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REVERSE-FLOW COMBUSTOR FOR SMALL GAS TURBINES WITH PRESSURE-ATOMIZING FUEL INJECTORS

by Carl T. Norgren, Edward J. Mularz,* and Stephen M. Riddlebaugh

Lewis Research Center

SUMMARY

A reverse-flow combustor suitable for a small gas turbine (2 to 3 kg/s mass flow) was used to evaluate the effect of pressure-atomizing fuel injectors on combustor performance. In these tests an experimental combustor was designed to operate with 18 simplex pressure-atomizing fuel injectors at sea-level takeoff conditions. To improve performance at low-power conditions, the fuel manifolding was modified so that only every other injector was operational. Combustor performance, emissions, and liner temperature are compared over a range of pressure and inlet-air conditions corresponding to simulated idle, cruise, and takeoff typical of a 16 to 1 pressure ratio turbine engine.

At simulated combustor inlet sea-level takeoff conditions with an overall fuel-air ratio of 0.014 the combustor with 18 fuel injectors operated with a combustion efficiency of 100 percent, a total pressure loss of 1.7 percent, a pattern factor of 0.21, and emission levels of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen of 0.1, 1.5, and 16 grams per kilogram of fuel, respectively, with a smoke number of 22. It was not possible to operate this combustor with 18 injectors at idle because of blowout caused by low fuel pressure and subsequent fuel spray deterioration. By reducing the fuel injector density it was possible to operate at idle. At idle the combustor with nine fuel injectors operated with a combustion efficiency of 92.4 percent, a total pressure loss of 1.3 percent, a pattern factor of 1.12, and emission levels of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen of 62.9, 96.9, and 3.9 grams per kilogram of fuel, respectively, with a smoke number of 24.

INTRODUCTION

As part of a continuing effort at the Lewis Research Center to improve performance, emissions, and reliability of turbine machinery, an investigation has been initiated to

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provide design criteria for small gas turbine combustors. The performance and pollutant emission levels are documented over a range of simulated flight conditions for a reverse-flow combustor configuration using simplex pressure-atomizing fuel injectors in which the effect of reducing the number of fuel injectors to improve idle performance has been investigated.

Small turbine machinery, whether used for primary propulsion or auxiliary power application, is inherently less efficient than its larger sized counterpart due to the small size of the components, manufacturing tolerances, and material limitations (ref. 1). An improvement in cycle efficiency can be obtained, however, with increased compression ratio, higher combustor inlet-air temperature, and increased turbine inlet temperature. Techniques used to improve performance characteristics of large combustors are not necessarily applicable to small combustors because of the problems which arise due to scaling. Problem areas of particular interest in small combustor technology include such items as combustion stability, liner cooling, and temperature distribution. Combustion stability is affected by many factors including method of fuel introduction, fuel and air distribution, and wall quenching. Liner cooling is of particular concern because of the high combustor surface to volume ratio and the trends toward high turbine inlet temperature to improve overall cycle efficiency. A uniform outlet temperature distribution is sensitive to mixing, upstream passage blockages, and perturbations in the flow.

While many types of combustor configurations are possible for use in small turbine machinery, the reserve-flow configuration offers several advantages (ref. 2). As a technique to improve performance and reduce manufacturing difficulty, small turbine machinery usually incorporates a final centrifugal stage in the compressor. A final centrifugal stage coupled with a reverse-flow combustor permits the use of a radial diffuser, which is highly efficient with respect to reducing pressure losses in the diffuser and improving flow distribution into the combustor. The reverse flow combustor provides a larger combustion volume than would otherwise be obtained with a straight through flow combustion chamber; thus, a potential gain in performance can be realized. In addition, engine packaging is favorably affected by permitting a shortening of the rotating shaft and by placing the fuel injectors in a readily accessible location.

Fuel distribution remains a problem in the reverse-flow combustor because of the relatively large number of fuel injectors required to effectively distribute the fuel at the large combustor diameter to obtain the uniform outlet temperature distribution required for takeoff. Simplex pressure-atomizing fuel injectors sized for takeoff cannot produce satisfactory spray characteristics at idle fuel flows. On the other hand, if the injectors are sized for idle fuel flows, the physical size of the fuel passages within each injector would be so small that excessive pressure losses would occur at higher flow rates and reliability would be adversely affected because of the increased susceptibility to clogging.

A technique which has been used in swirl-can combustors to improve efficiency at idle is to provide locally idealized burning zones (ref. 3). A similar technique to improve the fuel-air ratio in localized zones within the combustor was used in this investigation. In this technique a portion of the fuel injectors is rendered inoperable and the increased fuel flow to each of the remaining injectors provides improved spray characteristics.

To investigate the design criteria envolved in small combustor technology a reverse-flow combustor configuration was selected. The design of the reference combustor was based in as far as feasible on current technology. An investigation of varying fuel injector density was incorporated into the first phase of the program. The pressure atomizing injectors were sized for sea-level takeoff conditions, and it was anticipated that idle performance would deteriorate. Fuel injector density was varied by operating the combustor with 9 or 18 evenly spaced simplex pressure-atomizing fuel injectors. The effect on combustion efficiency, combustor total pressure loss, outlet-temperature profiles, and liner wall temperature was investigated for simulated idle, two cruise conditions, and takeoff for a 16 to 1 compression ratio gas turbine engine. A parametric variation of combustor reference velocity was also included. Exhaust emission levels of unburned hydrocarbons, carbon monoxide, nitrogen oxides, and smoke number were obtained. Although reducing the number of fuel injectors would be required only at idle, there is a possibility that this technique might improve performance at conditions other than idle; therefore, the effect of varying the fuel injector density was investigated at all test conditions.

APPARATUS

Test Facility

The test combustor was mounted in the closed-duct facility shown schematically in figure 1. The laboratory air supply can maintain airflow rates up to 15 kilograms per second at pressure levels up to 3000 kilopascals. Tests were conducted up to pressure levels of 1600 kilopascals. For these tests combustion air drawn from the laboratory high-pressure supply was indirectly heated to 717 K in a counterflow tube heat exchanger. 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.

