AD-P003 133

U.S. ARMY ALTERNATIVE GAS-TURBINE FUELS RESEARCH: MERADCOM

Dr. C. A. Moses
Southwest Research Institute
San Antonio, Texas USA

ABSTRACT

The U.S. Army's alternate fuels program is the responsibility of the Mobility Equipment Research and Development Command (MERADCOM). The research program on the effects of alternative fuels on gas turbine engine combustion is reviewed. Experimental programs have primarily concentrated on two areas of changing fuel properties; ~~one,~~ the effects of volatility on combustor performance characteristics such as ignition and combustion efficiency; and ~~two,~~ the effects of changing fuel chemistry on soot formation and flame radiation.

Introduction

Uncertainties about future production and supply of petroleum products have caused the U.S. Army, as well as other organizations responsible for fuel logistics and specifications, to study, in depth, the problems of combustion and engine performance and durability which are associated with fuel properties. The overall objectives of these studies are to develop the data and understanding necessary to consider the following options:

- Relaxing fuel specifications to increase availability
- Use of non-petroleum crude stocks to make "synthetic fuels"
- Temporary use of non-specification fuels in emergency situations.

Further goals are the development of design guidelines for engines which are more fuel tolerant, and the development of prophetic reference fuels to be used in the specification and qualification of power plants. The Army has these concerns for all three major engine types: spark ignition, compression ignition, and gas turbine; only the gas turbine engine and fuels will be addressed here.

The Mobility Equipment Research and Development Command (MERADCOM) has the responsibility within the U.S. Army for fuel specifications and R&D support for fuel-related field problems. However, the only mobility fuels for which MERADCOM has responsibility are gasoline and diesel fuel; the primary fuel for Army aircraft is JP4 (NATO F-40) which is the responsibility of the U.S. Air Force. Recognizing that the Army has a large inventory of gas turbine engines in its helicopter fleet, and having encountered some fuel-related field problems in Vietnam, MERADCOM has established a turbine-fuels research combustor laboratory at its Army Fuels and Lubricants Research Laboratory (AFLRL) located at Southwest Research Institute (SwRI). This facility enables the Army to conduct in-house research on combustor performance and durability problems which are related to fuel properties and to assist in the development and testing of new fuel concepts. The laboratory became operational in 1974 and has been used in a continuous sequence of programs to study ignition, flame stabilization, combustion efficiency, flame radiation, exhaust smoke, and gaseous emissions. The scope of fuels has included specification, alternative, and emergency fuels including synthetic fuels, alcohols and emulsified fuels.

To attain maximum flexibility for fuels/combustion research, the facility was designed as an air-factory to provide appropriate inlet conditions for the combustor being used. Conceptually any combustor can be plugged in and operated within the air flow, pressure, and temperature capabilities of the system. The operating envelope is as follows:

Air flow	0 to 1.1 kg/sec	(0 to 2.5 lb/sec)
Air pressure	100 to 1600 kPa	(1 to 16 atm)
Air temperature (heated)	150° to 800°C	(300° to 1500°F)
Air temperature (cooled)	-54°C to Ambient	(-65°F to Ambient)

Three combustor rigs are currently available.

- T63
- 2-inch
- Disc-in-duct

The T63 combustor is fabricated from T63 engine hardware. As illustrated in Figure 1, it is a single-can combustor with a dual-orifice pressure atomizer that is instrumented for flame radiation, liner temperatures, and exhaust emissions. Optical access is provided to view and photograph the combustion event. This combustor is especially useful in studying ignition, combustion efficiency, flame stabilization, and exhaust emissions; it also provides a means of verifying the results from the 2-inch research combustor on flame radiation and smoke. Turbine blade erosion and corrosion studies are also possible in this T63 combustor rig.

The 2-inch research combustor is a high-temperature, high-pressure combustor copied from the Phillips 2-inch combustor. Figure 2 shows the essential design features including the windows. It is capable of operating with burner inlet air temperatures up to 800°C at pressures up to 160 kPa and over a wide range of fuel/air ratio and reference velocity. This combustor is primarily used for flame radiation studies under high-pressure conditions. It can also be used for turbine blade erosion and corrosion studies.

The disc-in-duct combustor illustrated in Figure 3 is also a research combustor. Its main purpose is to simulate the primary zone of a real combustor and provide optical access to study ignition and atomization. Forward light-scattering techniques have been developed to measure drop-size distributions of evaporating fuel sprays.

