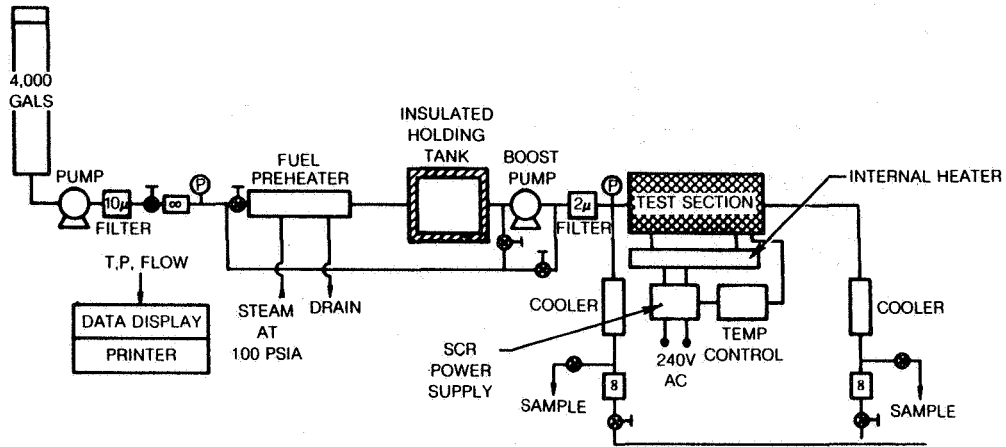


FIG. 1

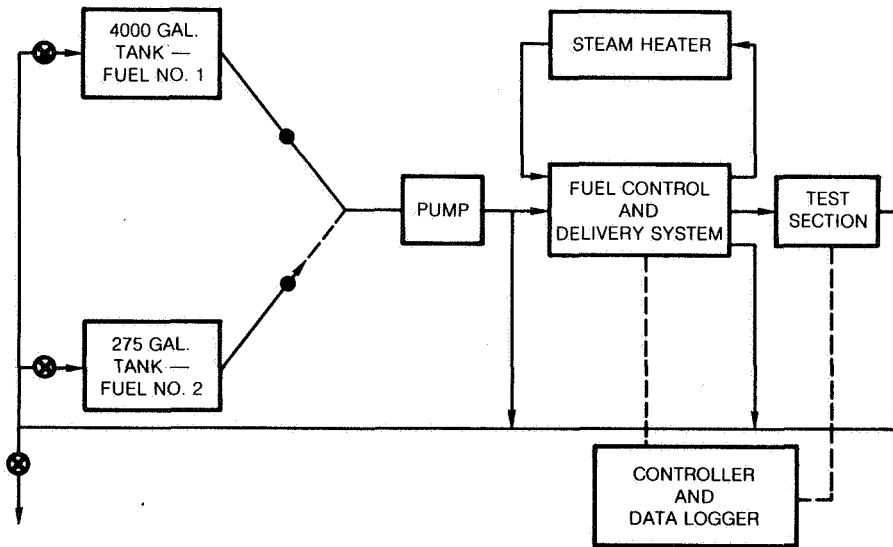


FIG. 2

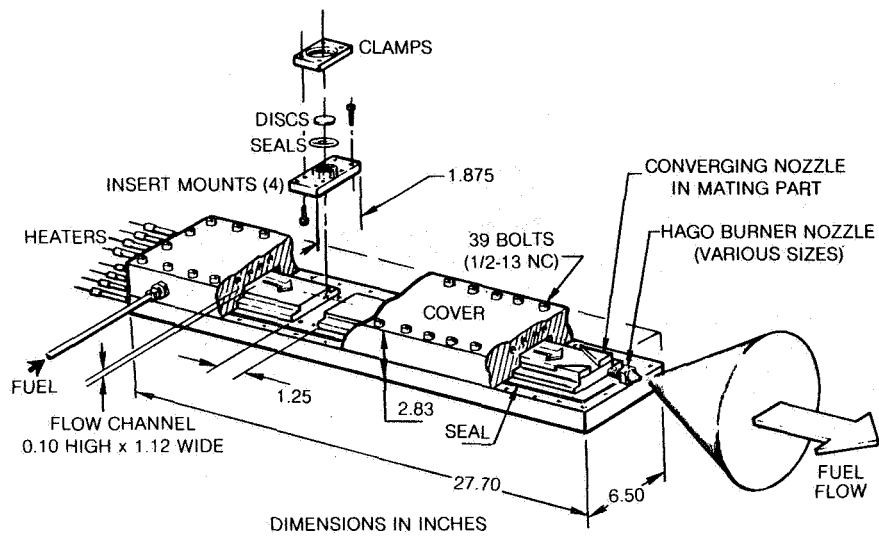


FIG. 3

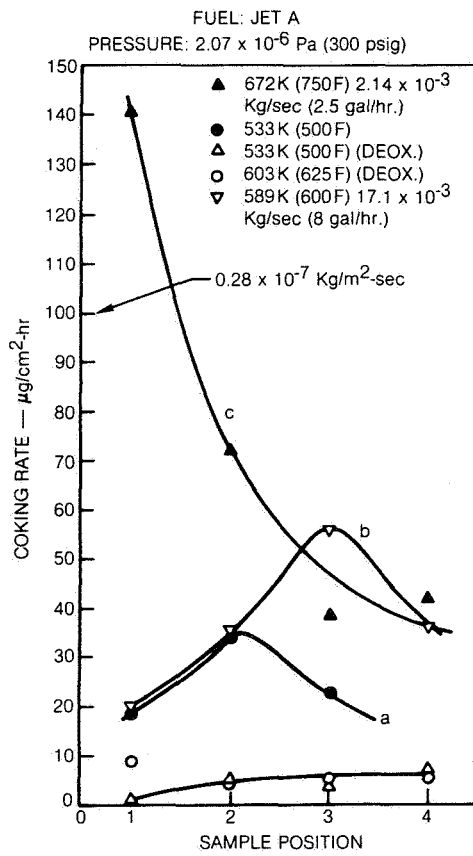


FIG. 4

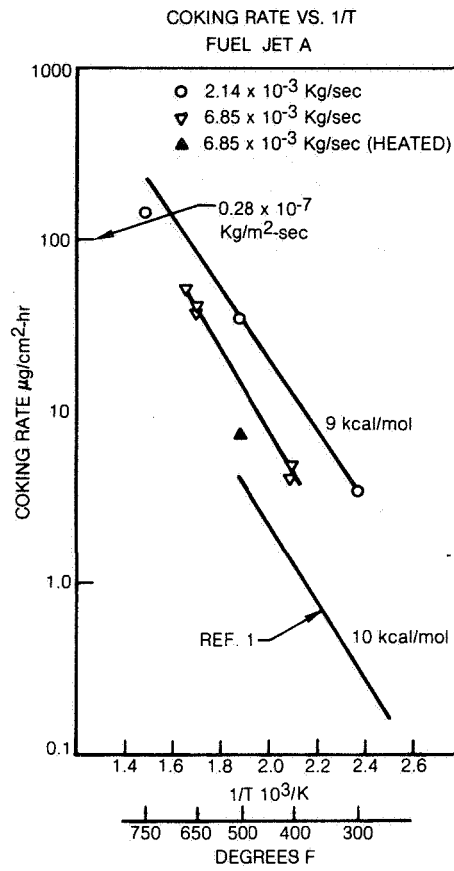


FIG. 5

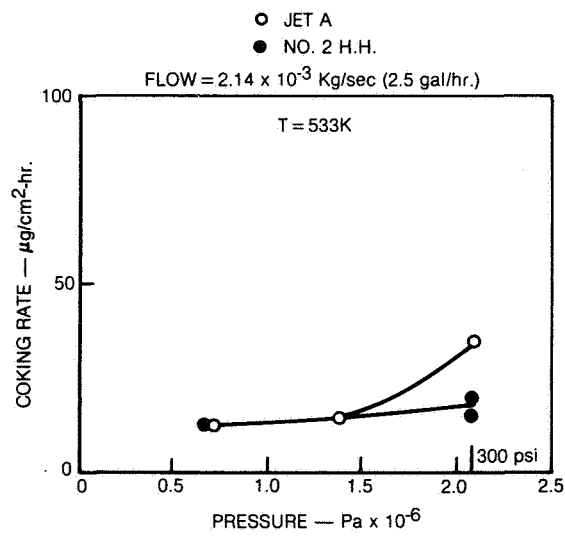


FIG. 6

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

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

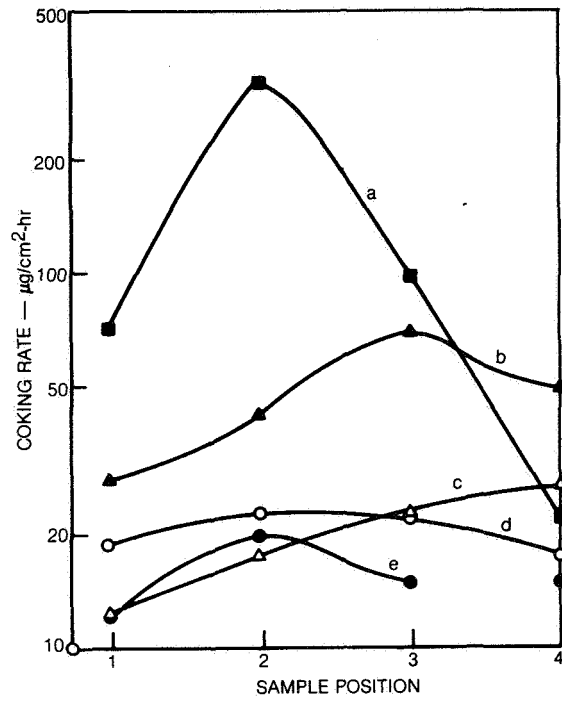


FIG. 7

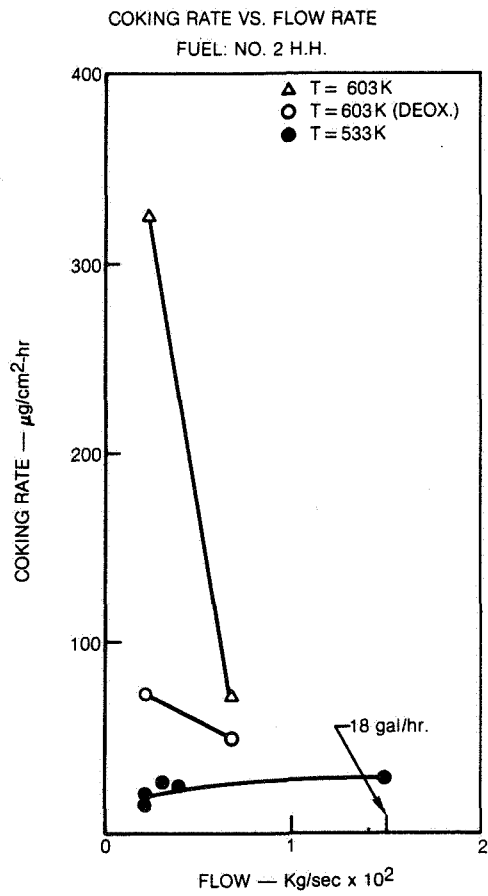


FIG. 8

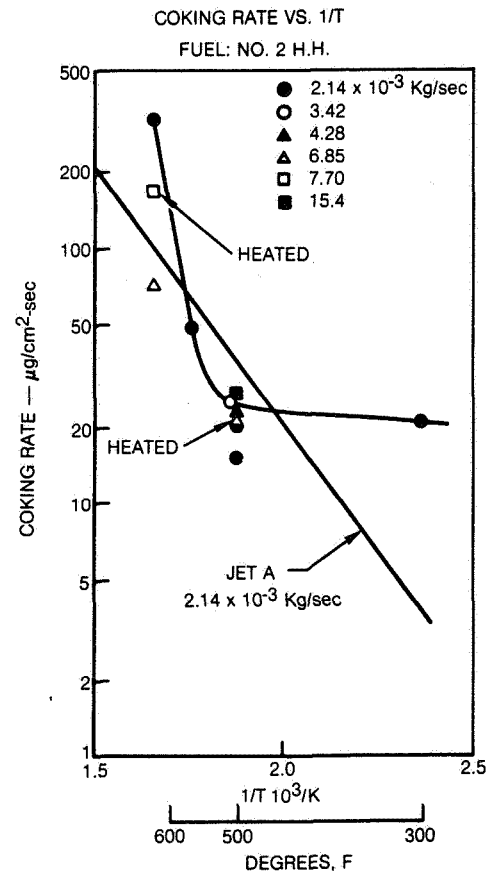


FIG. 9

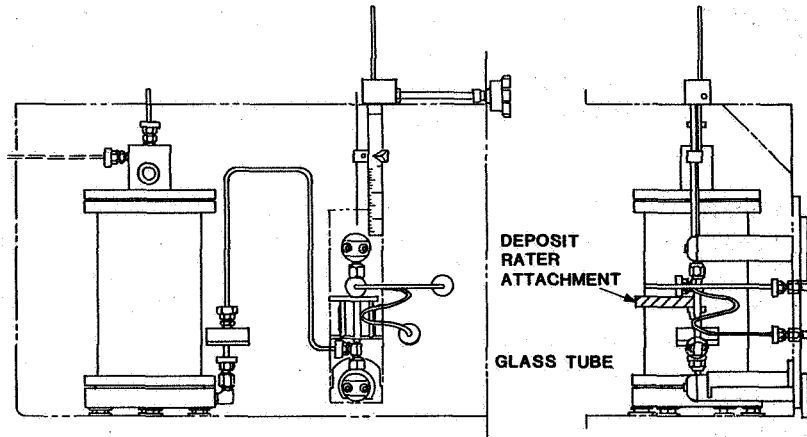
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DETERMINATION OF JET FUEL THERMAL DEPOSIT RATE USING A MODIFIED JFTOT

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Naval Air Propulsion Center

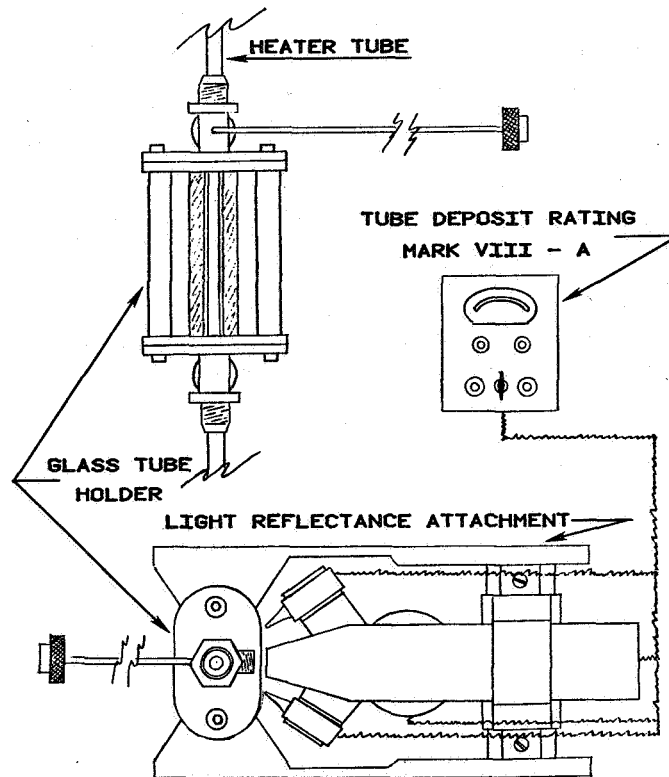
The current thermal oxidation stability limit for military and commercial aviation turbine fuels is a breakpoint temperature of no less than 260°C (500°F) as measured by the Alcor Jet Fuel Thermal Oxidation Tester (JFTOT). Today's engines are designed to tolerate a fuel with this stability limit, however, there are indications that fuel stability may be on the downtrend, which could affect future engines' performance. If future fuels are to have a lower stability, attempts must be made to provide a better definition of the breakpoint temperature in terms of a fuel performance parameter, for example, a deposit formation rate. In this study the JFTOT was modified with a glass tube enclosure of the heater test section and a light reflectance attachment, which permitted a direct measurement of deposit formation as a function of time.

Three fuels having different breakpoint temperatures were studied in the modified JFTOT. The lower stability fuel with a breakpoint of 240°C (465°F) was first stressed at a constant temperature. The cut-off point of the run is a deposit rating (TDR) of 12, as indicated by the Mark VIII, a light reflectance meter. After repeating this procedure at several different temperatures, an Arrhenius Plot was drawn from the data. The correlation coefficient and the energy of activation were calculated to be 0.97 and 8 kcal/mole respectively. Two other fuels having breakpoint temperatures of 271°C (520°F) and 285°C (545°F) were also studied in a similar manner. A straight line was drawn through the data at a slope equivalent to the slope of the lower stability fuel. The deposit formation rates for the three fuels were determined at 260°C (500°F), and a relative deposit formation rate at this temperature was calculated and plotted as a function of the individual fuel's breakpoint temperatures.

