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16. 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. The most pronounced effects of changes in fuel composition were observed at simulated cruise and takeoff conditions where smoke and liner temperatures increased significantly as the hydrogen content of the fuel decreased. At the simulated idle condition, emissions of CO and unburned hydrocarbons increased slightly and, accordingly, combustion efficiencies decreased slightly as the hydrogen content of the fuels decreased.

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SUMMARY

The performance of a JT8D single combustor was determined at simulated idle, cruise, and takeoff conditions with a number of petroleum-based fuels exhibiting wide variations in volatility and chemical composition. In addition, several fuels obtained from oil shale and refined to jet and diesel specifications were tested. The fuels and fuel blends were chosen to investigate the effect on combustor performance of broadened fuel specifications with particular emphasis on increased aromatic content and on increased final boiling point. Performance parameters investigated were combustion efficiency, pollutant emissions including smoke, and maximum liner temperatures. Hydrogen contents of the fuels investigated ranged from 11.0 to 15.3 percent.

The most pronounced effects of changes in fuel composition were observed at simulated cruise and takeoff conditions where smoke and liner temperatures increased significantly as the hydrogen content of the fuel decreased. Slight increases in NO_x emissions were observed with decreasing hydrogen content of the fuels. Combustion efficiencies, as determined by gas analysis, were 99.9 percent or above for all the fuels.

At the simulated idle condition, no significant effects of fuel quality on combustor performance were observed. Emissions of carbon monoxide and unburned hydrocarbons increased slightly and accordingly combustion efficiencies decreased slightly as the hydrogen content of the fuels decreased.

INTRODUCTION

An experimental investigation was conducted to determine the effect on combustor performance of burning jet fuels with properties differing appreciably from those of fuels presently supplied under current aircraft gas turbine fuel specifications. The principal differences were increases in aromatic content and in final boiling point. Additionally, several fuels obtained from oil-shale syncrudes were investigated.

In the past, the petroleum industry has been able to supply aircraft operators with an adequate supply of jet fuels refined to rather narrow specifications, tailored to minimize the problems of fire hazard and of fuel freeze-up at altitude and to promote clean burning in the engines (ref. 1). The ever-increasing reliance of the U.S. petroleum industry on foreign crudes, some with rather high aromatic contents, has not only made it more difficult to meet current jet fuel specifications, but has created a highly undesirable supply problem 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. Due to practical limitations in the degree of refining, such fuels may differ significantly from those produced under current jet fuel specifications. Accordingly, the test fuels used in the investigation being reported herein were chosen to give wide variations in chemical composition and in volatility. This investigation, which was an extension of a previous program (ref. 2), was conducted with a single-can JT8D combustor at simulated idle, cruise, and takeoff conditions. In the investigation reported in reference 2 a more limited number of fuels had been tested at idle and cruise conditions only. Combustor performance with the various fuels was judged primarily on the basis of combustion efficiency, pollutant emissions including smoke, and flame radiation as evidenced by changes in combustor liner temperatures.

TEST FACILITY AND COMBUSTOR INSTALLATION

The tests were conducted with a single JT8D combustor housed in a closed-duct test facility connected to the laboratory air supply and exhaust system. The test facility, shown schematically in figure 1, was capable of supplying the required flow rates at the specified combustor-inlet pressures and temperatures with nonvitiated air.

The JT8D liner, utilizing a standard duplex fuel nozzle, was installed in the test facility as shown in figure 1. Although the use of circular housings 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 and the other fuels tested.

The combustor instrumentation stations are shown in figure 2. Inlet-air temperatures were measured at station A-A with five chromel-alumel thermocouples while exit temperatures were measured at station B-B with eight five-point chromel-alumel thermocouple rakes. Combustor-inlet and exit static pressures were determined at stations A-A and B-B, respectively.

Exhaust-gas samples for gas analysis were obtained by means of four water-cooled sampling probes located at station C-C. Each probe had five sampling ports located at the centers of equal areas; the gas collected from all 20 ports was passed to a common manifold and from there through steam-heated lines to a gas analysis console. The exhaust gas was analyzed for concentrations of CO_2, CO, unburned hydrocarbons, and oxides of nitrogen in accord with the recommentations set forth in reference 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 soot in the sample. The smoke measurement technique is in accordance with SAE recommended practice, as described in reference 4.

Liner temperatures were measured by 10 chromel-alumel thermocouples installed on the liner at the locations shown in figure 3. The positions of the thermocouples were selected on the basis of previous experience and as a result of calibration tests with temperature-indicating paints. Since the number of thermocouples installed on the liner must necessarily be limited, it is possible that some locations on the liner experienced even higher temperatures than those surveyed. However, it is felt that the thermocouple locations were satisfactory from a comparative viewpoint and were sufficient to represent liner hot spots and to serve as a valid comparison between the various fuels tested. In all cases, maximum recorded liner temperatures were registered by either one of two thermocouples, as shown in figure 3. For takeoff and cruise, the thermocouple closest to the spark plug (fig. 3) consistently registered the highest liner temperatures while, for idle, the maximum liner temperature was recorded at the downstream position.

TEST CONDITIONS

Tests were conducted at the combustor-inlet conditions shown in table I. Although variations may exist among the various engine models, these conditions were considered to be typical of idle, cruise, and takeoff operation of the JT8D engine. At each condition fuel flows were varied over a sufficiently wide range so as to bracket the desired fuel-air ratios.

