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EFFECT OF FUEL PROPERTIES ON PERFORMANCE OF A SINGLE AIRCRAFT TURBOJET COMBUSTOR

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ABSTRACT

The performance of a single-can JT8D combustor was investigated with a number of fuels exhibiting wide variations in chemical composition and volatility. Performance parameters investigated were combustion efficiency, emissions of CO, unburned hydrocarbons and NO_x, as well as liner temperatures and smoke. At the simulated idle condition no significant differences in performance were observed. At cruise, liner temperatures and smoke increased sharply with decreasing hydrogen content of the fuel. No significant differences were observed in the performance of an oil-shale derived JP-5 and a petroleum-based Jet A fuel except for emissions of NO_x which were higher with the oil-shale JP-5. The difference is attributed to the higher concentration of fuel-bound nitrogen in the oil-shale JP-5.

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SUMMARY

The performance of a JT8D single combustor was determined at simulated idle and cruise conditions with a number of petroleum based fuels exhibiting wide variations in volatility and chemical composition. In addition, one fuel obtained from oil-shale and refined to JP-5 specifications was tested. The petroleum-based fuels and fuel-blends were chosen to represent the classes of chemical compounds that might be found in aviation fuels obtained from oil-shale and coal-derived crudes and to investigate the effects of widened fuel specifications. Performance parameters investigated were combustion efficiency, pollutant emissions including smoke, liner temperatures, and combustor blowout. Hydrogen content of the fuels investigated ranged from 11.0 to 15.3 percent.

At the simulated idle condition no significant differences in combustor performance were observed. Combustion efficiency values ranged from about 90 to 93 percent and increased slightly with increasing hydrogen content of the fuel. At the simulated cruise condition combustion efficiency values were 99.9 percent and above. However, smoke numbers and combustor liner temperatures increased sharply as the hydrogen content of the fuel decreased. Comparison of an oil-shale derived JP-5 and a petroleum-based Jet A showed no significant differences in performance except for emissions of NO_x. The oil-shale JP-5 which contained a high percentage of fuel-bound nitrogen produced significantly higher emissions of NO_x than the Jet A fuel. Combustor blowout tests, which were conducted at ambient combustor-inlet temperatures, showed no significant differences in blowout pressure among the various fuels tested.

INTRODUCTION

An experimental investigation was conducted to determine the effect on combustor performance of a number of fuels with properties simulating those that might eventually be found in fuels derived from nonpetroleum sources Additionally, one fuel obtained from oil-shale syncrude and refined to JP-5 specifications was investigated

Present U.S. consumption of liquid fuels is significantly greater than domestic petroleum crude-oil production. As a result, the U.S. has to import about 30 percent of the petroleum crudes used in this country. This is an undesirable situation, both from the standpoint of national security and of economic stability.

In the future aviation turbine fuels may be produced from a variety of sources including petroleum, tar sands, shale oil, and coal syncrudes. Since the properties of fuels derived from these various sources may differ significantly due to practical limitations in the degree of refining, such as hydrotreating, it is desirable to explore the range of fuel properties that might be utilized in aircraft gas turbine combustors. Accordingly, the test fuels were chosen to give wide variations in chemical composition, such as paraffins, aromatics, and naphthenes as well as in volatility.

The investigation was conducted with a single JT8D combustor at simulated idle and cruise conditions. Combustor performance with the various fuels was judged primarily on the basis of combustion efficiency, pollutant emissions including smoke, flame radiation as evidenced by changes in combustor liner temperature, and combustor blowout.

TEST FACILITY

The tests were conducted with a single JT8D combustor housed in a closed-duct test facility capable of supplying the required air-flow rates at the specified combustor-inlet pressures and temperatures with nonvitiated air. A more detailed description of the test facility can be found in Ref. 1.

COMBUSTOR INSTALLATION AND INSTRUMENTATION

A JT8D combustor liner, retrofitted to reduce smoke emissions (Ref. 2) and utilizing a standard Duplex fuel nozzle, was installed as shown in Fig. 1. An existing circular combustor housing was modified to accommodate the JT8D liner. Although this installation did not provide the actual engine combustor-inlet and exit geometry, it was felt that this expedient would not compromise the combustor performance parameters of interest in this investigation, especially since the tests were primarily comparisons between the standard Jet A fuel and the various other fuels tested.

The combustor instrumentation stations are shown in Fig. 1. Inlet-air temperatures were measured at station A-A with 5 chromel-alumel thermocouples while exit temperatures were measured at station B-B with 8 five-point chromel-alumel thermocouple rakes. Combustor-inlet and exit static pressures were determined at stations A-A and C-C, respectively.

