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Small Gas-Turbine Combustor Study—Fuel Injector Evaluation

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SMALL GAS-TURBINE COMBUSTOR STUDY - FUEL INJECTOR EVALUATION

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E-891

Abstract

As part of a continuing effort at the Lewis Research Center to improve performance, emissions, and reliability of turbine machinery, an investigation was undertaken to determine the effect of fuel injection technique and fuel type on similar improvements for small gas-turbine combustors. Performance and pollutant emission levels are documented over a range of simulated flight conditions for a reverse-flow combustor configuration using simplex pressure-atomizing, spill-flow return, and splash cone airblast injectors. A parametric evaluation of the effect of increased combustor loading with each of the fuel injector types was obtained. Jet A and an experimental referee broad specification fuel were used to determine and compare effects of burning different types of fuels in a small experimental gas turbine combustor.

I. Introduction

As part of the overall continuing research effort at the Lewis Research Center to improve performance, emissions, and reliability of turbine machinery, an investigation of the effect of fuel injection technique and fuel type on achieving such improvements was undertaken with small gas-turbine combustors. Performance and pollutant emission levels are documented over a range of simulated flight conditions for a reverse-flow combustor configuration using simplex pressure-atomizing, spill-flow return, and splash cone airblast fuel injectors with Jet A and an experimental referee broad specification fuel (ERBS).

The small gas-turbine engine is used extensively both in military and commercial applications and as a prime mover offers the potential for conserving fuel and natural resources through optimization of mission, payload, and performance. Improved performance with respect to cycle efficiency and specific fuel consumption can be achieved by increasing overall pressure ratio and turbine inlet temperature. However, material and manufacturing problems must also be considered, as well as the technical problems associated with contemporary combustors and especially those problems which are unique and add complexity to the design of small combustor systems.

Problems unique to small combustors were recently reviewed during a forum at NASA Lewis Research Center which was conducted by Arthur D. Little Inc.[1] One of the problem areas identified was that associated with fuel introduction. Fuel spatial distribution is a problem because of the narrow combustion height in annular configurations and the number of fuel injection locations required to effectively distribute small quantities of fuel. A fuel injection screening program in which pressure-atomizing, airblast, and air-assist techniques were evaluated has been reported in Ref. 2. A total of seven different injectors were used, four of which were specifically designed for the small combustor fuel injector program.[3] In the present investigation, the two most promising fuel injector schemes, the spill-flow return pressure atomizing injector and the splash cone injector, were tested with jet A fuel over a complete engine operating range and compared with simplex pressure-atomizing injectors.

Since future fuel supplies are uncertain there has been an effort towards establishing the effect of broadened fuel properties on aircraft engine performance. An experimental referee broad specification (ERBS) fuel has been established for test purposes.[4] Thus, as part of the overall investigation, performance and emissions data were also obtained with both jet A and ERBS fuels in order to compare results obtained with the same fuel injectors.

II. Apparatus

Test Facility

The test combustor was mounted in the closed-duct facility shown schematically in Fig. 1. Tests were conducted up to an inlet-air pressure of 1600 kPa with the air indirectly heated to about a temperature of 720 K. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold bypassed air. Airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves as shown in Fig. 1.

Combustor

A cross section of the reverse-flow combustor used in this investigation is shown in Fig. 2(a). An isometric sketch of the reverse-flow combustor is shown in Fig. 2(b). The combustor is a full scale experimental NASA design with a maximum diameter of 38.5 cm. The design stresses versatility so that interchanging fuel injectors and the modification or replacement of the swirlers, faceplate, liner, and turning sections can be readily accomplished. The design liner isothermal pressure loss is 1.5 percent and the diffuser dump loss is 0.24 percent. A symmetrical fuel injector spacing, based on 36 circumferential locations, is used so that 6, 9, 12, or 18 fuel injectors can be flow staged in the combustor by modification of the injector faceplate to maintain symmetry. Eighteen symmetrically spaced fuel injectors were used in this study except as noted. The airflow distribution and hole sizes in the liner are based on 36 primary and dilution holes. Photographs of the reverse-flow combustor are shown in Fig. 3.

Fuel Injectors

The three fuel injectors tested in this study were selected from the screening program described in Ref. 2.

Simplex pressure-atomizing injector - This commercially available injector was selected to establish a reference base as determined by operational limits, performance, and emission levels of the combustor configuration. The injector was 1.1 cm (7/16 in.) long with a 0.8 cm diameter (5/16 in., nEF-32-3A thread). All injectors used in this study were sized to provide most of the fuel flow required for simulated test conditions and parametric variations. The Flow Number was 4.8 (based on $W_f/\Delta p^{1/2}$, where W_f is weight of fuel in pounds per hour and p is in pounds per square inch differential pressure), and the spray angle 75°±5°. The Sauter Mean Diameter (SMD) was estimated to be 100 micrometers.

Spill-flow return injector - The spill-flow return injector is a pressure atomizing type which uses spin slots to achieve a tangential fuel velocity in the single discharge orifice. It is in effect a variable area injector due to the incorporation of a spill port which allows fuel to be returned from the spin chamber. This spill-flow reduces the apparent flow area of the spin slots so that the fuel supply pressure can be maintained high enough for good atomization and spray characteristics. The cross-sectional view of the injector is shown in Fig. 4(a).

The flow number for the spill-flow return injector was 3.1 with maximum spill flow. The SMD was approximately 100 μm throughout most of the flow range and decreased to about 75 μm at the maximum flow point. The spray angle was a well defined hollow cone with an included angle of about 90° which increased to 120° as the spill-flow valve was opened. The increase in cone angle with spill flow is expected and is caused by the apparent reduction of spin slot flow area. The patternator readings were relatively uniform over the spill flow range; however, as the spill-flow was reduced the pattern deteriorated.

Splash cone injector - This injector was selected on the basis of mechanical simplicity, large flow passages, and low fuel pressure requirements. This concept has shown promising potential as applied to large high-pressure combustors. The injector is an airblast type which uses simple orifices to distribute low pressure fuel into an air stream with subsequent atomization by a blast of swirling air. The splash cone consists of a concave surface around a center fuel tube. The tube has four radial jets impinging on the concave surface to deliver a uniform sheet of fuel into the airstream. The cross-sectional view of the injector is shown in Fig. 4(b).

The flow number for the splash cone injector is 6.4. The atomization characteristics of the splash cone were very difficult to determine except by direct observation. Problems were caused by the need to contain the fuel in the test stand and patternator. The cone angle ranged up to 200° over most of the operating range with four dense areas located radially from each orifice. Thus, all determinations of SMD and cone angle were distorted. Mean drop size ranged over 150 μm with patternator readings from 70 to 80 percent.

Instrumentation

The combustor instrumentation stations are shown in Fig. 5. Five total pressure probes, two static pressure taps, and five Chromel-Alumel thermocouples are located at station 2 to measure the inlet temperature and pressure. At station 3 a series of 18 total pressure probes are installed to determine the inlet-air profile and to determine the extent of any flow disturbance behind the struts which support the centerbody diffuser. At station 4 six pitot-static probes are positioned in the cold-air passages between the combustor liner and combustor housing to determine passage velocity and distribution. At station 5 outlet temperature and pressure measurements are obtained by means of a rotating probe. The probe contains 3 rakes spaced 120° apart: a five position radial rake containing Pt - Pt-13%Rd thermocouples; a five position total pressure rake; and a water cooled gas sampling rake. A 360° travel is used with increments as low as 1°.

III. Procedure

Test Conditions

The experimental reverse-flow combustor was operated at test conditions based on a gas turbine engine cycle with a compressor pressure ratio of 16 to 1. A tabulation of the test conditions simulated in this study are shown in Table I.