FUELS

The fuels used in this investigation were selected to give wide variations in chemical compositon and boiling range. Fuels containing varying percentages of paraffins, naphthenes, and single- and double-ring aromatics were used, either in pure form or blended with Jet A to give the desired composition. Variations in final boiling point were obtained with fuels in the diesel fuel range. In addition, three fuels obtained from oil-shale syncrude and refined to JP-4, JP-5, and Marine Diesel specifications were tested. The oil-shale derived fuels were part of a production run of 5765 bbl of various military fuels refined from 10 000 bbl of crude shale oil produced by the Paraho process using shale mined from the Naval Oil Shale Reserve located at Anvil Points, Colorado (ref. 5). A list of the fuels and fuel blends is given in table II.

In the past jet fuels have been characterized mainly by their physical properties; their chemical properties have been described primarily by limiting specifications of the sulfur, olefin, and aromatic contents. The practice of characterizing jet fuels by their aromatic content leaves a lot to be desired. In the first place, results obtained by different investigators using the ASTM test method (ref. 6) have not always been in good agreement, especially for aromatic concentrations greater than 20 percent by volume. Additionally, the test method does not distinguish between single- and multiple-ring aromatics or between simple unsaturated ring compounds and those having large aliphatic side chains.

In view of the shortcomings of the aromatic-content designation it has been suggested by many observers that jet fuels should be characterized by their hydrogen content. In general, the hydrogen content of a fuel decreases with increasing aromaticity. However, since the aromatic content designation does not uniquely specify the hydrogen content, the correlation can be described by a band rather than a single line.

One of the problems with using percent hydrogen as a measure of fuel quality is the fact that, at the present time, the determination of fuel hydrogen content has not been standardized. In the past, hydrogen content has been determined either by correlation or by one of several different analytical techniques (refs. 7 and 8), often with poor agreement between them. Recently, a new analytical technique, the "Nuclear Magnetic Resonance" method (ref. 9), has been introduced which claims simplicity of operation and a precision of ±0.1 percent hydrogen over the range from 13 to 15 percent hydrogen.

Because some of the more advanced analytical methods were not readily available at the time this program was conducted, it was necessary to use several different methods to get values of hydrogen and aromatic content for all the fuels listed in table II. In some cases, the blending stocks were commercial-grade pure fuels so that the hydrogen content could be computed from their chemical formulas.

Values of aromatic content, as determined by two different analytical techniques and, in some cases, calculated from the blending ratios, showed relatively poor agreement between the various methods. Thus, it was felt that hydrogen content is a much better measure of fuel quality than aromatic content. As a result, all the data presented in this report are shown as a function of fuel hydrogen content. A comparison of the values for hydrogen and aromatic contents obtained by the various analytical techniques and by calculation is shown in table III.

DISCUSSION OF RESULTS

The effects of changes in fuel composition on combustor performance were evaluated at simulated takeoff, cruise, and idle conditions. The only major effects were significant increases in smoke and in maximum liner temperatures with decreasing fuel hydrogen content. The other performance parameters, at all three test conditions, exhibited only minor effects as the result of changes in fuel hydrogen content. The effect of fuel volatility could not be determined directly since it is impossible to vary volatility independently while keeping the other fuel properties constant. Variations in volatility were probably responsible for some of the scatter experienced in the plots of performance against hydrogen content. The most pronounced effect of fuel volatility on performance would be expected at high altitudes where blowout and relight capabilities could be seriously impaired by reduced fuel volatility; however, this effect was not investigated in this program.

Takeoff and Cruise

Smoke. - The effects of decreasing fuel hydrogen content on smoke number are shown in figures 4 and 5 for both takeoff and cruise. At both conditions, smoke numbers increased sharply with decreasing hydrogen content. Although the effect of reduced hydrogen content on smoke formation has been well substantiated in the literature (ref. 10), the steepness of the curves emphasizes the severity of the problem. Thus, where fuels with hydrogen contents in the Jet A range produce smoke numbers near the visibility threshold, substantial increases in aromatic content of jet fuels could severely aggravate the smoke problem.

Maximum liner temperatures. - The effect of fuel hydrogen content on maximum liner temperatures is shown in figure 6. At both takeoff and cruise conditions, maximum liner temperatures increased greatly with decreasing fuel hydrogen content. As the aromaticity of the fuels increases, the flames become more luminous and radiation to the liner increases sharply. The steep slope of the curve at cruise suggests that fuels with hydrogen contents of 12.5 percent or less could bring about severe liner durability problems. One possible solution to the problem of excessive metal temperatures might be the use of thermal-barrier coatings. In an investigation in which a JT8D combustor liner was coated with a thermal-barrier ceramic coating (ref. 11), substantial reductions in maximum liner temperatures were achieved with both Jet A fuel and a highly aromatic fuel blend with a hydrogen content of 12.5 percent. Other approaches toward reducing metal temperatures might be found in combustor modifications, such as staged combustion and leaner primary zones (refs. 12 and 13).

Other performance parameters. - Emissions of NO_x as a function of fuel hydrogen content are shown in figure 7. At cruise, a very slight increase in NO_x emissions was observed as the fuel hydrogen content decreased; at takeoff the effect was more pronounced. The increase in NO_x emissions with increasing aromaticity, or conversely with decreasing fuel hydrogen content, is probably the result of increasing flame temperatures. From figure 8, it can be seen that maximum theoretical flame temperatures, as obtained from a computer program described in reference 14, increase with decreasing fuel hydrogen content for both cruise and takeoff conditions. At both takeoff and cruise, emissions of CO and unburned hydrocarbons were very low, often within the limits of accuracy of the instruments. Combustion efficiencies, which are computed from the CO and unburned hydrocarbon emission values, were 99.9 percent or above for all the fuels tested.

The performance of the three oil-shale derived fuels did not differ significantly from that of the petroleum-based fuels when correlated against fuel hydrogen content.

