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Small Gas Turbine Combustor Study— Fuel Injector Performance in a Transpiration-Cooled Liner

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SMALL GAS TURBINE COMBUSTOR STUDY - FUEL INJECTOR PERFORMANCE IN A TRANSPIRATION-COOLED LINER

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Abstract

An investigation determined the effect of fuel injection technique on the performance of an advanced reverse flow combustor liner constructed of Lamilloy (a multilaminate transpiration type material). Performance and emission levels are documented over a range of simulated flight conditions using simplex pressure atomizing, spill 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.

Introduction

The reverse flow combustor is a configuration well suited for small gas turbine engines.[1] These engines often have a final centrifugal stage in the compressor. A reverse flow combustor can be coupled to a centrifugal compressor through a radial diffuser, which is highly efficient with respect to reducing pressure losses in the diffuser and improving flow distribution to the combustor. The reverse flow combustor provides a larger combustion volume than would be available with a straight-through annular combustor; thus a potential gain in performance can be realized. In addition, engine packaging is favorably affected by permitting a close coupling of the compressor and turbine and placing the fuel injectors in a readily accessible location.

Two disadvantages of the reverse flow design are a comparatively large liner surface and a requirement for a large number of fuel injectors to adequately distribute the fuel throughout the large primary zone annulus. The large liner surface area results in a more severe liner cooling problem than with other small combustor designs. As engine cycles have "grown" (higher pressure ratios and temperature rises) the liner cooling problem has gotten worse. The fuel distribution requirements result in a large number of physically small injectors that have to perform well over a fuel flow range beyond the "turn down ratio" of the standard simplex pressure atomizing type. In addition the small passage sizes of these injectors make them susceptible to clogging and rather sensitive to fuel type.

It should be noted that these problems are not unique to the reverse flow combustor. They are common to most annular combustor designs for small gas turbine engines. As a group they have high surface to volume ratios. The current trend to ever shorter combustor lengths has made primary zone performance critical. Primary zone performance in turn is closely tied to the uniform distribution of fuel throughout the annulus. In recognition of these considerations, both liner cooling and fuel injection have been identified as highly important R&D efforts which must be conducted in the 1980 to 1990 time frame.[2]

The NASA Lewis Research Center small combustor research effort has placed major emphasis on developing advanced liner cooling techniques and advanced fuel injectors. As part of the liner cooling study, a series of similar reverse flow combustors have been designed, fabricated, and tested, utilizing advanced cooling concepts including convective cooling, transpiration cooling, and ceramic walls. As part of the fuel injector program, these liners are tested with advanced injector designs and their performance evaluated and compared.

Transpiration cooling is a technique that more effectively makes use of the heat sink capacity of the liner cooling air than is done in the film cooling systems in use on most current production combustors. Of the various concepts using the porous wall principle Lamilloy is in the most advanced stage of development, and has shown the potential of reducing the required amount of cooling air by as much as 50 percent.[3] The Lamilloy concept features an electrochemically etched, multilayer, diffusion bonded structure.[4]

Previous fuel injector studies[5] have identified several advanced concepts which show considerable potential. Two of these are the spill-return pressure atomizing injector and the splash cone airblast injector. Both designs are less sensitive to fuel type and give good atomization performance over a wider range of flow conditions than the simplex type of pressure atomizing injector.

In this study a reverse flow combustor with Lamilloy liner walls was operated with spill return and airblast injectors. The performance with these injectors was compared to that with a baseline simplex injector. Documentation of performance, pattern factor, and emission levels were obtained over a range of simulated flight conditions for a 16 to 1 compression ratio gas turbine engine operating with Jet A fuel. Parametric evaluation of the effects of increased combustor loading was also included.

The combustor used in this study was a NASA design sized and configured for a 1500 shp turboshaft engine. Such an engine would be used to power helicopters or medium sized turboprop aircraft such as are used for the commuter aircraft market.

Apparatus

Test Facility

The test combustor was mounted in a closed-duct facility (Fig. 1). Tests were conducted up to an inlet-air pressure of 1600 kPa with the air indirectly heated to a temperature of about 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 indicated in Fig. 1

Combustor

A schematic cross section and photograph of the reverse-flow combustor used in this investigation are shown in Fig. 2. 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. Eighteen symmetrically spaced fuel injectors were used in this study. The airflow distribution and hole sizes in the liner are based on 36 primary and dilution holes. The liner airflow distribution is summarized in Table 1.

The test combustor liner was transpiration cooled. The liner walls were made of Lamilloy, a commercial product composed of an electrochemically etched channel structure in several layers which are diffusion-bonded together to form a single sheet. Figure 3 compares the Lamilloy wall structure to a conventional film cooled liner wall structure.

The Lamilloy Combustor was fabricated under government contract. The basic design conditions were for a peak combustor operating pressure of 16 atm, 717 K inlet temperature, and 1390 K exit temperature with hot streaks up to 1922 K. The design of the combustor follows the general flow charts of Ref. 6. The performance of the Lamilloy combustor is compared to the performance of a conventional splash-film cooled reverse flow combustor of essentially identical configuration in Ref. 3.

Fuel Injectors

The three fuel injectors tested in this study were selected from the screening program described in Ref. 5. They are illustrated in Fig. 4(a).

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. The injector was 1.1 cm long with a 0.8 cm diameter. All injectors used in this study were sized to provide the fuel flow required for simulated test conditions and parametric variations. The Flow Number was 4.8 and the spray angle 75° with a $\pm 5°$ tolerance. The Sauter Mean Diameter (SMD) was estimated to be 100 μm.

Spill Flow Return Injector

The spill return injector is a pressure atomizing type which uses spin slots to achieve a tangential fuel velocity in the single discharge orifice. It behaves like a variable area injector due to the incorporation of a spill port which allows fuel to be returned from the spin chamber to the fuel tank. The spill flow rate is controlled by valves and flowmeters similar to those used to control the supply fuel flow. 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. A cross-sectional view of the injector is shown in Fig. 4(b). A typical fuel flow calibration is shown in Fig. 5. The spill port is opened only at low flow conditions; at high flow rates the injector is operated as a simplex.