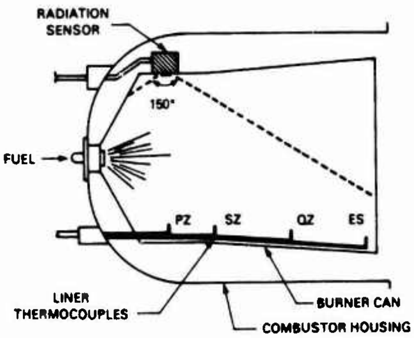


FIGURE 1. T63 ENGINE COMBUSTOR

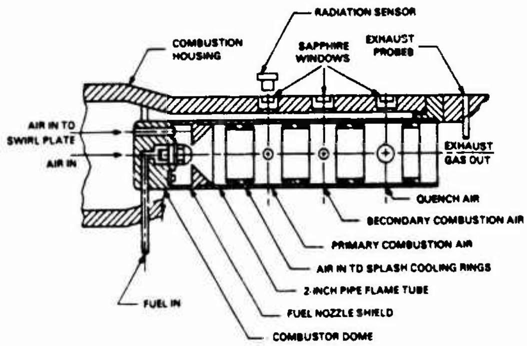
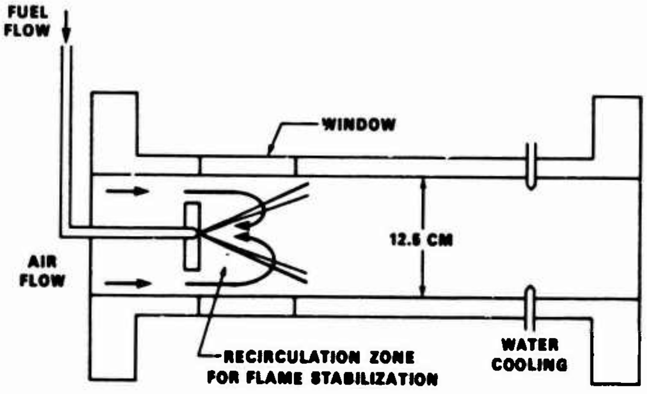


FIGURE 2. PHILLIPS 2-INCH COMBUSTOR



DISC DIAMETER - 7.18 CM

FIGURE 3. DISC-IN-DUCT COMBUSTOR

Future Fuels for Turbine Engines

Fuel properties of specification fuels can be expected to change for three reasons:

1. a relaxation of certain fuel property specifications which currently limit production in some producing regions
2. changes in refining procedures to upgrade lower-quality crude oils, generally higher in aromatics and sulfur, and to crack heavier crude stocks into light and middle distillate products
3. use of synfuels converted from shale oil and tar sands.

The use of non-specification fuels in emergencies as mentioned previously would most likely imply the use of diesel fuel or fuel oil either straight or as blending stock to extend jet-fuel supplies.

A number of studies have been reported in the literature on changing crude sources and refining trends and their impact on future gas turbine fuels (e.g., 1-3). Generally speaking, petroleum crudes will require more extensive use of mild hydrotreating to remove sulfur, and of hydrogenation to reduce aromatics and/or increase hydrogen content. Also there will be an increasing trend towards hydrocracking heavier fractions to increase the supply of middle and light distillate products. Hydrocracking and hydrogenation will also be used to make distillate from shale oil and tar sands.

The major impact of mild hydrotreating is fuel cost. More severe hydrotreating reduces the lubricity of the fuel as aromatics are saturated, and undefined contaminants, which also add to natural lubricity, are removed. Hydrocracked kerosene is distinguished by significant increases in naphthenes and in tetralin, decalin, and other multi-ring compounds as naphthalenes become saturated. Fuels from shale oil and tar sands appear to be similar to hydrocracked kerosene in that relatively large concentrations of tetralin and perhaps decalin are expected depending on the degree of hydrogenation. The presence of tetralin and decalin in the fuel leads to the formation of peroxides in the fuel, which can lower the stability of the fuel and cause problems with certain elastomers. Other contaminants found in shale oil, especially nitrogen, also reduce stability.

Emergency fuels, such as diesel fuel or blends of diesel fuel with aviation fuel, can be characterized primarily as having a higher end-point and viscosity, a higher freeze point, lower thermal stability, and lower volatility. Data are presented in Figure 4 for blends of JP5 and two different DFM's to illustrate the potential impact on thermal stability, viscosity, and final boiling point.(4) Other possibly significant degradations in the quality of emergency fuels are reduced hydrogen content, increased aromatics, and increased naphthalenes.

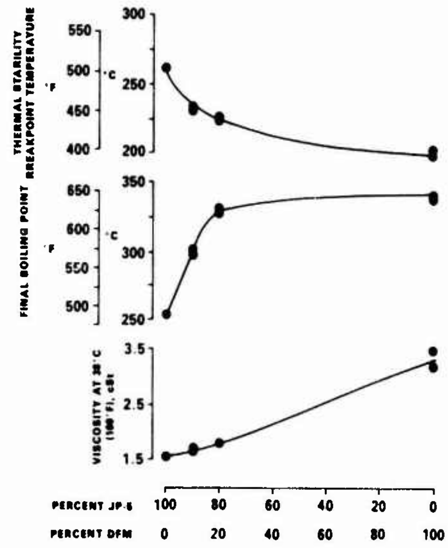


FIGURE 4. EFFECTS OF BLENDING DFM INTO JP5

Impact of Future Fuels on Vehicle Systems

Table I summarizes the initial fuel properties identified above and identifies the area of impact in the performance and durability of vehicle fuel systems and engines. Only three of the properties, hydrogen content, viscosity, and boiling point distribution directly affect combustion and will be the subject of the remainder of this paper.