Data were obtained at combustor inlet conditions simulating sea-level take-off, cruise, and idle. Simulated flight data were obtained at a fuel-air ratio of approximately 0.024, low power at 0.014, and idle at 0.008. The simulated combustor test conditions are based on a reference velocity of 5.49 meters per second (m/s). The reference velocity quoted is based on unidirectional total mass flow and the maximum cross-sectional area of the housing prior to the reverse turn as shown in Fig. 2(a). Parametric variations in velocity of 5.49, 7.32, and 9.14 m/s were also obtained during the experimental testing at a fuel-air ratio of approximately 0.024. The test program was conducted using Jet A and an experimental referee broad specification fuel referred to as ERBS in this paper. A comparison of selected fuel properties is shown in Table II.

Emission Measurements

Exhaust gas samples were obtained according to the procedures recommended in Refs. 5 and 6. Exhaust gases were withdrawn through the water cooled rotating probe mounted approximately in the stator plane and in the center of the exhaust duct at station 5 (see fig. 5). Concentrations of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were determined with the gas analysis system described in Ref. 7. The gas sample temperature was held at approximately 423 K in the electrically heated sampling line. Most of the gas sample entered the analyzer oven, while the excess flow was bypassed to the exhaust system. To prevent fuel accumulation in the sample line, a nitrogen purge was used just before and during combustor ignition.

After passing through the analyzer oven, the gas sample was divided into three parts, and each part was analyzed. Concentrations of oxides of nitrogen, carbon monoxide and carbon dioxide, and hydrocarbons were measured by the chemiluminescence, nondispersed-infrared, and flame-ionization methods, respectively. The combustion efficiency data presented in this paper were based on stoichiometry determined by gas analysis.

IV. Results and Discussion

Preliminary screening of seven fuel injectors has previously been reported in Ref. 2. From this study the spill-flow return and splash-cone injectors were selected for further testing. Prior to final testing the minimum number of probe positions required to define the outlet temperature distribution was determined. Since a relatively uniform circumferential temperature distribution was obtained a 10° increment for a total of 36 radial positions was used to obtain performance and emission data.

Performance and Emissions

Combustor efficiency - The combustion efficiency data are shown in Fig. 6 over a range of simulated engine operating conditions. At simulated flight conditions the combustion efficiency is essentially 100 percent. At reduced power levels and idle differences in combustion efficiency and stability become apparent.

Reduction in combustion efficiency at low power is primarily due to poor spray characteristics resulting from a low pressure drop across the fuel injector. By reducing the actual number of injectors for a constant total fuel flow rate the pressure drop across the remaining injectors must be increased which results in improved efficiency. By reducing the number of simplex injectors from 18 to 9, the idle efficiency was improved from a blowout condition to a 92.4 percent combustion efficiency as shown in Ref. 2. Another way to improve efficiency under adverse conditions would be to improve spray characteristics of the injector. Two injector techniques were selected from Ref. 2: the spill-flow and the splash-cone.

Since the spill-flow injector provides good spray characteristics even at low fuel flows and low power level, combustion efficiency was above 90 percent as shown in Fig. 6. The advantage of the spill-flow injector is that it provides a relatively high fuel pressure drop at low fuel flow rates thereby maintaining good atomization. This is accomplished by supplying sufficient fuel to the spin chamber to maintain an adequate return flow to the fuel reservoir. As fuel flow decreases, the spray angle increases due to the apparent reduction of the spin slot flow area caused by the vortex of the fuel returning from the spin chamber back to the reservoir.

The flow characteristics of the spill-flow injector are shown in Fig. 7 and illustrate flow conditions required for practical operation. Essentially two extremes can be considered: one, in which the spill-flow is wide open; and two, in which the spill-flow is closed. Assuming that startup would normally dictate a wide open spill return line the cross-over between the two extremes is accomplished by closing off the spill at a preselected pressure level. If a constant spin chamber pressure is selected it is apparent that in order to maintain the required fuel flows through engine acceleration that the spill pressure could be used as the sensor for programming the fuel flow.

The splash cone injector represents the so called "airblast" atomization technique. It does not require high fuel pressure for atomization since the spray is produced by the shearing stresses between the slow moving fluid, fuel in this case, and the high velocity airstream (obtained by utilizing the pressure drop across the liner). As noted in Ref. 8 the airblast injector provides a relatively constant fuel distribution over the entire range of fuel flows. The splash cone was quite effective in providing high efficiency over the simulated flight operating range as shown in Fig. 6. However, at low power combustion efficiency deteriorated abruptly to 82 percent. By manifolding four adjacent injectors together to provide the temperature rise required at the low power condition an efficiency of 98 percent was obtained at the simulated idle condition (note no fuel was supplied to the other 14 of the original 18 injectors).

Pattern factor - The outlet temperature distribution as indicated by pattern factor is shown in Fig. 8. The pattern factor ranged from 0.17 to 0.31 for the fuel injectors at simulated SLTO and cruise flight conditions. In general the pattern factor was similar at the operating fuel-air ratio of 0.024 as that previously reported at a fuel-air ratio of 0.014 used in the screening program,[2] (i.e., pattern factor from 0.17 to 0.28).

Although not readily apparent the spill-flow produced a relatively constant pattern factor over the entire operating range including idle; whereas, the pattern factor deteriorated sharply prior to blow out for the simplex and splash cone injectors. The spill-flow injector demonstrated the beneficial effect of improved spray characteristics at low fuel flows. Both the simplex and splash cone injection showed deterioration in pattern factor at low fuel flows. However, with injector manifolding of the splash cone injectors the outlet temperature profile was just as good at idle as it was without manifolding at the higher flow rates.

The circumferential temperature distribution was relatively uniform for all injectors; however, it was noted that peak temperature always occurred at the same location. The peak temperature could be directly related to the combination of fuel injector and flow splitter in-line with the peak temperature. Each injector is installed with a commercially available flow restrictor to evenly distribute the fuel in the manifold. By interchanging injector and restrictor the peak temperature could be repositioned. It was assumed that by a more careful match of restrictor and injector that the pattern factor could be reduced; however, all reported data were obtained without attempting to match each injector with a restrictor.

Emission levels - Even though it is unlikely that emission standards will be established for small turbine engines in the under 6000 pound thrust class, emission levels are presented in this paper to document injector performance. The emission index levels of uHC were less than one and CO less than two with the injectors at simulated cruise. The emission indices of uHC and CO at a lower power condition and NO_x at simulated take-off are presented in Fig. 9. The CO and uHC emission index at an equivalent compressor pressure ratio of 5.1:1 show that the spill-flow injector produced very low emission levels. The splash cone and simplex injectors produced very high uHC levels indicating large amounts of unburned fuel. The poor performance can probably be attributed to poor atomization rather than incomplete combustion otherwise the CO emission levels would have been much higher (i.e., less than 2 percent inefficiency due to CO and 15 to 53 percent inefficiency due to uHC). The emission index of NO_x at simulated take-off with the three different injector types were similar and corresponded to approximately an emission index of 19.

If emission levels are a primary concern it should be noted that the emission levels produced with the spill-flow injector were influenced by the back pressure in the spill chamber. It would be possible to minimize emission levels only at low power levels by varying the spill chamber pressure for a constant fuel flow. At high power levels there was a negligible affect of spill chamber pressure on emissions.

In general all the injectors produced negligible smoke. At the most severe condition of sea-level take-off the smoke number was 4.5 for the simplex and less than 1 for the spill-flow and splash cone injectors.

Parametric Variation of Reference Velocity

The effect of increasing the mass flow for a given inlet pressure and temperature in the reverse-flow combustor was investigated to determine the effect on performance and emission at higher combustor loading. Nominal mass flow increases of 33 and 66 percent were tested at simulated cruise and sea-level take-off. An increase in mass flow at the simulated test conditions is directly proportional to reference velocity.

Combustion efficiency - The combustion efficiency obtained with the three injector types was not appreciably affected by an increase in reference velocity. It remained at approximately 100 percent.