The flow number for the spill return injector was 3.1 with maximum spill flow. The SMD was ~100 μm throughout most of the flow range and decreased to about 75 μm at the maximum flow point. The spray was a well defined hollow cone with an included angle of about 90°, which increased to 120° as the spill flow valve was opened.

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 fuel tube has four radial jets impinging on the concave surface to deliver a uniform sheet of fuel into the airstream. A cross-sectional view of the injector is shown in Fig. 4(b).

The flow number for the splash cone injector was 6.4. The spray cone angle could range up to 200° over most of the operating range.

Instrumentation

The combustor instrumentation stations are shown in Fig. 6. 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 used to determine the inlet-air profile and to determine the extent of any flow disturbance behind the struts supporting the centerbody diffuser. At station four, six pitot-static probes are positioned in the cold air passages between the combustor liner and combustor housing to determine passage velocity and air distribution. At station five combustor exit conditions are measured by a rotating probe containing three rakes spaced 120° apart; a five position radial rake containing Pt-Pt-13 percent Rd thermocouples; a five position total pressure rake; and a water cooled gas sampling rake. A 360° traverse is used with step increments as low as 1°.

Liner thermocouple locations were based on thermal paint indications and positions representative of primary, secondary, and dilution regions. Twelve Chromel-Alumel thermocouples were mounted on the cold side of the Lamilloy in the axial locations shown in Fig. 2. These thermocouples were located at different circumferential locations on the liner; however, for the sake of clarity the figure shows them all in the same plane.

Test Procedure

The reverse flow combustor was operated at test conditions based on a gas turbine engine cycle with a compressor pressure ratio of 16. A tabulation of the heat conditions simulated in this study is given in Table 2.

Data were obtained at combustor inlet conditions simulating sea level take-off (SLTO), cruise, and idle. Simulated flight data were obtained at a fuel-air ratio of ~0.024, low power at 0.020, and idle at 0.008. The simulated combustor test conditions were based on a reference velocity of 5.49 m/s. The reference velocity is based on unidirectional total mass flow and the maximum cross-sectional area of the housing prior to the reverse turn. Parametric variations in velocity of 5.49, 7.32, and 9.14 m/s were also obtained during the experimental testing over a range of fuel-air ratios up to about 0.024. The program was conducted using Jet A fuel.

Emissions data were taken using instruments and techniques that are standard throughout industry and academia and are described in detail in Refs. 7 and 8.

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

Results and Discussion

This study was part of a continuing research program involving reverse flow combustors. Test procedures, sampling frequency, and conditions were based on the experience gained in previous testing.[3,5,9] Mechanical failure of the splash cone injector fuel struts prevented running a full set of test conditions with these injectors, but their performance can be inferred by comparison of the data with previous performance data reported in Refs. 5 and 9.

Combustor Efficiency

When operated at their design points all three injectors produced combustion efficiencies of essentially 100 percent. At reduced power levels, low power conditions, and the idle condition differences in combustion efficiency and stability became apparent.

Figure 7 presents the combustion efficiencies produced by the three injectors at the low altitude cruise condition. Injector performances at the high altitude cruise and SLTO conditions were essentially the same.

The reduction in combustor efficiency at lower fuel-air ratios is primarily due to a deterioration of spray quality produced by the injector. The simplex injector experienced the most rapid falling-off of performance. The simplex design depends upon the fuel pressure drop across the injector to provide the energy needed for good atomization. However, the fuel flow rate is also determined by this pressure drop. As a result, when fuel pressure is reduced to lower the fuel flow rate, atomization performance also is reduced.

The splash cone injector is an airblast type, which achieves atomization through the breakup of a film or thin sheet of fuel by a high velocity air stream. For a series of fuel-air ratios at a single operating condition, such as the low altitude cruise condition presented in Fig. 7, the airstream is not changing. The drop off in performance at lower fuel-air ratios of the splash cone injector, as seen in the figure, is probably attributable to the four metering holes not producing a uniform film of fuel on the conical filming surface.

The spill return injector produced combustion efficiencies above 99 percent over the entire range of fuel-air ratios tested. While the spill return type is a pressure atomizing injector, the net fuel flow to the combustor is not determined by fuel pressure drop. At the low fuel requirement conditions, the spill port is opened and the excess fuel returned to the the tank. A high fuel pressure drop can be maintained even at low net fuel flow rates.

Figure 8 presents combustor exit temperature pattern factors produced at a high fuel-air ratio over the range of operating pressures. All three injectors produced low pattern factors at the cruise conditions (inlet pressures above 1000 kPa). This good performance reflects the benefits to be obtained when using a transpiration cooling system such as Lamilloy; the liner cooling air is less disturbing to the combustor internal airflow patterns than in more conventional liner cooling schemes.[3]

All three injectors produced constant pattern factors at the cruise conditions. At the simulated low power conditions (inlet pressure below 1000 kPa), the pattern factor generated by the simplex injector deteriorated quite rapidly. This is a result of the deterioration in fuel spray quality at low flow rates. The better spray quality at low flow rates produced by the spill return injector is reflected in the better pattern factors at low power conditions.

Low power data for the splash cone injector are not available due to the mechanical failure of the fuel struts. Previous tests with a conventional film cooled liner[9] indicate that the pattern would deteriorate rapidly at low power conditions. The lower combustor inlet air pressures produce less "airblast" effect.

The effect of increased combustor reference velocity on pattern factor is presented in Fig. 9. Pattern factor was either uneffected or slightly improved with increased loading. While splash cone data are not available for this liner, similar data for a similar film cooled liner[9] indicate pattern factor would be improved by increased combustor loading. The two pressure atomizing injectors benefit from the increased fuel flow rate, while the airblast injector benefits from the increase in liner pressure drop resulting from the increased airflow rate. It is also apparent that the primary and dilution zone airflow patterns in the combustor did not deteriorate at the increased loading.

Emissions

Oxides of nitrogen, carbon monoxide, and unburned hydrocarbons emissions produced by the three injectors are presented in Fig. 10. At fuel-air ratios above 0.016, all three injector types produced equally low amounts of CO and hydrocarbons. The spill return injectors produced slightly greater amounts of NO_x. At lower fuel flow rates, hydrocarbons and CO emissions increased rapidly for the simplex and splash cone injectors; this was most likely due to the deterioration in spray quality.