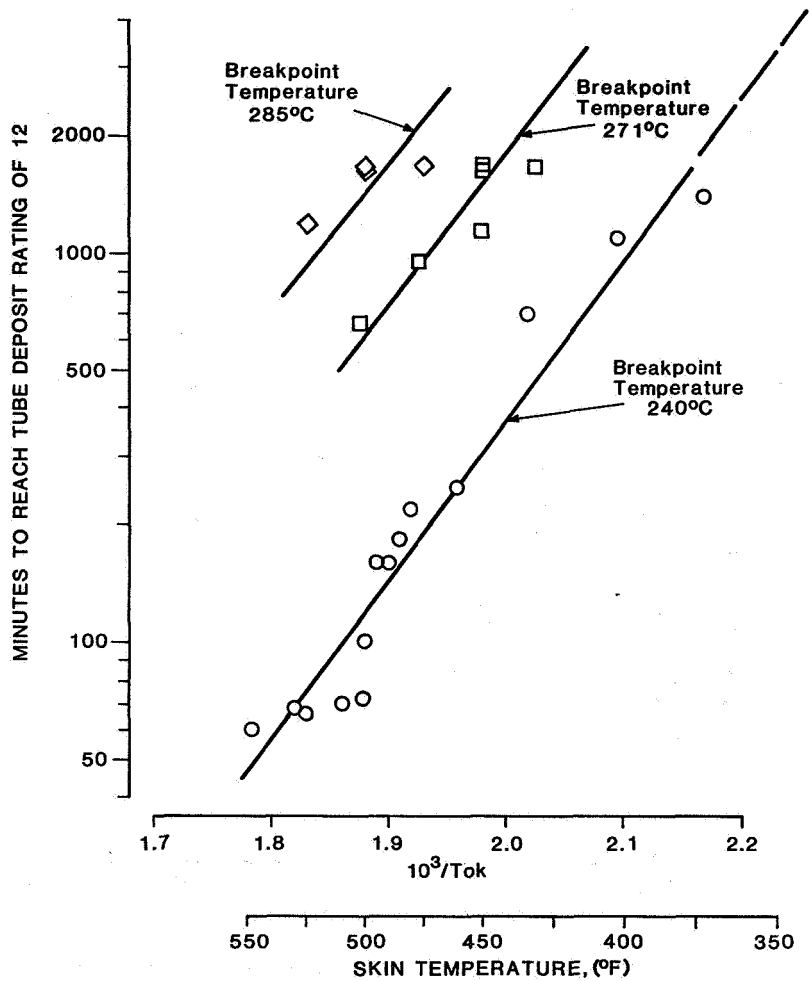


ALCOR JET FUEL THERMAL OXIDATION TESTER

NAPC



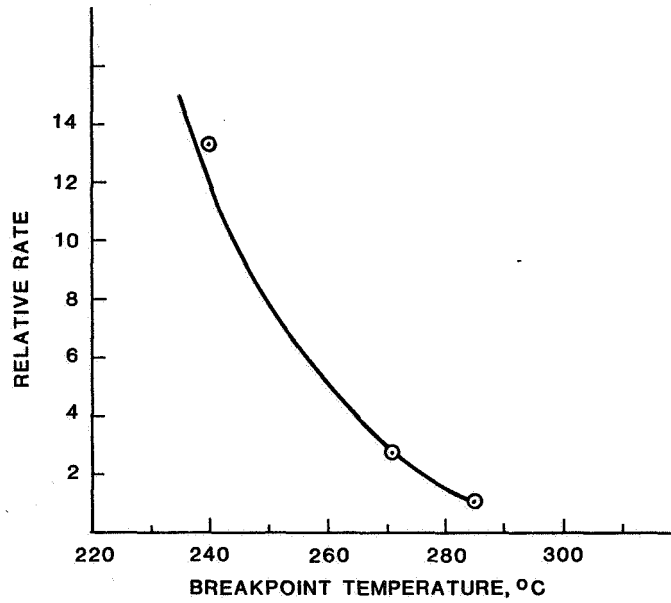
MODIFICATION OF THE ALCOR JFTOT



TIME (MINUTES) TO REACH TUBE DEPOSIT RATING OF 12
VS.
SKIN TEMPERATURE $10^3/T_{ok}$

<u>FUEL</u>	<u>BREAKPOINT TEMP. °C (°F)</u>	<u>TIME (Min) TDR 12 AT 260°C</u>	<u>RELATIVE DEPOSIT FORMATION RATE</u>
10% DFM/5P-5	240 (464)	120	13.33
JP-5	271 (520)	600	2.66
JP-5 (OIL SHALE)	285 (545)	1600	1.00

EXPERIMENTAL DATA



RELATIVE DEPOSIT FORMATION RATE AT 260°C
vs.
BREAKPOINT TEMPERATURE, °C

MECHANISMS OF NITROGEN HETEROCYCLE INFLUENCE ON TURBINE FUEL STABILITY*

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Colorado School of Mines

Lewis bases were extracted from a Utah COED syncrude via ligand exchange. Addition of this extract to Jet A at levels as low as 5 ppm N produced deterioration of stability in both JFTOT and accelerated storage tests (7 days at 394°K with 13:1 air to fuel ratio). Comparable effects on Jet A stability were obtained by addition of pyridine and quinoline, while pyrrole and indole were less detrimental at the same concentration level. These four compounds represent the compound classes predominant in the extract.

The weight of deposit produced in accelerated storage tests was found to be proportional to the concentration of added nitrogen compound. Over the narrow temperature range accessible with the experimental method, Arrhenius plots obtained by assuming specific rate to be proportional to the weight of material deposited in seven days exhibit greater slopes in the presence of those nitrogen compounds producing the greater deposition rates. Despite variation in appearance the elemental composition and spectral characteristics of the deposits are unaffected by addition of the nitrogen compounds. The linearity of the Arrhenius plots and of a plot of Arrhenius slope versus intercept for all the compounds suggests a constancy of mechanism over the range of temperature and heterocycles studied.

A suite of twenty-three nitrogen heterocycles representing a wide range of basicities and electronic and steric environments at the nitrogen atom was selected. Added to Jet A at the level of 5 ppm N, these compounds increased deposition rates in proportion to their basicities within a given compound class (pyridines, pyrroles, indoles, and quinolines). No general correlation with basicity between compound classes was found. Compounds in which the nitrogen atom is sterically hindered were found to be much less detrimental than expected on the basis of basicity. Analogous experiments were performed using a Diesel fuel. Although higher absolute deposition rates were obtained, the nitrogen compound effects were entirely parallel. Silica gel treatment greatly increased stability of the fuel, even in the presence of added heterocycles.

A model system composed of tetralin in dodecane was shown to exhibit behavior very similar to that observed for Jet A and Diesel fuels. Although the absolute deposition rate was significantly lower, nitrogen heterocycles produced increases in deposit formation in approximate proportion to their basicities. However, the rate of decrease in tetralin concentration was not significantly altered. Decomposition of tetralin hydroperoxide, the primary auto-oxidation product, markedly increased upon addition of quinoline. While tetralin hydroperoxide in dodecane produced deposits more rapidly than did tetralin itself, much greater deposition occurred when both tetralin hydroperoxide and tetralone (one of the decomposition products of the hydroperoxide) were

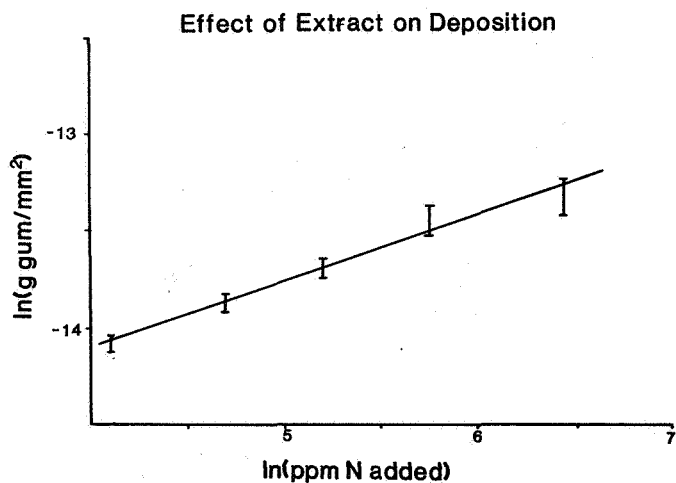
*NASA Grant NSG-3122.

present. These observations and that of base catalysis by the nitrogen heterocycles is consistent with the involvement of condensation reactions (perhaps between the hydroperoxide and the ketone) in the rate-controlling step of deposit formation in the model system. Multiple-internal-reflectance infrared spectra demonstrate the presence of carbonyl and hydroxyl groups in both model system and Jet A deposits.

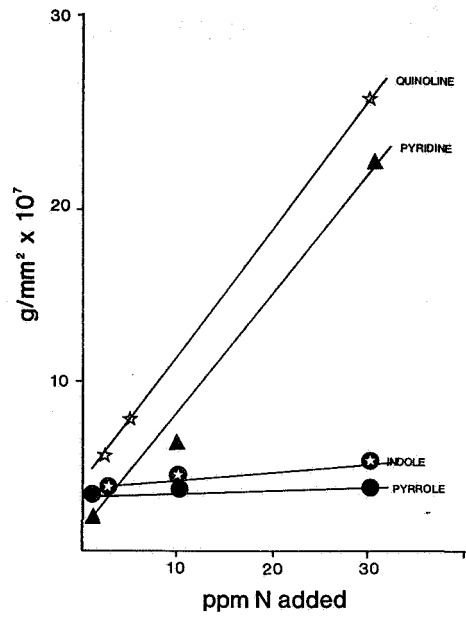
Elemental analyses, spectra, and chromatographic results all indicated remarkable similarities between the model system deposits and those obtained from Jet A. Parallelism in the mechanism of deposition is therefore inferred.

Deposit (168 hr, 120°C) from Spiked Jet A

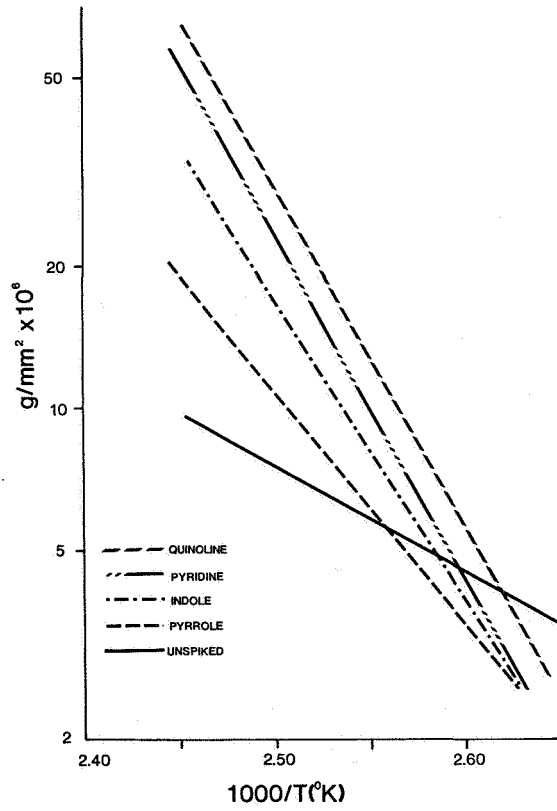
Spiking Compound	(g deposit/mm) x 10 ⁷	PKa
Control (no spike)	3.4 ± .3	--
Pyrrole	3.5 ± .5	-3.8
N-Methylpyrrole	8.7 ± .6	-2.90
2-Pyrrolidone	4.2 ± .8	--
1,2,5-Trimethylpyrrole	3.7 ± .3	- .24
Indole	3.9 ± .3	-2.4
N-Methylindole	3.6 ± .3	-1.80
2-Methylindole	5.9 ± .3	- .10
3-Methylindole	2.3 ± .5	-3.35
Indoline	6.7 ± .2	--
Carbazole	2.6 ± .3	--
N-Ethylcarbazole	4.4 ± .6	--
Pyridine	3.6 ± .3	5.22
2-Acetylpyridine	3.5 ± .5	--
2-Methylpyridine	7.9 ± .8	5.94
4-Methylpyridine	8.8 ± .5	6.03
2-Ethylpyridine	5.9 ± .3	5.93
2,6-Dimethylpyridine	10.0 ± 1.4	6.64
2,4,6-Trimethylpyridine	4.7 ± .2	7.43
Quinoline	7.7 ± .0	4.85
2,4-Dimethylquinoline	8.2 ± .7	5.12
7,8-Benzoquinoline	2.8 ± .5	4.3
4-Hydroxy-2-methylquinoline	9.1 ± .4	--
8-Hydroxyquinoline	8.1 ± .2	4.91



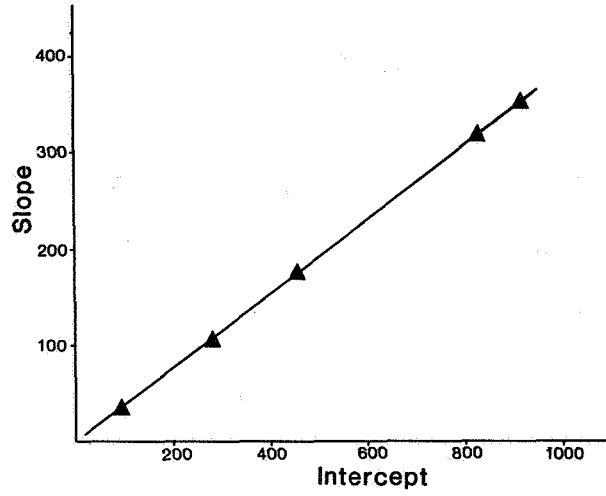
Effect of Added Nitrogen Concentration on Deposition Rate



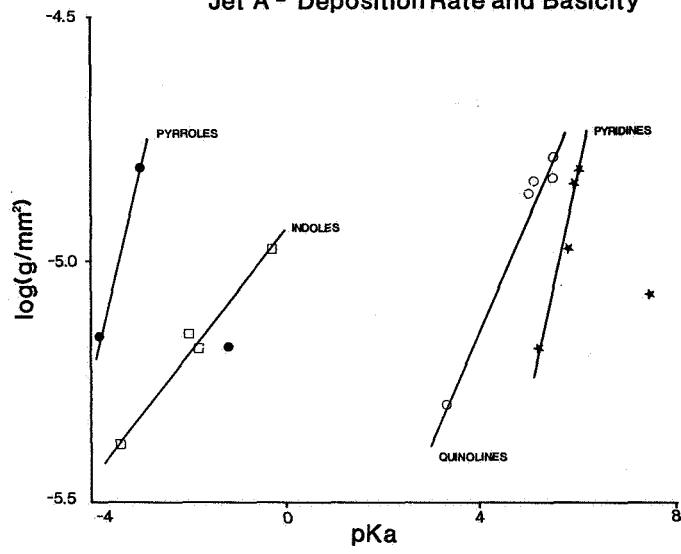
Temperature Dependence of Deposit Formation



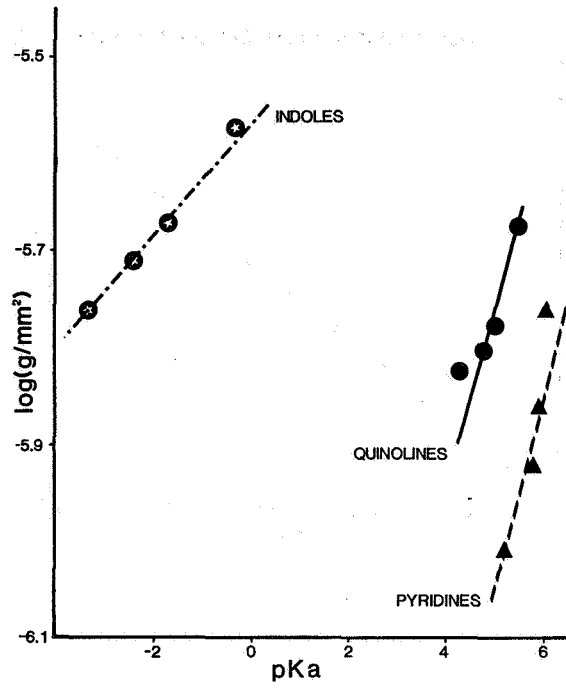
Arrhenius Slope/Intercept Relationship



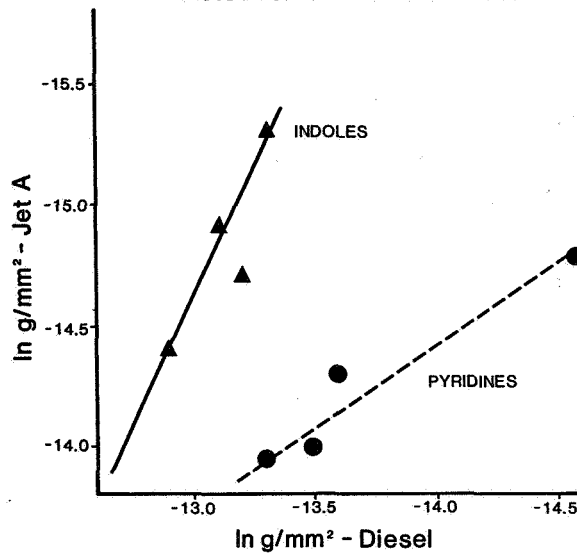
Jet A - Deposition Rate and Basicity



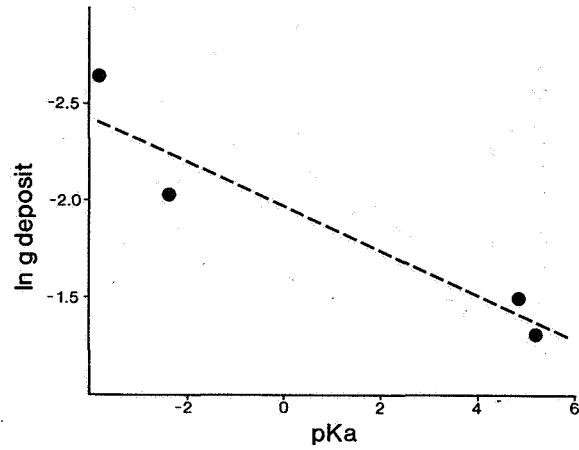
Diesel - Deposition Rate and Basicity



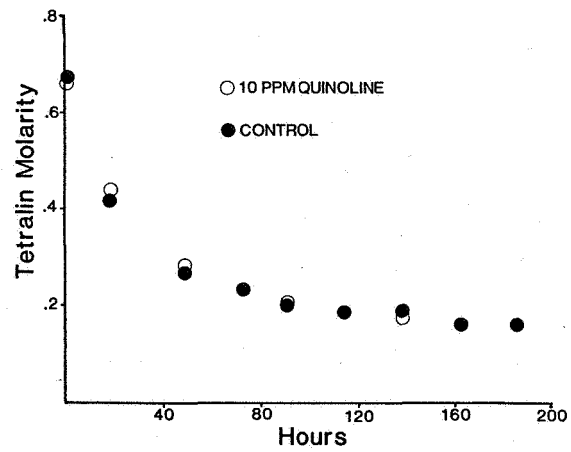
Comparison of Nitrogen Compound Effects in Jet A and Diesel Fuels