Test Hardware

A cross section of the reverse-flow combustor used in this investigation is shown in figure 2(a). An isometric sketch of the reverse-flow combustor is shown in figure 2(b). The combustor is an experimental NASA design with a maximum diameter of 38.5 centimeters. The design stresses versatility so that modification or replacement of the swirlers, faceplate, liner, and turning sections can be accomplished. The design liner pressure loss is 1.5 percent and the diffuser dump loss is 0.24 percent. A symmetrical hole pattern based on 36 circumferential locations is used so that 9, 12, or 18 fuel injectors can be staged and still maintain a symmetrical air entry pattern (in this investigation the combustor is operated with 9 or 18 injectors, see fig. 2(c)). The airflow distribution and hole sizes are shown in table I. Photographs of the reverse-flow combustor and housing are shown in figure 3. In figure 3(a) an aft view of the combustor is shown before assembly. In figure 3(b) the combustor is shown partly assembled, and in figure 3(c) it is shown completely assembled.

In the first phase of this study, pressure-atomizing simplex fuel injectors are used with flow restrictors ahead of each injector to aid in obtaining an even distribution of fuel. The injector spray angle was $75^{\circ} \pm 5^{\circ}$ and the orifice was sized to provide a flow of 0.0032 kilogram per second (25 lb/hr) for a pressure drop across the orifice of 690 kilopascals (100 psid).

Instrumentation

The combustor instrumentation stations are shown in figure 4. 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. Four gas sample probes, evenly spaced on the circumference, are also located at station 5.

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 II.

Data were obtained at combustor inlet conditions simulating sea-level takeoff, cruise, and idle. Data were obtained over a range of fuel-air ratios from about 0.009 to 0.016. However, because of thermocouple limitations, the overall fuel-air ratio was limited to approximately 0.014 at sea-level takeoff. At the idle condition the fuel-air ratio was 0.01. The combustor was operated with a parametric variation of reference velocity at sea level and cruise (24 and 30 m/s in addition to the reference velocity of 18 m/s). The reference velocity quoted is based on the assumption of unidirectional total mass flow and maximum cross-sectional area of the housing prior to the reverse turn as shown in figure 2(a). The combustor was also operated at simulated reduced power at a constant fuel-air ratio of 0.014. For the reduced power conditions a pressure level lower than cruise was selected, and the corresponding inlet temperature was calculated using a compressor efficiency of 80 percent. Also presented in table II are the simulated compressor pressure ratios. These ratios as presented are referenced to sea-level pressure.

The combustor was operated with two fuel staging configurations. Combustor models A-1 and A-2 had 18 injectors each, but in model A-2 every other injector was made inoperative by closing off its fuel lines (see fig. 2(c)). For check purposes to determine the effect of combustor symmetry on performance, the nine even nozzles and the nine odd nozzles were activated in turn, and the combustor performance was compared. Since no change in performance was expected or experienced, only one set of data is presented for combustor model A-2. The test program was conducted using Jet A fuel.

Emission Measurements

Exhaust gas samples were obtained according to the procedures recommended in references 4 and 5. Exhaust gases were withdrawn through four air-cooled stationary probes mounted approximately in the stator plane and in the center of the exhaust duct (see fig. 4). Concentrations of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were determined with the gas analysis described in reference 6. 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.

Gas samples used to determine oxides of nitrogen and carbon monoxide were passed through a refrigerated dryer and analyzed on a dry basis. Readings for oxides of nitrogen and carbon monoxide were corrected so that they could be reported on a wet basis, as were those for unburned hydrocarbons.

Fuel-air ratios calculated from a carbon balance agreed to within 10 percent with values obtained from fuel-flow and airflow measurements. The combustion efficiency data presented in this report were based on stoichiometry determined by gas analysis.

RESULTS

The following data were obtained in the reverse-flow combustor to investigate the effects of fuel staging with pressure atomizing simplex fuel injectors. Data were obtained for simulated inlet conditions typical of operating a 16 to 1 pressure ratio turbine engine at the test conditions tabulated in table I. The outlet temperature level was limited to approximately 1350 K because of instrumentation constraints. The combustor was operated with 18 and 9 evenly spaced simplex fuel injectors, designated as combustor models A-1 and A-2, respectively, using Jet A fuel. Performance and emission data are presented in figures 5 to 14 for simulated inlet flight conditions. Idle data are tabulated in table III. The experimental performance and emissions data are tabulated in table IV.

Performance

Combustion efficiency. - Combustion efficiency data are shown in figure 5. In figure 5(a) the efficiency is shown for a range of fuel-air ratios. The combustion efficiency is essentially independent of fuel-air ratio over the range of fuel flows investigated for all simulated flight conditions with a combustion efficiency level greater than 99 percent except for the high altitude cruise which dropped somewhat at low fuel-air ratios.

The effect of off-design operation at lower compressor pressure ratio on combustion efficiency is shown in figure 5(b). The reference velocity and fuel-air ratio were held constant at 5.5 meters per second (18 ft/sec) and 0.014, respectively, as indicated in table II. As shown in figure 5(b), the combustion efficiency fell off sharply for pressure ratios below 8.5 to 1 with model A-1 (18 fuel injector configuration); blowout occurred before the idle pressure level could be achieved. With model A-2 (9 fuel injector configuration) the combustion efficiency had fallen off to approximately 94 percent at a pressure ratio of 4.1 to 1. Note the test condition in figure 5(b) at a 4.1 to 1 pressure ratio corresponds approximately to idle; differences occur in fuel-air ratio (0.014 as compared to 0.01 at idle) plus nominal differences in mass flow (see table II). At the idle conditions the combustion efficiency for model A-2 was 92.4 percent (see table III). At these lower pressure levels the combustion efficiency is sensitive to further pressure reductions as noted by the sharp dropoff in efficiency (fig. 5(b)).

The reverse-flow combustor was also operated with increased airflow loading (increased reference velocity). A parametric variation of increased mass flow rates corresponding to increases in reference velocity from 5.5 to 7.32 or 9.14 meters per second had no appreciable effect on combustion efficiency (see table IV).

Pressure loss. - The reverse-flow combustor pressure loss data are shown in figure 6. The total pressure loss for the design mass loading at a reference velocity of 5.5 meters per second (diffuser inlet Mach number of 0.054) was 1.2 percent. A 67-percent increase in reference velocity increased the total pressure loss by approximately 0.4 percent over the range of temperature rise levels investigated.