The deterioration in performance of the splash cone injector was not due to reduced airblast effect, as the data in Fig. 10 are all at one operating condition. A possible explanation is that at the lower fuel flow rates the four metering orifices that deposit the fuel on the filming surface are not flowing full, thus producing a nonuniform fuel film. Observed carbon deposits on the tips of the splash cone injectors also indicated a nonuniform film deposit.

In general all three injectors produced negligible smoke over the entire range of test conditions.

The effect of reference velocity on oxides of nitrogen emissions is presented in Fig. 11. Increased reference velocity resulted in reduced NO_x emissions for two reasons. One was improved atomization and mixing as a result of the increased pressure drop of the airstream across the combustor liner. The other factor was reduced residence time due to the higher reference velocity.

Figure 12 presents the effect of reference velocity on CO emissions. The increased combustor loading had little effect on the spill return injector's CO production, but the simplex injector's performance was greatly improved. This is almost certainly due to the increased mixing effect resulting from the increased liner pressure drop. The effect was less noticeable with the spill return injector due to its already good atomization performance. The decreased residence time due to the higher reference velocities had no observed effect on CO production, indicating very good mixing in the primary zone.

The dominant mechanism controlling CO and hydrocarbon emissions in this study apparently was poor atomization and mixing in the primary zone at low fuel flow rates, creating fuel rich pockets in the primary zone. Increased loading of the combustor broke up and mixed these pockets and allowed the fuel to be more completely burned.

The good performance of the splash cone injectors in this study is characteristic of the performance gains to be had with airblast injection. The specific design of the injectors used in this study are not presented as or should be considered to be an optimum design. Two problems encountered with this design were mechanical integrity problems and carbon deposition on the tips under low power conditions.

The spill return injector gave excellent performance over a wide range of fuel flows. Its performance was especially good at the low power and low fuel flow conditions, where it produced combustion efficiencies of about 99 percent at fuel flow rates below the blow out point for the baseline simplex. This injector would be a good candidate for combustor applications where low power performance is important. Operating the injector in spill mode at higher fuel flow conditions produces no noticeable benefit in performance, while carrying a penalty in requiring a fuel system capacity far in excess of what would be dictated simply by the combustor's requirements. The spill return injector also carries the penalty of requiring a considerably more complex fuel control and manifolding than the simplex or airblast injector.

Conclusions

1. Both the spill return and splash cone injectors produced improved performance over the simplex injectors in all areas of consideration, including combustion efficiency, emissions, and pattern factor.

2. The spill return injector produced a dramatic impovement in combustion efficiency at low power levels. This was expected; the spill return design is in effect a variable geometry simplex specifically designed to extend good atomization performance into the very low flow range.

3. The spill return injector produced the most oxides of nitrogen at the standard reference velocity. Apparently the improved atomization produced a more intense primary zone temperature, resulting in increased thermal NO_x production. The increase was most pronounced at the low power settings. At higher power settings the simplex injector produced comparable levels of NO_x. At low power settings the poorer atomization performance of the simplex injectors apparently produced poorer fuel-air mixing in the primary zone, with local fuel-rich zones that reduced the primary zone temperature.

4. The splash cone injector produced greater overall efficiencies than the simplex injector, although not as good as the spill return injector. It produced the lowest pattern factors and oxides of nitrogen. Unburned hydrocarbons and carbon monoxide emissions were lower than those produced by the simplex injector, but higher than the spill return injector.

5. The difference in emissions performance of the splash cone and spill return injectors illustrates the trade-off between NO_x production versus incomplete combustion products that has been a major problem designers face when trying to reduce overall emissions levels.

6. The splash cone injector's good performance is characteristic of airblast designs. The spill return injector's performance reflects performance gains to be expected from variable geometry injector designs. The spill flow injector does carry a penalty in requiring a more complex control and fuel delivery system - in effect, a doubling of the fuel manifolding, supply lines, and valving needed. Factoring in the desirability of reducing overall system complexity, the results of this study indicate that the airblast type of injector offers the better potential for improved combustor performance.

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TABLE 1. - LINER AIRFLOW DISTRIBUTION

Air entry	Type of entry	Mass flow, percent of total	Comments
Faceplate	Swirler	24.8	25.4 cm from firewall, 36 holes in outer wall, and 36 holes in inner wall
Primary	Primary holes	18.6	5.72 cm from firewall, 36 holes in outer wall, and 36 holes in inner wall
Dilution	Dilution holes	24.1	--------------------------
Concentric around fuel injector	Annulus	3.2	--------------------------
Liner cooling	Film cooling	13.2	--------------------------
Outer 180°	Film cooling	13.1	--------------------------
Inner 180°	Film cooling	3.0	--------------------------

TABLE 2. - 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 f/a 0.014	2.12	4.66	862	125	627	668	↓	↓	8.5 to 1
	1.83	4.02	689	100	581	585	↓	↓	6.8 to 1
	1.51	3.33	517	75	526	486	↓	↓	5.1 to 1
	1.23	2.70	414	60	474	394	↓	↓	4.1 to 1