Pattern factor - The effect of reference velocity on pattern factor at the selected test conditions is shown in Fig. 10. As shown, it increased somewhat with increasing velocity for the simplex and spill-flow fuel injectors. With the splash cone injection system it was not appreciably affected by an increase in reference velocity.

Pressure loss - The effect of reference velocity on total isothermal pressure loss is shown in Fig. 11. The pressure loss increased from 1.4 to 3.5 percent as the inlet diffuser Mach number increased from 0.054 to 0.088 as combustor reference velocity increased from 5.5 to 9.2 m/s.

Emission levels - The effect of reference velocity on the oxides of nitrogen is shown in Fig. 12. The decrease in oxides of nitrogen with increasing reference velocity is attributed in part to improved atomization and mixing, as a result of the increased pressure drop of the airstream and in part due to decreased residence time.

Although a small quantity of smoke was detected at the simulated flight conditions the effect of increased reference velocity was to further decrease smoke. Consequently, for the combination of injector type and reverse-flow combustor geometry smoke was not a problem.

Liner durability - The liner used in these tests buckled slightly in the primary zone indicating that an improvement in dispersing the fuel in the primary would be desirable. The maximum liner temperature in the primary zone obtained at simulated sea-level take-off is shown in Fig. 13. As the reference velocity increased, liner temperature decreased. However, splash cone operation indicated a relatively high liner temperature level in particular at the reference velocity of 5.5 m/s. It was assumed that the aerodynamic force of the stream was not of sufficient intensity to prevent fuel from impinging on the primary wall. As noted under INJECTORS a 200° spray angle was possible with the splash cone. At the higher pressure drop levels inherent with increased velocity a marked reduction in liner wall temperature was experienced, indicating that fuel was being entrained in the air stream rather than penetrating to the wall.

Comparison of Jet A Fuel and an Experimental Referee Broad Specification Fuel

In order to determine the effect that alternative fuels may have on fuel injector technique, an experimental referee broad specification (ERBS) fuel was included in the fuel injector evaluation program. Performance and emission data were obtained at simulated flight inlet conditions and low power. However, tests were limited to a f/a value of 0.014. A comparison of fuel properties is listed in Table II.

Combustion efficiency - The combustion efficiency data at simulated flight conditions were essentially 100 percent. At low power conditions efficiencies similar to that obtained with Jet A fuel were experienced as shown in Fig. 14. An unexpected difference occurred with the splash cone airblast injector, in that although efficiency dropped off at low power, it was still possible to maintain combustion even at idle. Similar conditions with Jet A fuel resulted in blowout. Spray tests with the splash cone injector using a range of fluids with different viscosities indicated that there would not be much difference in SMD with ERBS fuel as compared to Jet A fuel. However, a 10 percent increase in fuel pressure at low flow rates was required due to added viscous drag even though at high flow rates no effect was noted. Improvement in stability was probably due to a complex interaction between spray characteristics and localized evaporation and droplet burning.

Pattern factor - The outlet temperature distribution with ERBS fuel compared with Jet A is shown in Fig. 15 for the three injector configurations. The experimental data indicate that pattern factor was not appreciably affected at simulated flight conditions. This would be expected due to similar spray characteristics between the reference Jet A and ERBS fuel at high flow rates.

Emissions - NO_x emissions obtained with ERBS fuel as compared to Jet A are shown in Fig. 16. As noted even at low power emission indices of uHC and CO are similar as is the NO_x level at high power with the experimental spill-flow and splash cone fuel injectors.

The smoke number obtained with ERBS fuel is generally higher as compared with Jet A in Fig. 17 for the three fuel injectors. It was observed that as the f/a was increased with Jet A operation the smoke number decreased so that at a f/a of 0.024 no appreciable smoke was evident. The smoke number is compared in Fig. 17 at an operating f/a ratio of 0.014. Using simplex injectors the smoke number doubled with ERBS fuel as combustor pressure was nearly doubled. With the spill-flow injector smoke increased about 70 percent and with the splash cone, no change was noted. These results agree with previous studies. For example, Butze[9] has shown that the percentage of hydrogen could be correlated with smoke number. In the study of Ref. 9 a conventional pressure atomizing injector was used in a modified JT8D combustor. The increase in smoke number was approximately 100 percent based on the weight percentage of hydrogen of the two fuel types. In the current study the pressure atomizing injectors (simplex and spill-flow) also indicated relatively high increases in smoke number. A comparison of more advanced concepts, such as those discussed by Smith[10] indicated that an increase in smoke number did not necessarily occur in changing from Jet A to ERBS fuel. A similar result was obtained with the airblast concept using the splash cone injector at a pressure of 1600 kPa.

V. Concluding Remarks

The following generalizations based on performance and design of each of the experimental injector configurations are noted:

1. Of the pressure-atomizing injectors involved in the basic screening program the spill-flow return injector appeared to offer the potential for wide operational range and appeared most promising for further study. The spill-flow injector is in effect a variable area injector due to the incorporation of a spill port which allows fuel to be returned from the spin chamber. At low fuel flows out of the injector, the cone angle is approximately 120° due to high tangential liquid velocities produced by the apparent reduction of the spin slot flow area. As fuel flow is increased the cone narrows down to approximately 90°, thereby preventing fuel from impinging on the wall. The resulting design is not sensitive to fuel contamination due to large passages, fabrication costs are low, and a wide performance range is inherent in the design as shown experimentally.

2. The splash cone injector was the most promising of the airblast injectors designed for this study even though several areas of concern were identified. The injector was originally selected on the basis of mechanical simplicity, large flow passages, and low fuel pressure requirements. The concept has shown promising potential as applied to large high pressure combustors. In the small combustor application the low fuel flow characteristics were critical. By maintaining fuel flow to each injector above a minimum value relatively complete combustion could be achieved-if not-performance deteriorated abruptly. By selective manifolding to maintain sufficient fuel pressure high performance could also be obtained at idle and deterioration of the spray could be avoided. In cold flow tests, the injector produced a spray of relatively large fuel droplets with a SMD of the order of 150 μm. However, due to rapid aerodynamic mixing obtained with the air swirlers, very low smoke numbers were experienced along with good performance. Liner temperatures indicated that the fuel spray penetrated close to the walls at low reference velocities. To overcome this problem additional pressure drop across the combustor can be maintained by increasing the combustor mass flow loading. A similar approach would be to use larger airblast passages yet maintain pressure drop to avoid liner overtemperature levels.

3. The performance of the experimental referee broad specification fuel as compared to Jet A with the simplex, spill-flow, and splash cone injectors indicated that parameters such as combustion efficiency and outlet temperature distribution would be similar. The only discernable changes were with respect to emissions. The simplex produced less NO_x with ERBS; whereas, the spill-flow and splash cone produced more NO_x with ERBS. All three injectors produced considerably more smoke with ERBS than with Jet A.

VI. References

1. Demetri, E. P., Topping, R. F., and Wilson, R. P., Jr., "Study of Research and Development Requirements of Small Gas-Turbine Combustors," Arthur D. Little, Inc., Cambridge, MA, ADL-83381-2, Jan. 1980. (NASA CR-159796.)

2. Norgren, C. T. and Riddlebaugh, S. M., "Effect of Fuel Injector Type on Performance and Emission of a Reverse-Flow Combustor," NASA TP-in preparation (E556).

3. Smith, B. P., "Phase II, Technical Report Nozzle Development Program NAS3-16817. Research, Development, and Testing of Small Size Fuel Atomizers, 1973." (Robert D. Ingebo, NASA Project Manager.)

4. Longwell, J. P. and Grobman, J. S., "Alternative Aircraft Fuels," NASA TM-73836, 1977.

5. "Control of Air Pollution from Aircraft and Aircraft Engines - Emission Standards and Test Procedures for Aircraft," Federal Register, Vol. 38, No. 136, Pt. 2, Tues., July 17, 1973, pp. 19088-19103.