Outlet temperature distribution. - The data obtained for the pattern factor are shown in figure 7. The pattern factor is of the order of 0.21 to 0.24 with model A-1 and approximately 0.6 with model A-2 as shown in figure 7(a) over the range of fuel-air ratios investigated at a reference velocity of 5.5 meters per second. The effect of increased reference velocity is shown in figure 7(b). At a reference velocity of 9.14 meters per second the pattern factor was degraded with model A-1 to approximately 0.3; with model A-2, however, the pattern factor was improved to approximately 0.46. These changes were probably due to the higher mass loading of the combustor at the higher reference velocity. In model A-1 the dilution zone was designed for a lower reference velocity. An increase in reference velocity caused excessive penetration, which resulted in a poorer temperature distribution. With model A-2 a poorer fuel distribution existed in the primary and the increased mixing intensity would aid in dispersing hot zones.

Typical radial temperature profile data are shown in figure 8 for simulated takeoff conditions. Included in figure 8 is an ideal profile reproduced from one which is considered desirable for larger turbine machinery (ref. 6) and would also be applicable for small engines considering fatigue, creep, and erosion of the turbine blade. Both combustor models A-1 and A-2 produced similar outlet profiles that were slightly cooler than the required profile at the hub.

Liner temperature. - The combustor liner temperature pattern was observed with thermal paint. From this observation the thermocouple locations were selected on the basis of the highest liner temperature level indicated for a particular liner location. Six locations were selected to observe the liner temperature - the primary combustion zone, the outer turn, and the inner turn; specific locations are indicated in figure 2.

In all cases the inner turn exhibited the highest wall temperature. Typical liner temperatures observed at this location are shown in figure 9. As the test conditions increased in severity or the fuel-air ratio level increased the peak liner temperature increased in a uniform manner. With model A-1 for the sea-level takeoff inlet conditions the maximum liner temperature was 908 K (1175° F) at an overall fuel-air ratio of 0.014. Similar trends were obtained with combustor model A-2 as indicated in figure 9.

Emissions

Unburned hydrocarbons. - The emission index data for unburned hydrocarbons are shown in figure 10. In order to compare the data for model A-2 with model A-1 at a fuel-air ratio of 0.014 it was necessary to extrapolate the A-2 data obtained at lower fuel-air ratios. In figure 10(a) the effect of compressor pressure ratio is shown for combustor models A-1 and A-2. As the pressure level was reduced with model A-1 the hydrocarbon emission index increased rapidly below a compression ratio of 8.5 to 1. With combustor model A-2 the increase in hydrocarbon emission occurred at a lower compressor pressure ratio (approximately 6 to 1) and the rate of increase was significantly reduced. At the sea-level takeoff condition, combustor model A-1 operated with an unburned hydrocarbon emission index of 0.1 gram per kilogram of fuel. At the idle condition with combustor model A-2 the hydrocarbon emission index was 62.9 grams per kilogram of fuel (see table III). As previously noted, model A-1 could not be operated at idle.

The effect of increased reference velocity is shown in figure 10(b). No appreciable hydrocarbon emission was observed at the cruise or sea-level takeoff condition. The maximum hydrocarbon emission index of 0.63 gram per kilogram of fuel with model A-1 was obtained at the high altitude cruise condition.

Carbon monoxide. - The emission index data for carbon monoxide are shown in figure 11. In figure 11(a) the effect of compressor pressure ratio is shown for combustor models A-1 and A-2. As the pressure and temperature levels were reduced with models A-1 and A-2 the carbon monoxide level increased. The shapes of the two curves are similar; however, the carbon monoxide level with model A-2 was significantly lower than it was with model A-1 (approximately 1 g/kg of fuel for model A-2 as compared to 15 g/kg of fuel with model A-1 at a compressor pressure ratio of 10 to 1). At the simulated sea-level takeoff condition model A-1 produced an emission index value of 2 grams per kilogram of fuel. At the idle condition with combustor model A-2 the carbon monoxide emission index was 96.9 grams per kilograms of fuel (see table III).

The effect of increased reference velocity is shown in figure 11(b). As the compressor pressure increased (corresponding to a decrease in altitude) or as the reference velocity increased, the carbon monoxide emission index decreased for model A-1. The extrapolated data for model A-2 indicated a decrease in the carbon monoxide level with increased pressure and, in general, a slight increase in the carbon monoxide level at the higher reference velocity.

Oxides of nitrogen. - The emission index data for the oxides of nitrogen are shown in figure 12. In figure 12(a) the effect of compressor pressure ratio is shown for combustor models A-1 and A-2. As the pressure and temperature levels were reduced the oxides of nitrogen decreased. Model A-1 exhibited a lower level of the oxides of nitrogen than did model A-2. The lower level with model A-1 may in part be attributed to the lower combustion efficiency and reduced inlet temperatures at reduced pressure ratios; however, at a condition where the combustion efficiency was essentially 100 percent (compressor pressure ratio of 10 to 1 - corresponding to high altitude cruise), the emission index was approximately 10 grams per kilogram of fuel for model A-1 and 12 grams per kilogram of fuel for model A-2. At sea-level takeoff model A-1 produced an emission index value of 16 grams per kilogram of fuel. At the idle condition with combustor model A-2 the oxides of nitrogen emission index was 3.9 grams per kilogram of fuel (see table III).

In figure 12(b) the effect of increased reference velocity on the emission of oxides of nitrogen is shown. In general, at the higher reference velocity the oxides of nitrogen decreased. The extrapolated emission index level for model A-2 was slightly higher than that for model A-1 at the cruise condition. At sea-level takeoff a comparison between models A-1 and A-2 was not obtained because of the sensitivity of the oxides of nitrogen emission with fuel-air ratio. It was considered that the extrapolation required for model A-2 would be misleading.

Smoke number. - The smoke number data are shown in figure 13. The combustor model A-1 produced smoke levels of the order of 9 to 25 over the range of test conditions. Combustor model A-2 produced smoke levels from 24 to 50 over a similar range of test conditions. At sea-level takeoff model A-1 produced a smoke number of 22. At the idle condition with combustor model A-2 the smoke number was 24 (see table III). It would be expected that the increase in smoke observed with model A-2 would be due to the locally rich zones set up by fuel injector spacing.