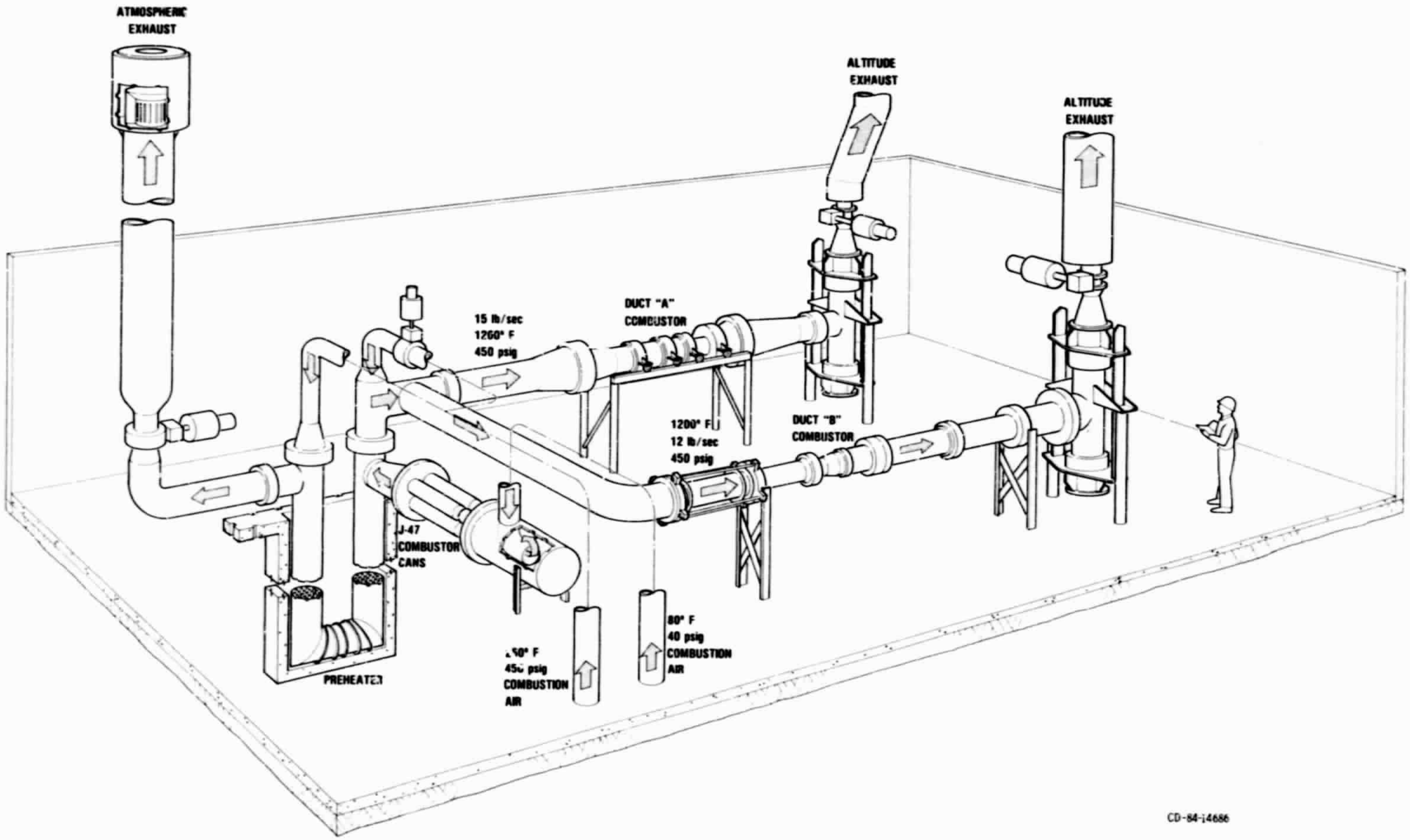
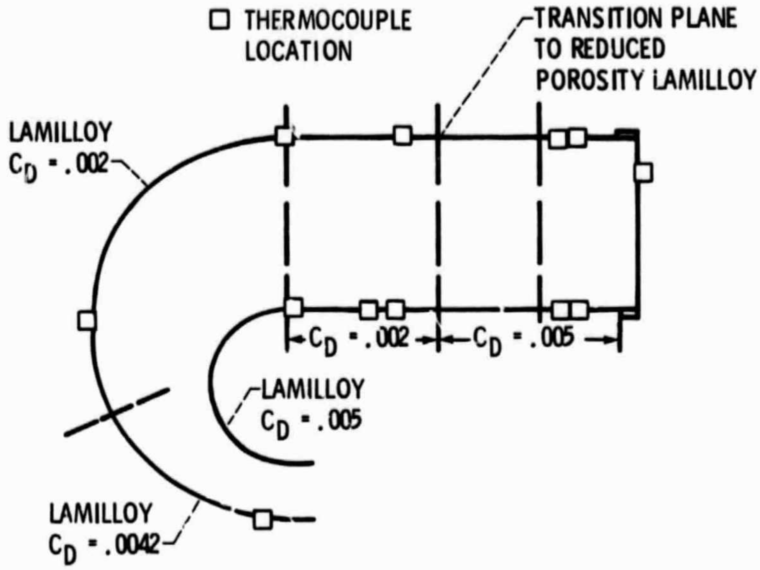
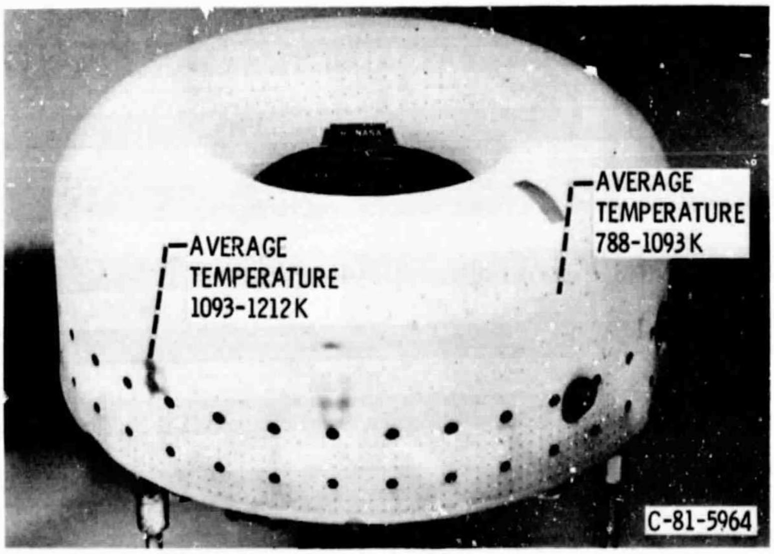


Figure 1. - Schematic of test facility.