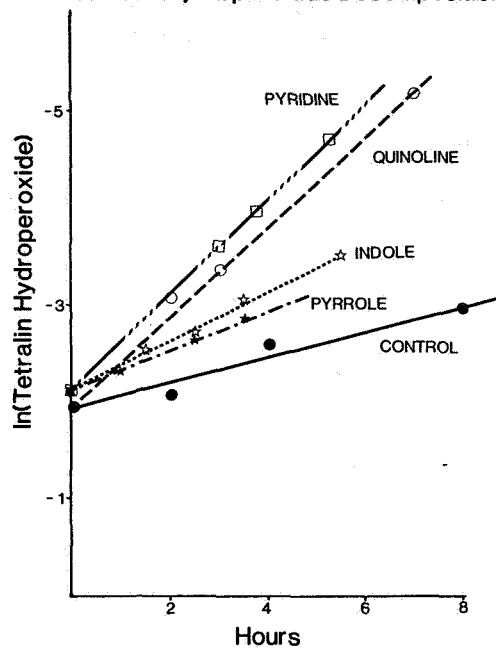
Effect of Nitrogen Heterocycles on Deposit Formation in the Model System



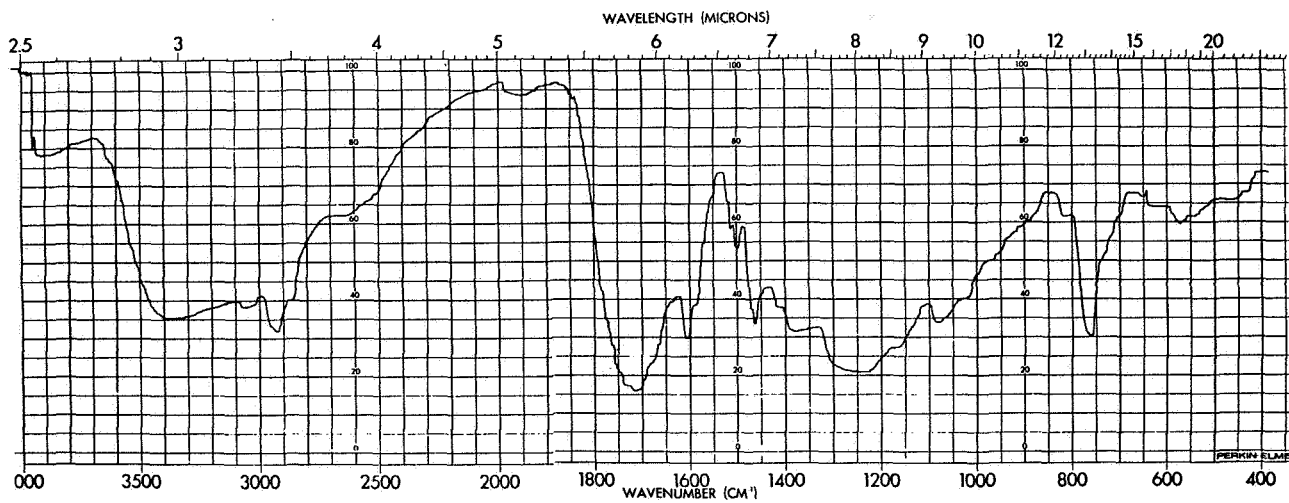
Effect of Quinoline on Tetralin Auto-oxidation



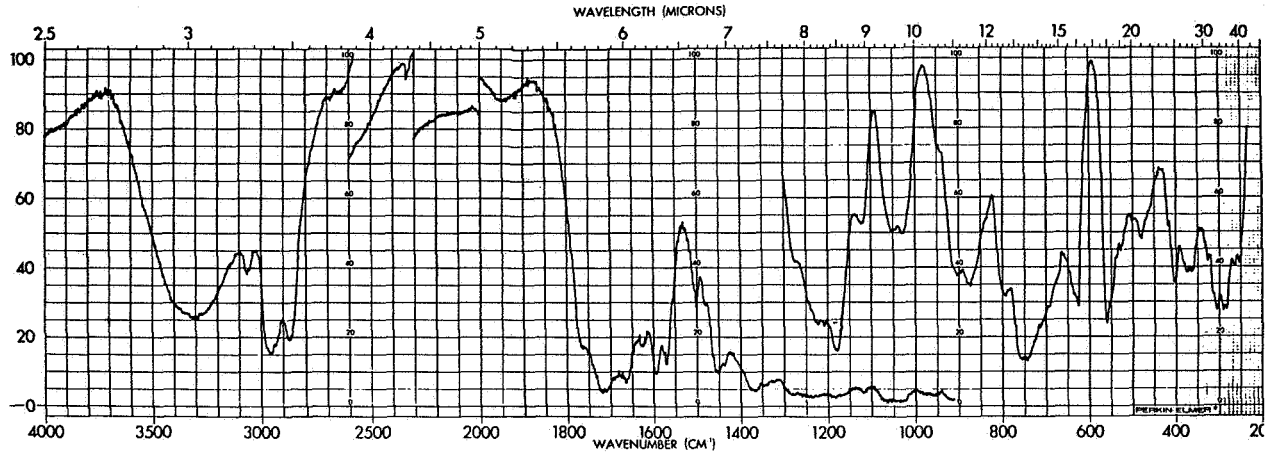
Effect of Nitrogen Heterocycles on
Tetralin Hydroperoxide Decomposition



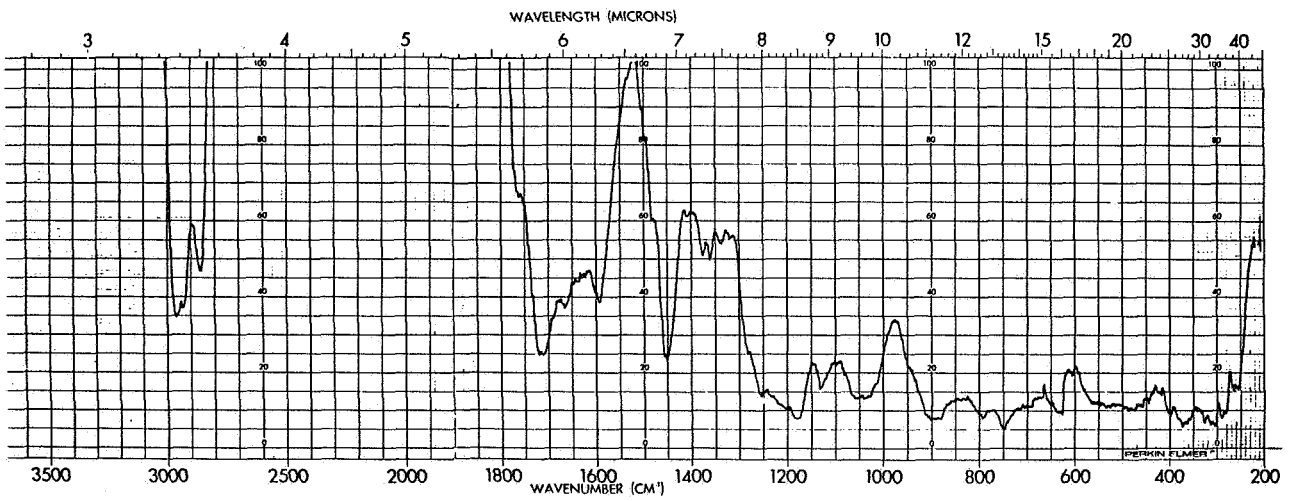
TRANSMISSION SPECTRUM OF MODEL SYSTEM STORAGE DEPOSIT



MULTIPLE INTERNAL REFLECTANCE SPECTRUM OF MODEL SYSTEM STORAGE DEPOSIT



MULTIPLE INTERNAL REFLECTANCE SPECTRUM OF JET A STORAGE DEPOSIT



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FUEL SYSTEMS TECHNOLOGY OVERVIEW

Robert Friedman
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Fuel system research and technology studies are being conducted to investigate the correlations and interactions of aircraft fuel system design and environment with applicable characteristics of the fuel.

Fuel Properties and the Fuel System

Voluntary industry standards for aviation turbine fuel (ASTM D 1655, ref. 1) include over 25 items of specification, but only a few of these are of concern to the fuel system design and operation. The proceedings of a 1977 NASA-sponsored workshop on fuels (ref. 2) identified several fuel properties worthy of further research with respect to their influence on the performance of present and future aircraft fuel systems. These properties include water solubility, viscosity, flashpoint, aromatics content, and freezing point. Water solubility is a minor characteristic, but it is a property sensitive to fuel composition; and changes in the fuel chemical constituents may increase the solubility and cause cleanliness problems. Viscosity is of concern with respect to low-temperature pumpability, but proposed research on viscosity can be included with the freezing-point studies discussed later. Flashpoint was not included among the cited properties in the reference 2 workshop proceedings. The workshop participants discussed flashpoint but concluded that safety and altitude boiloff limits made any changes or research on flashpoint unlikely. Subsequent to this workshop, an ASTM symposium reviewed the question of jet fuel flashpoint, its measurement, and the advantages and disadvantages of changes in the flashpoint specification. A compilation of the flashpoint symposium papers has been recently published (ref. 3).

The significance of increased content of aromatic compounds in jet fuels has already been discussed in this symposium, with respect to combustion and emission effects. Aromatic compounds can also degrade the performance of polymeric materials used as seals in the fuel system. Limited laboratory tests of material compatibility have been conducted by the Jet Propulsion Laboratory (ref. 4) and other organizations. In some of the JPL tests a test specimen was supported in a bath of fuel within a constant-temperature oven. The tension required to maintain a fixed gage length was measured by a load cell. Test results on one elastomer are shown in figure 1 as a plot of stress relaxation over a period of time. Tests were conducted in air and with the elastomer exposed to Jet A (20 percent aromatics) and Jet A blended with tetralin (40 and 60 percent aromatics). The rapid degradation of elastic qualities with increased aromatics content is obvious in the results of these accelerated tests. Figure 2 shows test results with

the 60-percent aromatics fuel at three temperatures. Comparison of figures 1 and 2 shows that an increase from 20 to 60 percent aromatics is analogous to a decrease of 30° C in operating temperature.

Freezing Point

The jet fuel property which is of greatest concern to the fuel system performance is, of course, the freezing point (refs. 5 and 6). The 1977 NASA fuels workshop (ref. 2) made five recommendations for continuing and future research on freezing point and its relation to fuel system performance. These are

- (1) Analyses of in-flight temperatures
- (2) Design of aircraft fuel systems for use with high-freezing-point fuels
- (3) Experimental study of low-temperature pumpability
- (4) Full-scale fuel tank simulator studies
- (5) Development of a rapid freezing-point measurement technique

Analysis of in-flight fuel temperatures. - In the past two decades, some flight fuel temperature data have been collected by airlines and airframe companies. Recently, the Boeing Company made a comprehensive analysis of 8000 fuel and ambient minimum temperature measurements furnished by flight crews of cooperating International Air Transport Association airlines (ref. 7). Figure 3 is one example from this survey, a distribution plot of percent of flights for stated minimum fuel temperatures over a given route. The data are separated according to airplane type, but the different curves reflect the variations in flight speed and fuel management rather than inherent differences in fuel system design. Despite the large number of data points, this study still covers a small statistical range of limited seasonal and geographic variations. The principal purpose of the compilation was the corroboration of a Boeing in-flight fuel temperature computing routine (refs. 8 and 9). The fuel temperature calculations were shown to be accurate by comparison with the data. The fuel temperature computer program permits the prediction of fuel temperatures for a large range of ambient conditions, flight times, fuel management, and tank configurations, including military and general-aviation airplanes as well as commercial models. The calculations and the measurement data are single-point, bulk fuel temperatures. A refinement of the computing program is being devised to include realistic temperature gradients within the fuel tank. The paper by Frederick Tolle of Boeing describes the computing program modification. A NASA program is now under way to obtain selected in-flight measurements of these temperature gradients.

Fuel systems for high-freezing-point fuels. - Heat transfer from the fuel during flight can be reduced by insulation or the fuel temperature can be increased by heating in order to increase the minimum fuel temperature and remove some restrictions on the freezing-point specification. Boeing design analyses (refs. 8 to 10) have concluded that, at present, fuel heating, using engine heat rejection or conversion of a small fraction of engine

power, is most feasible. Suggested techniques are discussed in the paper by Tolle.

Experimental study of low-temperature pumpability. - The relationship of fuel flow or pumpability at low temperature to the freezing point has been investigated in several programs. A NASA-supported study by the Lockheed-California Company (refs. 11 and 12) used a scale-model apparatus that represented a segment of an airplane fuel tank. The upper and lower surfaces of the tank were chilled to duplicate the in-flight fuel tank environment. The paper by Francis Stockemer discusses these tests and their results in terms of the unpumpable "holdup" of frozen fuel. Other results from laboratory and scale-model tests conducted by the Boeing Company are included in Tolle's paper. Continuing studies by Lockheed use an apparatus which adds a heated fuel recirculating system to the chilled tank model (fig. 4). These tests can thus simulate the behavior of fuel in an advanced fuel system with in-flight fuel heating.

Full-scale fuel tank simulation. -The 1977 fuels workshop recommended that studies be conducted in a full-scale fuel tank demonstrator to relate the fuel pumpability findings to behavior at realistic conditions and configurations. No program of this scope has been initiated, however.

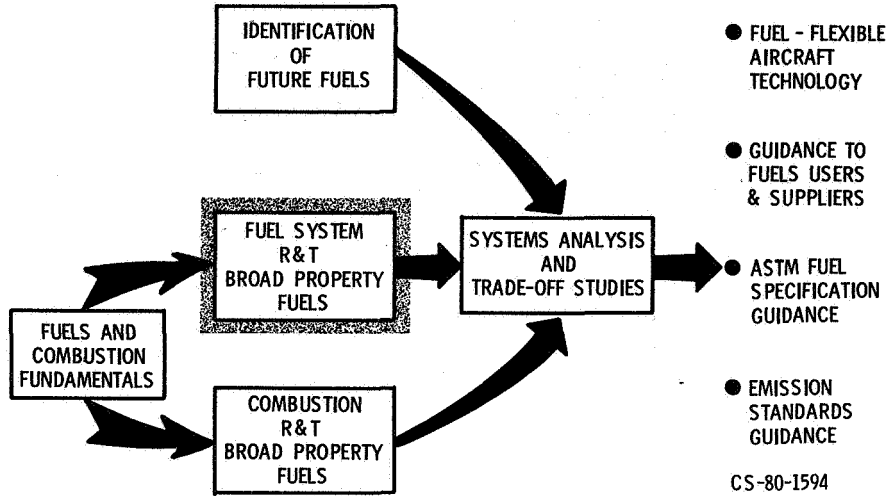
Rapid freezing-point measurement. - If the freezing point of a jet fuel were determined at the time of delivery to the airplane, minimum in-flight temperature limits could be permitted near the actual rather than the conservative specification freezing point. The present means of measurement, while accurate and precise, is cumbersome and unsuited for field measurements. A NASA program, to start in 1980, will investigate techniques suitable for rapid freezing-point measurements.