DISCUSSION

Performance

Reducing the number of fuel injectors was investigated to determine the improvement in combustor performance which could be obtained at low power conditions by improving the fuel injector spray characteristics. As previously discussed, it was not possible to operate model A-1 at idle conditions because of blowout, which was attributed to poor spray characteristics. The pressure drop data across the injectors used in combustor models A-1 and A-2 are shown in figure 14. The idle total fuel flow was of the order of 44 kilograms per hour (97 lb/hr). The corresponding pressure drops were approximately 27 kilopascals (4 psid) for model A-1 and 122 kilopascals (17.9 psid) for model A-2. The injector pressure drop for model A-1 is included for comparison even though sustained combustion was not possible. As fuel flow requirements increased, the pressure drop across the injectors increased at a considerably faster rate for model A-2 than for model A-1. As shown in figure 5(b), the combustion efficiency for model A-2 approached 100 percent at a much faster rate than did model A-1 as the compressor pressure increased.

Based on a combustion efficiency viewpoint, it is apparent that performance began to deteriorate at low fuel injector pressure. However, it could be improved by reducing the number of injectors and thereby increasing the pressure differential for a given fuel flow. The extra injectors were not removed for the A-2 configuration nor was the combustor geometry altered. Fuel flow to the extra injectors was cut off, but the air flow was not. However, combustor performance was not adversely affected and stability was improved. It is probable that fuel injector programming of the type investigated in this study could be incorporated into a combustion system to improve low-power combustion efficiency.

There was no apparent effect of varying the number of fuel injectors on total pressure loss with either model A-1 or model A-2.

The outlet temperature profile obtained with model A-1 was considered satisfactory. The outlet temperature profile with model A-2 deteriorated; however, even with an idle pattern factor of 1.12, a maximum temperature of only 1300 K (1940° F) would be experienced at the turbine stator plane because of the lower temperature levels associated with reduced power. The value of 0.6 for the pattern factor at cruise for model A-2 would be unacceptable because of the high turbine inlet requirements (turbine inlet temperature, 1565 K (2360° F)). The high pattern factor points out that in this configuration (model A-2) nine fuel injectors could not provide the outlet temperature distribution required for flight conditions. The radial profile for model A-2 was acceptable, however.

Emissions

At low-power conditions the emission levels of unburned hydrocarbons and carbon monoxide are usually of most concern. From the data obtained with model A-1 it is apparent that the unburned hydrocarbons level is unusually high and accounts for most of the inefficiency as compared to the carbon monoxide level. This would be consistent with the deterioration of the fuel spray at a low injector pressure level. With the model A-2 combustor the increase in the unburned hydrocarbon level is reduced as compared to the carbon monoxide level; this condition indicates that the carbon monoxide reaction is quenched rather than never initiated as would be the case with unburned fuel droplets. The fuel spray could probably be further improved with model A-2 as evidenced by the still high unburned hydrocarbon emission index at idle (62.9 g/kg of fuel).

At the high-power conditions the oxides of nitrogen are essentially the major pollutant. In this combustor configuration the oxides of nitrogen reached a peak around an emission index of 16 grams per kilogram of fuel for model A-1. At the low-power conditions a higher index level was observed with model A-2 than with model A-1. At high reference velocities the emission index decreased as would be expected with a shorter residence time. The oxides of nitrogen were higher with combustor model A-2 than with model A-1. In model A-2 locally rich zones are set up which contribute to higher oxides of nitrogen levels by increasing flame temperature. At the higher fuel flows the emission level is also high, probably due to preferential high flame temperature surrounding the rich core. Improving the distribution of fuel and air, as in model A-1 (18 injectors), provides better mixing, which is accompanied by a reduction in the oxides of nitrogen (see ref. 7).

The effect of fuel injector density on smoke number was to increase the smoke level with model A-2. It was suspected that the increase in smoke with model A-2 would in part be due to the locally rich zones. The smoke produced in the locally rich zones during combustion could also be prematurely quenched before any appreciable burnout would occur because of the cool zones produced by swirlers in which the fuel injectors were inoperative.

SUMMARY OF RESULTS

A reverse-flow combustor suitable for a small gas turbine engine was used to evaluate the effects of fuel injector density on combustor performance and emissions. Data were obtained at pressure and inlet-air temperature levels corresponding to simulated idle, cruise, and takeoff conditions of a 16 to 1 pressure ratio engine. The outlet temperature was limited to approximately 1350 K because of the instrumentation. The following results were obtained with 9 and 18 evenly spaced simplex pressure-atomizing fuel injectors using Jet A fuel:

1. It was not possible to operate at idle with 18 fuel injectors because of blowout.
2. The combustor with 18 fuel injectors at simulated sea-level takeoff conditions

operated with a combustion efficiency of 100 percent, a total pressure loss of 1.7 percent, a pattern factor of 0.21, and emission levels of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen of 0.1, 1.5, and 16 grams per kilogram of fuel, respectively, with a smoke number of 22.

3. The combustor with 9 fuel injectors at idle operated with a combustion efficiency of 92.4 percent, a total pressure loss of 1.3 percent, and emission levels of unburned hydrocarbons, carbon monoxide, and oxides of nitrogen of 62.9, 96.9, and 3.9 grams per kilogram, respectively, with a smoke number of 24.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 15, 1978,
505-04.

REFERENCES

1. Munt, Richard; Danielson, Eugene; and Deimon, James: Aircraft Technology Assessment; Interim Report on the Status of the Gas Turbine Program. U.S. Environmental Protection Agency, Dec. 1976.
2. Norster, E. R.; and Demetri, E. P.: Analysis and Design of Combustors for Small Gas Turbines for Advanced Helicopters. Rep. 1208-1, Northern Research and Engineering Corporation, 1974.
3. Niedzwiecki, Richard W.; Trout, Arthur M.; and Mularz, Edward: Performance of a Swirl-Can Combustor at Idle Conditions. NASA TM X-2578, 1972.
4. 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.
5. Procedure for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines. Aerospace Recommended Practice 1256, Oct. 1971, SAE.
6. Ingebo, Robert D.; and Norgren, Carl T.: High Pressure Combustor Exhaust Emissions with Improved Air-Atomizing and Conventional Pressure-Atomizing Fuel Nozzles. NASA TN D-7154, 1973.
7. Jones, Robert E.: Advanced Technology for Reducing Aircraft Engine Pollution. NASA TM X-68256, 1973.