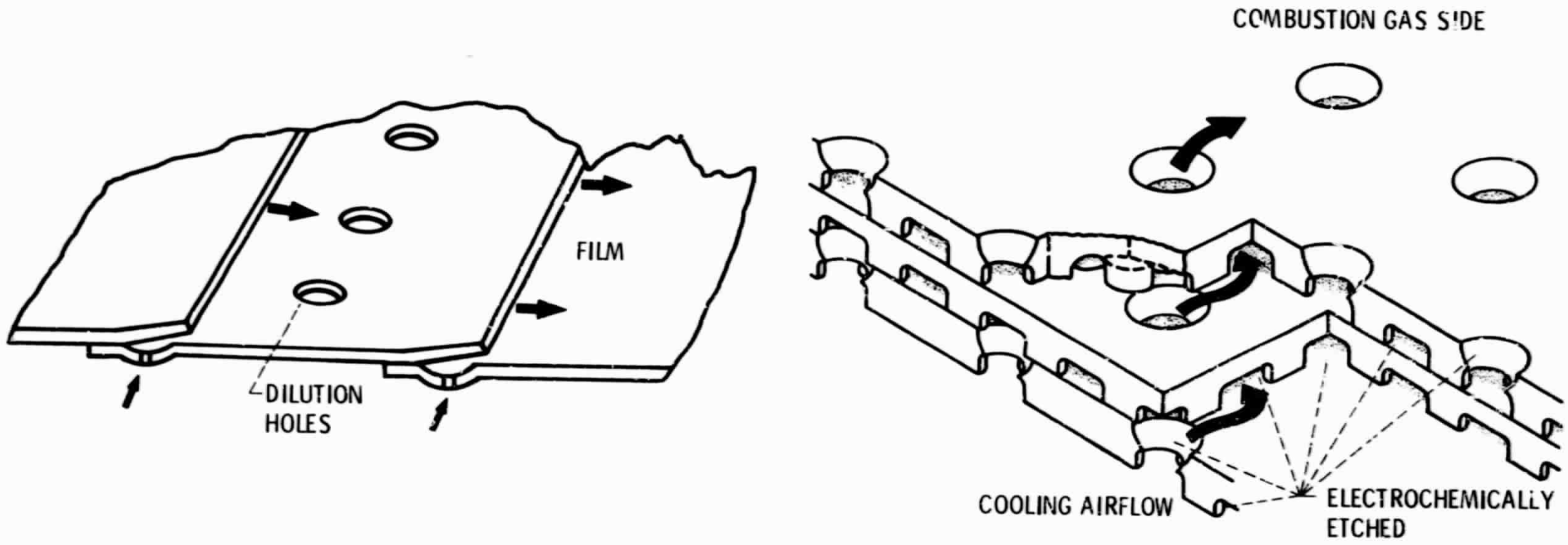


(a) Lamilloy identification for reverse flow annular combustor.



(b) Photograph of lamilloy combustor after firing.

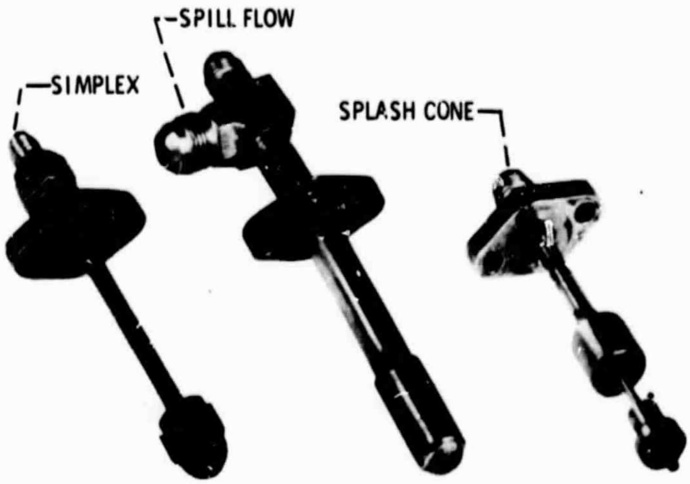
Figure 2. - Lamilloy reverse flow combustor.



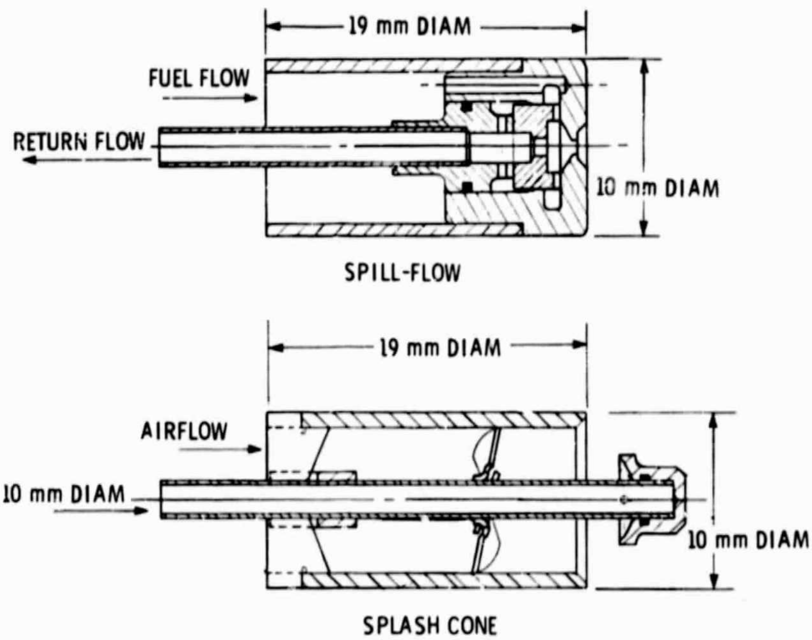
(a) FILM COOLED.

(b) LAMILLOY.

Figure 3. - Schematic of liner wall cooling configurations.



(a) Fuel injectors.



(b) Fuel injector schematic.

Figure 4. - Fuel injectors used in the Lamilloy reverse flow combustor.