Table I. Summary of Critical Fuel Properties and Their Impact on Aircraft Systems

Fuel Property	Impact Area	Performance/Durability Problem
Reduced hydrogen content	Soot formation	Combustor liner durability Exhaust smoke
Hydrocarbon composition Contaminants	Materials compatibility	O-rings, seals, and diaphragms in valves, fuel controls, etc.
Lubricity	Wear	Fuel pumps and controls
Thermal stability	Hot fuel deposits	Flow-divider valves Fuel atomizers
Viscosity and boiling-point distribution	Atomization and fuel/air mixing	Cold-day ignition Altitude relight Combustion efficiency Gaseous emissions

For convenience, the following technical discussion is organized according to problem areas rather than by fuel properties. The discussion is a summary of several studies conducted in the AFLRL combustor lab on fuel properties and their impact on turbine combustion; these studies were either conducted for MERADCOM or sponsored by the Navy, Air Force, or NASA with MERADCOM approval.

Soot Formation: Flame Radiation and Exhaust Smoke

Soot formation is important in gas turbine combustion for two reasons: increased flame radiation and exhaust smoke. An increase in flame radiation will increase the heat load to the liner, thus raising the liner temperatures and reducing the thermal fatigue-life of the liner. Exhaust smoke is that soot which is not oxidized in the secondary and quench zones; the major military concern is the increase in visible signature of the vehicle.

Soot formation in the primary zone is to a large part determined by combustor design, i.e., the stoichiometry and mixedness of the primary zone; however, fuel properties can play an important role. Currently, the soot-forming tendencies of jet fuels are controlled by the aromatic content and the so-called smoke point. Other distillate fuels, such as diesel fuel, are not controlled for this property. These controls have proved satisfactory for light-distillate jet fuels composed primarily of paraffins and single-ring aromatics (alkylbenzenes). The validity of these tests becomes suspect as fuel chemistry changes, e.g., more cycloparaffins, tetralins, and naphthalenes, and as viscosities increase; viscosity affects both the diffusion flame on the wick lamp used for the smoke point test and the FIA (ASTM D-1319) test used for measuring aromatic content.

One of the objectives of a series of combustor studies has therefore been to determine which fuel properties, physical and chemical, are important to soot formation in gas turbine combustors. Figure 5 reproduces data from an early program(5) using the 2-inch combustor to evaluate chemical properties. "Wt% ring carbon" is a measure of how much of the carbon is in aromatic ring structures as opposed to side-chains or saturated molecules; it differs from "aromatic content" in that the former procedure effectively counts only the aromatic rings while the latter counts aromatic molecules. If "aromatic content" were the fundamental fuel parameter, then the ring structure itself should be important. In Figure 5, hydrogen content and aromatic content appear to be of about equal value as correlating parameters, while ring-carbon is seen to be a relatively poor correlating parameter. This suggests that the aromatic ring structure itself is not important, and that aromatic content correlates the data well only because of the lower hydrogen content of the aromatic molecules.