6. "Procedures for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines," Aerospace Recommended Practice 1256, Oct. 1971, SAE.

7. Ingebo, R. D. and Norgren, C. T., "High Pressure Combustor Exhaust Emissions with Improved Air-Atomizing and Conventional Pressure-Atomizing Fuel Nozzles," NASA TN D-7154, 1973.

8. Lefebvre, A. H., "Airblast Atomization," Progress in Energy Combustion Science, Vol. 6, No. 3, 1980, pp. 233-261.

9. Butze, H. F. and Ehlers, R. C., "Effect of Fuel Properties on Performance of a Single Aircraft Turbojet Combustor," NASA TM X-71789, 1975.

10. Smith, A. L., "Analytical and Experimental Evaluation of the Effect of Broad Property Fuels on Combustors for Commercial Aircraft Gas Turbine Engines," NASA TM-81496, 1980.

TABLE I. - REVERSE-FLOW TEST CONDITIONS

Test condition	Airflow		Inlet pressure		Inlet temperature		Reference velocity		Compressor pressure ratio
	kg/s	lb/sec	kPa	psia	K	°F	m/s	ft/sec	
SLTO base	3.63	8	1620	235	717	830	5.5	18	16 to 1
f/a to 0.024	4.61	10.2	1620	235	717	830	7.3	24	16 to 1
	5.77	12.7	1620	235	717	830	9.1	30	16 to 1
Cruise	2.27	5	1014	147	686	775	5.5	18	10 to 1
f/a to 0.024	3.01	6.63	1014	147	686	775	7.3	24	10 to 1
	3.76	8.29	1014	147	686	775	9.1	30	10 to 1
Idle @f/a 0.008	1.23	2.7	405	58.8	474	394	5.5	18	4 to 1
Low power	2.12	4.66	862	125	627	665	5.5	18	8.5 to 1
@f/a 0.014	1.83	4.02	689	100	581	585	5.5	18	6.8 to 1
	1.51	3.33	517	75	526	486	5.5	18	5.1 to 1
	1.23	2.70	414	60	474	394	5.5	18	4.1 to 1

TABLE II. - FUEL PROPERTIES

	Jet A	ERBS
Specific gravity (288 K)	0.813	0.836
Distillation temp., K (R)		
Initial	442 (796)	442 (795)
10 percent	460 (829)	466 (840)
Final	544 (980)	625 (1126)
Aromatics, vol.%	16.8	27.46
Hydrogen, wt.%	13.7	12.9
Freeze point, K (R)	233 (420)	244 (440)
Viscosity, m^2/s (cs)	1.52×10^{-6} (1.52)	1.64×10^{-6} (1.64)
Heating value, J/g (BTU/lb)	43 000 (18 600)	41 900 (18 170)

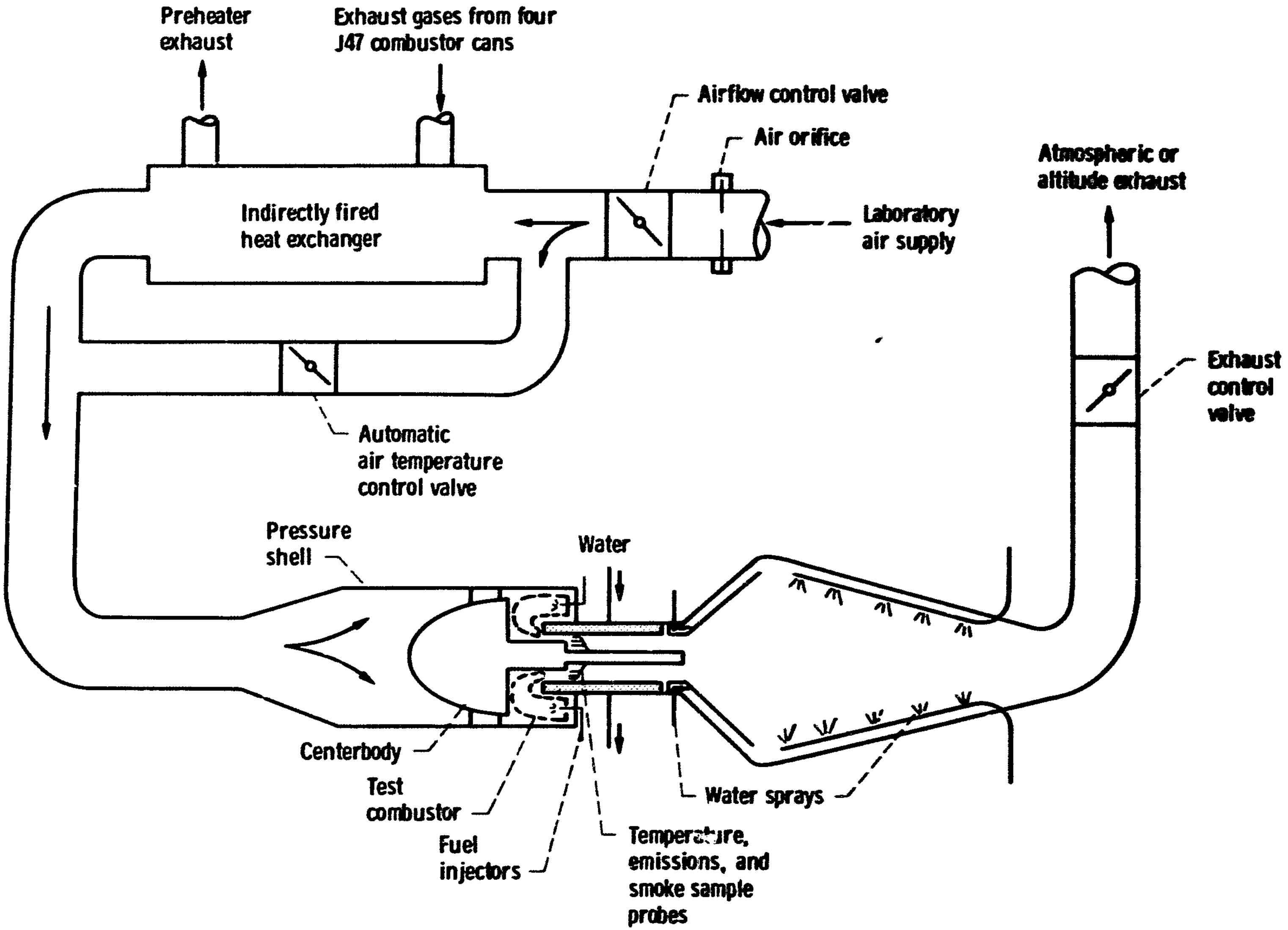


Figure 1. - Schematic of test facility.