TABLE I. - LINER AIRFLOW DISTRIBUTION

Air entry	Type of entry	Percent of total mass flow	Comments
Faceplate	Swirler	11.2	--------------------------------
Primary	Primary holes	24.88	2.54 cm from firewall, 36 holes outer wall and 36 holes inner wall
Dilution	Dilution holes	30.80	5.72 cm from firewall, 36 holes outer wall and 36 holes inner wall
Concentric around fuel injector	Annulus	3.17	--------------------------------
Liner cooling	Film cooling	13.12	--------------------------------
Outer 180°	Film cooling	13.84	--------------------------------
Inner 180°	Film cooling	3.02	--------------------------------

TABLE II. - REVERSE-FLOW COMBUSTOR TEST CONDITIONS

Total airflow		Inlet pressure		Inlet temperature		Reference velocity		Simulated compressor pressure ratio	Comments
kg	lb/sec	kPa	psia	K	°F	m/s	ft/sec		
2.27	5	1014	147	686	775	5.5	18	10 to 1	High-altitude cruise
3.05	6.71	1358	197	703	805	5.5	18	13.4 to 1	Low-altitude cruise
3.63	8	1620	235	717	830	5.5	18	16 to 1	Sea-level takeoff
1.23	2.70	405	58.8	474	394	5.2	16.9	4 to 1	Idle
2.12	4.66	862	125	627	668	5.5	18	8.5 to 1	Simulated reduced power at fuel to air ratio of 0.014
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	

TABLE III. - IDLE CONDITIONS

	Model A-1	Model A-2
Combustor efficiency, percent	Blowout	92.4
Total-pressure loss, kPa	↓	7.15
Pattern factor		1.12
Hydrocarbon emission index, g/kg		62.9
Carbon monoxide emission index, g/kg		96.9
Oxides of nitrogen emission index, g/kg		3.9
Smoke number		23.8

TABLE IV. - EXPERIMENTAL PERFORMANCE AND EMISSIONS DATA

Airflow rate, kg/sec	Combustor inlet temperature, K	Combustor inlet pressure, kPa	Combustor pressure drop, percent	Reference velocity, m/s	Fuel-air ratio	Fuel pressure drop, kPa	Pattern factor	Gas sample combustion efficiency, percent	Exhaust emissions index: Oxides of nitrogen	Exhaust emissions index: Hydrocarbons	Exhaust emissions index: Carbon monoxide	Exhaust emissions index: Ratio of fuel-air ratios	Smoke number
Model A-1													
2.237	696.20	1020.3	1.39	5.49	0.0095	94.47	0.23	97.8	7.3	7.7	65.6	1.020	13.5
2.209	680.86	971.4	1.58	5.57	.0119	156.64	.19	98.9	7.3	2.6	40.8	1.024	15.7
2.216	685.59	1015.9	1.57	5.37	.0119	154.80	.19	98.9	8.0	2.2	39.6	1.029	----
2.257	685.80	1007.2	1.63	5.52	.0140	235.94	.22	99.6	12.0	.6	15.5	1.050	12.3
2.213	685.71	1022.5	1.65	5.34	.0161	303.92	.20	99.8	13.0	.3	7.0	1.014	14.5
2.239	695.22	1023.9	0.95	5.47	0.0093	3.96	1.74	97.9	6.5	7.7	57.1	1.054	20.6
2.250	687.66	1039.6	1.19	5.35	.0142	25.97	.91	99.7	11.5	.9	8.8	1.059	16.4
2.283	682.46	1019.6	1.06	5.49	.0097	95.33	.39	98.0	5.2	7.1	55.9	.997	13.5
2.283	688.60	993.2	1.69	5.69	.0118	157.96	.41	99.2	8.3	1.7	28.8	1.006	17.8
2.260	679.82	1007.5	1.36	5.48	.0139	231.11	.38	99.6	10.8	.6	13.0	1.016	17.0
2.285	682.78	1002.9	1.40	5.59	0.0098	103.83	0.36	97.3	7.2	8.8	77.5	0.963	----
2.285	689.80	1024.4	1.46	5.53	.0099	105.62	.34	98.6	8.5	3.8	43.9	1.024	26.0
2.275	681.40	1021.9	1.59	5.45	.0096	97.80	.32	97.7	7.5	7.2	67.0	.999	17.0
2.253	683.49	1011.4	1.47	5.47	.0143	240.65	.28	99.7	10.5	.3	10.9	1.029	20.2
3.002	702.95	1372.4	1.38	5.53	.0099	200.66	.21	99.4	9.9	1.3	19.1	1.024	19.5
2.994	703.04	1366.2	1.59	5.54	0.0121	315.47	0.22	99.8	12.7	0.4	7.6	1.032	21.2
3.029	702.10	1334.0	1.73	5.73	.0141	444.99	.24	99.9	14.1	.2	3.4	1.039	17.0
3.663	712.39	1702.4	1.41	5.51	.0098	308.34	.21	99.8	12.7	.4	7.0	1.035	26.0
3.634	713.95	1615.0	1.68	5.77	.0123	497.56	.21	99.9	15.0	.2	2.5	1.022	24.5
3.654	718.40	1617.6	1.69	5.83	.0138	647.60	.21	100.0	16.2	.1	1.5	1.038	19.3
3.554	709.71	1616.4	1.21	5.61	0.0101	261.91	1.33	99.8	12.7	0.3	7.1	1.004	28.2
3.564	705.58	1641.8	1.06	5.51	.0104	83.15	1.42	99.7	12.5	1.1	7.1	1.043	30.0
3.561	707.41	1638.1	1.16	5.53	.0125	146.93	.37	99.9	15.2	.1	2.7	1.064	31.2
3.606	715.54	1642.9	.93	5.65	.0101	315.06	.43	99.8	13.7	.3	5.9	1.008	28.2
3.599	714.95	1602.0	1.41	5.77	.0123	505.95	.41	99.9	16.0	.1	2.4	1.027	27.2
3.670	717.87	1666.2	1.33	5.68	0.0138	683.74	0.31	100.0	-----	0.1	1.3	1.042	----
2.087	625.53	865.8	1.76	5.42	.0099	87.86	.73	78.3	4.1	171	199	.972	17.5
2.094	621.08	862.3	2.08	5.42	.0144	203.01	.35	98.8	6.1	2.8	38	.988	24.0
1.812	577.23	714.0	1.59	5.26	.0140	138.20	.54	79.9	2.6	157	189	.956	22.4
1.813	578.72	706.5	1.96	5.34	.0122	100.16	1.14	65.9	2.6	305	151	.794	15.0
1.522	532.10	533.1	2.33	5.46	0.0141	93.61	2.03	98.9	-----	4.2	25.1	1.199	----
1.533	524.67	533.3	2.13	5.42	.0140	91.31	1.80	45.4	1.7	526	86	.483	8.4
1.247	485.08	413.4	1.93	5.26	.0196	115.90	1.14	72.5	1.3	236.4	173.6	.699	24.2
1.244	479.71	391.2	1.96	5.48	.0164	72.40	1.80	62.5	1.3	347.1	120.5	.611	20.0
									[illegible]	[illegible]	6.6	1.016	9.2