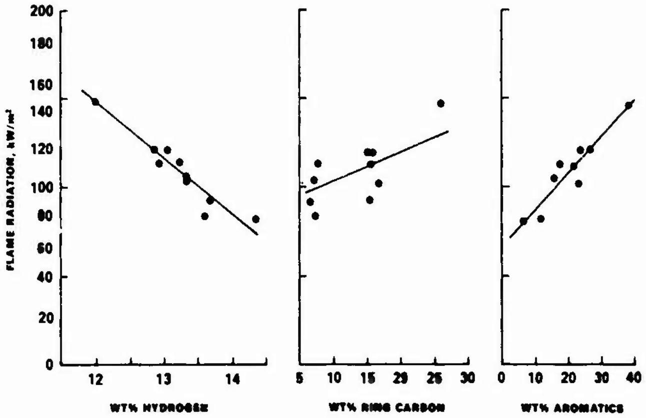


FIGURE 5. CORRELATIONS OF FLAME RADIATION WITH FUEL PROPERTIES

Subsequently, these same fuels along with 17 others were evaluated in the T63 combustor for their effects on flame radiation and smoke.(6) The additional fuels emphasized physical properties, such as viscosity and boiling-point distribution, as well as water/fuel emulsions and blends of methanol and aromatics. Figures 6 and 7 present the flame radiation data from these fuels as correlated against aromatic content and hydrogen content. Here the strength of the hydrogen correlation is more dramatic than in the previous example. The solid line in Figure 6 is drawn through the data for fuels which are simple blends of petroleum JP5 with aromatics. This illustrates that while the aromatic content correlates the soot-forming tendencies of petroleum-derived fuels, it is less acceptable for the synthetic hydrocarbon fuels and not at all adequate for the more unorthodox fuels. Contrast this with Figure 7 which shows that hydrogen-carbon ratio adequately correlates all of the data. These results indicate that soot formation is essentially independent of molecular structure. Note also that some of the jet fuels were blended with 10, 20, and 40 percent diesel fuel (DFM) and two of the fuels were DFM's. Since these increases in viscosity and end point did not affect their correlation, the combustion quality of such emergency fuels can be controlled by hydrogen content.

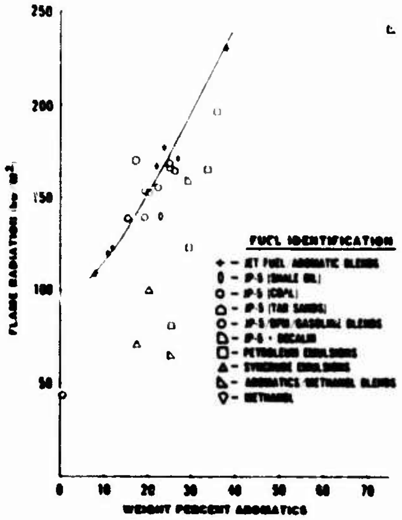


FIGURE 6. EFFECT OF AROMATIC CONTENT ON FLAME RADIATION

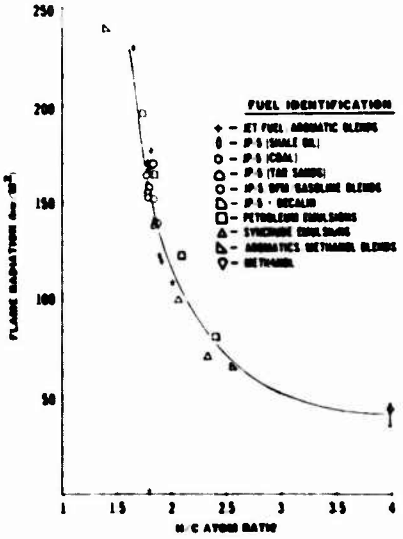


FIGURE 7. EFFECT OF HYDROGEN TO CARBON RATIO ON FLAME RADIATION

The fuels used in the above discussion did not contain significant amounts of such compounds. There have been some suggestions that polycyclic aromatics such as tetralins and naphthalenes might not follow the simple hydrogen correlation discussed above. For this reason, a study was conducted in the 2-inch combustor using 6 test fuels which all had a hydrogen content of 12.8 percent, but which stressed end point and polynuclear compounds, i.e. decalin, tetralin, naphthalene, and anthracene.(7) Again there was no effect of increased end point. The fuels with single-ring aromatics, single-ring cycloparaffins (naphthenes), and double-ring cycloparaffins (decalin) followed a simple hydrogen correlation; however, the fuels with the polynuclear aromatics produced more soot than their hydrogen content would suggest. Also this increase in radiation varied with combustor operating conditions. However, when these same fuels were burned in the T63 combustor, there was no difference in the measured flame radiation between the polycyclic aromatics fuels and the base fuels blended to the same hydrogen content. Thus the evidence indicates that fuels containing significant amounts of polynuclear aromatics (>5%) can produce more soot than their hydrogen content would predict, but that the increase is dependent on the combustor design and operating conditions.

A further study was then conducted with 14 test fuels containing alkyl-benzenes, methyl naphthalenes, tetralin, and indene blended into a Jet A fuel to produce hydrogen contents of 11.5, 12.5, and 13.5 percent.(8) These fuels were than burned in the 2-inch combustor over a wide range of operating conditions to determine the separate effects of temperature, pressure, fuel-air ratio, and reference velocity.

The sooting tendencies of the polycyclic aromatics themselves was determined by comparing the sensitivity to H/C ratio of fuels containing polycyclic aromatics to those with only single-ring aromatics. The difference was assumed attributable to the polycyclic aromatics. These trends are reproduced in Figure 8 showing the individual effects of temperature, fuel-air ratio, density, and reference velocity. The actual values are probably unique to this combustor, but the trends may apply to other combustors. If so, one would expect that engines would tend to be less sensitive to polycyclic aromatics at the full power condition where fuel-air ratios are greatest as are the burner inlet temperature and density. This is a desirable trend, since the full power condition is associated with the highest levels of soot formation and the highest liner temperatures, i.e., at the worst condition there is the least sensitivity to the polycyclic aromatics.