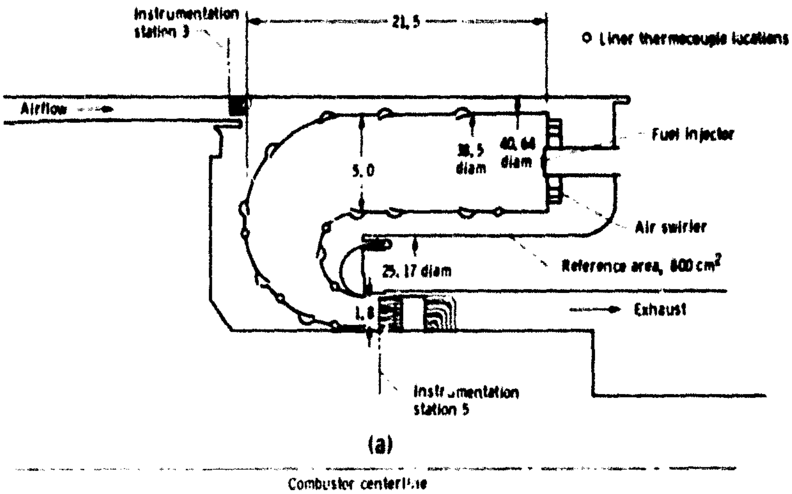
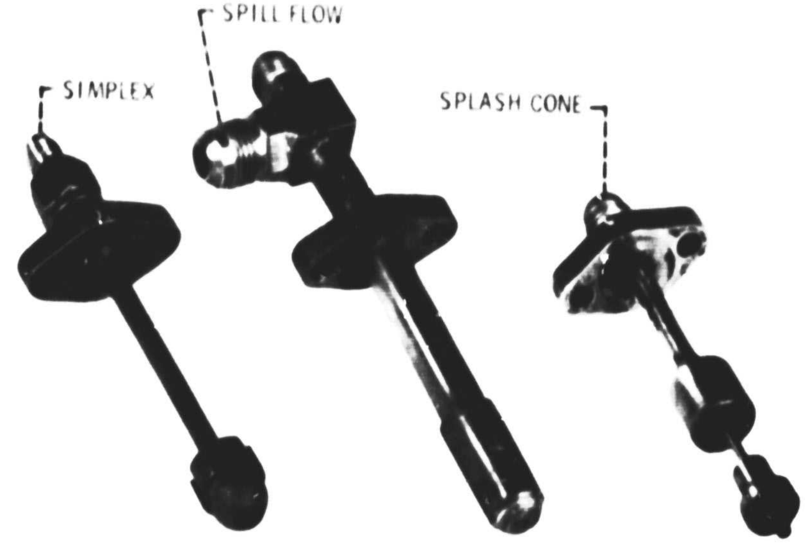
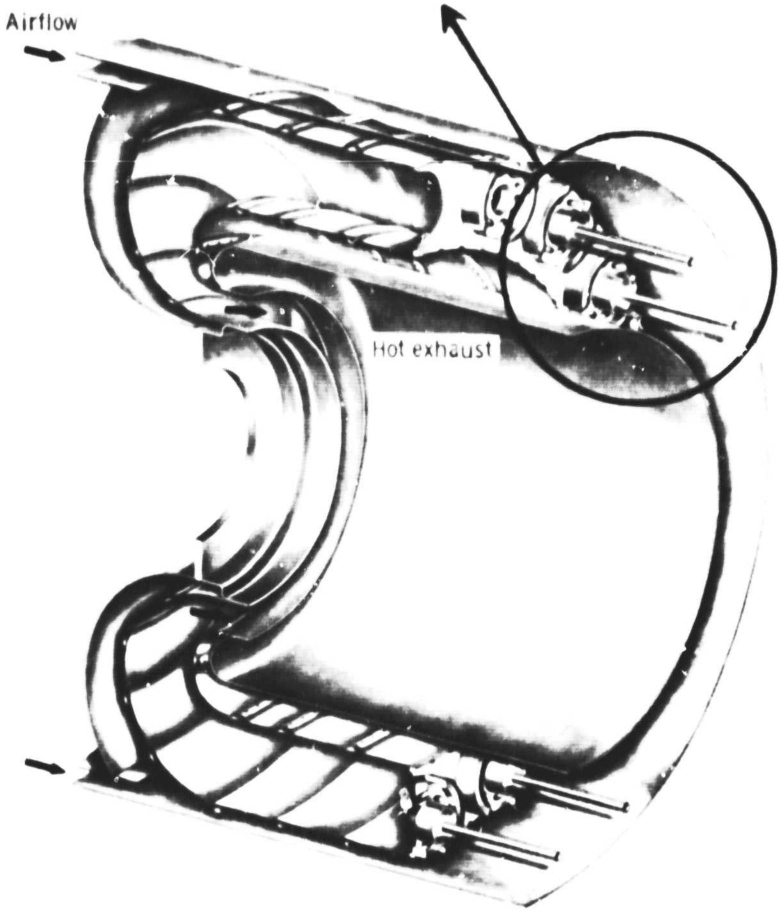


Figure 2. - Reverse-flow combustor. (All dimensions in centimeters.)



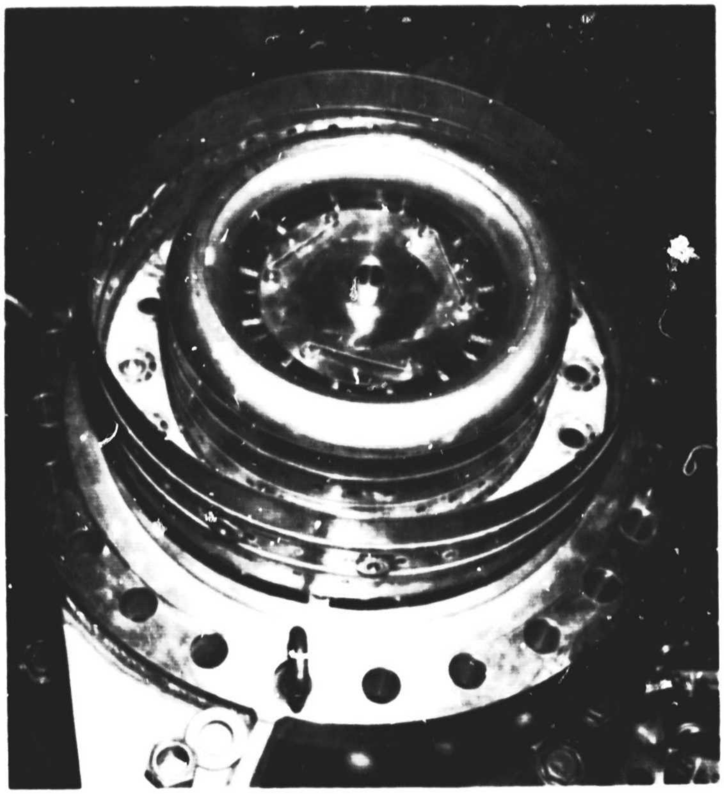
Fuel injectors



(b) Isometric view.

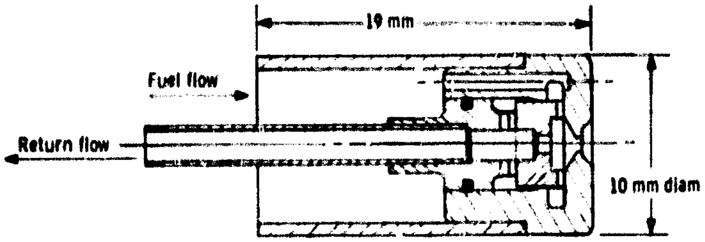
Figure 2. - Reverse-flow combustor. (All dimensions are in centimeters.)

(a) Aft view of combustor.

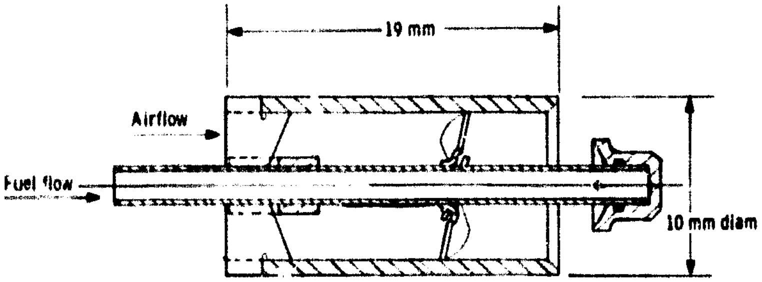


(b) Combustor liners.

Figure 3. - Photographs of reverse-flow combustor.