Idle

Emissions of CO and unburned hydrocarbons. - Emissions of CO and unburned hydrocarbons at idle are shown in figure 9. Although there is a great amount of scatter among the data, there is a slight trend toward increased emissions of CO and unburned hydrocarbons with decreasing fuel hydrogen content. Similarly combustion efficiencies, which are computed from the gas analyses, decreased slightly with decreasing fuel hydrogen content, as shown in figure 10. As pointed out before, the large scatter in the data points may be due in part to the effects of variations in fuel volability.

Smoke. - Smoke numbers as a function of fuel hydrogen content are shown in figure 11. In the Jet A range smoke values at idle are very low. However, for hydrogen contents below 13 percent, smoke numbers increase rapidly with decreasing fuel hydrogen content. Thus, while smoke emissions at idle are not normally considered objectionable with fuels in the Jet A range, smoke could become a serious problem if the fuel hydrogen content were reduced to values of 12 percent or lower.

CONCLUDING REMARKS

Tests conducted with a single-can JT8D combustor with a number of fuels exhibiting wide variations in volatility and chemical compositon revealed two potential problem areas: increased liner temperatures and increased emissions of smoke with decreasing fuel hydrogen content. Other parameters, such as emissions of NO_x, CO, and unburned hydrocarbons, exhibited only minor changes as either the hydrogen content or the volatility of the fuel was decreased. However, altitude blowout and relight were not investigated in this program, and it is quite likely that decreases in volatility will have a significant effect on these parameters.

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TABLE I. - TEST CONDITIONS

Condition	Idle	Cruise	Takeoff
Combustor-inlet pressure, N/cm^2	27.3	71.0	176.5
Combustor-inlet temperature, $^{\circ}$K	400	621	714
Fuel-air ratio	0.0100	0.0138	0.0182
Airflow, kg/sec	1.84	3.57	7.46

TABLE II. - TEST FUELS

Fuel blended with Jet A	Percent by weight of fuel blended with Jet A	Hydrogen, percent by weight	Aromatics, percent by volume	Boiling range, °K	Lower heating value, cal/g	Viscosity at 311° K, $\frac{m^2}{s} \times 10^6$	Principal fuel characteristic
Jet A	100	13.9	17.2	411 - 531	10 350	1.6	Base fuel
Toluene	30.2	12.3	40.9	375 - 526	10 134	1.1	Single-ring aromatic
Methyl cyclohexane	100	14.4	----	374	10 363	0.7	Single-ring naphthene
Xylene bottoms	41.9	12.1	52.0	414 - 528	10 143	1.4	Two- and three-ring aromatics
Naphthalene charge stock	25.6	12.0	34.0	428 - 540	10 187	1.8	Two- and three-ring aromatics
Xylene	19.9	13.0	32.7	400 - 532	10 237	1.2	Single-ring aromatic
Xylene	41.9	12.0	50.3	394 - 531	10 104	1.0	Single-ring aromatic
Shale-oil JP-5	100	13.7	24.2	417 - 533	10 332	1.6	Syncrude-derived fuel
Shale-oil JP-4	100	14.5	12.7	318 - 488	10 338	0.8	Syncrude-derived fuel
Shale-oil Marine Diesel	100	13.0	30.6	481 - 637	10 177	5.2	Syncrude-derived fuel
Decalin	100	13.1	----	433 - 479	10 146	2.2	Double-ring naphthene
Shell Jet A	100	13.5	21.4	381 - 536	10 316	1.6	Alternate source Jet A
Soltrol 130	100	15.3	----	438 - 478	10 561	1.7	Low-boiling paraffinic
Hi Sol 3	61.6	11.8	59.1	406 - 510	10 162	1.1	Mixture single-ring aromatics
Tetralin	40	12.1	34.9	442 - 531	10 193	1.5	Two-ring aromatic, partially hydrogenated
Tetralin	60.4	11.0	63.5	422 - 522	9 947	1.3	Two-ring aromatic, partially hydrogenated
Texaco Diesel	100	12.4	38.0	450 - 597	10 179	2.6	High-aromatic Diesel fuel
Sohio Diesel	100	13.5	17.4	467 - 563	10 318	2.5	Low-aromatic Diesel fuel
#2 Home-heating oil	100	11.8	54.5	439 - 578	10 125	2.2	High-aromatic heating oil

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TABLE III. - HYDROGEN AND AROMATIC CONTENTS OF TEST FUELS

Fuel blended with Jet A	Percent by weight of fuel blended with Jet A	Hydrogen, percent by weight					Aromatics, percent by volume			
		Analine point correlation	Calculated from formula	Hallikainen	Neutron transmission	Other analyses (c)	FIA Lab. 1	FIA Lab. 2	High performance liquid chromium	Calculated from formula
Jet A	100	[a]13.8	-----	13.7	13.4	-----	[b]17.2	17.5	13.4	-----
Toluene	30.2	13.4	[a]12.3	12.5	12.4	-----	53.2	37.0	29.4	[b]40.9
Methyl cyclohexane	100	-----	[a]14.4	----	-----	-----	-----	-----	-----	-----
Xylene bottoms	41.9	12.4	-----	12.3	12.2	[a]12.1	[b]52.0	51.0	41.8	-----
Naphthalene charge stock	25.6	12.8	-----	12.3	12.2	[a]12.0	[b]34.0	36.0	35.3	-----
Xylene - blend 1	19.9	13.2	[a]13.0	----	-----	-----	37.9	-----	-----	[b]32.7
Xylene - blend 2	41.9	12.3	[a]12.0	12.1	12.1	-----	58.5	50.0	38.8	[b]50.3
Shale-oil JP-5	100	13.7	-----	13.5	[a]13.7	-----	[b]24.2	24.0	17.0	-----
Shale-oil JP-4	100	[a]14.5	-----	14.3	14.2	-----	[b]12.7	10.0	10.5	-----
Shale-oil Marine Diesel	100	[a]13.0	-----	12.9	12.6	12.8	-----	100	[b]30.6	-----
Decalin	100	-----	[a]13.1	13.0	12.5	-----	-----	-----	-----	-----
Shell Jet A	100	[a]13.5	-----	13.8	12.6	-----	[b]21.4	21.0	17.6	-----
Soltrol 130	100	[a]15.3	-----	15.1	14.9	-----	-----	-----	-----	-----
Hi Sol 3	61.6	11.5	-----	11.6	11.6	[a]11.8	76.0	67.0	51.0	[b]59.1
Tetralin - blend 1	40	12.1	[a]12.0	----	-----	-----	40.1	-----	-----	[b]34.9
Tetralin - blend 2	60.4	10.1	[a]11.0	----	-----	-----	67.8	-----	-----	[b]63.5
Texaco Diesel	100	[a]12.4	-----	----	-----	-----	[b]38.0	-----	-----	-----
Sohio Diesel	100	[a]13.5	-----	----	-----	-----	[b]17.4	-----	-----	-----
#2 Home heating oil	100	[a]11.8	-----	----	-----	-----	[b]54.5	-----	-----	-----