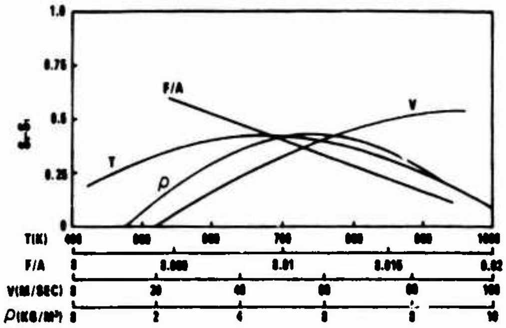


FIGURE 8. EFFECTS OF OPERATING PARAMETERS ON THE INCREASED SENSITIVITY OF THE SOOTING TENDENCY DUE TO POLYCYCLIC AROMATICS

In summary, this series of studies has shown that hydrogen content (or hydrogen-carbon ratio) is the essential fuel property for controlling soot formation in fuels which do not contain appreciable amounts of polycyclic aromatics. This is in agreement with other researchers, but the extension to include alcohols as well as emulsions of water or alcohol with hydrocarbon fuels strengthens this claim significantly. The presence of polycyclic aromatics in the fuel can lead to higher levels of soot formation depending upon the combustor operating conditions. Such compounds are not generally found in fuels in concentrations greater than a couple percent naphthalenes and a few percent tetralines/indenes; the impact of such concentrations is not significant.

Atomization and Fuel/Air Mixing

The ignition characteristics of an engine are highly dependent upon the design characteristics, e.g., ignitor energy and location, air flow pattern and velocity, and air-fuel ratio; however, fuel properties play an important role in determining how the air and fuel are mixed. Viscosity is the major fuel property that controls the size(s) of the droplets in the fuel spray; density and surface tension are also factors but do not change as much as viscosity over the range of candidate fuels. A typical relationship for a simplex pressure atomizer as correlated by Jasuja(9) is given in equation (1):

$$\mathrm{SMD} = \nu^{0.16}\ \sigma^{0.6}\ W_f^{0.22}\ \Delta P_f^{-0.43} \tag{1}$$

where ν and σ are the viscosity and surface tension of the fuel and W_f and ΔP_f are the fuel flow rate and pressure drop across the nozzle. Higher viscosity fuels result in larger SMD's (Sauter mean diameter).

The boiling point distribution, i.e., volatility, governs the evaporation rate and hence the mixing of the fuel with the combustion air. Equation (2) shows the D^2-law for droplet evaporation in quiescent air (the modifications for convection are not necessary for this discussion):

$$\tau = \frac{D_o^2\ \rho_f\ C_{pa}}{8\ K_a\ \ln(1+B)} \tag{2}$$

where τ is evaporation time for a drop of initial diameter D_o and density ρ_f, C_{pa} and K_a are the heat capacity and thermal conductivity of the air. The important parameter here is the transfer number B; physically it represents the ratio of energy available for evaporation to the energy required, or

$$B = \frac{C_{p,a}\ (T_\infty - T_f)}{L + C_{p,f}\ (T_f - T_i)} \tag{3}$$

Here T_∞ is the temperature of the surrounding medium and T_f is the boiling point of the liquid. For most fuels, T_f is not unique, but rather there is a boiling point distribution. Foster and Straight(10) and Peters and Mellor(11) have correlated ignition limits using the 10 percent evaporation point of the fuel. It is not clear, however, what should be used for T_∞ for an ignition problem. Peters and Mellor used the average of the ambient and the stoichiometric, adiabatic flame temperatures (approximately 1300K). Such argument is beyond the scope of this paper. It is sufficient to note that fuels with higher boiling ranges give a smaller value for B and hence a longer evaporation time.

Figure 9 reproduces some data from Ballal and Lefebvre(12) illustrating a combined effect of viscosity (drop size, SMD) and boiling range on the ignition energy. As would be expected, higher ignition energies are required for fuels of lower volatility and higher viscosity (larger SMD).

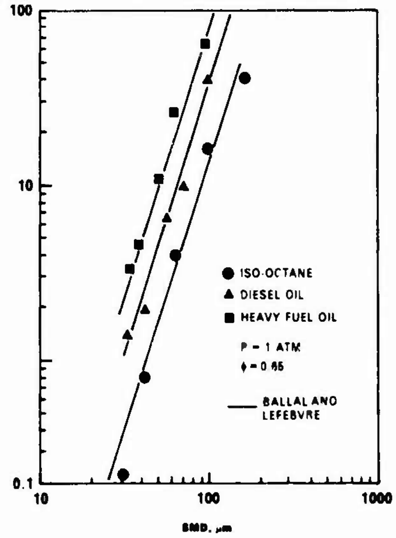


FIGURE 9. MINIMUM IGNITION ENERGY VERSUS SMD FOR QUIESCENT MIXTURES (Data from Ballal and Lefebvre(12))

In a gas turbine engine, these effects would be manifested in those performance areas which are mixing controlled rather than kinetic controlled, e.g.,

- ignition and altitude relight
- flame stabilization (lean blow-off)
- combustion efficiency and gaseous emissions
- exhaust temperature pattern factor.