Exhaust-gas samples for gas analysis were obtained by means of four steam-cooled sampling probes located at station C-C. Each probe had five sampling ports located at the centers of equal areas; the gases collected from all 20 ports were connected to a common manifold and from there were passed through steam-heated lines to a gas-analysis console, shown in Fig. 2. The exhaust gas was analyzed for concentrations of CO_2, CO, unburned hydrocarbons and oxides of nitrogen in accord with the recommendations set forth in Ref. 3.

Smoke content of the exhaust gas was determined by passing metered volumes of gas through a filter paper with resultant deposition on the paper of the soot particles contained in the gas. The darkness of the stain on the paper, as determined by optical means, is a measure of the concentration of the soot in the sample. The smoke measurement technique is in accordance with SAE recommended practice, as described in Ref. 4.

In order to measure the effect of flame radiation on liner temperatures 6 chromel-alumel thermocouples were installed on the liner walls at the locations shown in Fig. 3. In all cases the maximum liner temperature was registered by the same thermocouple, as shown in Fig. 3.

TEST CONDITIONS

Tests were conducted at the combustor-inlet conditions shown in Table I. Although small variations may exist among the various engine models, these conditions were considered to be typical of idle and cruise operation of the JT8D engine. In addition, blowout tests were conducted with most of the fuel blends. Tests were conducted at three different airflow rates, 1.81, 2.27, and 2.72 kilograms per second. At each airflow rate the fuel-air ratio was held constant at a value of 0.02.

Inlet-air temperatures were ambient and ranged from about 294 to 308 K; no attempt was made to control the temperature within these limits. After ignition, the combustor-inlet pressure was gradually lowered, at constant airflow rate and fuel-air ratio, until blowout occurred.

Fuel Selection

The objective of this investigation was to determine if aviation fuels produced from coal and oil-shale derived syncrudes and refined to aviation fuel specifications could be utilized effectively in modern turbojet combustors, and, at the same time, to determine if these specifications could be broadened in order to increase the yield of jet fuels or to increase refinery flexibility. As a result, fuels were chosen to give wide variations in chemical composition and in boiling range. Inasmuch as some syncrude derived fuels are expected to be high in aromatics, and upon hydrogenation, in naphthenes, the selection of fuels was weighted heavily in that direction. Additionally, one fuel obtained from oil-shale and refined to JP-5 specifications was tested. The fuel was part of a production run of 5765 bbl of various military fuels from 10 000 bbl of crude shale oil produced by the Paraho process from the shale mined from the Naval oil shale reserve located at Anvil Points, Colorado (Ref 5). A list of the fuels and fuel blends and their properties is given in Table II.

RESULTS AND DISCUSSION

Petroleum-Based Fuel Blends

Idle. - In general, combustor performance at simulated idle conditions showed no significant differences among the various fuel blends tested. Combustion efficiency values, as determined by gas analysis, ranged from 89.5 to 92.0 percent (Fig. 4) and increased slightly with increasing hydrogen content of the fuel. Correspondingly, emission indices of CO and unburned hydrocarbons decreased slightly with increases in the percentage of hydrogen (Fig. 5). However, there was considerable scatter in the data, especially in the CO emission values, suggesting that other factors such as fuel volatility affected emissions. NO_x emission indices, shown in Fig. 6, were too low for any meaningful evaluation of the effect of fuel properties on NO_x emissions. At a fuel-air ratio of 0.008 an emission index of 2 g NO_2/kg of fuel corresponds to about 10 ppm of NO_x and any small deviations from this value are not considered significant. Similarly values of smoke and liner temperatures were too low to draw any meaningful conclusions as to the effect of fuel properties on these parameters.

Combustion efficiency values reported herein may be somewhat lower than those reported by the manufacturer of the engine. Slight variations in combustor geometry and in the severity of the combustor-inlet conditions could probably account for the difference. However, since the scope of this investigation was a comparison of fuel properties rather than the establishing of absolute values, the discrepancy is not considered significant.

Cruise. - At the simulated cruise condition values of CO and unburned hydrocarbons were very low. Combustion efficiencies, which are computed from the CO and unburned hydrocarbon emission values, were always 99.5 percent or above. Emission indices of NO_x, shown in Fig. 7, varied from 10.5 to 12.7 g NO_2/kg of fuel, but did not correlate with the hydrogen content of the fuel. Similarly, although NO_x formation is generally considered to increase with increasing flame temperatures, no such trend was observed, as shown in Fig. 8. Maximum flame temperatures which were obtained from a computer program described in Ref. 6, are equilibrium flame temperatures. As can be seen from Table II, the spread in temperatures was not great, ranging from 2476 to 2515 K. However, because of the large differences in local fuel-air ratio in the primary zone of a combustor, the spread in local flame temperatures within the reaction zone probably obscured the effect of the differences in equilibrium flame temperature among the various fuels.