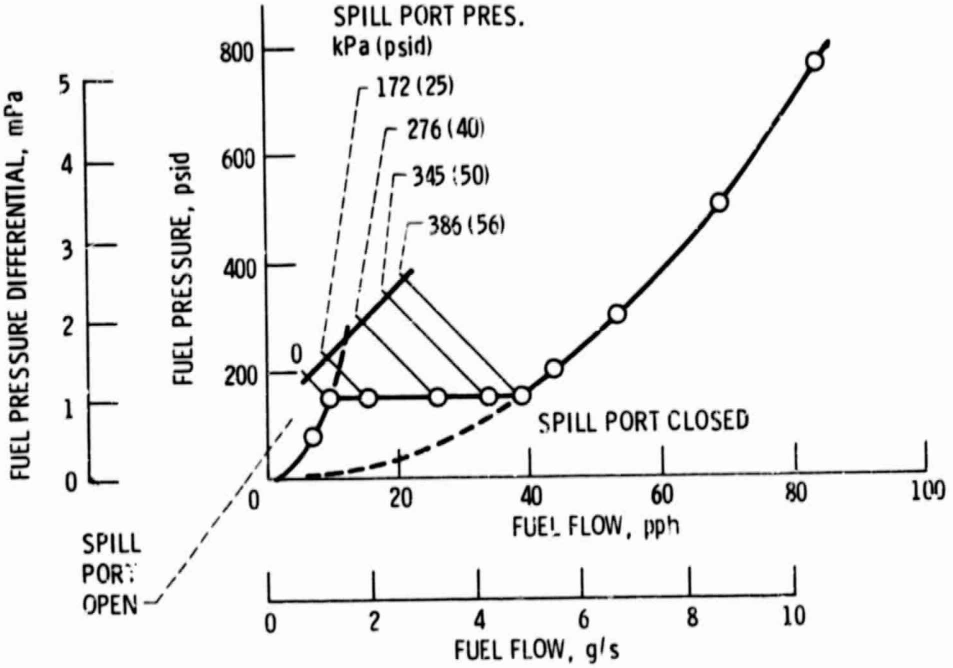


Figure 5. - Typical fuel flow calibration for spill-flow pressure-atomizing injector.

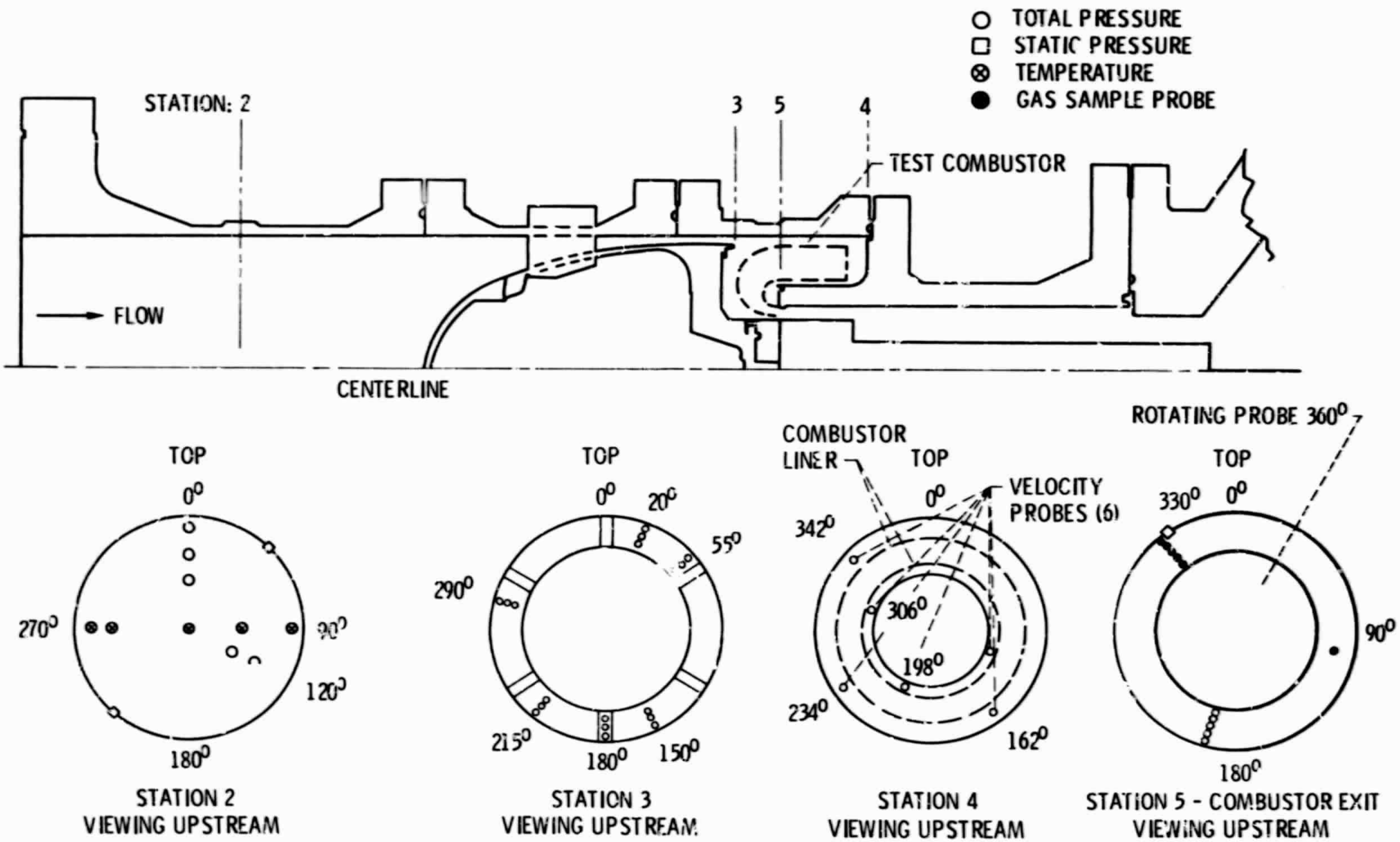


Figure 6. - Research instrumentation.