[a] Method used in table II for hydrogen.

[b] Method used in table II for aromatics.

[c] Analytical technique not known.

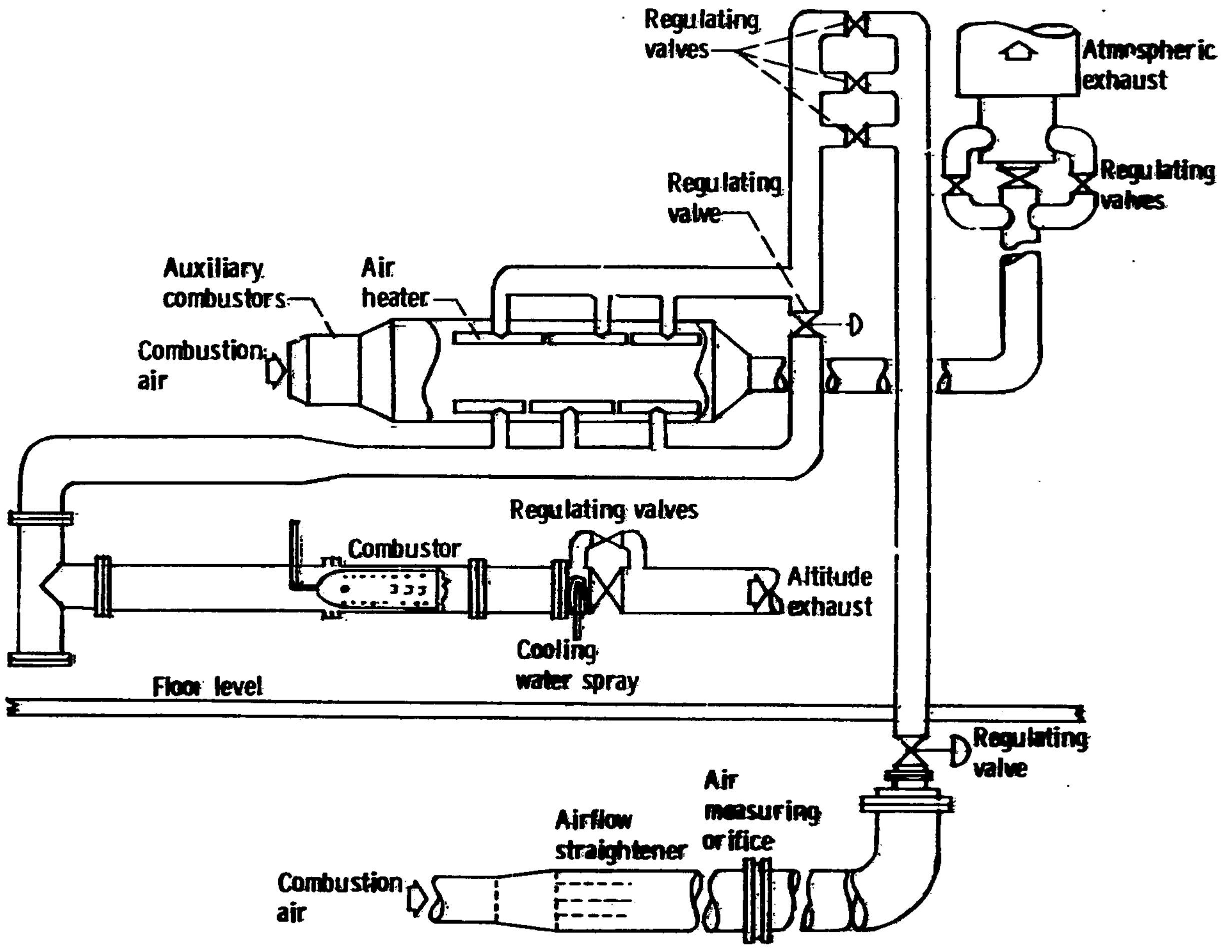

Figure 1. - Test facility and auxiliary equipment.