Although differences in fuel composition produced no significant changes in combustion efficiency and gaseous emissions, they did have a pronounced effect on smoke and on flame radiation, as evidenced by changes in liner temperature. From Fig. 9 it can be seen that smoke numbers increased sharply as the hydrogen content of the fuel decreased. In the same manner maximum liner temperatures (Fig. 10) increased markedly with decreasing hydrogen content of the fuel. The effects of reduced hydrogen content of fuels on increased smoke formation and flame radiation are well substantiated in the literature (e.g., Refs. 7 and 8). However, the steepness of the curves emphasizes the problem with liner cooling and with excessive smoke formation that could arise from the use of highly aromatic fuels. It might thus become necessary to improve fuel atomization by the use of air atomizers or of premixed, prevaporized fuels to combat smoke, and the use of ceramic-coated liners to improve combustor durability.

Oil-Shale Derived JP-5

A sample of fuel derived from oil shale and refined to JP-5 specifications was tested at simulated idle and cruise conditions. The results of the tests at idle, presented in Fig. 11, show no significant differences in combustion efficiency and emissions of CO and unburned hydrocarbons between the oil-shale JP-5 and the standard petroleum-based Jet A fuels. Values of NO_x emissions, liner temperatures, and smoke were too low for any meaningful comparisons between the two fuels.

Smoke numbers, maximum liner temperatures, and NO_x emission indices obtained with the two fuels at the simulated cruise condition are shown in Fig. 12. As in the case of the petroleum-based fuel blends, emission of CO and unburned hydrocarbons were very low and combustion efficiencies were 99.9 percent and above for both fuels. Maximum liner temperatures and smoke numbers were slightly higher for the shale-oil JP-5, but the differences are not considered significant.

NO_x emission indices for the shale-oil JP-5 were noticeably higher than those obtained with the Jet A fuel. Because of limitations in the degree of hydrogenation employed in the Anvil Points production run, the JP-5 fuel contained a considerably higher percentage of fuel-bound nitrogen (about 800 ppm) than the Jet A fuel (generally less than 50 ppm). Studies (Refs. 9 and 10) have shown that 50 to 90 percent of the fuel-bound nitrogen can be converted to NO_x in the primary zone of a combustor. A nitrogen content of 800 ppm at 100 percent conversion would produce a NO_x emission index of about 2.6. Thus, the differences in NO_x between the Jet A and the shale-oil JP-5 can be attributed almost completely to the presence of fuel-bound nitrogen in the oil-shale derived fuel.

The tests at both idle and cruise conditions have shown that there was little difference in the combustion performance of the petroleum based Jet A and the oil-shale derived JP-5 fuels. However, if concentrations of organic nitrogen in the syncrude derived fuels remain high, problems could arise in those combustors which are already marginal from a NO_x emission standpoint.

Blowout

No significant differences in pressure at which blowout occurred were observed. However, the tests were conducted at ambient combustor-inlet temperatures, ranging from about 294 to 308 K. It is quite possible that, if the tests had been conducted at the combustor-inlet conditions prevailing at the altitudes and flight Mach numbers of interest, differences in blowout pressure would have been observed.

CONCLUDING REMARKS

Tests conducted with a single-can JT8D combustor with a number of fuels exhibiting wide variations in volatility and chemical composition showed that no severe problems should be encountered with these fuels at the idle condition. However, at cruise, smoke numbers and liner temperatures increased sharply as the hydrogen content of the fuel decreased. Thus, fuels high in aromatic content could present severe problems with smoke emissions and with liner durability.

Based on the results of the above tests it would be expected that no significant differences in performance should be obtained between an oil-shale derived and a petroleum-based fuel refined to essentially the same specifications. Comparison tests of the oil-shale JP-5 and the Jet A fuels did, indeed, show very little difference in the performance of these two fuels except for emissions of NO_x. The oil-shale derived fuel contained a high percentage of fuel-bound nitrogen resulting in significantly higher NO_x emissions. Inasmuch as reduction of NO_x emissions already presents a formidable challenge to the combustor designer, the presence of large amounts of organic nitrogen could greatly aggravate the problem.