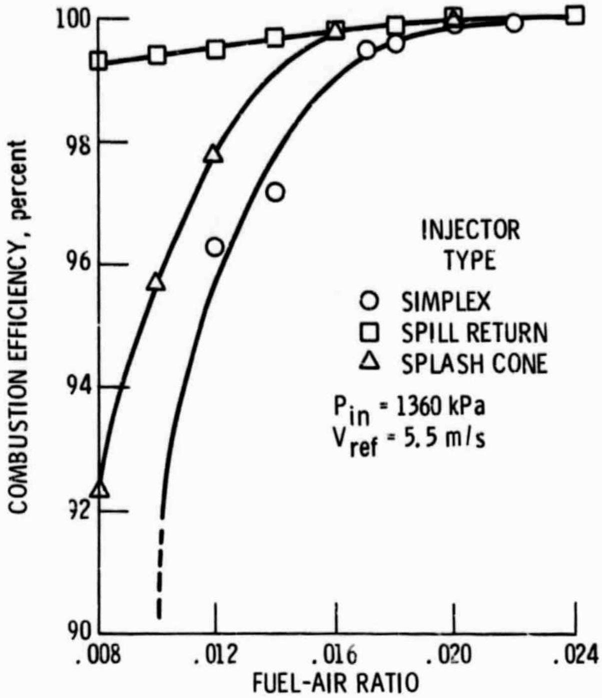


Figure 7. - Effect of fuel injector type on combustion efficiency at the low altitude cruise condition.

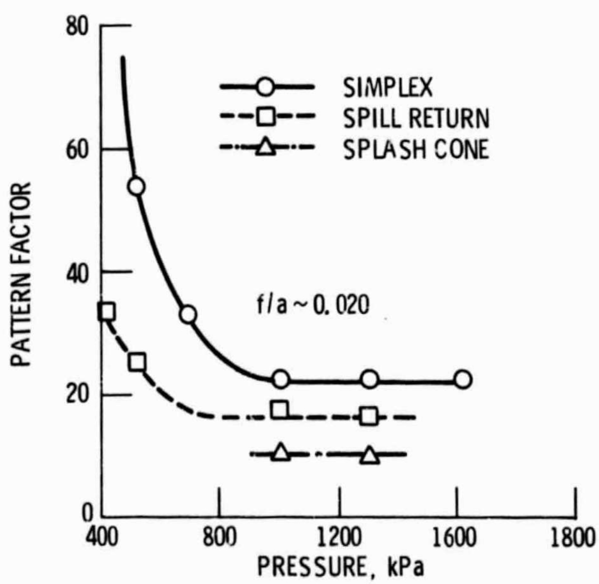
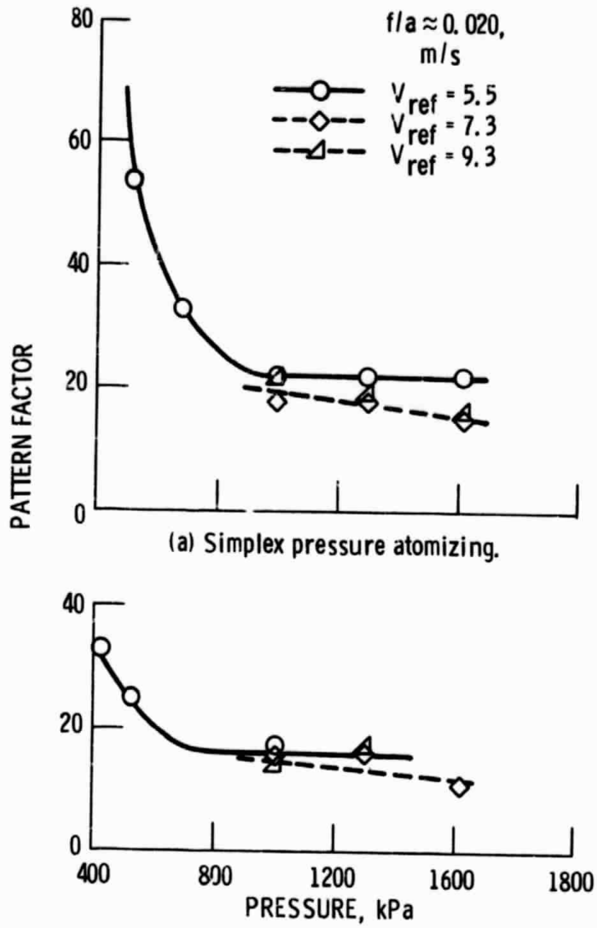


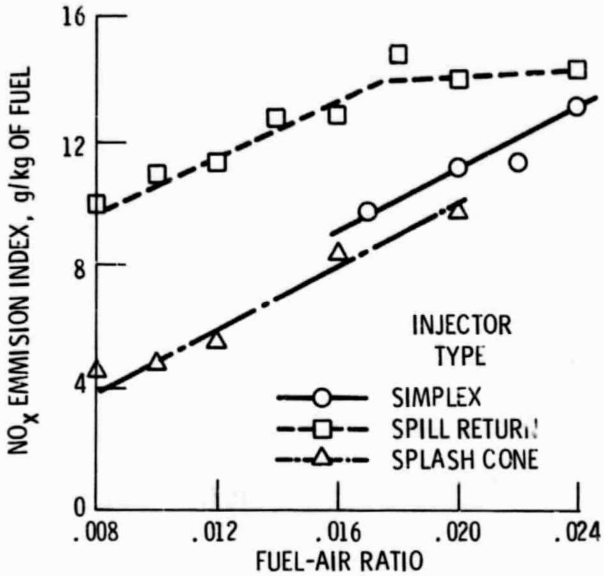
Figure 8. - Effect of fuel injector type on pattern factor.



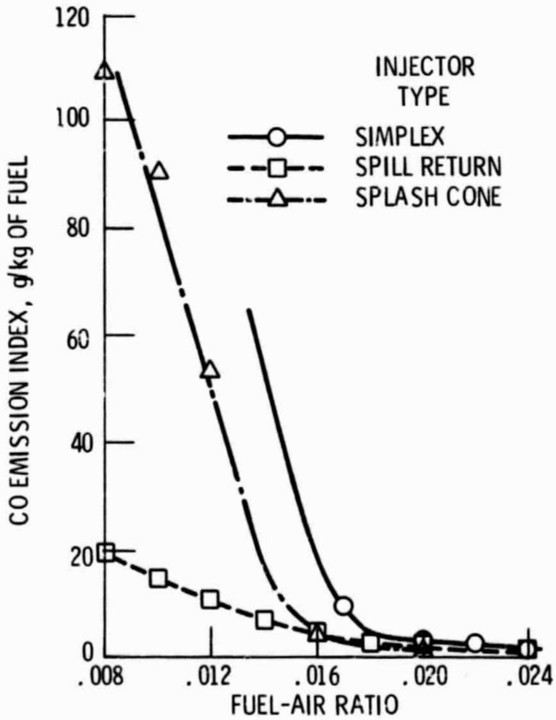
(a) Simplex pressure atomizing.