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10. Pasion, A. J.: Design and Evaluation of Aircraft Heat Source Systems for Use with High-Freezing-Point Fuels. Boeing Commercial Airplane Company, NASA CR-159568, 1979.
11. Stockemer, Francis J.: Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model. Lockheed-California Company, NASA CR-159615, 1979.
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AIRCRAFT RESEARCH AND TECHNOLOGY FOR FUTURE FUELS

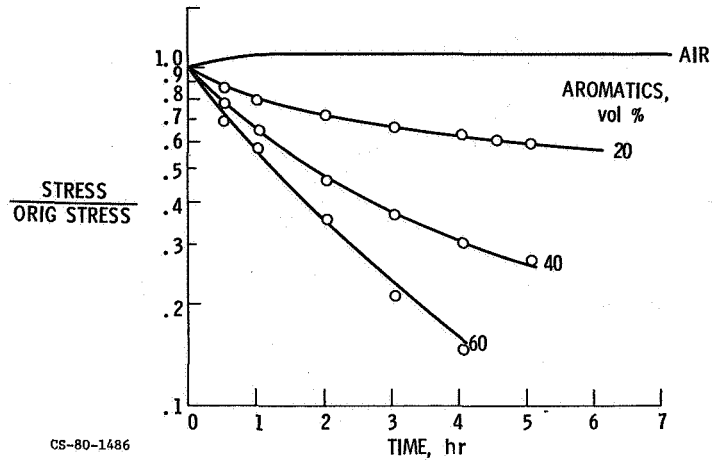


RECOMMENDED RESEARCH FOR FUEL SYSTEMS-1977 NASA WORKSHOP

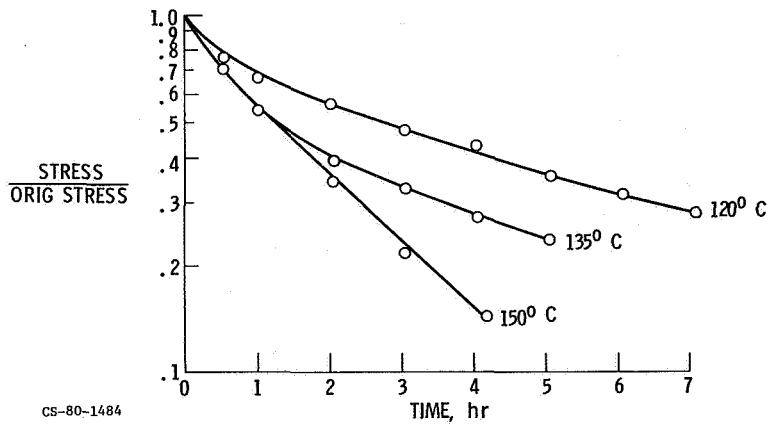
JET FUEL PROPERTY	RESEARCH AND TECHNOL NEEDS
WATER SOL AND CLEANLINESS FLASH POINT VISCOSITY AROMATIC CONTENT FREEZING POINT <div style="text-align: center; margin-top: 10px;">↓</div>	TRENDS WITH FUEL COMPOSITION NO RECOMMENDATION LOW TEMPERATURE BEHAVIOR MATERIAL COMPATIBILITY ANALYSIS OF IN-FLIGHT TEMPERATURES DESIGN OF SYSTEM MOD. FOR HIGH F. P. EXPERIMENTAL STUDY OF LOW TEMP PUMPABILITY FULL-SCALE WING TANK SIMULATOR RAPID FREEZING PT MEASUREMENT METHOD

CS-80-1485

STRESS RELAXATION OF ELASTOMER AT 150° C
BUTADIENE-ACRYLONITRILE RUBBER



STRESS RELAXATION OF ELASTOMER IN 60% AROMATICS FUEL
BUTADIENE-ACRYLONITRILE RUBBER

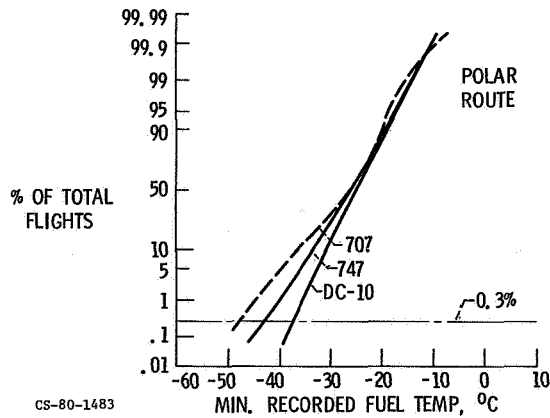


STATUS OF RECOMMENDATIONS ON FREEZING POINT RESEARCH

RECOMMENDATION	RESEARCH PROGRESS
ANALYSIS OF IN-FLIGHT FUEL TEMPERATURES	COMPLETED BOEING SURVEY; COMPLETED BUSINESS JET CALCULATIONS NASA IN-FLIGHT TEMP PROFILE SURVEY IN PROGRESS
DESIGN OF AIRCRAFT SYSTEMS FOR USE WITH HIGH F. P. FUELS	COMPLETED BOEING STUDIES
EXPERIMENTAL STUDY OF LOW TEMPERATURE PUMPABILITY	COMPLETED LOCKHEED STUDY; COMPLETED BOEING-A.F. STUDY; LOCKHEED HEATED FUEL STUDY IN PROGRESS
FULL-SCALE FUEL TANK SIMULATOR STUDIES	FUTURE
RAPID FREEZING POINT MEASUREMENT	PROJECT TO START IN 1980

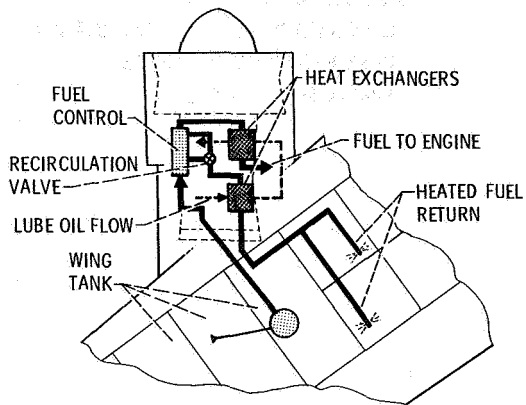
CS-80-1487

STATISTICAL SUMMARY OF FLIGHT DATA



CS-80-1483

FUEL HEATING SYSTEM STUDY-BOEING
 FUEL/OIL HEAT EXCHANGER SYSTEM



ADVANTAGES

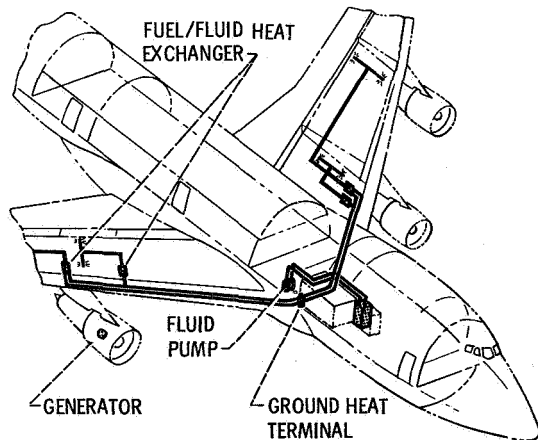
- USES EXISTING HEAT REJECTION HARDWARE
- LOW COST - LOW PENALTY
- SIMPLE SYSTEM, RELATIVELY MINOR MODIFICATION

DISADVANTAGES

- LIMITATION TO QUANTITY OF HEAT AVAILABLE (-34° C FREEZE PT MAX.)
- VARIABLE HEAT AVAILABLE, DEPENDENT ON ENGINE OPERATING POINT

CD-12314-07
 CS-78-2880

FUEL HEATING SYSTEM STUDY-BOEING
 ELECTRICAL HEATING SYSTEM



ADVANTAGES

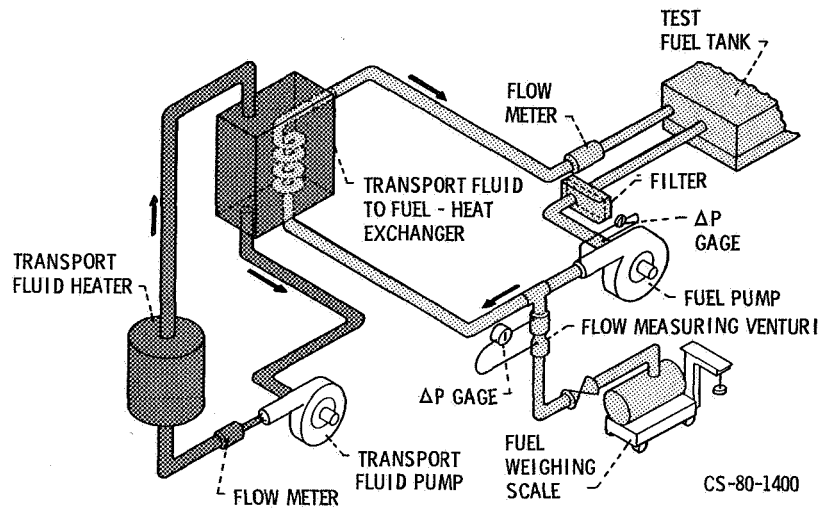
- UNLIMITED HEAT AVAILABLE (UP TO -18° C FREEZE PT)
- INDEPENDENT CONTROL
- ADAPTABLE TO GROUND HEATING FOR LAYOVER

DISADVANTAGES

- MAJOR MODIFICATION-ADDITIONAL SYSTEM
- WEIGHT PENALTY
- CYCLE PENALTY WHEN USED

CD-12315-07
 CS-78-2881

FUEL PUMPABILITY APPARATUS WITH ADDED HEATING LOOP



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HIGH-FREEZING-POINT FUEL STUDIES

Frederick F. Tolle
Boeing Military Airplane Company

Proposals to use heavier hydrocarbons as a means of obtaining more abundant and less costly aviation turbine fuel raise a number of concerns, among them being low temperature flowability. Long duration high altitude flights expose airplanes to static air temperatures in ranges as low as -72 C on a one time/year basis (fig. 1); for typical subsonic jet airplanes ($M\ 0.84$), aerodynamic heating increases the potential cold soak temperature for the fuel system to the vicinity of -47 C . Existing specifications aimed at insuring jet fuel flowability at such low temperature stipulate a maximum allowable freeze point. Even so, infrequent but costly instances of fuel temperature difficulties do occur which interfere with large range flight operations. It can be anticipated that the frequency of these instances would increase with higher freeze point fuels.

A few background observations on the nature of low temperature fuel systems behavior provide perspective on the problem. Fuels consist of a mixture of paraffinic, naphthenic, and aromatic hydrocarbons with a variety of crystallization temperatures as pure compounds (fig. 2); on dropping the temperature of a mixture of these compounds, the high freezing point materials which would solidify if pure tend to be soluble in the lower freezing fuel constituents. As a result, the first appearance of solids in a mixture is deferred; however, as temperature is further decreased, a solid phase consisting of isolated crystals of long chain paraffins begins to appear. At still lower temperatures, the crystals merge into a spongelike matrix which eventually traps the remaining liquid phase. At this point the semi-solid may resist flow to the fuel tank outlet. Agitation or the use of flow improvers interferes with matrix formation and maintains the flowable two phase slurry. The stages of conversion from liquid to solid as a function of airplane altitude are depicted in figure 3, and properties of interest are defined in figure 4. It is of interest that fuel is a very good thermal insulator (akin to rubber) with relatively high heat capacity (about half that of water). As fuel temperature drops below the freeze point, the transition from a flowable to a non-flowable fuel often occurs over a range of a few degrees of temperature. A device known as the Shell-Thornton tester has been used to study holdup (amount of non-flowable fuel) as a function of temperature, with results for a typical commercial fuel as shown in figure 5.

Military JP-4 fuel has such a low freeze point that flowability problems have never developed in service. However, other fuels (commercial Jet A and Jet A-1, and military JP-5 and JP-8) and certainly fuels with relaxed restrictions on freeze point can experience operational difficulties. In

recognition of this fact, many commercial airplanes already incorporate fuel tank thermocouples; in the case of the 747, when the sensed fuel temperature is within 3 C of the specification freeze point, the airplane flight manual requires that the flight profile be altered to increase skin temperature by changing altitude, Mach number or route. For the 747, the fuel consumption penalty for an 1850 KM (1000 NMI) deviation was assessed for a 9260 KM (5000 NMI) flight; data shown on figure 6 translate into added cost and reduced range for either descent to a lower altitude, or a Mach number increase. In order to avoid these penalties, airline operators along polar routes may be forced to use Jet A-1, the higher cost lower freeze point alternative to Jet A, during severe low temperature operations.

Concern about safe operation limits with existing fuels, as well as the question of the acceptability of higher freeze point alternative fuels indicated the need for detailed studies of the flowability problem. These studies initially focused on understanding freezing phenomena as a function of temperature along a flight trajectory, using a combination of

- o in-flight measurements
- o ground simulation
- o analysis

More recently, additional effort has been expended on devising techniques to mitigate low temperature flowability problems by adding heat to fuel.

In-flight observations of 707 fuel tank temperatures showed significant vertical variations in fuel temperature (fig. 7), attributable to the very low thermal conductivity of fuel, and limited mixing. However, the study of actual freezing phenomena could not be carried out in flight for reasons of safety and practicality. Accordingly, a fuel tank simulator representing a section of a 747 outboard wing tank (fig. 8) was constructed, containing typical wing tank structures and plumbing in which controlled experiments could be conducted. The simulator (figs. 9 and 10) has been mounted on a slosh/vibration table to represent airplane motions. Slosh was modeled in one test as shown in figure 11. Upper and lower simulator skin temperature can be closely controlled in the range of -72 C to 35 C as a function of time. A central array of thermocouples gives continuous temperature data.

The simulator was recently used for CRC/USAF (ref. 1) sponsored experiments on five fuels, with the objective of measuring unavailable (holdup) fuel using severe thermal exposure. Fuel characteristics are listed in figure 12. The mission which was simulated was launch of airplanes from an Artic base to airborne alert status, calling for low speed flight in a holding pattern in Artic air masses. The experimental procedure called for pre-chilling the fuel to a temperature 10 to 20 C above the freeze point, and then rapidly dropping the skin temperature to 10 C below the freeze point. The temperatures in the tank were monitored to establish the shape of the thermal profile in the tank (fig. 13). The

experiment was stopped when a thermocouple mounted 2.5 cm above the lower skin sensed a "target" temperature, at which time a holdup measurement was made by weighing the liquid fuel which could be drained from the simulator. The target temperatures used were +2.8, 0.0, -2.8 and -5.6 C with respect to the measured freeze point of the fuel.

Only limited interpretation of the data is reported here (a detailed report will be published by the CRC in the near future). For example, holdup data on one of the Jet A fuels indicates decreased holdup resulting from slosh/vibration agitation (fig. 14). It also appears from this test that slosh is more effective than vibration in reducing holdup. The thermal profile data is also useful in understanding the heat transfer mechanisms between the fuel and the tank walls. For full fuel tanks, the time variable thermal profiles (fig. 15) reveal three distinct regions:

- o at the lower skin, a steep gradient in a zone controlled by conductive heat transfer
- o at the upper skin, a very steep gradient in a zone where heat is transferred by free convection giving rise to downward movement of cold dense fuel
- o at the center, a zone of little or no gradient resulting from convectively driven mixing, with cold fuel descending and warm fuel rising; the cold fuel does not possess enough momentum to penetrate the lower zone controlled by conduction.

If fuel is withdrawn from the tank, the appearance of the thermal profile changes markedly. As the fuel loses contact with the upper surface, convection currents damp out, and the primary heat transfer is by conduction through the lower surface (fig. 16).

These insights have been translated into a computer technique for calculating fuel temperature profiles in full tanks; a comparison of calculation and experiment shows good agreement (fig. 17). The computer program is being extended to include the case of partially empty tanks. Ultimately, the completed package will be incorporated into Boeing's aircraft fuel tank thermal analyser (AFTTA) code to permit the designer to "fly" various thermal exposure patterns, study fuel temperatures versus time, and determine holdup.

If analysis shows holdup to be unacceptable, Boeing studies funded by NASA (ref. 2, 3) of fuel tank heating or skin insulation provide the basis for a designer to do trade studies of fuel properties versus airplane fuel tank complexity and operating costs. Two conceptual designs for fuel heating system appear feasible based on analysis conducted with the existing AFTTA code (which uses bulk mean fuel temperature rather than thermal profiles). The first design (fig. 18) uses heat rejected by hot engine lubricating oil, while the second (fig. 19) uses a dedicated

electrical generator driven directly by the engine to heat the fuel electrically. A return on investment study (fig. 20) was made on each heating system to determine what incremental cost reduction in fuel price would be required to offset the cost of acquisition, installation, maintenance and loss of payload. As noted in the figure, engine oil heat was found to be insufficient to permit use of -18 C freeze point fuel. Offsetting fuel cost reductions are in the fractional cents/gallon for a 5500 kilometer (3000 NMI) range, but became as high as 17 cents/gallon at 9200 kilometer (5000 NMI) range.

The same AFTTA code was used to conduct a CRC/NASA sponsored study (to be published) of a new class of long range high altitude business jets (ref. 1). Two fuel loading temperatures and two thermal exposure profiles were used to assess the magnitude of the freezing problems that might be encountered. The study used actual fuel tank geometry, fuel withdrawal data and time variable thermal exposure to calculate bulk mean temperature. The results presented in figure 21 show that the fuel temperature at the end of five hours depend primarily on the lowest temperature of exposure, and little on loading temperature or on variations in the thermal exposure profile. An evaluation of the accuracy of the computations was made by comparing actual business jet inflight data and the results of computer analysis. A plot of the data (fig. 22) indicates good agreement.