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TABLE I. - TEST CONDITIONS

Condition	Pressure		Temperature		Airflow		Fuel-air ratio
	N/cm^2	psia	K	F	kg/sec	lb/sec	
Idle	27.3	39.6	400	260	1.84	4.06	0.0074
Cruise	71.0	103.0	620	657	3.57	7.87	0.0138

TABLE II. - TEST FUELS

Blend of base fuel with Jet A	Percent by weight of base fuel	Percent hydrogen	Percent aromatics	Boiling range, K	Lower heating value, cal/g	Viscosity at 294 K, $\frac{m^2}{s} \times 10^6$	Maximum flame temperature at cruise, K	Principal fuel characteristic
Jet A	100	13.88	16.8	442-544	10 350	1.3	2487	Base fuel
Soltrol 130	100	15.30	0	335-477	10 554	---	2479	Low-boiling paraffinic
JP-4	100	14.70	----	309-508	10 422	---	2476	Typical jet fuel (low boiling)
No. 2 diesel	100	13.00	36.0	450-608	10 250	4.0	2496	High end point fuel
Toluene	33	12.60	44.3	391-532	10 128	[a]0.9	2491	Single-ring aromatic (low-boiling)
Xylene	42	12.00	51.7	-	10 098	---	2500	Single-ring aromatic (low-boiling)
Xylene	20	13.00	33.4	417-537	10 230	1.5	2494	Single-ring aromatic (low-boiling)
HISol [illegible]	63.2	11.76	60.5	446-524	10 155	1.4	2515	Mixture single-ring aromatic
HISol [illegible]	25.9	13.01	34.7	432-532	10 270	[a]1.7	2498	Mixture single-ring aromatic
Xylene bottoms	41.7	12.09	49.9	427-535	10 136	1.3	2504	Two- and three-ring aromatics
Naphthalene charge stock	25.5	12.50	35.1	453-539	10 181	2.1	2500	Two- and three-ring aromatics
Tetralin	42	11.89	51.7	465-529	10 063	2.0	2500	Two-ring aromatic-partially hydrogenated
Tetralin	60.4	11.00	67.0	468-531	9 938	2.1	2506	Two-ring aromatic-partially hydrogenated
Methyl cyclohexane	100	14.37	0	374	10 357	[a]0.7	2476	Single-ring naphthene
Decalin	100	13.12	----	457-492	10 139	2.9	2479	Double-ring naphthene
Shale-oil JP-5	100	13.89	25.1	430-551	10 325	2.0	2484	Syncrude-derived jet fuel

[a]Viscosity at 311 K.

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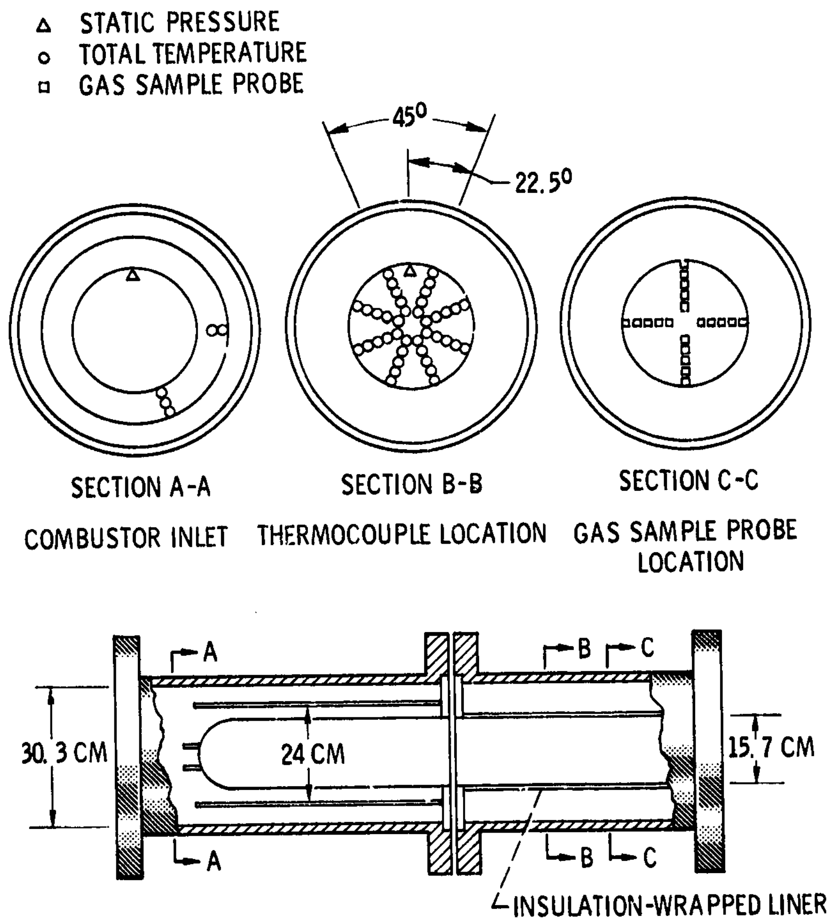

Figure 1. - Combustor assembly and instrumentation sections.