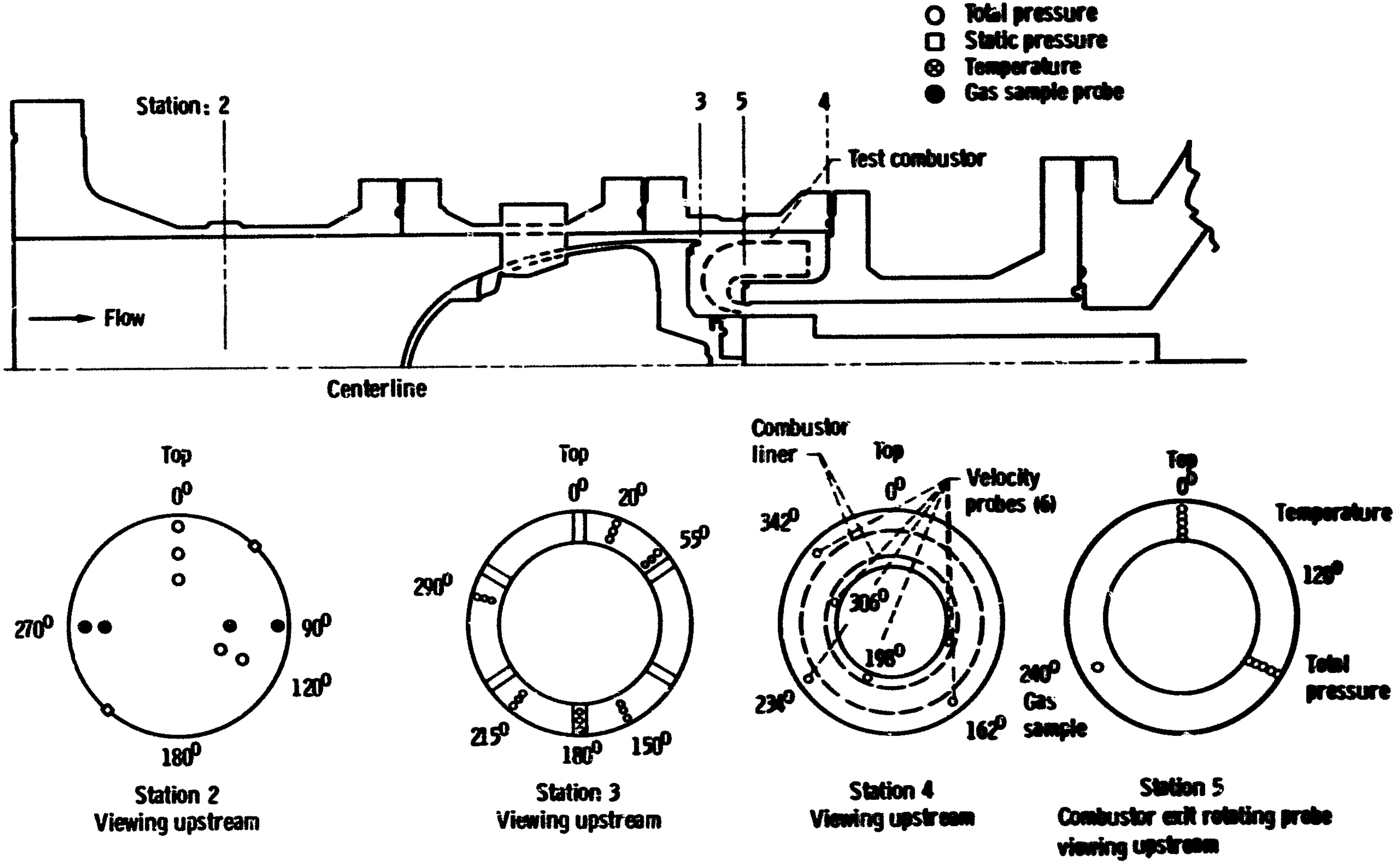


(a) Spill-flow.



(b) Splash cone.

Figure 4. - Fuel injector schematic.



Station 2
Viewing upstream

Station 3
Viewing upstream

Station 4
Viewing upstream

Station 5
Combustor exit rotating probe viewing upstream

Figure 5. - Research Instrumentation.

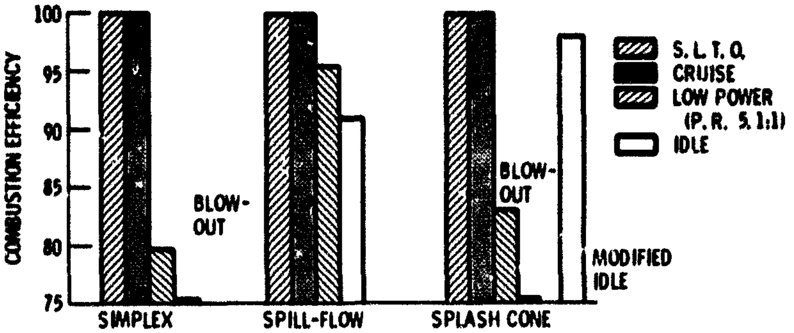


Figure 6. - Combustion efficiency at selected test conditions with Jet-A fuel.

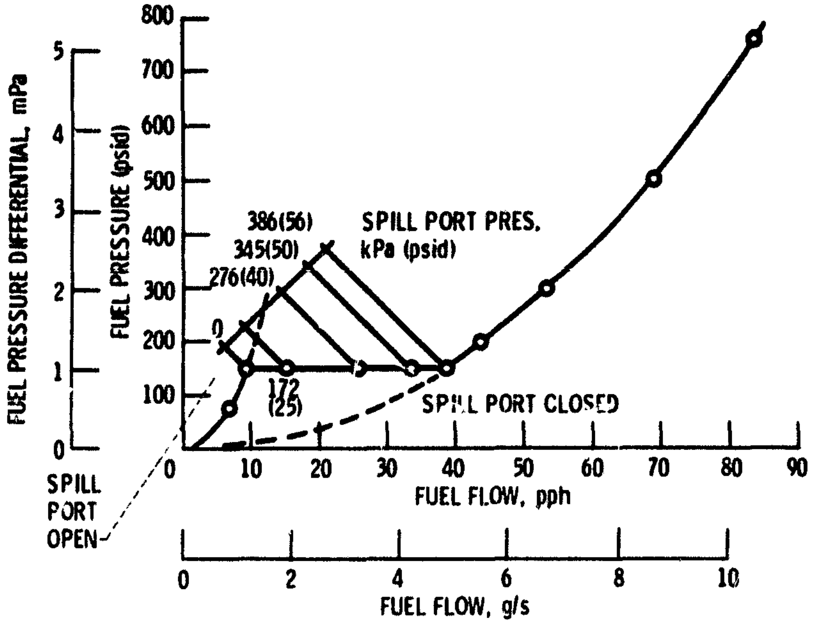


Figure 7. - Typical fuel flow calibration for spill-flow pressure-atomizing injector.

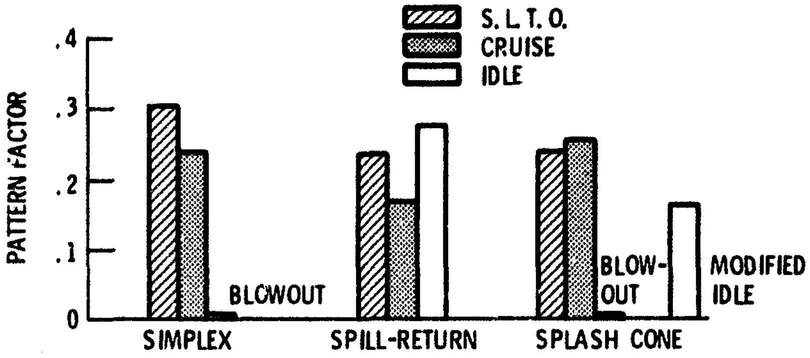


Figure 8. - Pattern factor at selected test conditions with Jet-A fuel.