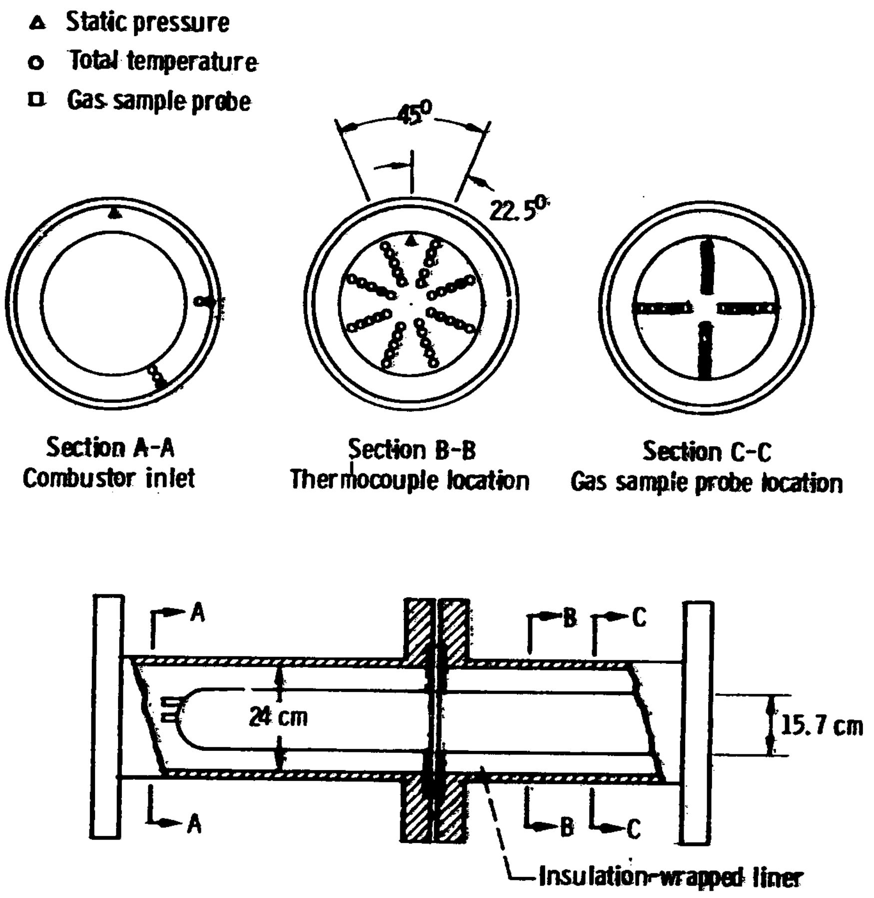

Figure 2. - Combustor assembly and instrumentation sections.

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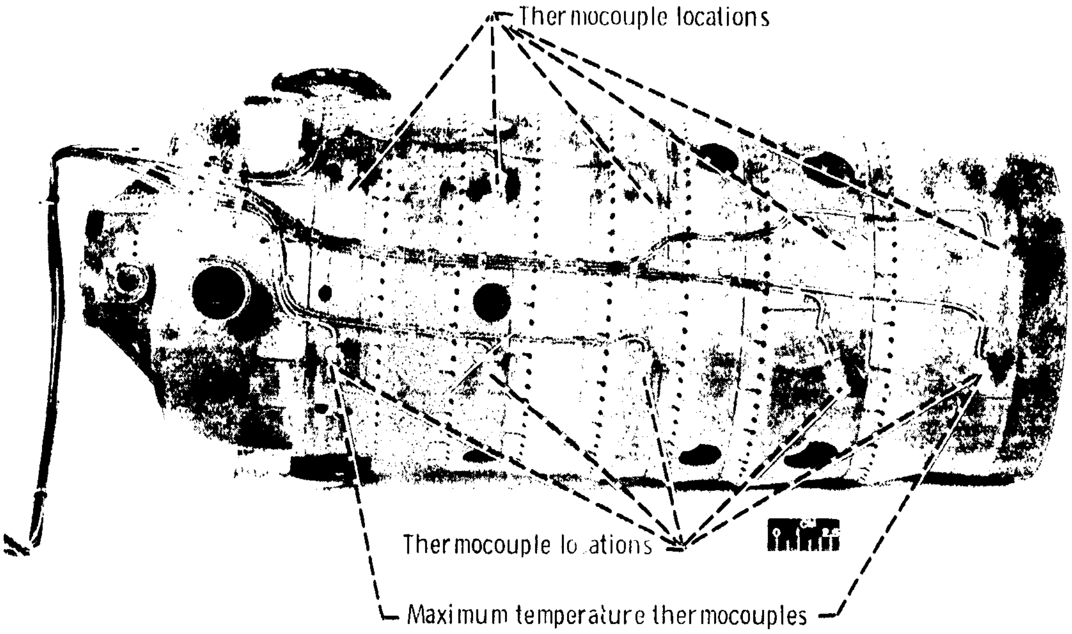

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Figure 3. - Location of thermocouples on liner.

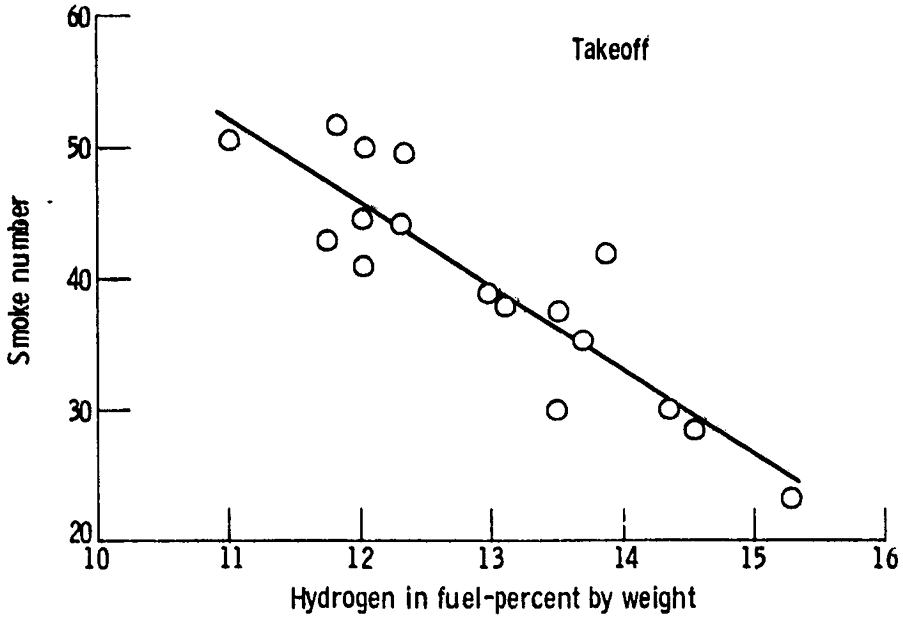

Figure 4. - Effect of hydrogen content of fuel on smoke number at takeoff condition.