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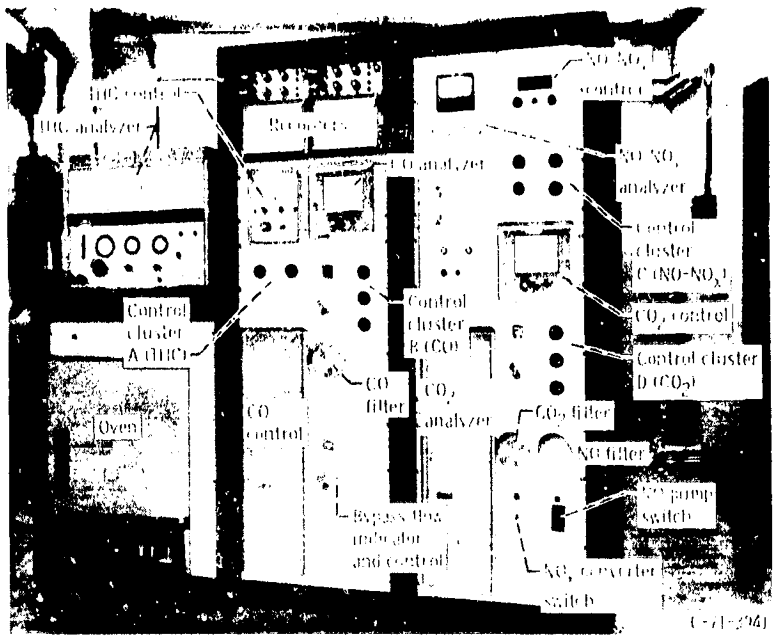
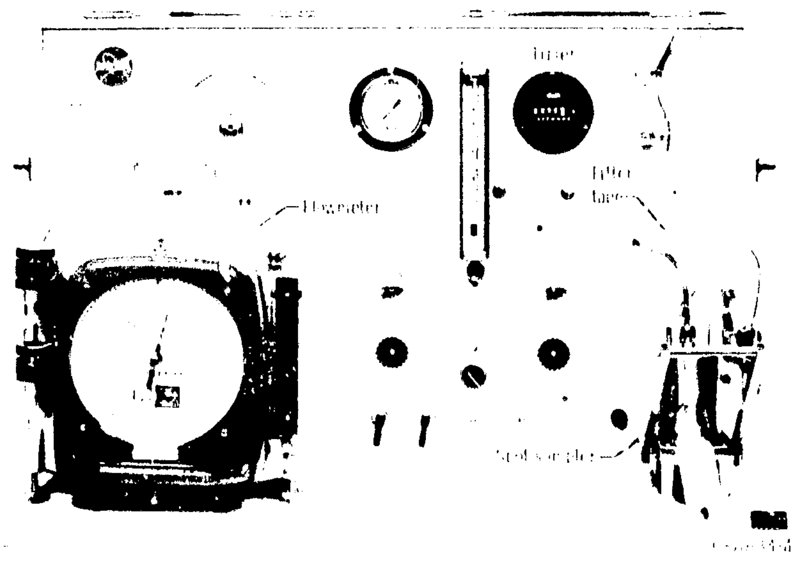


Gas analysis equipment



Smoke meter

Figure 2. - Gas analysis equipment and smoke meter.

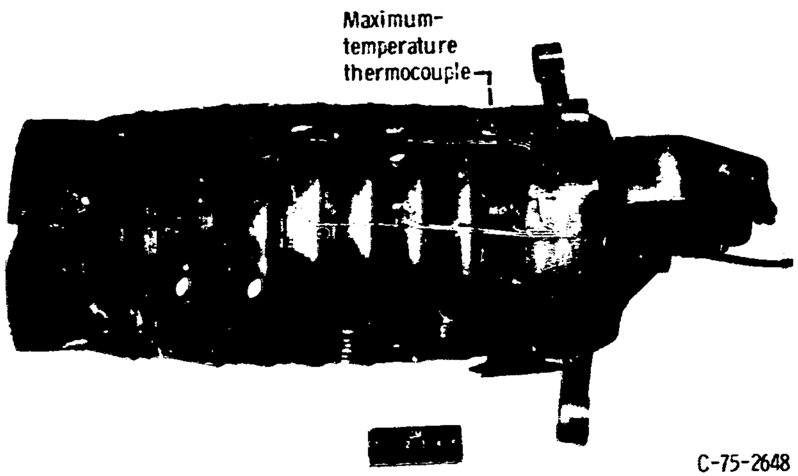


Figure 3. - JT8D liner showing location of thermocouples.