2.988	687.81	1011.7	2.90	7.30	0.0124	318.69	0.25	99.7	10.0	0.6	12.6	1.013	15.0
3.942	699.03	1383.0	2.58	7.16	.0117	544.05	.20	99.9	12.2	.2	4.0	1.056	16.6
4.011	697.82	1355.7	2.80	7.42	.0136	753.44	.22	99.9	13.2	.1	2.3	1.043	15.5
4.549	713.45	1640.9	2.38	7.11	.0121	783.04	.24	99.9	14.8	.2	2.0	1.051	20.0
4.569	712.04	1634.2	2.59	7.15	.0138	1049.40	.22	100.0	14.9	.1	1.3	1.044	14.0
3.783	685.62	1011.6	4.65	9.22	0.0100	282.37	0.30	99.6	7.5	1.0	13.5	1.017	9.6
3.779	685.09	1030.7	4.11	9.03	.0122	431.89	.93	99.8	9.5	.4	8.4	1.001	10.0
3.766	682.96	995.9	4.12	9.28	.0139	718.91	.43	99.9	11.2	.1	4.4	1.019	9.5
3.770	689.48	1077.1	3.41	8.67	.0119	515.72	.57	99.8	10.8	.2	6.5	1.004	10.5
3.772	685.35	1004.7	4.22	9.25	.0120	513.65	.41	99.8	8.0	.3	7.5	1.009	----
3.770	687.47	987.5	3.76	9.43	0.0099	342.13	0.41	99.6	8.7	0.8	12.9	1.005	8.5
4.822	699.41	1340.0	3.49	9.05	.0102	482.97	.28	99.8	10.3	.4	7.3	.988	13.6
4.866	698.77	1368.5	2.98	8.93	.0101	622.60	.38	99.8	10.8	.4	5.8	1.003	20.5
4.895	704.64	1380.2	3.10	8.98	.0120	913.42	.44	99.9	12.1	.3	3.4	1.014	19.5
4.882	695.39	1365.4	3.49	8.94	.0141	1259.7	.41	100.0	12.4	.2	2.3	.999	19.3
5.682	710.15	1613.4	3.73	8.99	0.0103	723.10	0.24	99.9	12.2	0.2	3.7	1.014	19.0
5.575	715.60	1632.5	3.35	8.78	.0104	840.61	.34	99.9	12.2	.3	3.6	.966	25.0
5.626	717.68	1646.3	3.28	8.82	.0124	1256.60	.40	99.9	12.8	.2	2.2	.986	21.3
5.695	720.04	1627.8	3.90	9.05	.0142	1717.80	.44	100.0	13.8	.2	1.2	1.004	23.0
						Model A-2							
2.255	686.77	986.0	1.40	5.65	0.0095	452.05	0.40	99.7	9.4	0.8	8.5	1.021	33.0
2.242	685.94	1027.6	1.40	5.38	.0119	748.79	.40	99.9	12.8	.2	2.3	1.018	26.0
2.302	691.41	1013.3	1.62	5.64	.0137	1047.50	.59	99.96	14.5	.1	1.2	1.028	27.0
2.291	688.22	1023.0	1.51	5.54	.0115	730.23	.41	99.9	12.9	.1	2.7	1.031	38.4
2.279	683.96	1021.4	1.40	5.49	.0099	409.07	.68	99.7	9.7	.7	9.1	.940	----
2.264	685.83	1049.9	1.26	5.32	0.0121	626.81	0.77	99.9	12.5	0.2	3.1	0.940	----
2.256	683.43	1006.1	1.37	5.51	.0102	440.90	.62	99.7	10.4	.7	8.5	.920	----
3.054	697.76	1341.5	1.41	5.71	.0097	945.25	.45	99.9	14.1	.2	1.8	1.064	33.5
3.037	697.61	1360.6	1.38	5.60	.0118	1397.20	.63	99.9	15.9	.1	1.3	1.043	34.7
2.997	704.05	1344.0	1.21	5.64	.0101	770.16	.68	99.9	13.1	.1	2.4	.890	----
3.016	702.25	1338.9	1.51	5.69	0.0121	1140.90	0.68	99.9	15.0	0.1	1.8	0.860	----
3.594	717.10	1575.1	1.45	5.88	.0103	1394.50	.50	99.9	6.8	.2	1.3	.988	32.4
3.603	715.48	1615.9	1.38	5.73	.0116	1926.20	.57	99.97	7.2	.1	.9	1.071	2.7
3.626	715.45	1600.3	1.55	5.83	.0100	1122.60	.82	99.9	14.9	.2	1.9	.880	----
1.244	472.58	407.5	1.76	5.19	.0103	124.12	1.12	92.4	3.9	62.9	96.9	.980	23.8
2.131	621.86	868.4	1.63	5.49	0.0135	863.48	0.44	99.9	10.0	0.2	3.8	1.008	50.1
2.103	622.73	865.4	1.51	5.44	.0137	697.01	.66	99.9	10.1	.3	5.4	.950	----
1.831	576.18	669.7	2.01	5.66	.0137	645.36	.40	99.5	8.0	1.7	13.9	.992	34.6
1.804	575.49	686.1	1.66	5.44	.0143	531.35	.56	99.6	7.8	1.3	13.7	.920	----
1.547	527.20	517.1	1.97	5.67	.0136	434.93	.38	97.9	6.1	12.6	37.3	.982	32.8
1.514	527.39	521.2	1.69	5.51	0.0123	244.27	1.18	73.5	2.8	309.0	43.7	0.830	----
1.243	476.02	407.0	1.84	5.23	.0141	277.66	.46	94.3	4.3	45.2	68.5	.936	23.6
1.207	484.33	403.8	1.70	5.20	.0146	200.77	1.06	76.3	2.1	289.0	58.7	.780	----
3.733	682.01	1009.6	3.70	9.06	.0122	2160.10	.48	99.6	11.7	.1	3.1	.996	19.0
3.782	680.35	1014.4	3.72	9.12	.0098	1467.40	.46	99.9	10.5	.2	4.4	1.045	21.0
4.901	697.05	1349.7	3.40	9.10	0.0097	2404.40	0.49	99.9	12.1	0.2	3.2	1.045	24.6
5.849	711.86	1594.4	3.30	9.39	.0077	2264.70	.39	99.8	12.6	.2	3.2	1.072	29.2