In summary, the work reported demonstrates considerable progress in developing the experimental and analytical techniques that will be needed if it is necessary to design airplanes to accommodate fuels with less stringent low temperature specifications.

REFERENCES

1. CRC Contract No. CA-58-78, "Low Temperature Jet Fuel Study", 5 March 1979.
2. Pasion, A. J. and Thomas, I., "Preliminary Analysis of Aircraft Fuel Systems for Use with Broadened Specification Jet Fuels", NASA CR-135198, May 1977 (Contract NAS3-19783).
3. Pasion, A. J., "Design and Evaluation of Aircraft Heat Sources Systems for Use with High Freezing Point Fuels", NASA CR-159568, May 1979 (Contract NAS3-20815).

Figure 1. Inflight Altitude Ambient Temperature Profile

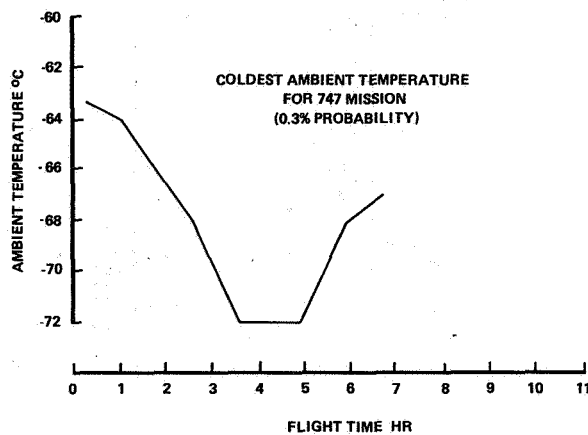


Figure 2. Variation in Crystallization Temperature for Various Single Compound Classes of Fuel Hydrocarbons

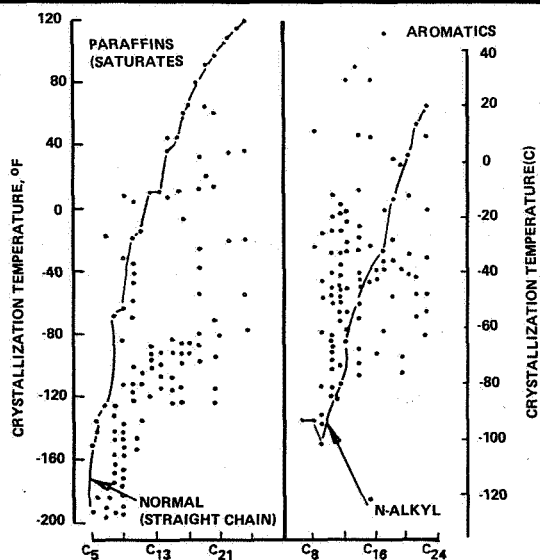


Figure 3. Low Temperature Behavior of Hydrocarbon Fuel

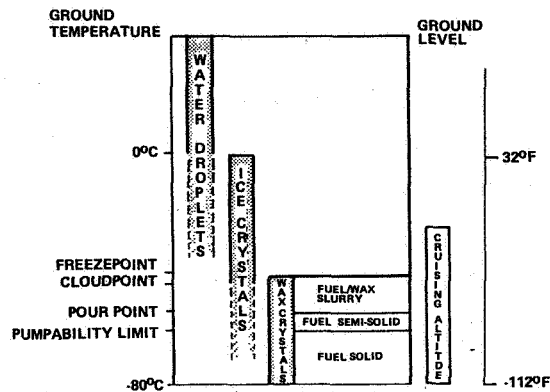


Figure 4. Low Temperature Properties

FREEZING POINT - THAT TEMPERATURE AT WHICH CRYSTALS OF HYDROCARBONS FORMED ON COOLING DISAPPEAR WHEN THE TEMPERATURE OF AN AGITATED FUEL IS ALLOWED TO SLOWLY RISE. - ASTM D-2386

JET A	JET A-1	JP-4	JP-5	JP-8	BROAD SPEC FUEL
-40 C	-50 C*	-58 C	-48 C	-50 C	-34 C

* NOTE: ASTM HAS VOTED CHANGING TO -47 C

POUR POINT - RELATED TO THE LOWEST TEMPERATURE AT WHICH QUIESCENT FUEL WILL JUST POUR FROM A STANDARD GLASS CYLINDER OF 1-1/4" DIAMETER. THE POUR POINT IS 3°C ABOVE THAT FUEL TEMPERATURE WHERE NO FUEL MOVEMENT OCCURS WITH CYLINDER IN HORIZONTAL POSITION. ASTM D-97. (POUR POINT IS USUALLY FROM 3 TO 10 C LESS THAN FREEZE POINT)

HOLDUP - THAT FRACTIONAL AMOUNT OF FUEL WHICH WILL NOT FLOW BY GRAVITY FROM A CONTAINER BECAUSE OF PARTIAL FREEZING. IN THE SHELL-THORNTON TESTER, THE CONTAINER IS ESSENTIALLY ISOTHERMAL, AND 100% HOLDUP OCCURS BETWEEN FREEZE AND POUR POINT.

<u>SPECIFIC HEAT</u> (-40 C)	1.76 KJ/Kg - C
<u>THERMAL CONDUCTIVITY</u> (-40 C)	0.143 W/M - C

Figure 5. Shell - Thornton Holdup Data - Paraffinic Jet A

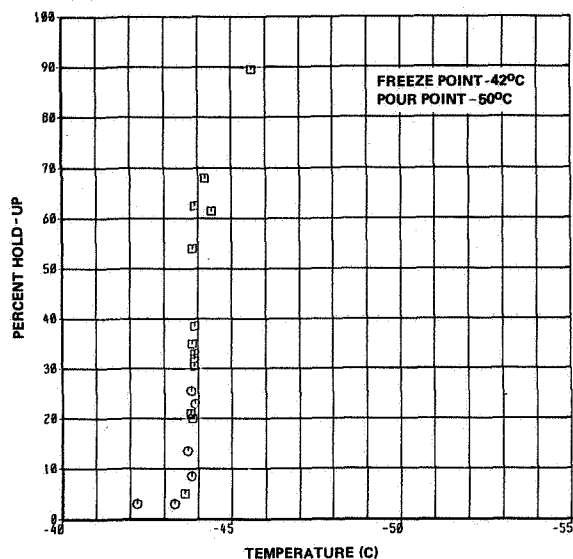


Figure 6. 747 Fuel Penalties for Flight in Cold Air Mass

BASELINE MISSION	
TRIP LENGTH	9,260 KM (5000 NM)
CRUISE MACH	.84
TRIP FUEL	117,930 KG (260,000 LB)
TRIP TIME	10.5 HRS
RESERVE FUEL	18,780 KG (41,400 LB)
ADDED FUEL FOR 1000 LOWER ALTITUDE	
-1220M (-4000 FT)	820 KG (1800 LB)
-2440M (-8000 FT)	2770 KG (6100 LB)
-3660M (-12000 FT)	5940 KG (13,000 LB)
ADDED FUEL FOR 1000 MILES AT INCREASED MACH NO.	
M = 0.87	1720 KG (3800 LB)
(TAT RISE +2.5°C)	

**Figure 7. Stratification in an Airplane Fuel Tank
(707 Outboard Reserve Tank)**

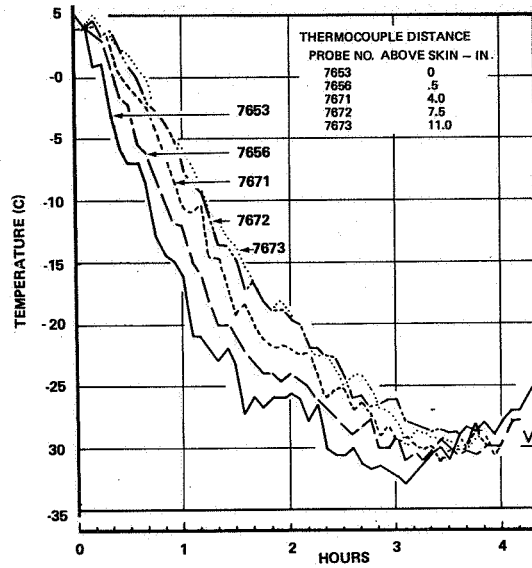


Figure 8. 747 Fuel Tank System

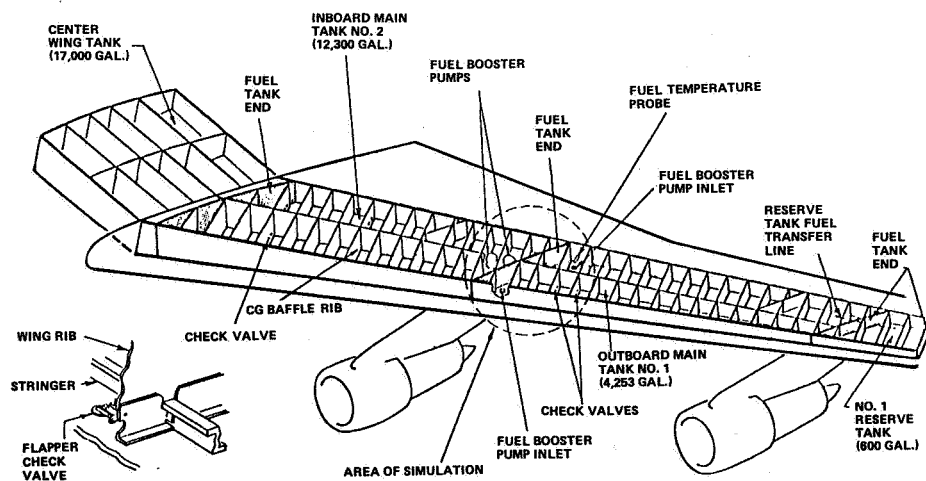


Figure 9. Fuel Tank, Thermal Simulator

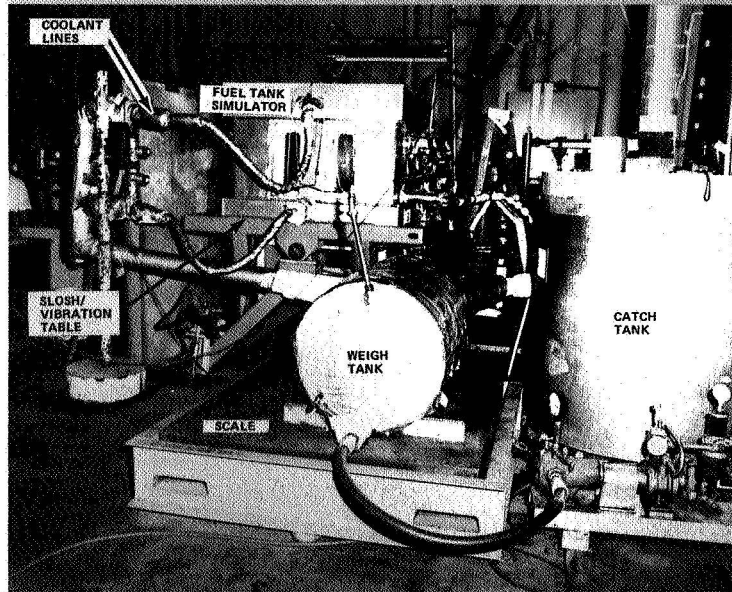


Figure 10. Interior of Fuel Tank Simulator

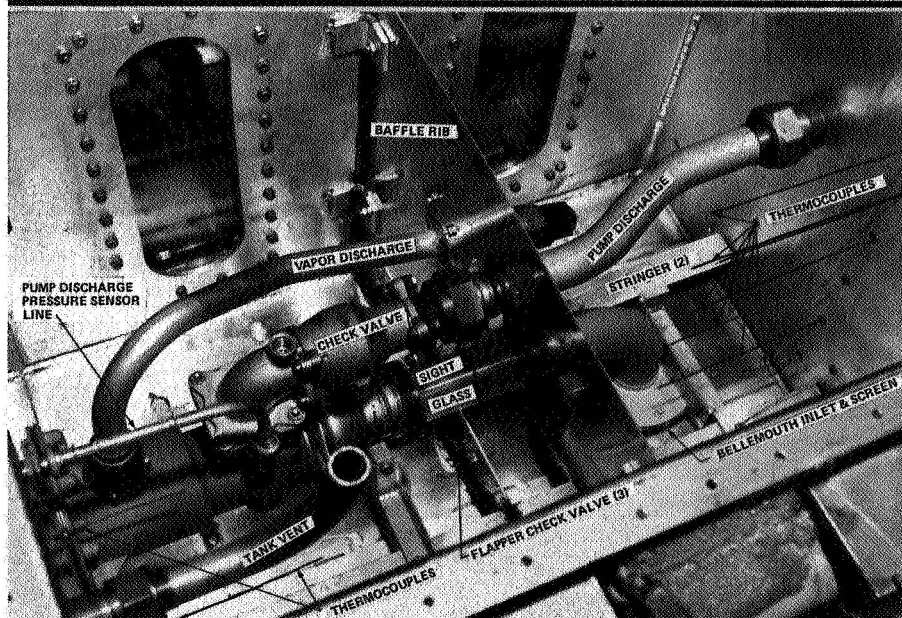


Figure 11. Simulated Gust and Maneuver (Slosh) Cycles

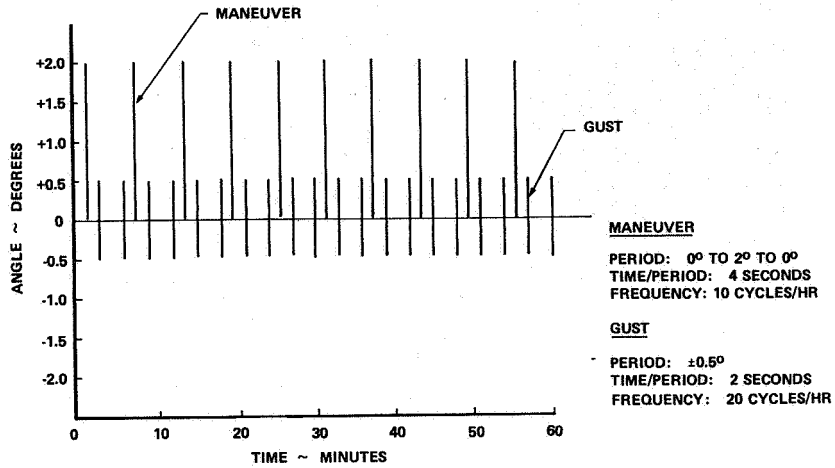


Figure 12. Test Fuel Characteristics

FUEL DESIGNATION	TYPE CRUDE	CRUDE SOURCE	FREEZE PT. °C (°F)	POUR PT. °C (°F)
JET A	PARAFFINIC	59% MINAS INDONESIAN 41% MURBAN (ABU DHABI)	-42 (-43.6)	-50 (-58)
JET A	NAPHTHENIC	89% ALASKAN NO. SLOPE 9% CALIF. 2% MISC.	-51.1 (-60)	-52 (-61.6)
JP-8 (SHALE) MIL-T-83133	SHALE		-50 (-58)	-53.9 (-65)
JP-5 + 9% DFM MIL-T-83133			-25 (-13)	-51.1 (-60)
JP-8 (OUT OF SPEC)			-44 (-47)	-48 (-55)

Figure 13. Time Variation of Fuel Tank Temperature

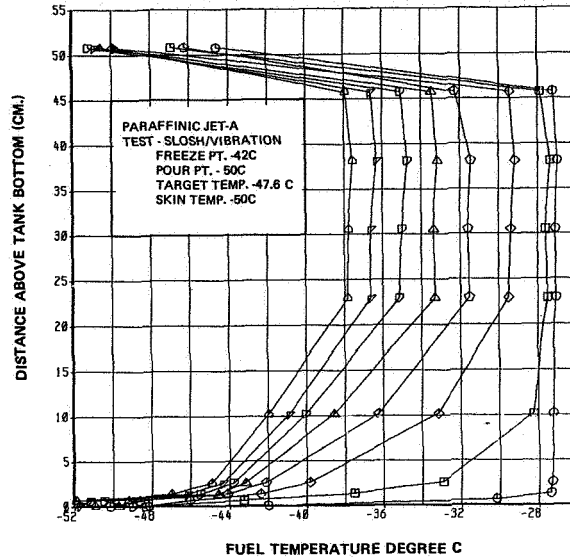
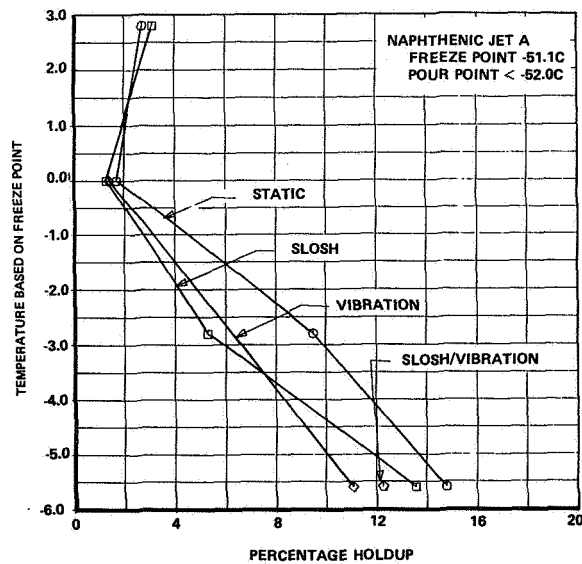
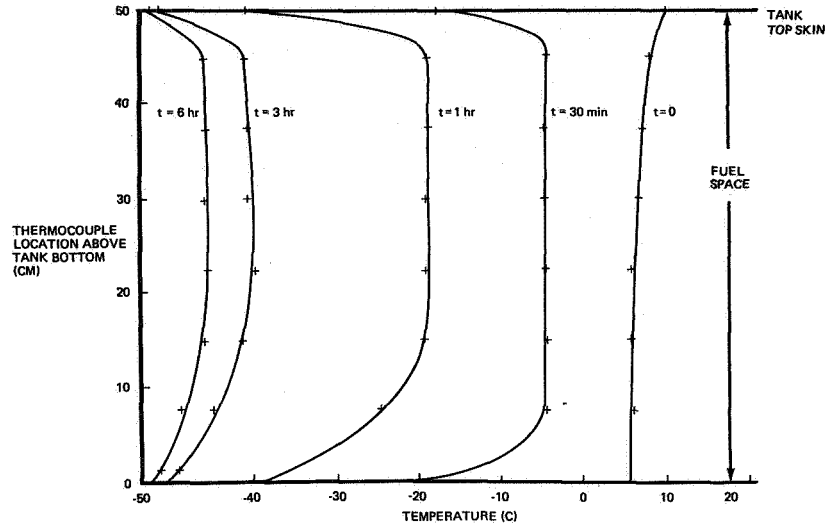