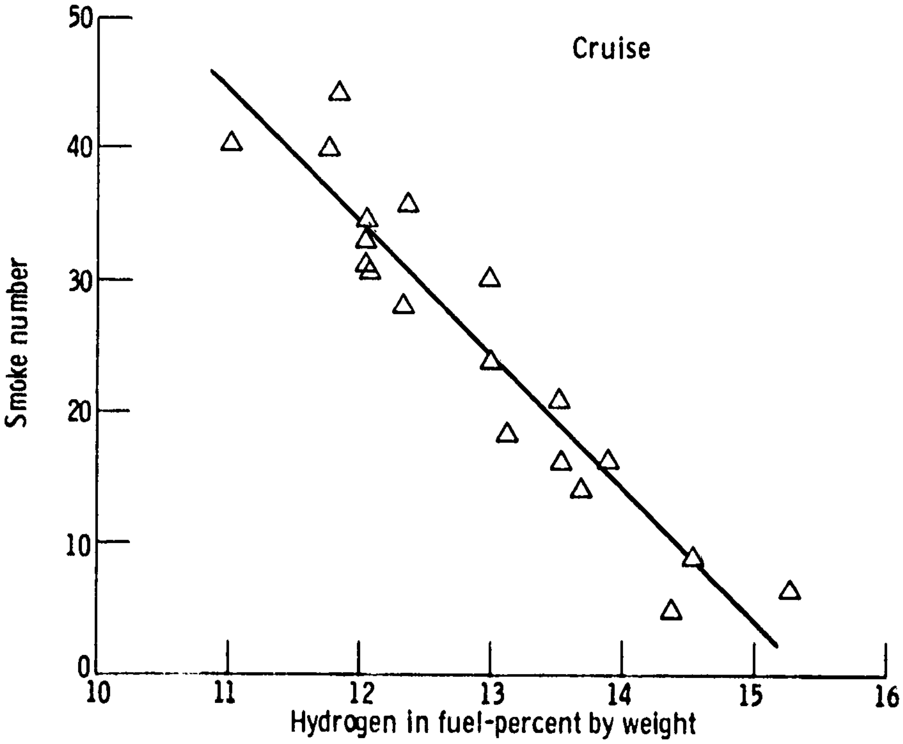

Figure 5. - Effect of hydrogen content of fuel on smoke number at cruise condition.

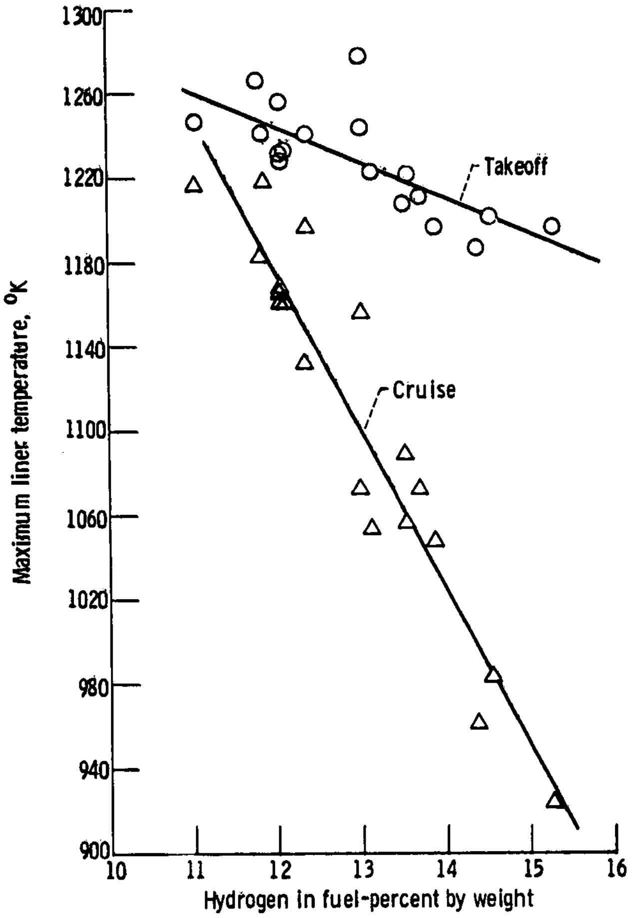

Figure 6. - Effect of hydrogen content of fuel on maximum liner temperatures at cruise and takeoff conditions.

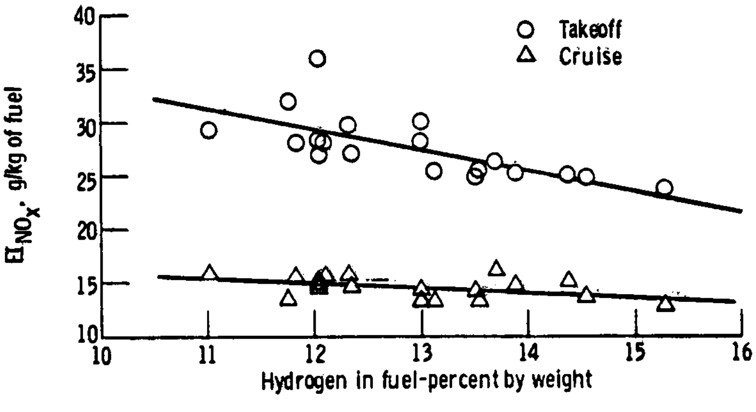

Figure 7. - Effect of hydrogen content of fuel on NO_x emissions at takeoff and cruise conditions.