Of these, ignition and altitude relight are the most significantly affected.

The first MERADCOM/AFLRL investigation into the fuel effects on ignition was conducted using JP4, Jet-A, and DF2 fuels.(13) Figure 10 shows the relative ignition characteristics of these fuels as the time required for ignition for a given fuel flow rate, all air-flow conditions and spark energy being held constant. For a given fuel, the characteristics are typical: at low flow rates, there is no ignition; then as the flow rate is increased, ignition becomes marginal; and finally, at sufficiently high flow rates, ignition is almost immediate. The more volatile and less viscous JP4 was ignitable at lower flow rates than the Jet-A which was easier to light than the DF2. Also included in Figure 10 are the ignition limits for blends of pentane with the DF2 to show that blending a more volatile material into the heavier diesel fuel will improve the ignition characteristics. About 8 percent pentane was required to match the vapor pressure of the JP4, but adding 10 percent to the Jet-A and 20 percent to the DF2 did not reduce their ignition limits to that of the JP4. Thus, adding more volatile components to increase the vapor pressure is helpful, but vapor pressure may not be a sufficient parameter to predict ignition limits with blends.

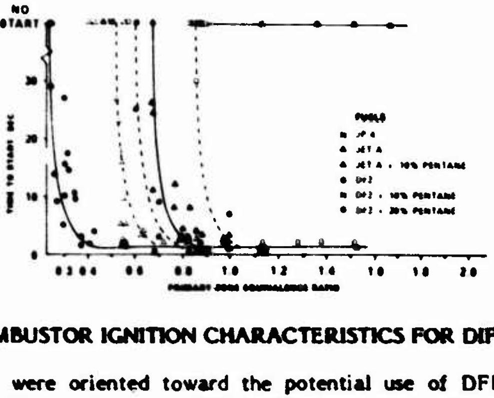


FIGURE 10. COMBUSTOR IGNITION CHARACTERISTICS FOR DIFFERENT FUELS

Subsequent ignition studies were oriented toward the potential use of DFM as a blending stock for Navy aircraft.(5) Test fuels included 10, 20 and 40 percent DFM in JP5 along with gasoline, two DFM's, and a gasoline/DFM blend. Figure 11 shows the thresholds for instantaneous ignition, but without the detailed data points of Figure 10. As would be expected, the gasoline had the leanest limit and the DFM's were the most difficult to ignite requiring much higher fuel flow rates. Adding 30 percent gasoline to the DFM made a significant improvement in the ignition limit. There is an inconsistency in the JP5/DFM blends; in some cases the limits appear to have been improved by the addition of DFM. Unfortunately the inlet air temperature was dictated by the ambient air and could not be controlled. During the tests the air temperatures varied by several degrees which accounts for the relative positioning of the ignition limits for these blends rather than according to their viscosity (increasing DFM). While this precludes a quantitative evaluation, it appears that blending DFM into JP5 would not seriously degrade the ignition requirements on warm days. Subsequent combustor studies by the Navy and Air Force have shown some degradation of cold-start and altitude relight limits.

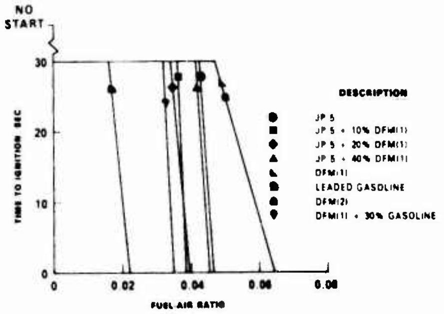


FIGURE 11. FUEL EFFECTS ON FUEL-AIR RATIO REQUIRED FOR IGNITION

The following is a brief look at the other, less critical performance areas listed above. Figure 12 compares the lean blow-off equivalence ratios for the nine fuels mentioned earlier ranging from gasoline through JP5 to diesel fuel (DFM) and blends thereof.(5) The data were taken at four different power conditions in the T63 combustor --10%, 40%, 50%, and 100%; engine power is represented by the air loading parameter, θ :

$$\theta = P^{1.75}\ A_{ref}\ D_{ref}^{0.75}\ \exp\ (T/300)$$

where P and T are the combustor inlet air pressure and temperature; A and D are reference area and dimension of the combustor. The fuel effects are more pronounced at the lower power conditions where the gasoline could be burned under much leaner conditions. There was very little difference among the jet/diesel fuel blends, however.