(b) Spill return pressure atomizing.

Figure 9. - Effect of increasing combustor reference velocity on pattern factor.

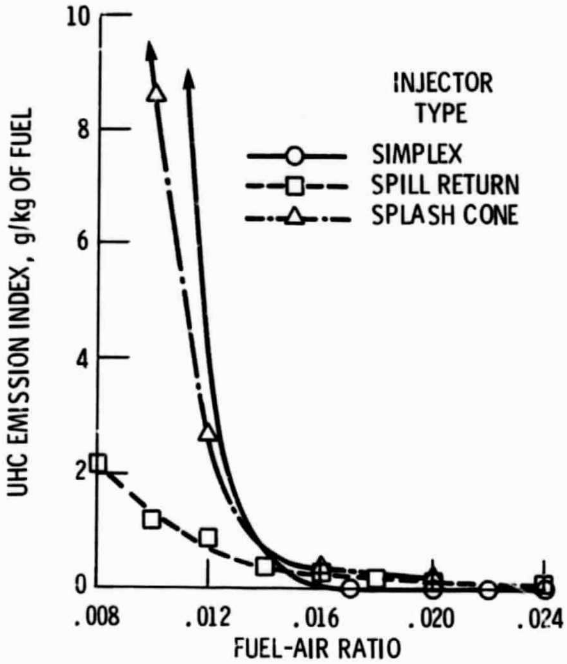


(a) Oxides of nitrogen.



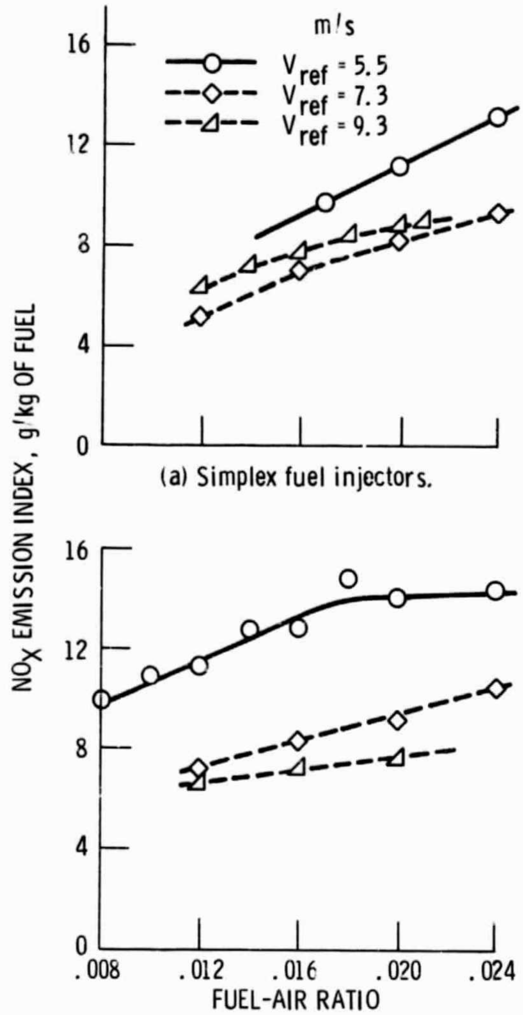
(b) Carbon Monoxide.

Figure 10. - Effect of injector type on emissions produced by a lamilloy reverse-flow combustor at the simulated low altitude cruise condition.



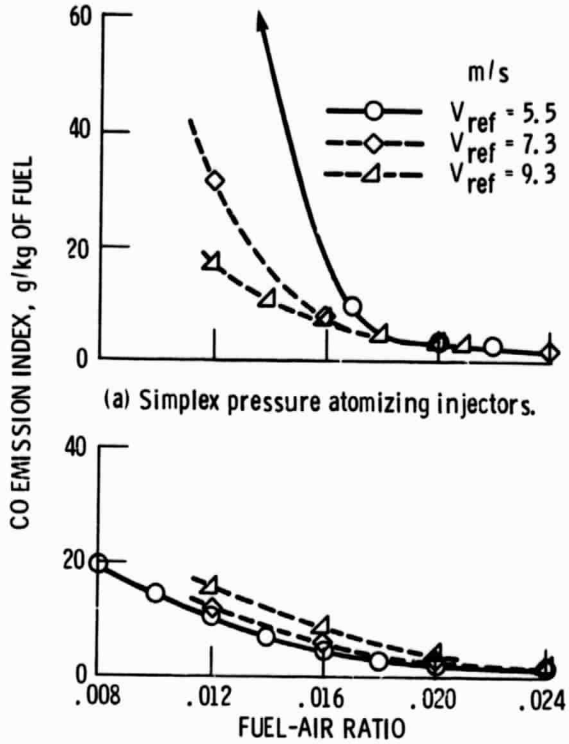
(c) Unburned hydrocarbons.

Figure 10. - Concluded.



(b) Spill return injectors.

Figure 11. - Effect of increasing combustor reference velocity on oxides of nitrogen emissions at the simulated low altitude cruise condition.



(a) Simplex pressure atomizing injectors.

(b) Spill return pressure atomizing injectors.

Figure 12. - Effect of increasing combustor reference velocity on carbon monoxide emissions at the simulated low altitude cruise condition.

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16. Abstract

An investigation determined the effect of fuel injection technique on the performance of an advanced reverse flow combustor liner constructed of Lamilloy (a multilaminate transpiration type material). Performance and emission levels are documented over a range of simulated flight conditions using simplex pressure atomizing, spill 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.

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