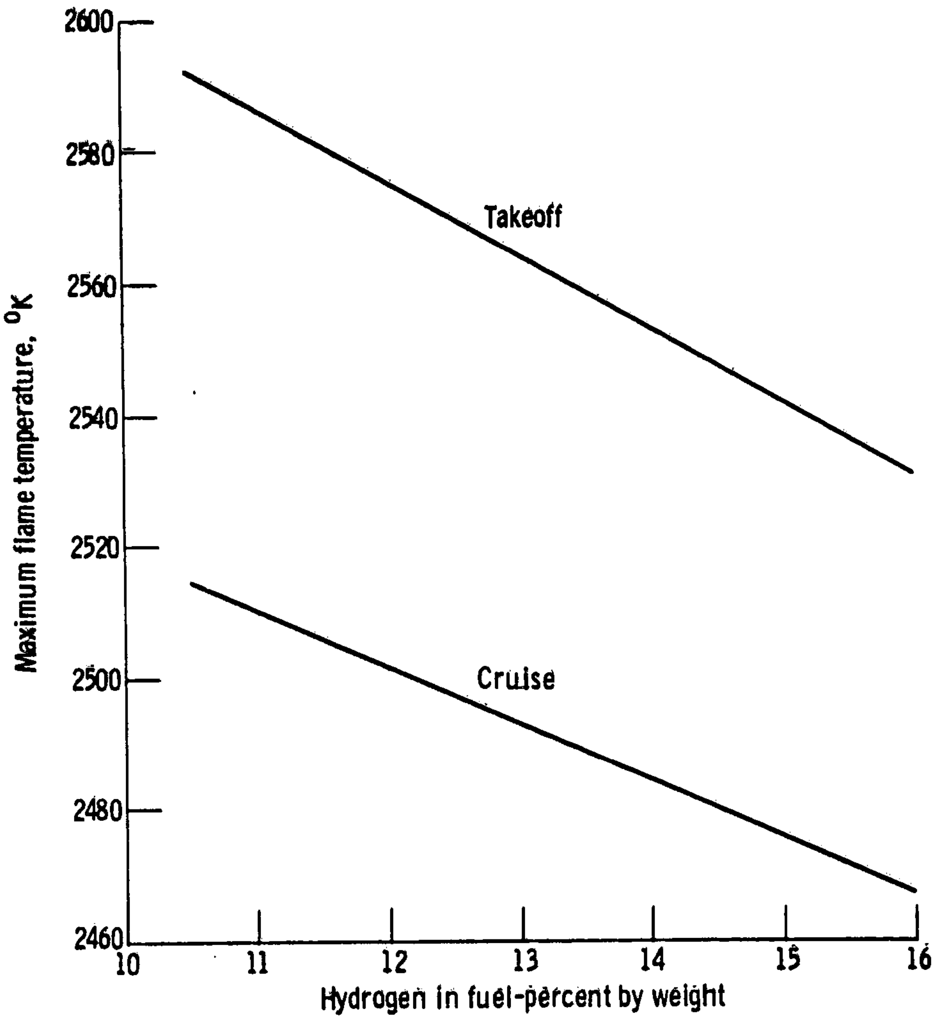

Figure 8. - Effect of hydrogen content of fuel on maximum flame temperatures.