Figure 14. Effect of Tank Motion on Fuel Holdup



**Figure 15. Temperature - Position Profiles for Jet A-1
Fuel and Wet Top Skin**



**Figure 16. Temperature-Position Profiles for
Jet A-1 and Dry Top Skin**

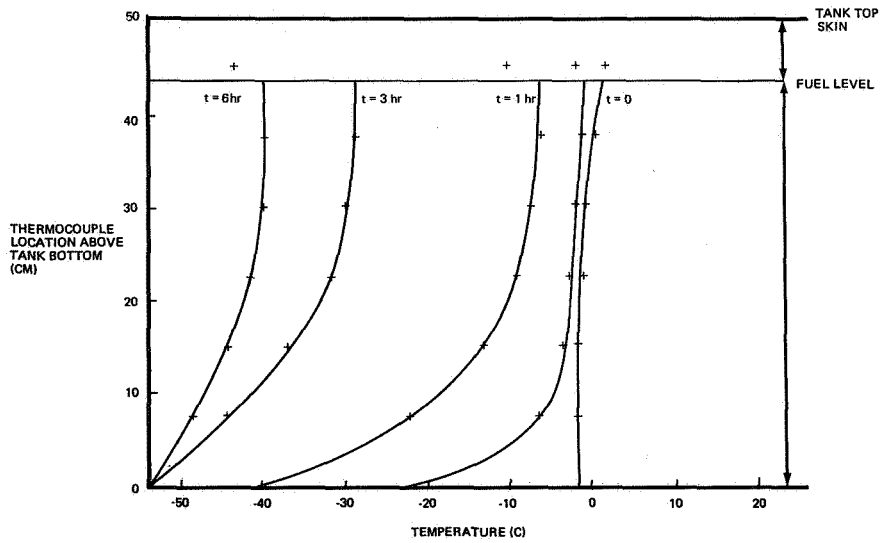


Figure 17. Comparison of Calculated and Experimental Fuel Tank Temperatures

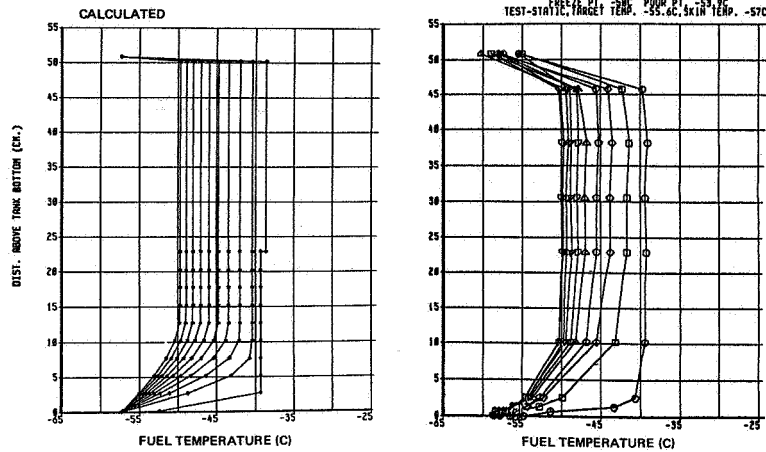


Figure 18. Fuel Heating with Engine Oil

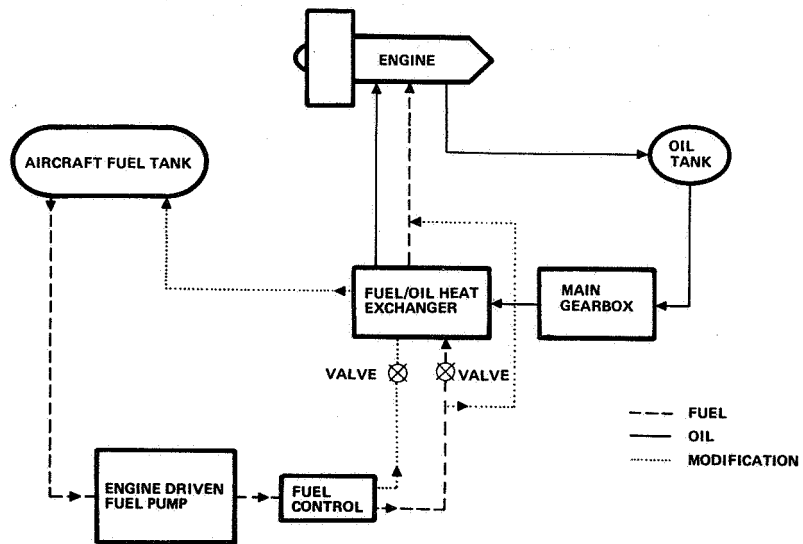


Figure 19. Fuel Heating with Electric Heaters

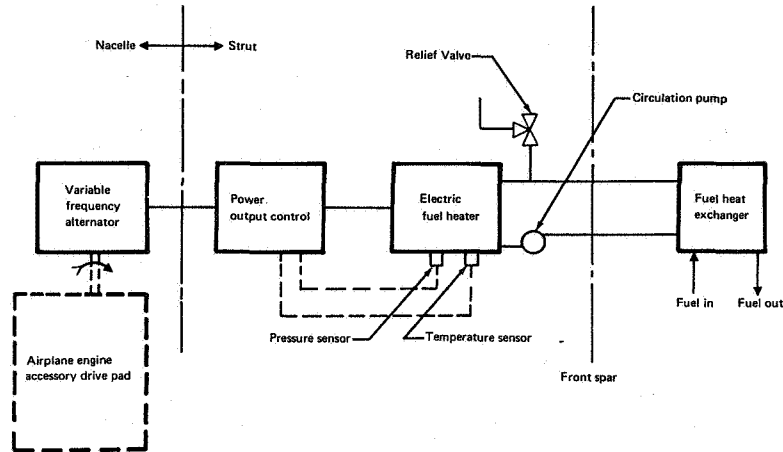


Figure 20. Return on Investment Study - 747 Airplane

FUEL PRICE INCREMENT REQUIRED TO BALANCE COST OF HEATING SYSTEM

FUEL PRICE BASIS: 45¢/GAL

3000 NMI FLIGHT

	-18°C F.P. FUEL	-29°C F.P. FUEL
ENGINE OIL HEAT EXCHANGER SYSTEM	XXXX	-0.29¢/GAL
ELECTRICAL HEATING SYSTEM	-0.90¢/GAL	-0.77¢/GAL

5000 NMI FLIGHT

ENGINE OIL HEAT EXCHANGER SYSTEM	XXXX	-2.6¢/GAL
ELECTRICAL HEATING SYSTEM	-17.0¢/GAL	-12.3¢/GAL

xxxx CANNOT MAINTAIN ACCEPTABLE FUEL TEMPERATURE

**Figure 21. Calculated Business Jet
In-Flight Fuel Temperature**

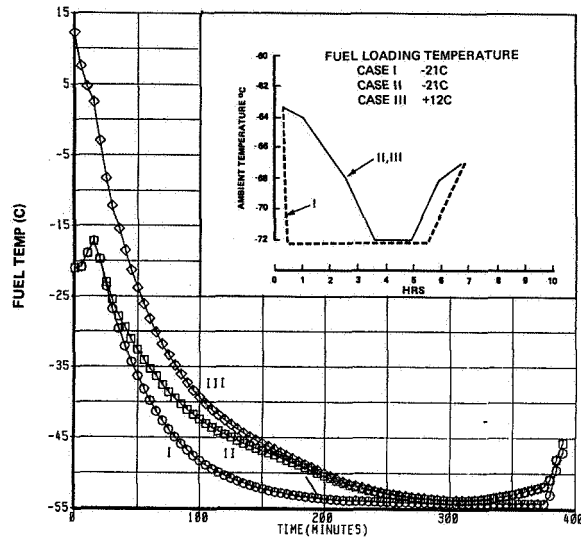
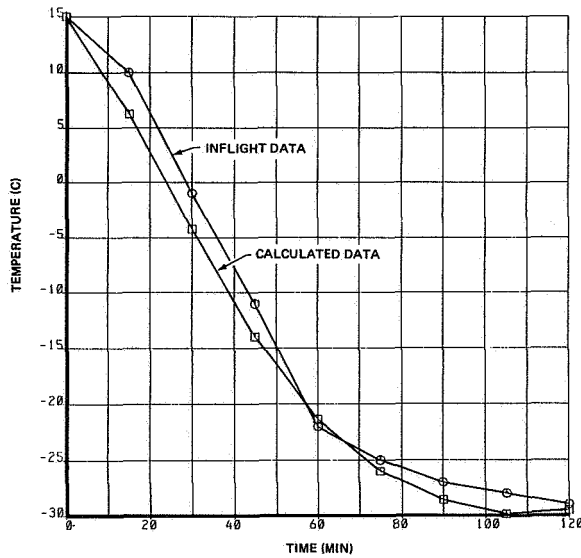


Figure 22. Business Jet, Wing Tank Fuel Temperature



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LOW TEMPERATURE FUEL BEHAVIOR STUDIES

Francis J. Stockemer
Lockheed-California Company

An experimental investigation was performed by the Lockheed-California Company* to study aircraft fuels at low temperatures near the freezing point. The principal objective was an improved understanding of the flowability and pumpability of the fuels in a facility that simulated the heat transfer and temperature profiles encountered during flight in the long range commercial wing tanks.

A test tank simulating a section of an outer wing integral fuel tank, approximately full scale in height, was designed and fabricated. Internal tank construction included stringers, scavenging ejectors, pump inlet surge box, and other details corresponding to an airplane wing tank construction. The test tank was chilled through heat exchange plates on the upper and lower horizontal surfaces. Other surfaces were insulated. A viewing port was installed in each vertical panel. Figure 1 shows a cross-section of the apparatus. Figure 2 is a photograph of the test tank during final assembly. Figure 3 is a view of the lower portion of the completed tank; thermocouple rack 2 is at the center. Table 1 designates thermocouple locations.

Fuels used during the program included commercially obtained Jet A and Diesel D-2, a special JP-5 type derived from oil shale, paraffinic and naphthenic Jet A, Diesel D-2, and intermediate freeze point fuels, and the paraffinic intermediate treated with a pour point depressant; these fuels are itemized in Table 2. The pour point depressant and most of the fuels were furnished through the Coordinating Research Council (CRC) Group on Low Temperature Flow Performance of Aviation Turbine Fuels.

Tests were generally conducted by chilling the tank skins to a nearly constant temperature. During cooldown, cross lighting provided visual evidence of convective currents in the fuel. Fuel was withdrawn from the tank by gravity flow after the fuel reached a desired temperature with time. Suspensions of solid fuel particles were readily withdrawn and presented no obstacle to flow. The accumulation of solid particles remaining at the bottom of the tank, after the liquid was withdrawn, was defined as gravity holdup. For cases where 10% or less of the fuel was held up, the holdup was essentially a solid deposition. At greater holdups, entrapment of liquid fuel within the matrix of solids was discernible. Solid buildup commenced on the bottom of the tank, spread over the lower stringers, then began to form on the upper surfaces and vertical panels. At large holdups, accretions on the walls and upper surfaces sometimes fell and could obstruct gravity flow.

Temperatures measured at the approximate location of a commercial aircraft fuel temperature probe (10 centimeters or above) provided a good measurement of bulk temperature, but ignored lower temperatures near the chilled walls;

*NASA Contract NAS3-20814

this effect is illustrated in Figure 4. Tests were also conducted at a varying wall temperature schedule, with fuel withdrawal occurring over the final 3-hour period to represent an extreme cold condition, long range flight; this schedule is shown in Figure 5, from data in Reference 1. With specification Jet A fuels, all fuel could be withdrawn, but there was evidence (from temperature gradients) of some solid formation at the time of minimum temperatures, and subsequent melting of the solid material. This is illustrated by the sequence of temperature profiles shown in Figure 6.

Sloshing, recirculation, and use of ejectors tended to decrease the temperature difference between the chilled walls and the bulk fuel and indirectly affected the holdup by altering the temperature profiles; this effect is seen in Figure 7. Tests with an internal baffle or with dehydrated fuel showed no change from comparable baseline tests.

Tests with an intermediate distillate fuel, treated with the addition of a suitable pour point depressant, provided a significant reduction in gravity holdup, compared to that of the undoped fuel. For the same temperature schedule, the treated fuel (No. 7) produced 10.2% holdup, compared with 25.5% for the untreated LFP-5 fuel. Tank results agreed with laboratory data reported by the manufacturer of the additive.

Figures 8, 9, 10, and 11 illustrate varying quantities of holdup.

Table 3 itemizes temperatures pertinent to freezing and subsequent gravity holdup.

Figure 12 shows the change in temperature at a specific height for various holdup quantities. Extrapolation of the curves to zero holdup always resulted in a temperature greater than freeze point. However, the effect was useful in controlling tests so as to produce variations in gravity holdup.

This experimental investigation provided considerable insight into the behavior of fuel at low temperatures representative of flight conditions. A rather large quantity of test data was obtained which could furnish material for further analysis.

Results of this investigation are reported in NASA CR-159615 "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model". References 1, 2, and 3 provide additional information relative to the use of aviation fuels at low temperatures.

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2. Pasion, A. J. "In-flight Fuel Tank Temperature Survey Data" NASA CR-159569, May 1979.
3. Pasion, A. J. "Design and Evaluation of Aircraft Heat Source Systems for Use with High-Freezing Point Fuels" NASA CR-159568, May 1979.

TABLE 1
DESIGNATION OF THERMOCOUPLE LOCATIONS

HEIGHT ABOVE BOTTOM		INITIAL LOCATION					T58 thru 100	
Cm.	In.	Rack 1	Rack 2	Rack 3	Rack 4	Rack 5	Rack 2	Rack 3
0	0	1	13	25	37	44	13	25
0.6	0.25	-	-	-	-	-	14	26
1.3	0.50	2	14	26	-	-	15	27
2.5	1.00	3	15	27	38	45	-	-
5.1	2.00	4	16	28	-	-	16	28
10.2	4.00	5	17	29	39	46	17	29
20.3	8.00	6	18	30	-	-	18	30
25.4	10.00	-	-	-	40	47	-	-
30.5	12.00	7	19	31	-	-	19	31
40.6	16.00	8	20	32	41	48	20	32
45.7	18.00	9	21	33	-	-	21	33
48.3	19.00	10	22	34	42	49	22	34
49.5	19.50	11	23	35	-	-	-	-
50.2	19.75	-	-	-	-	-	23	35
50.9	20.00	12	24	36	43	50	24	36

Thermocouples 51, 52, and 53 at centers of tank walls (fixed panels).
Thermocouples 54 and 55 on upper skin each side of longitudinal center.