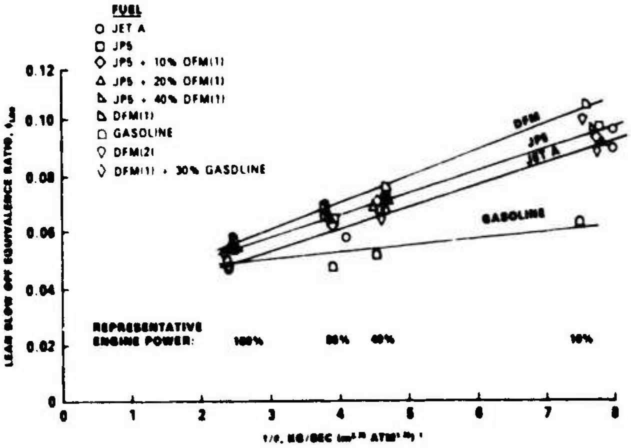


FIGURE 12. FUEL EFFECTS ON FLAME STABILIZATION

Combustion efficiency calculations were made for these same fuels burned in the T63 combustor from measurements of CO, CO_2, and HC as a ratio of energy actually released in the reaction to the energy that would have been released if the fuel had been totally oxidized to CO_2 and H_2O. Figure 13 shows that the range of the fuel effects is relatively minor except at the idle condition. Although the details are excluded, the jet fuels gave the highest efficiency, the diesel fuels the lowest, with the blends in between.

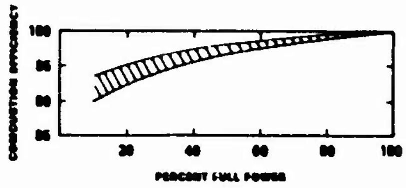


FIGURE 13. RANGE OF FUEL EFFECTS ON COMBUSTION EFFICIENCY

A similar result is seen in Figure 14 for the gaseous exhaust emissions, CO, HC, and NO_X. For the CO and hydrocarbons, the fuel effects are greatest at idle where the emissions are highest due to poorer mixing and lower temperatures which are aggravated by the poorer atomization and evaporation of the diesel fuels. The oxides of nitrogen exhibit the opposite trend with engine power since their formation is so highly temperature dependent. The fuel effects are fairly uniform across the power spectrum, and, while the more viscous fuels generally yielded higher concentrations of NO_X, the highest concentrations were obtained from the gasoline. This is presumably because of the high local stoichiometry in the primary zone caused by the rapid vaporization of the gasoline.

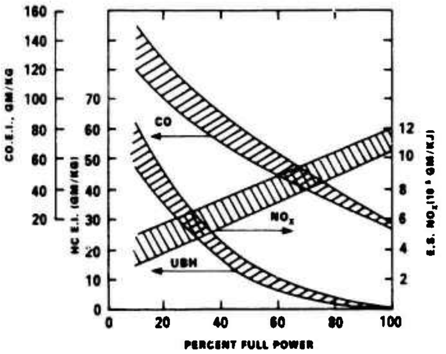


FIGURE 14. RANGE OF FUEL EFFECTS ON GASEOUS EMISSIONS

None of these fuel effects on emissions or combustion efficiency is considered critical. While the magnitude of such fuel effects are certain to be dependent on the combustor design, these conclusions have been confirmed in recent years in U.S. Air Force and Navy sponsored combustor programs on a variety of engine design and sizes.

Summary

Combustor test programs on alternative and emergency fuels have been conducted in the U.S. Army Fuels and Lubricants Research Laboratory over a period of years to identify which fuel properties appear to control certain problems in combustor performance. The types of fuels and the range of fuel properties have encompassed the fuels likely to be used in aircraft gas turbines over the next 20-30 years.

The most important problem areas would appear to be the following:

Performance Area	Controlling Fuel Property	Performance Problem
Ignition	Viscosity, Volatility	Degradation of cold-day ignition and altitude relight limits
Soot Formation	Hydrogen content	Reduced liner life increased exhaust smoke

Other non-combustion problems not addressed in this paper include thermal stability, materials compatibility, and lubricity.

Research on the influence of the physical and chemical properties of fuels on engine and aircraft performance and durability is very important right now as opposed to simply qualifying a system on a fuel specification. By identifying the critical fuel/hardware interfaces and developing quantitative models and impact statements, the impact of potential changes in fuel specifications, crude sources, and refining techniques can be minimized. More importantly, the high cost of requalifying every engine and aircraft to ensure their compatibility with new fuels can be reduced by concentrating on critical or representative systems and components.

REFERENCES

1. Sefer, N.R. and Moses, C.A., "Crude Sources and Refining Trends and Their Impact on Future Jet Fuel Properties," SAE Paper No. 811056, October 1981; SAE Transactions, Vol. 90, 1981.

2. Dickson, J.C. and Karvelas, L.P., "Impact of Fuel Properties on Jet Fuel Availability," AFAPL-TR-76-7, U.S. Air Force Air Propulsion Laboratory, Wright-Patterson AFB, OH, April 1976.