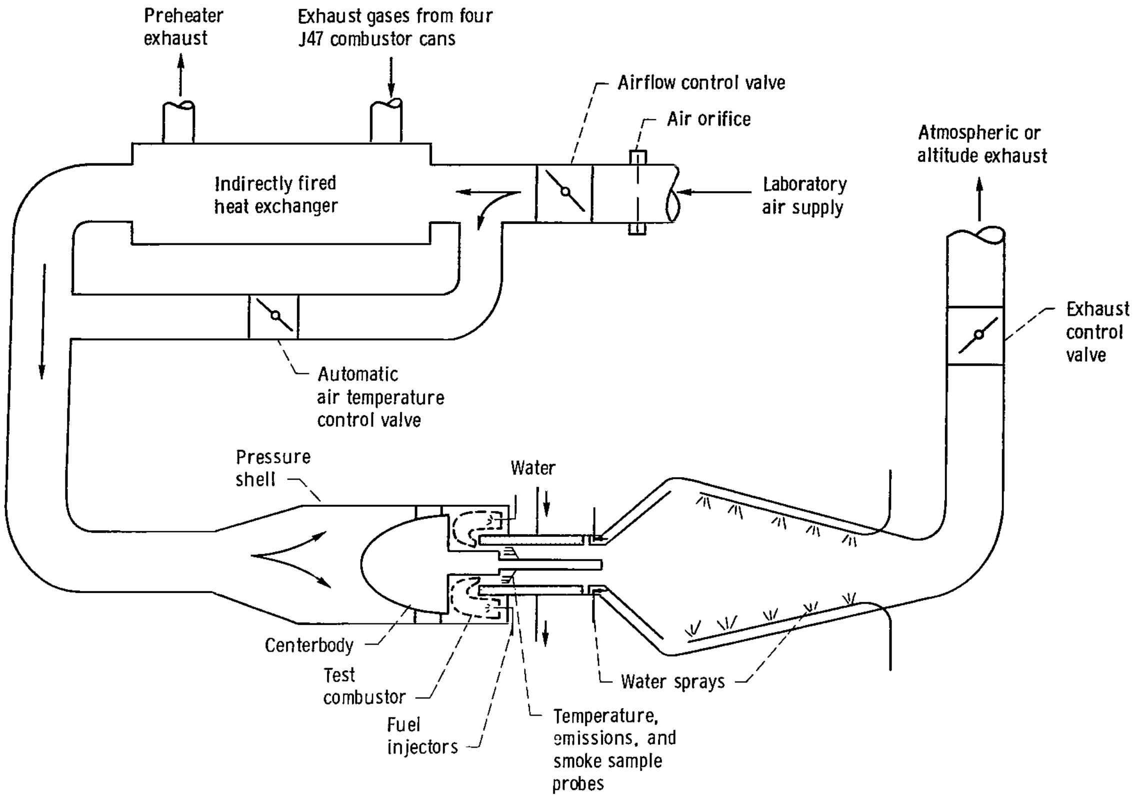
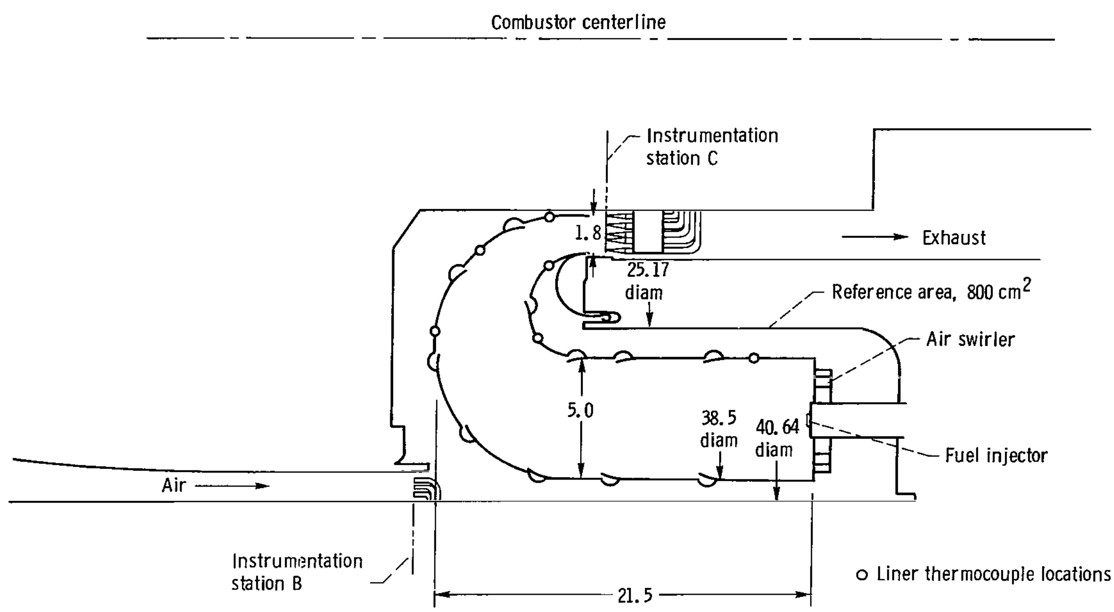
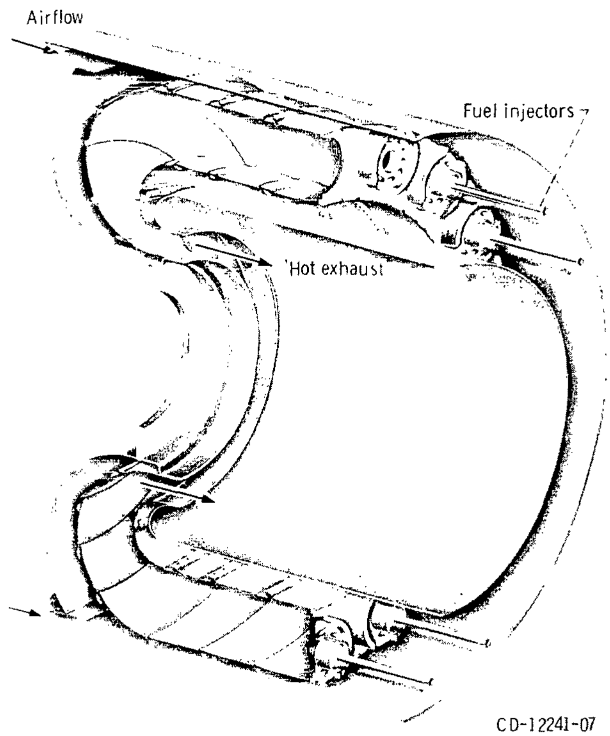