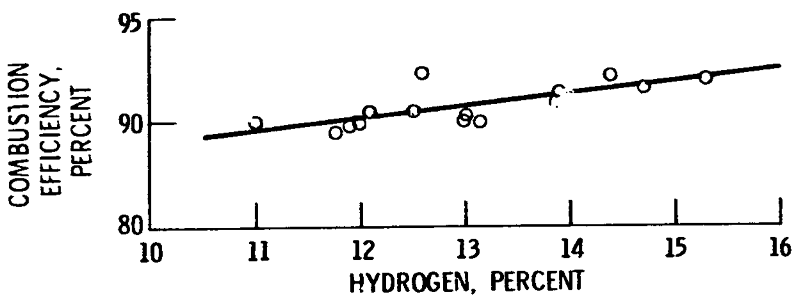


Figure 4. - Effect of hydrogen content of fuel on combustion efficiency at idle conditions.

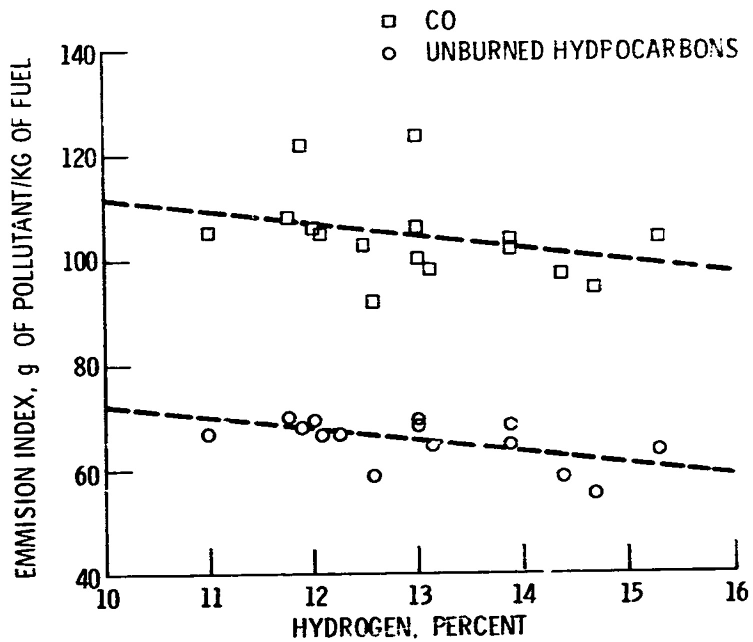


Figure 5. - Effect of hydrogen content of fuel on emissions of CO and unburned hydrocarbons at idle conditions.

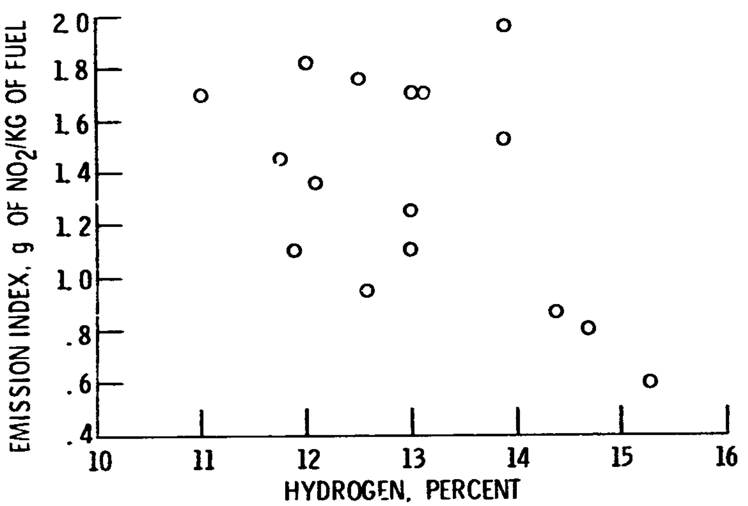


Figure 6. - Effect of hydrogen content of fuel on NO_x emissions at idle conditions.