3. Liberman, M. and Taylor, W.F., "Effect of Refining Variables on the Properties and Composition of JP5," Final Report Contract No. N00140-78-C-1491. Naval Air Propulsion Center, Trenton, NJ, November 1980.

4. Speck, G.E., "Feasibility of Marine Diesel Fuel as an Emergency Aircraft Fuel, "Report No. NAPC-PE-44, Naval Air Propulsion Center, Trenton, NJ, February 1981.

5. Moses, C.A. and Naegeli, D.W., "Fuel Property Effects on Combustor Performance," ASME Paper No. 79-GT-178, March 1979.

6. Naegeli, D.W. and Moses, C.A., "Effects of Fuel Properties on Soot Formation in Turbine Combustion," SAE Paper No. 781026, November 1978.

7. Naegeli, D.W. and Moses, C.A., "Effect of Fuel Molecular Structure on Soot Formation in Gas Turbine Engines," ASME Paper No. 80-GT-62, March 1980.

8. Naegeli, D.W., Dodge, L.G. and Moses, C.A., "Sooting Tendencies of Fuels Containing Polycyclic Aromatics in a Research Combustor," AIAA Paper 82-0299, Journal of Energy, Vol. 7, No. 2, March-April 1983, p 168.

9. Jasuja, A.K., "Atomization of Crude and Residual Fuel Oils," ASME Paper No. 78-GT-83.

10. Foster, H.H. and Straight, D.M., "Effect of Fuel Volatility Characteristics on Ignition Energy Requirements in a Turbojet Combustor, NACA RME52J21, 1953.

11. Peters, J.E. and Mellor, A.M., "An Ignition Model for Quiescent Fuel Sprays," Combustion and Flame, Vol. 38, p 65, 1980.

12. Ballal, D.R. and Lefebvre, A.H., "Ignition and Flame Quenching of Quiescent Fuel Mists," Proc. R. Soc. Lond. A. 364, p 277, 1978.

13. Moses, C.A., "Studies of Fuel Volatility Effects on Turbine Combustor Performance," presented at the 1975 Joint Meeting of Western and Central States Sections of The Combustion Institute, San Antonio, Texas April 1975.

DISCUSSION

J.Tilston, UK

This paper contains references to differences in liner temperatures of the order of 11°C due to changes of fuel type. In our research we would expect very much higher differences than this, due entirely to day to day variations in rig operation or errors in establishing datum conditions after an in-run fuel change. Could Dr Moses please explain how these measurements are made?

Author's **Reply**

These data were not mine but taken at General Electric so if I may I will refer the question to Mr Willard Dodds of that company.

W.Dodds

We at General Electric have acquired much experience in alternative fuels testing, and often detect temperature changes of 11°C or less, using surface mounted thermocouples on the combustor liners. We have consistently seen this effect in dozens of combustor tests. Also, we see consistent changes in the output of a majority of the thermocouples mounted on the combustor liners (20 to 40 thermocouples are normally used for this type of test). In fact, we have repeatedly observed a larger change in liner temperature in the forward positions of the combustor (where flame radiation effects are strongest) than in the aft portions. There are three additional considerations. Firstly, we always report liner temperature relative to combustor inlet temperature. This corrects for small variations in inlet temperature. Secondly, we use exactly the same thermocouples for comparisons. Reinstrumentation of a combustor liner can make a significant difference in details of measured liner temperature. Finally, we measure temperatures at several different operating conditions with many different fuels, over a fairly wide range of properties (typically 12 to 14.5% hydrogen content), and use statistical analyses to establish fuel effects, so it is not merely a comparison of two test data.

J.Odgers, Ca

In your discourse you stated that a difference of 11°C in wall temperature could reduce the combustor life by some 25 percent. I find this very disturbing since when I was in industry two production combustors taken from the assembly line could show a temperature difference of 20°C, or even 40°C when measured at the same position. Since we can rarely measure wall temperatures better than ±20°C in regions of steep temperature gradients, the statement is even of greater concern. I would welcome your comments on this matter.

Author's Reply

I did not develop the data to which you refer myself and would again like to refer the question to Mr Willard Dodds from General Electric.

W.Dodds

When you say that you measured two different combustors in the same position, I would not be surprised if you observed 20°C difference in the temperature. In fact, if you ran a test with a thermocouple in a certain location and attempted to replace it with an identical thermocouple in the identical location, you would probably measure a different temperature in a subsequent test. However, if the combustor and instrumentation are not disturbed, very close agreement can be obtained. As for life analyses, these are described in two reports by Gleason et al. (references 2 and 3 in my paper). A simplified life estimation procedure from a paper by Foltz and Kenworthy (presented at the 1982 ASME International Gas Turbine Conference in London) would also be of interest.