TABLE 2 - FUELS EMPLOYED IN TEST PROGRAM

FUEL IDENTIF'N.	FUEL TYPE	CRUDE SOURCE	APPROX. FREEZE POINT, °C	APPROX. FINAL BOIL. PT., °C	SPECIFIC GRAVITY, 15°C
No. 1	Jet A	Unknown	-44	257	0.8132
No. 3	Distillate (Diesel D-2)	Unknown	+ 2	326	0.8612
No. 7	Intermediate with Additive	Paraffinic, Same as LFP-5	-31	294	0.8294
No. 8	JP-5	Shale Oil	-34	261	0.8029
LFP-1	Jet A	Paraffinic	-41	267	0.8017
LFP-3	Distillate	Paraffinic	-17	314	0.8285
LFP-4	Distillate	Naphthenic	-14	346	0.8545
LFP-5	Intermediate	Paraffinic	-28	295	0.8299
LFP-6	Intermediate	Naphthenic	-28	282	0.8478
LFP-7	Distillate	Paraffinic, Same as LFP-1	-10	316	0.8251
LFP-8	Jet A	Naphthenic, Same as LFP-6	-52	263	0.8273
LFP-9	Jet A	Paraffinic, Same as LFP-3	-46	255	0.8001

TABLE - 3 COMPARISON OF SOLID-LIQUID TEMPERATURES

CHARACTERISTIC	FUEL No. 1	FUEL No. 3	FUEL No. 7	FUEL No. 8	FUEL LFP-1	FUEL LFP-3	FUEL LFP-4	FUEL LFP-5	FUEL LFP-6	FUEL LFP-7	FUEL LFP-8	FUEL LFP-9
Average Freeze Point (from Appendix A)					-41	-17	-14	-28	-28	-10		-46
NASA Freeze Point	-38	-14	-31	-34	-42	-19	-16	-30	-29	-7	-52	-45
Shell Cold Flow Test, Zero Holdup					-43	-15	-24	-30	-30	-15		-45
Shell Pour Point					-47	-30	-37	-32	-36	-18		-48
Lockheed Pour Point	-52	-21	-46	-37	-51	-27	-26	-38	-38	-18	-53	-48
Solid/Liquid Interface	-47	-24	-45	-33	-44	-20	-22	-31	-32	-12	-54	-46

(All temperatures in °C)

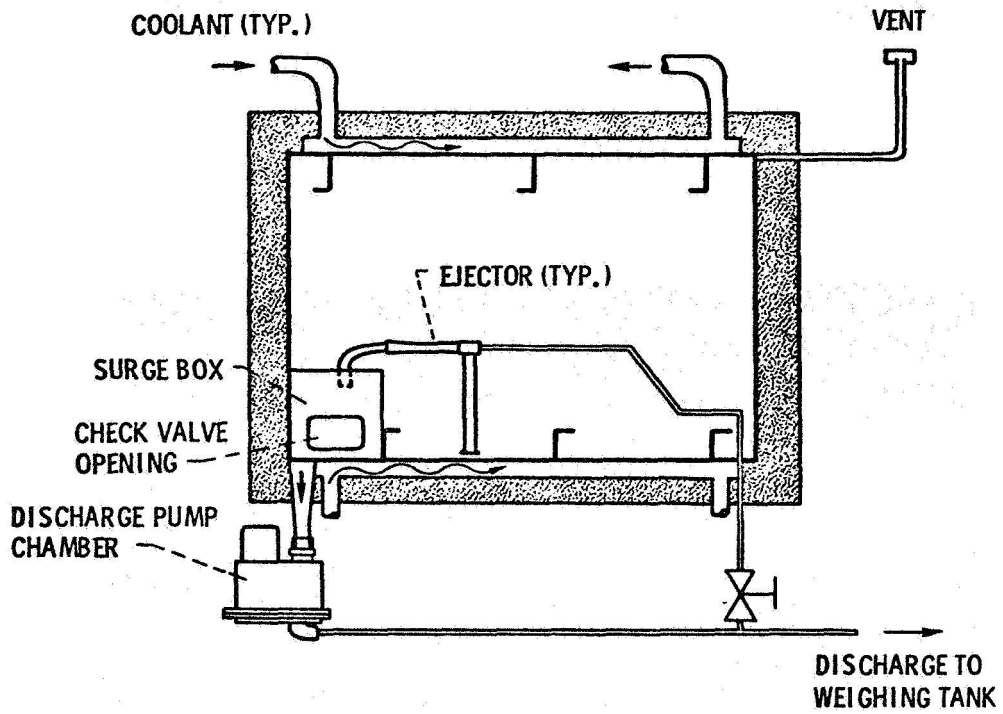


Figure 1. - Cross-section of apparatus.

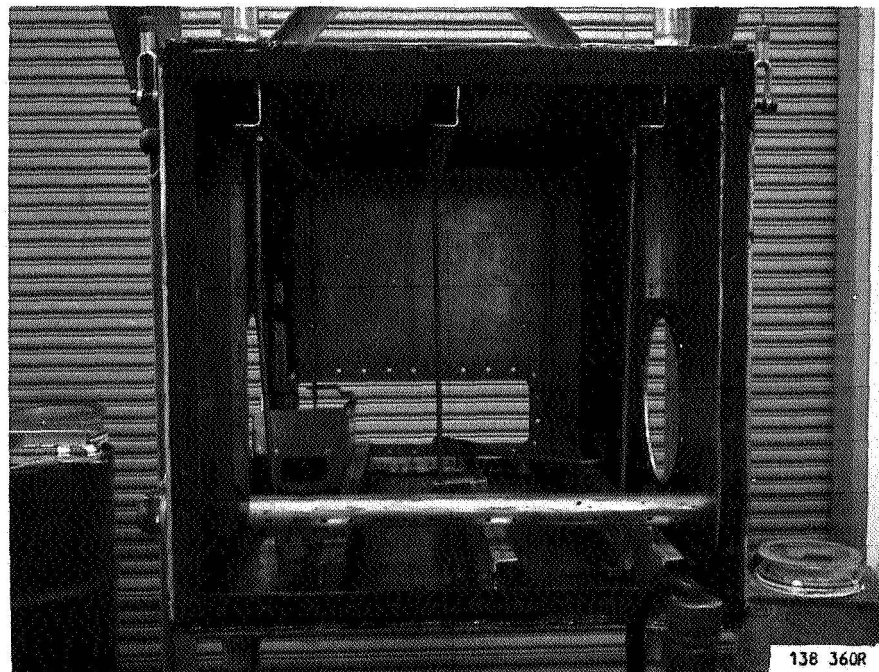


Figure 2 - Test Tank During Final Assembly, End Panel Removed

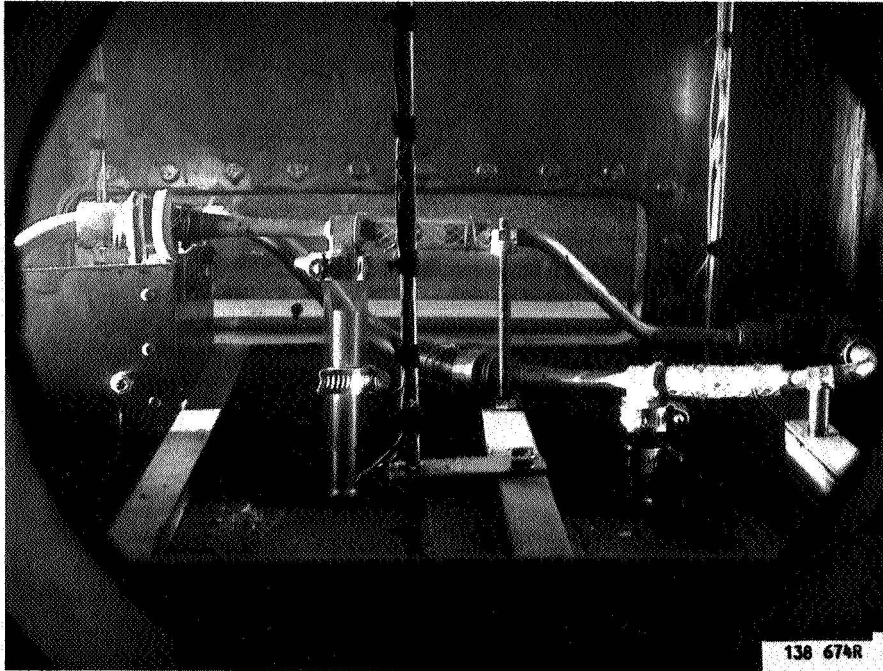


Figure 3 - Looking Through Fuel in Tank At Start of Test

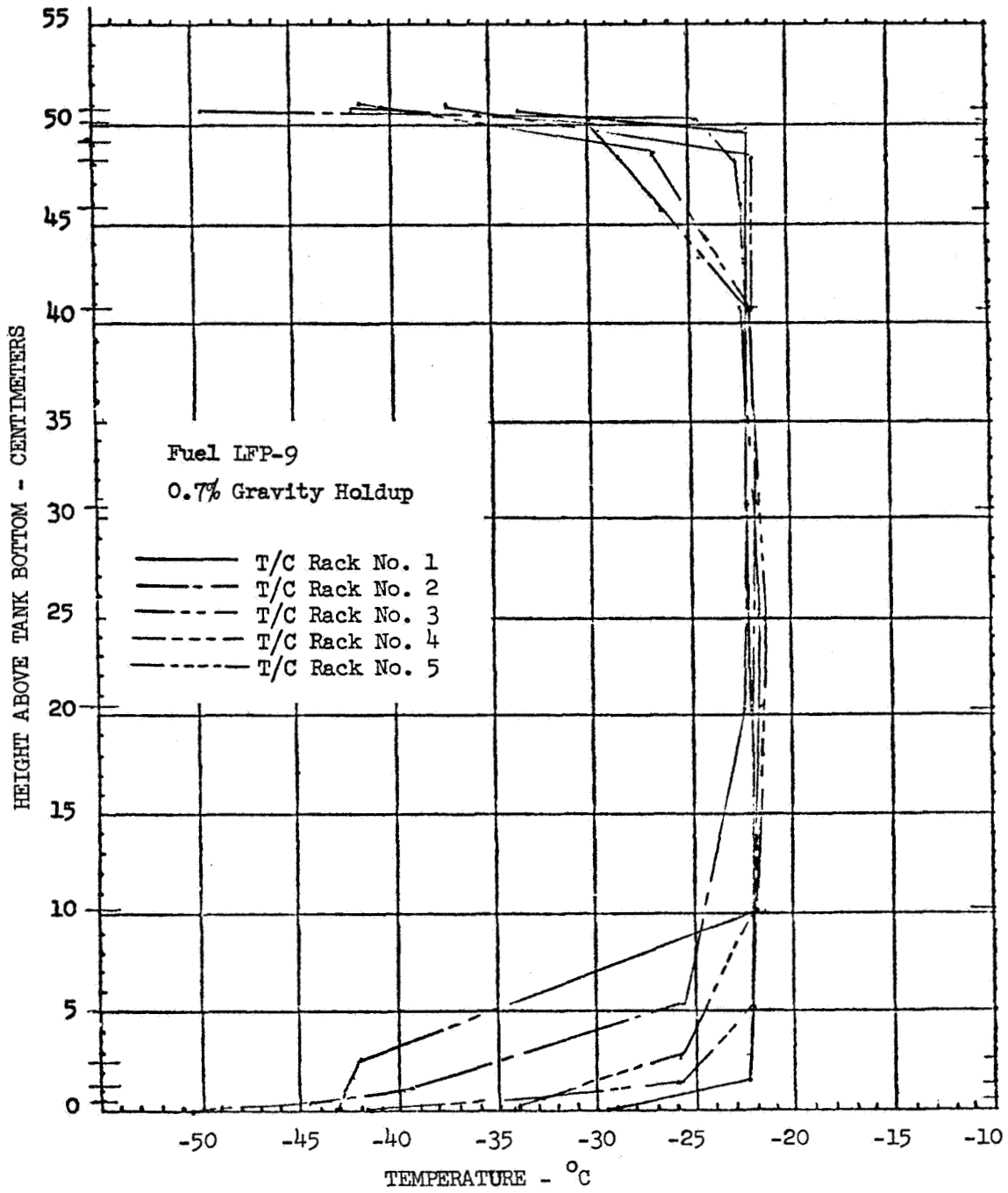


Figure - 4 Temperature Distribution at End of Test 75

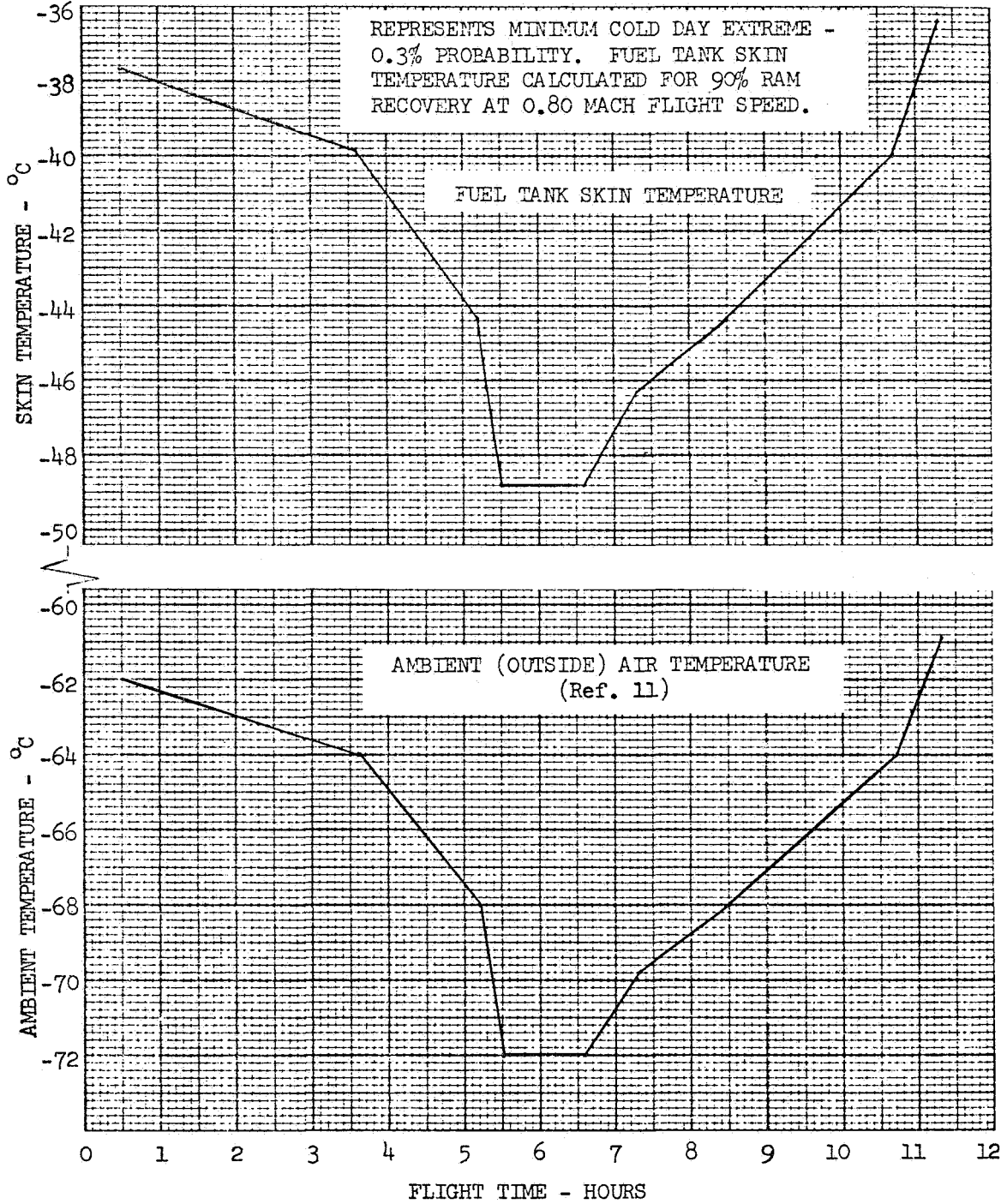


Figure - 5 Temperature Schedule for Scheduled Withdrawal Tests

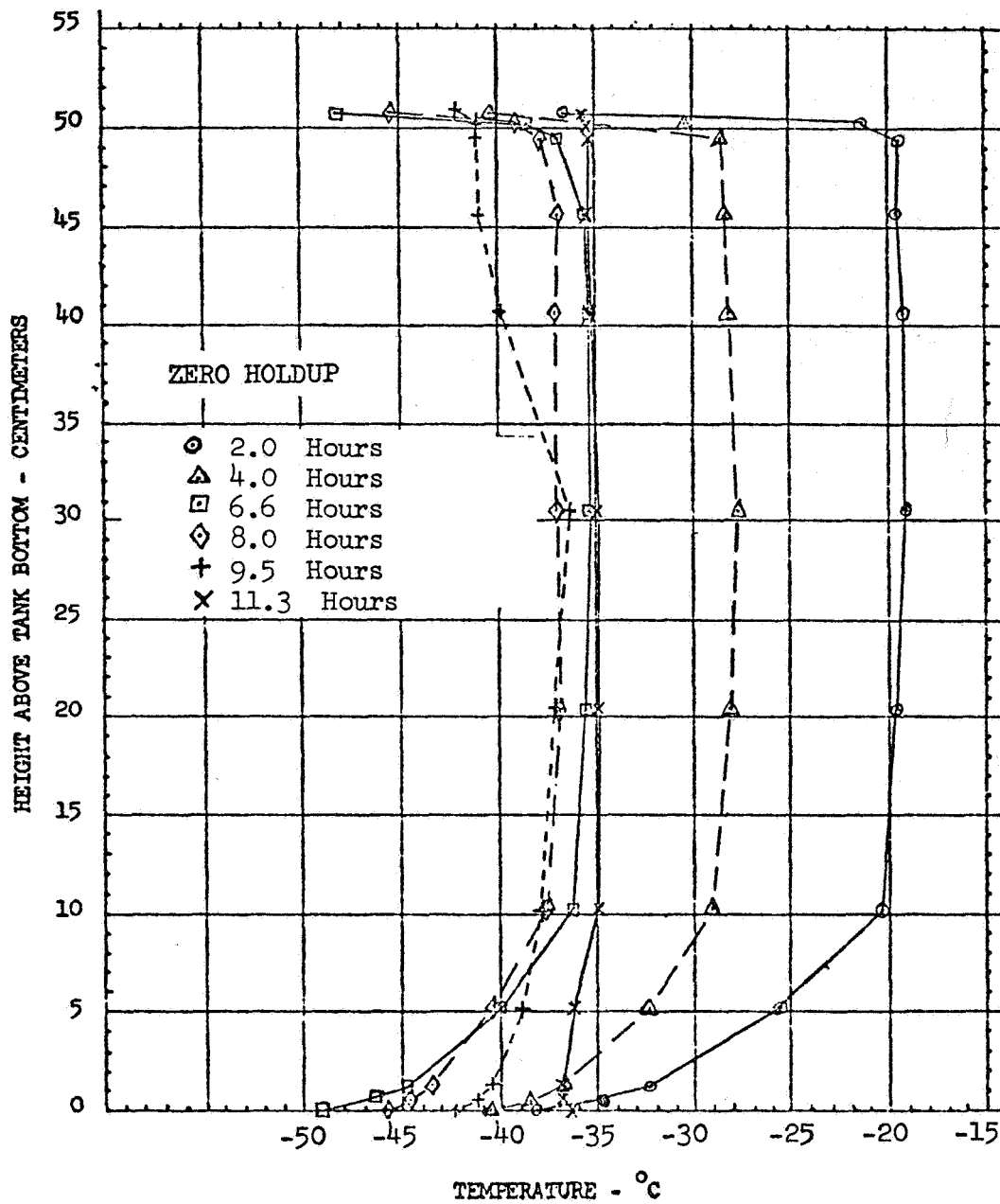


Figure - 6 Temperature Profiles at Center of Tank, Test 94
Scheduled Withdrawal, LFP-9 Fuel