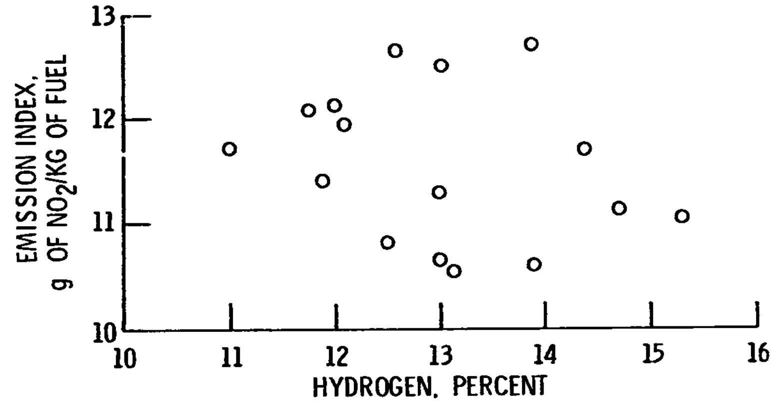


Figure 7. - Effect of hydrogen content of fuel on NO_x emissions at cruise conditions.

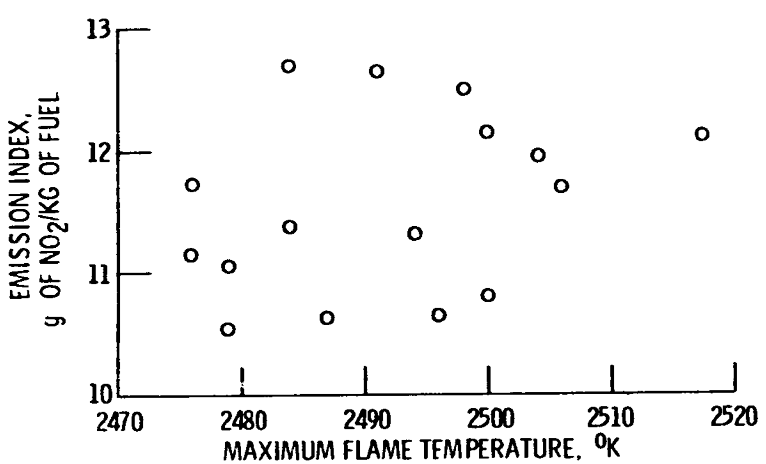


Figure 8. - Effect of maximum flame temperature on NO_x emissions at cruise.

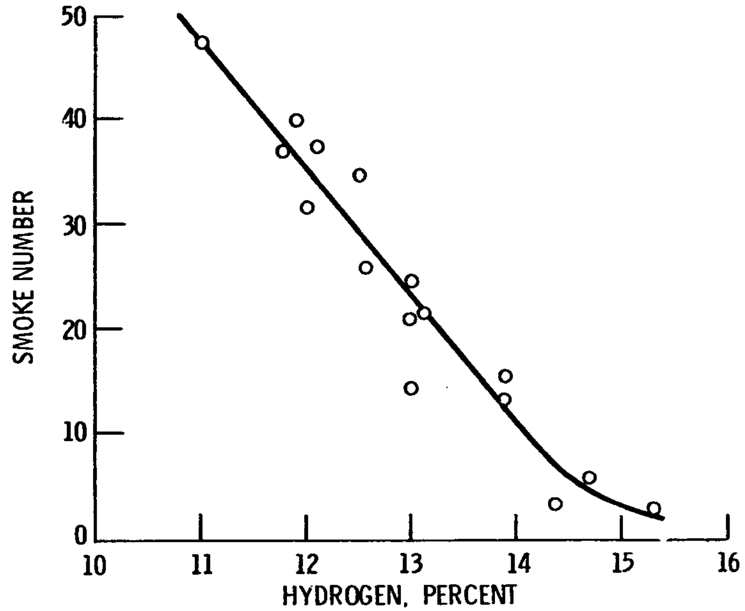


Figure 9. - Effect of hydrogen content of fuel on smoke number at cruise conditions.