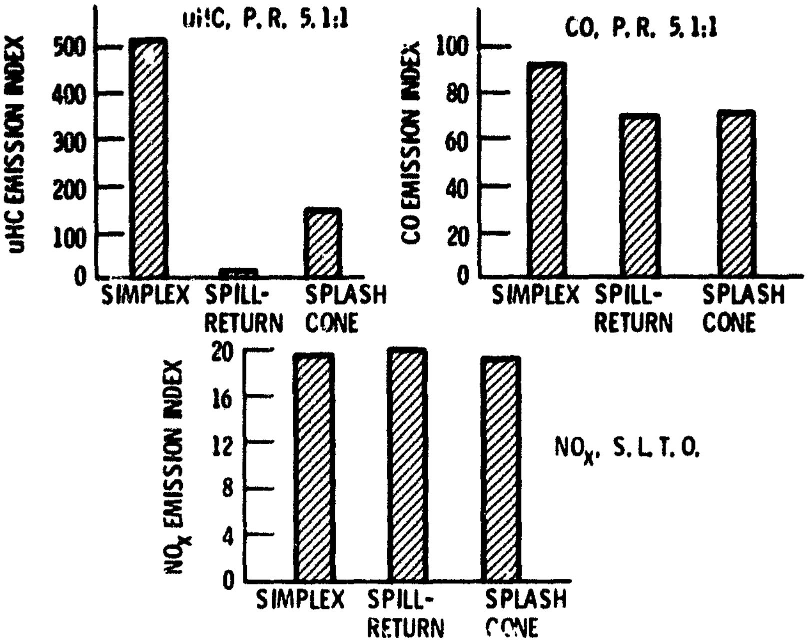


Figure 9. - Emissions at selected test conditions with Jet-A fuel.

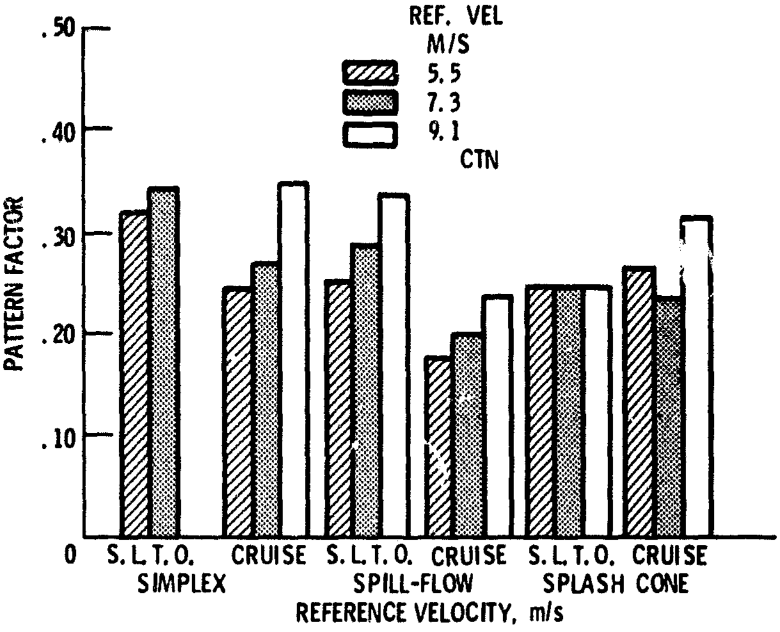


Figure 10. - Effect of parametric variation of reference velocity on pattern factor with Jet-A fuel.

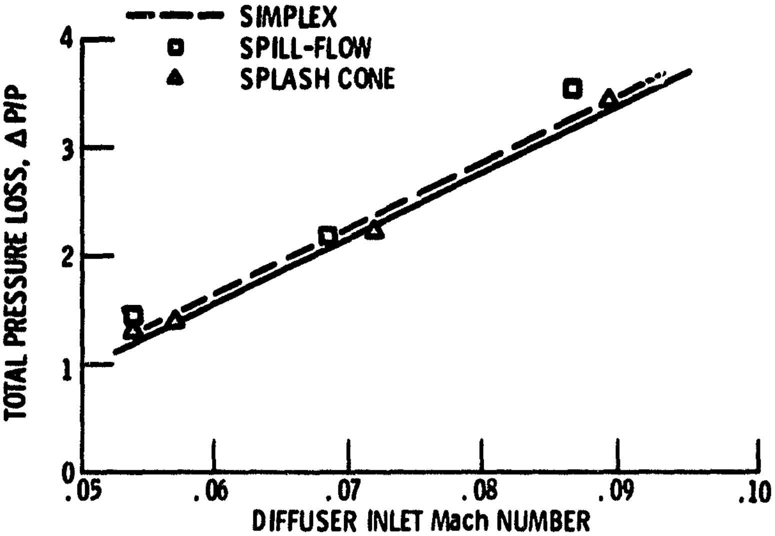


Figure 11. - Reverse-flow combustor total isothermal pressure loss over a range of inlet diffuser Mach numbers.

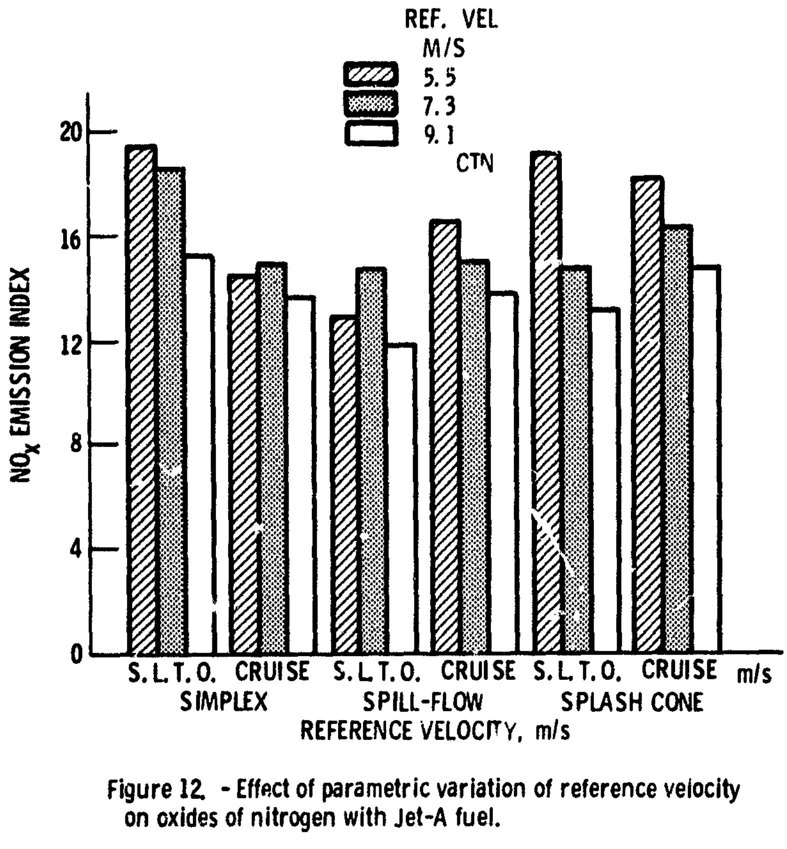


Figure 12. - Effect of parametric variation of reference velocity on oxides of nitrogen with Jet-A fuel.