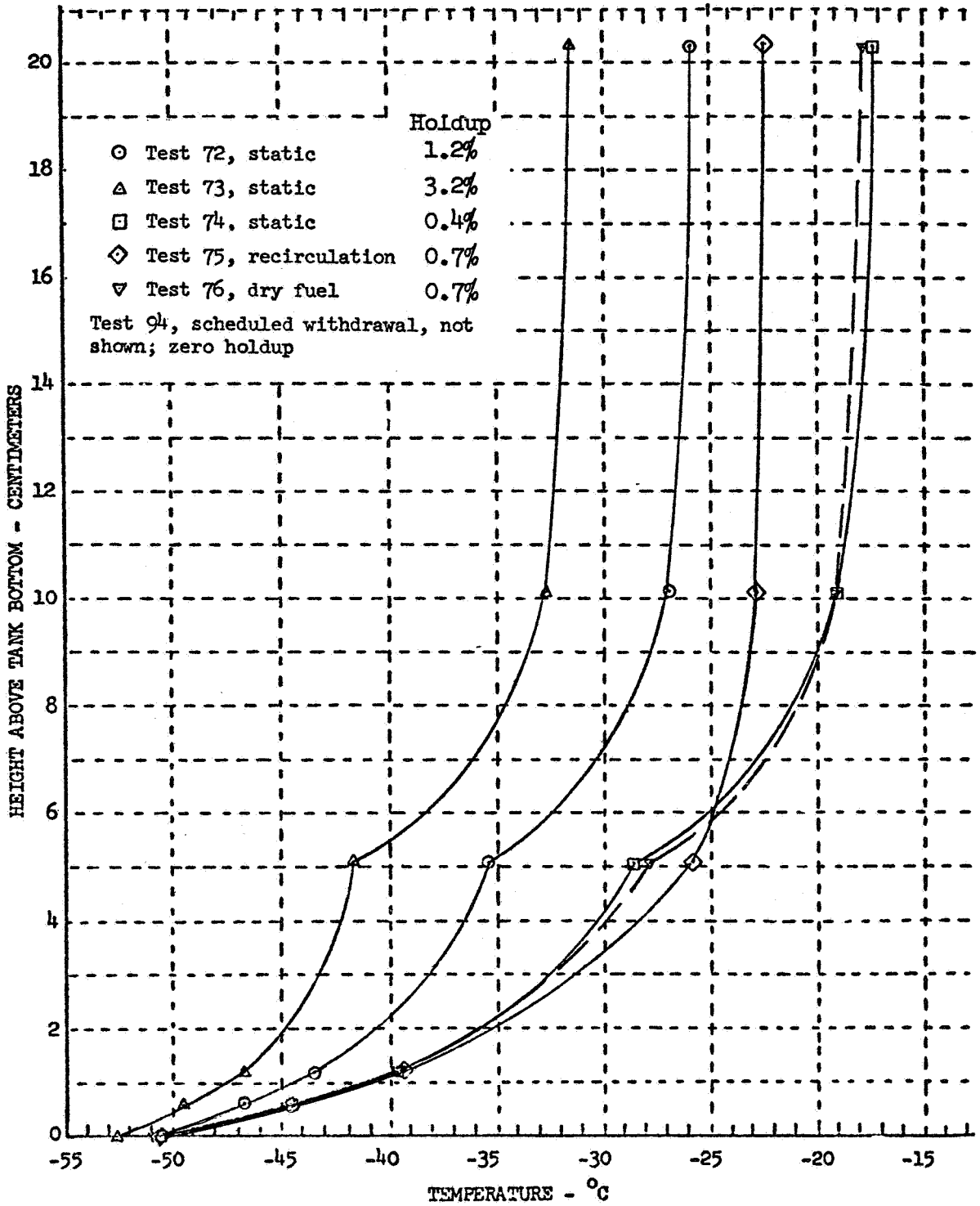


Figure - 7 Temperature Profiles from Center of Tank at End of Tests - Fuel LFP-9

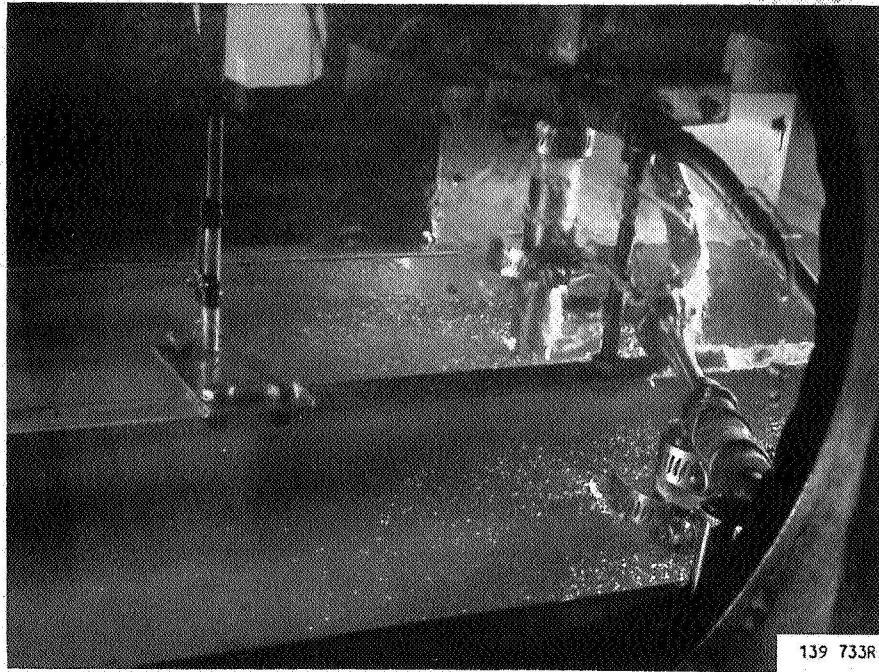


Figure 8 - Gravity Holdup of 3.2% at End of Test 73, LFP-9 Fuel

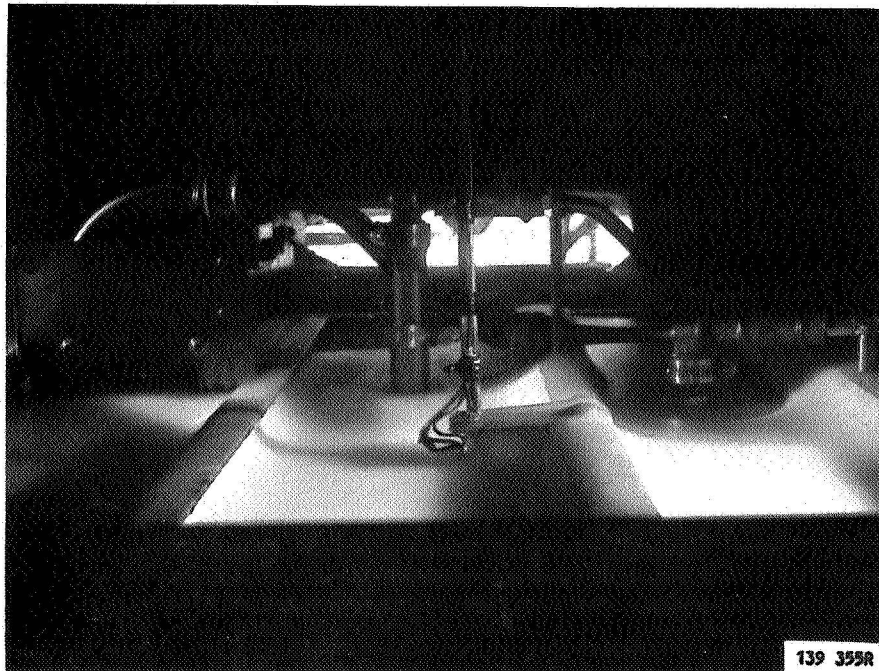


Figure 9 - Gravity Holdup of 4.5% at End of Test 46, LFP-7 Fuel

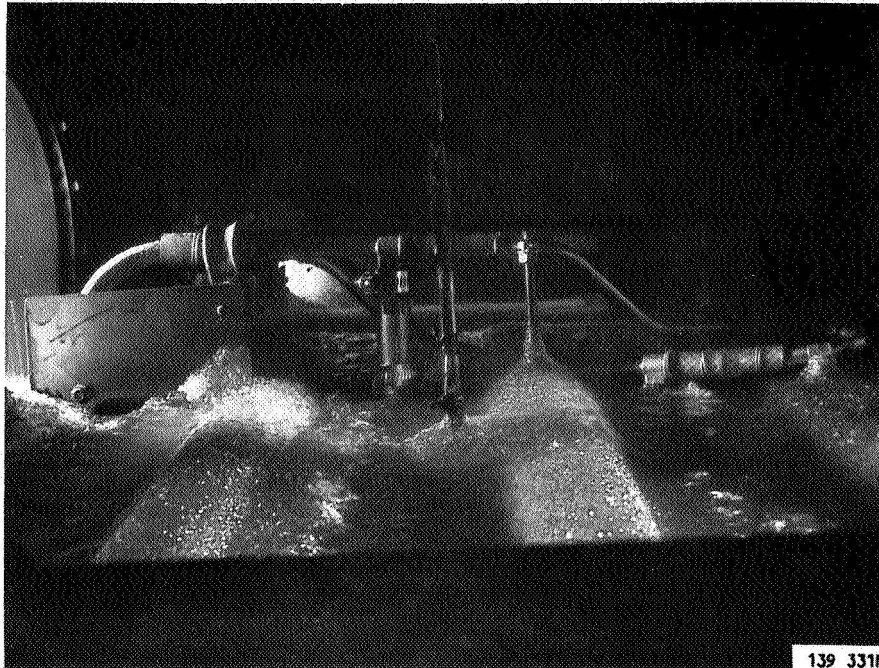


Figure 10 - Gravity Holdup of 8.8% at End of Test 41, LFP-6 Fuel

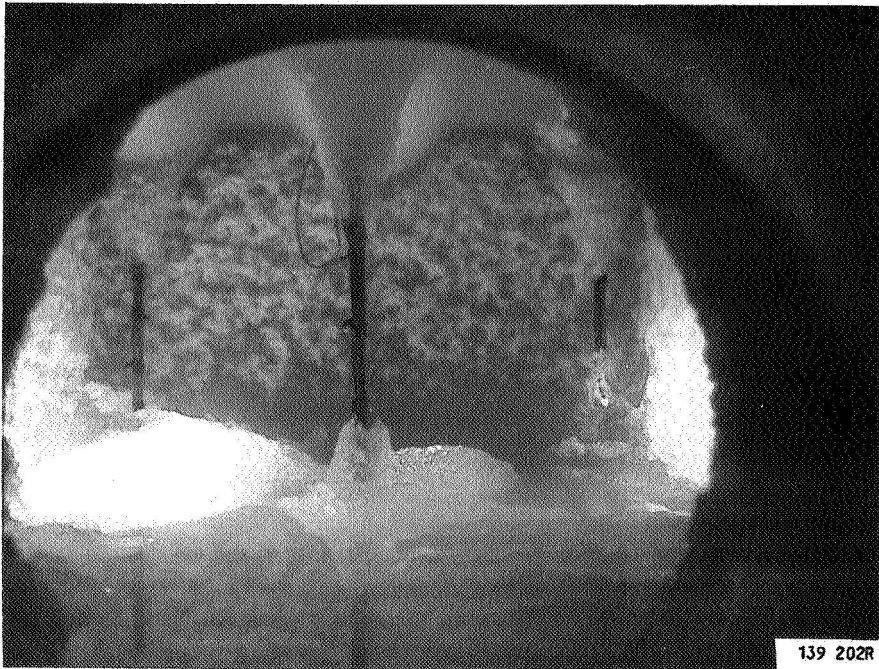


Figure 11 - Gravity Holdup of 57.2% at end of Test 36, LFP-1 Fuel

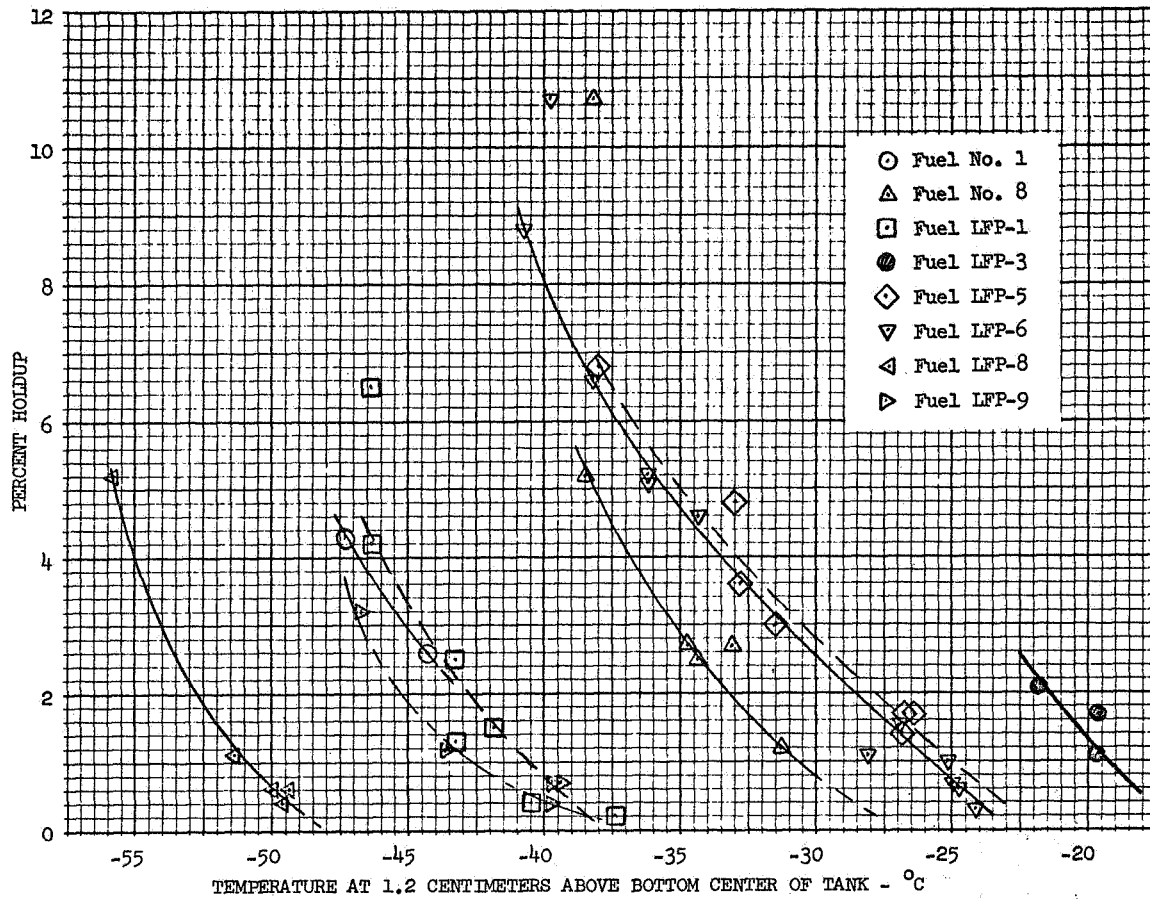


Figure - 12 Temperature at 1.2 Centimeters Above Bottom vs Percent Holdup

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