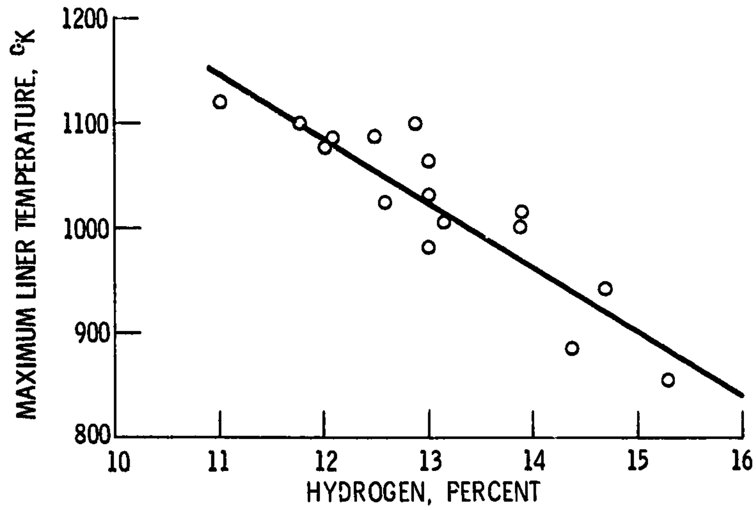


Figure 10. - Effect of hydrogen content of fuel on maximum liner temperatures at cruise conditions.

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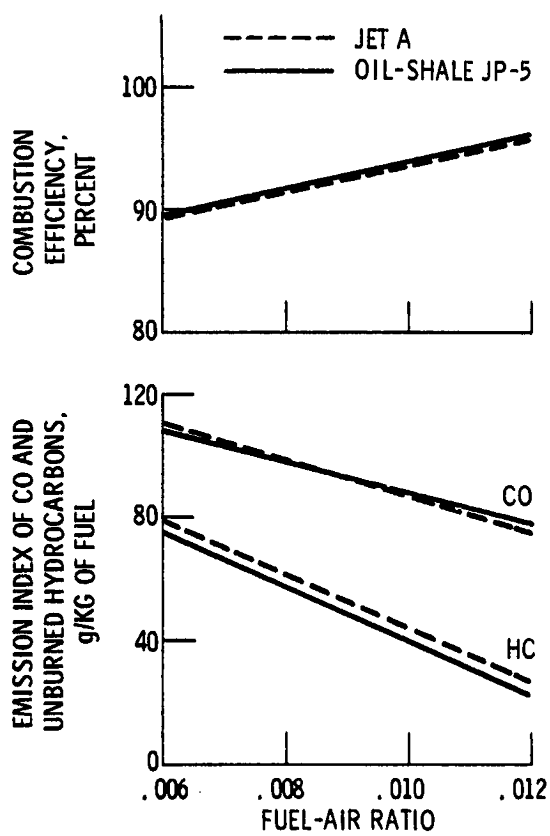

Figure 11. - Comparison of shale-oil JP-5 and Jet A fuels at idle conditions.

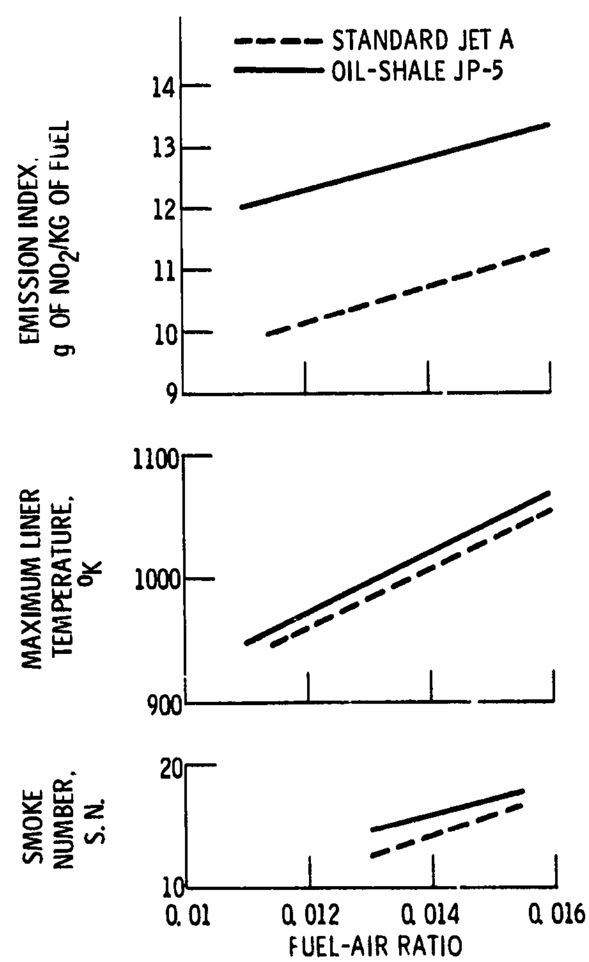

Figure 12. - Comparison of shale-oil JP-5 and Jet A fuels at cruise conditions.