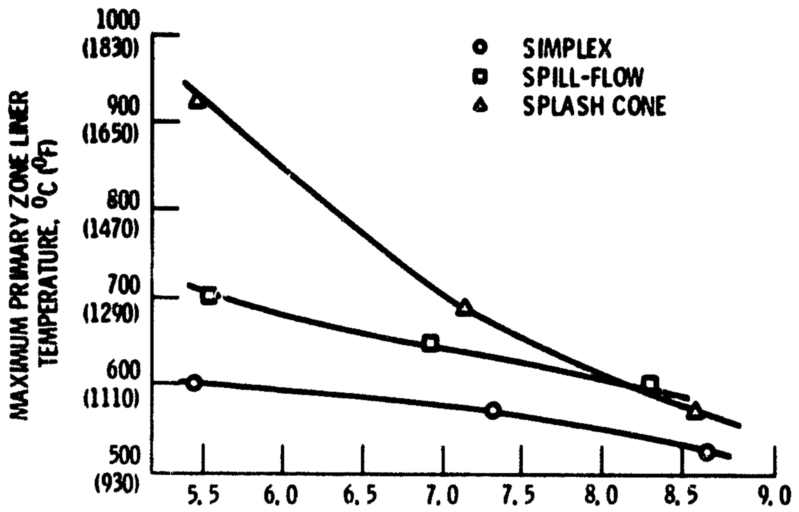


Figure 13. - Effect of parametric variation of reference velocity on maximum liner temperature with Jet-A fuel.

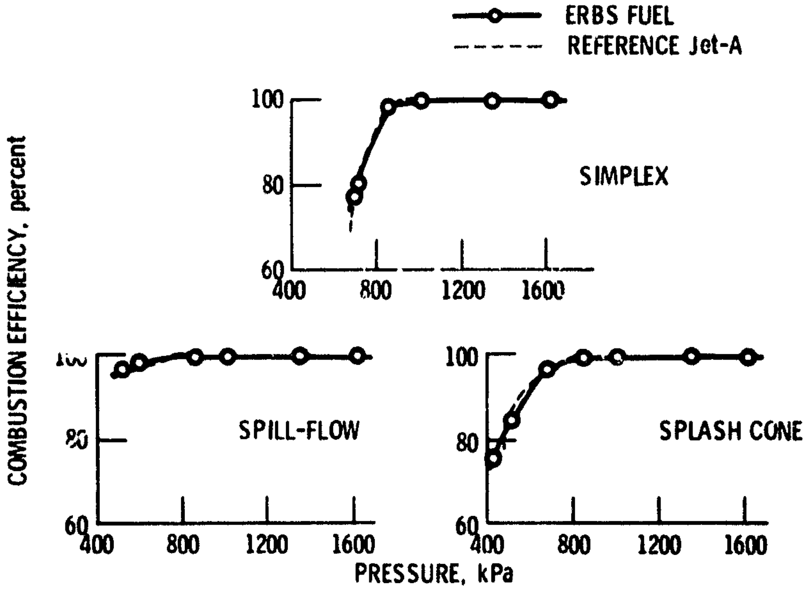


Figure 14. - Comparison of combustion efficiency with Jet-A and ERBS fuel at selected test conditions at an overall f/a of 0.014.

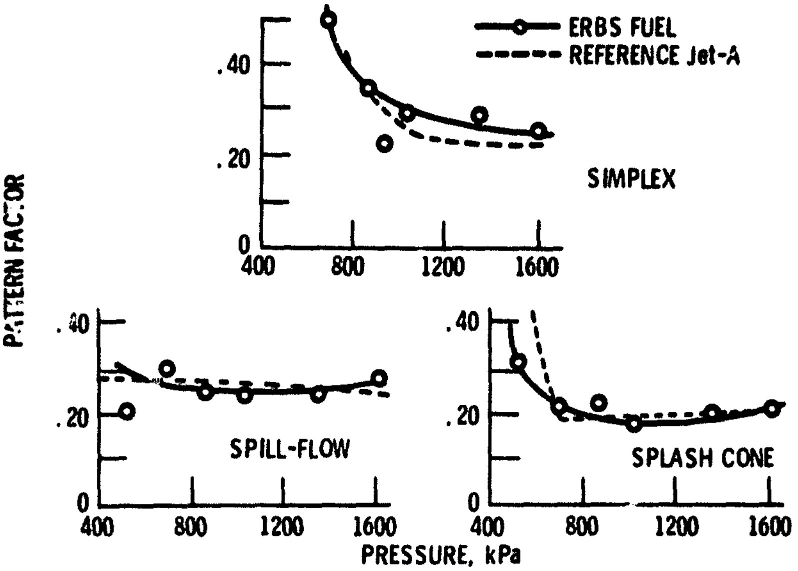


Figure 15. - Comparison of pattern factor with Jet-A and ERBS fuel at selected test conditions at an overall f/a of 0.014.

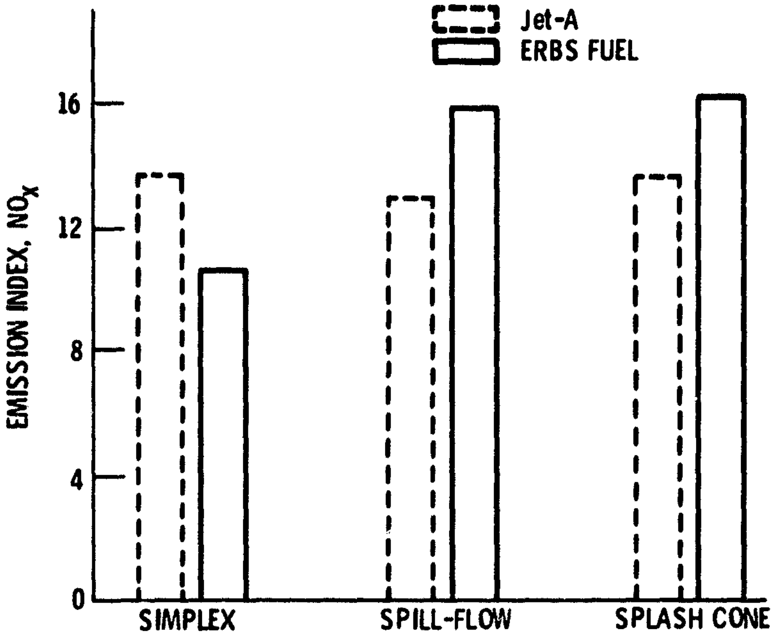


Figure 16. - Comparison of oxides of nitrogen emissions with Jet-A and ERBS fuel at selected test conditions at an overall f/a of 0.014.

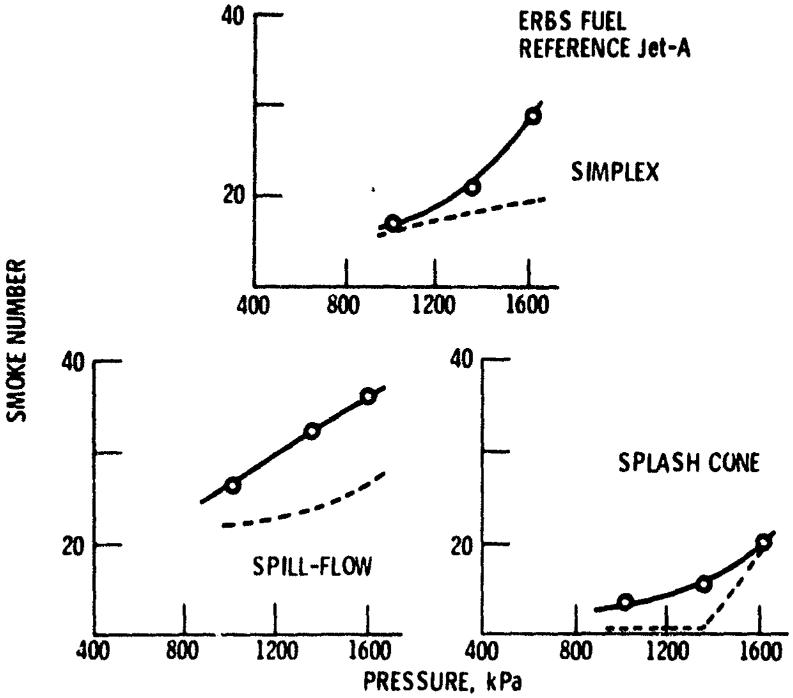


Figure 17. - Comparison of smoke number with Jet-A and ERBS fuel at selected test conditions at an overall f/a of 0.014.