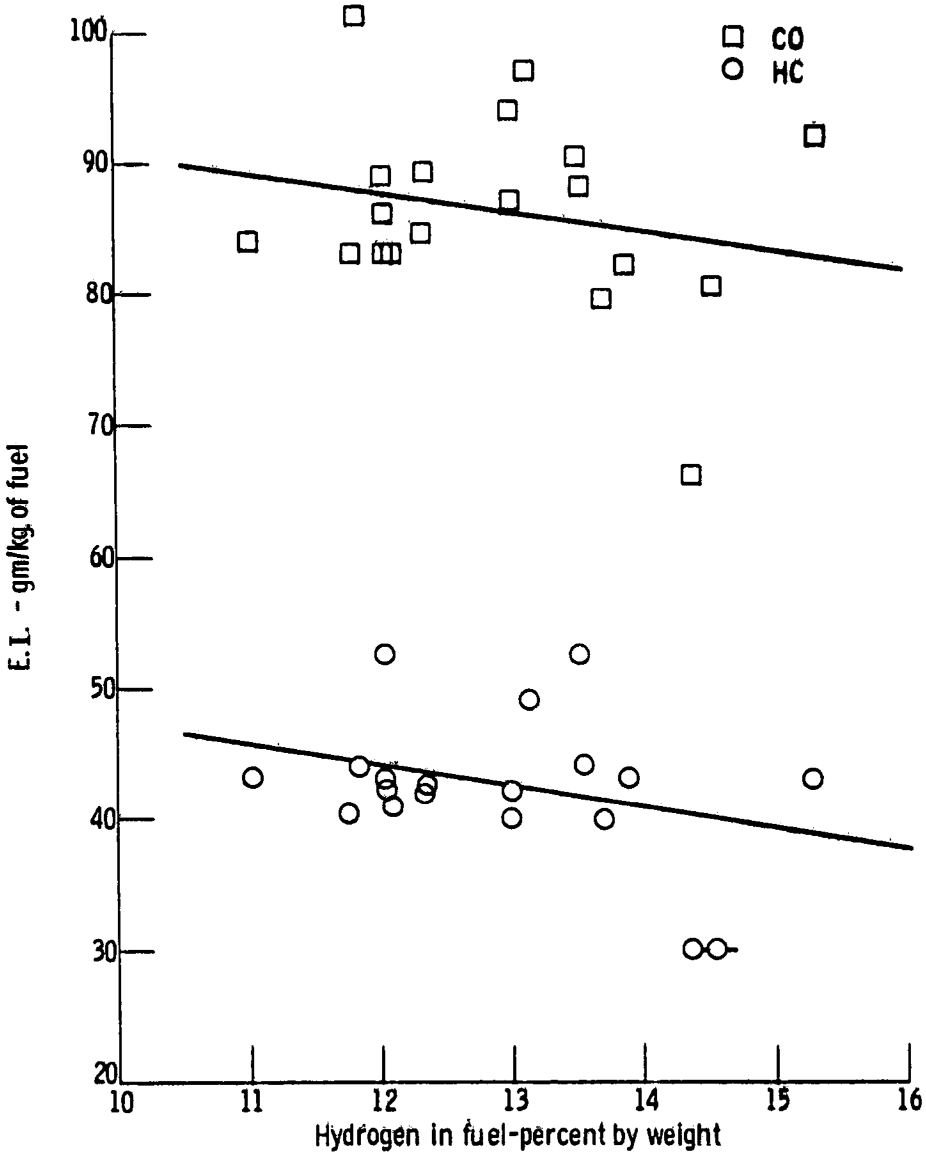

Figure 9. - Effect of hydrogen content of fuel on emissions of CO and unburned hydrocarbons at idle condition.

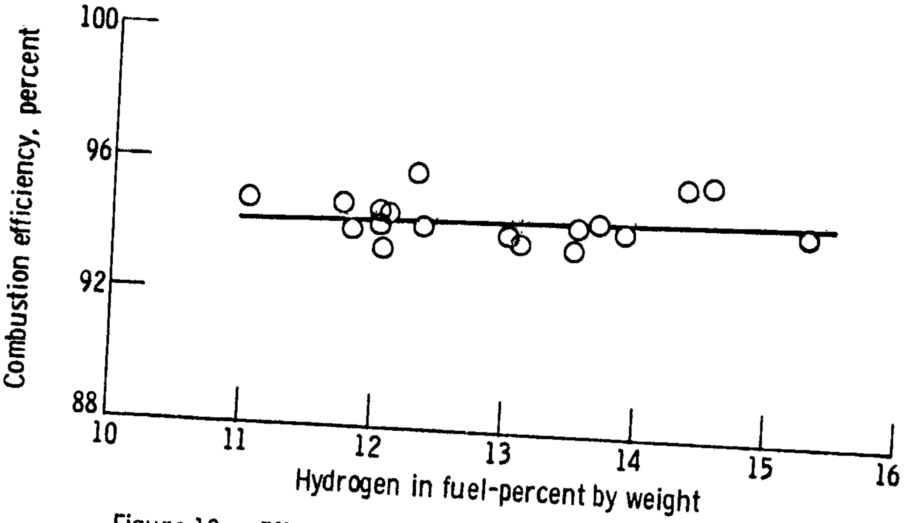

Figure 10. - Effect of hydrogen content of fuel on combustion efficiency at idle condition.

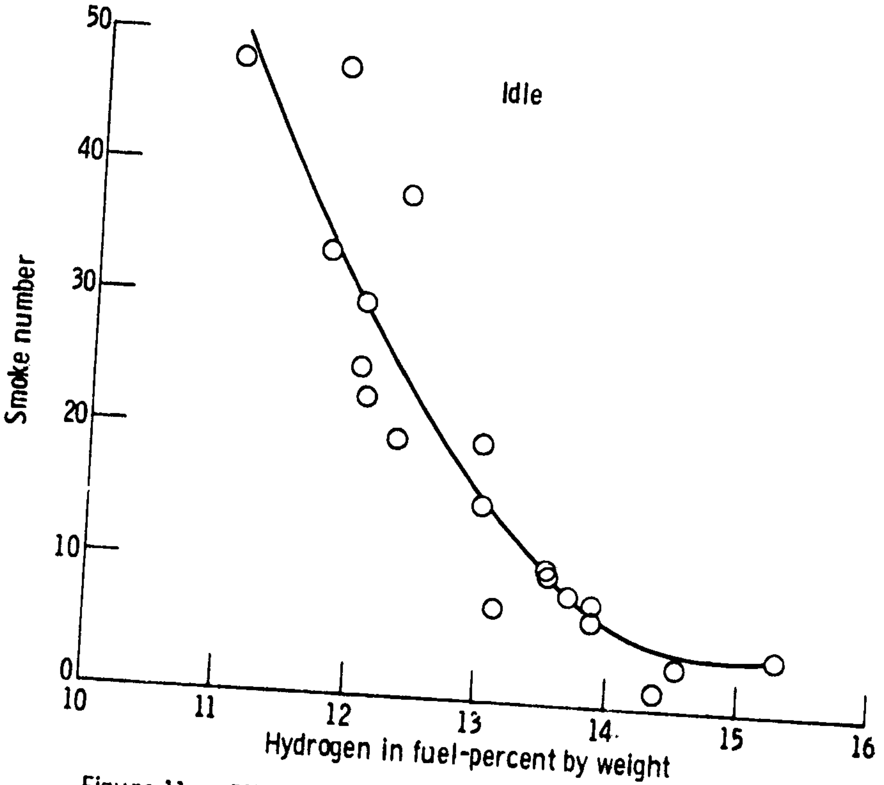

Figure 11. - Effect of hydrogen content of fuel on smoke number at idle conditions.