Figure 1. - Test facility.

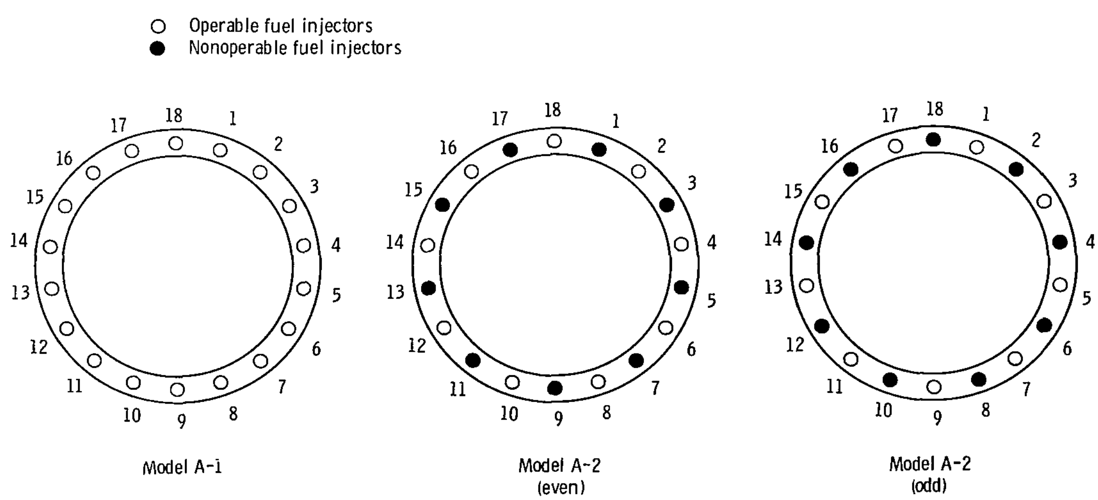


(a) Cross section.

Figure 2. - Test combustor. All dimensions in centimeters.

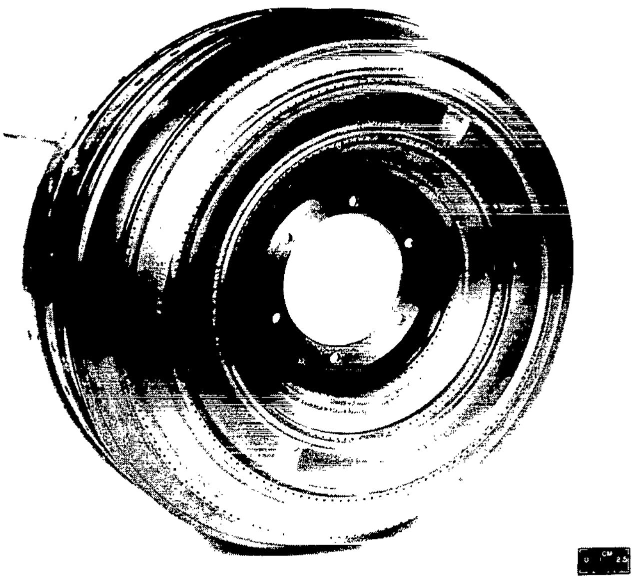


(b) Isometric view.

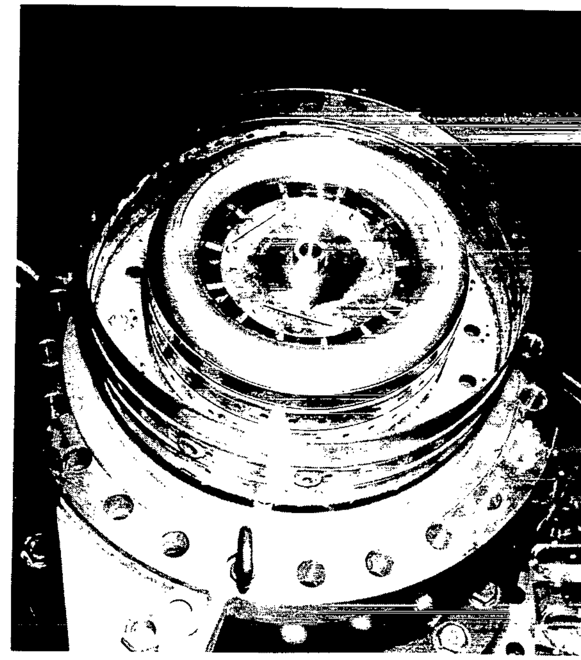


(c) Fuel injector density and location.

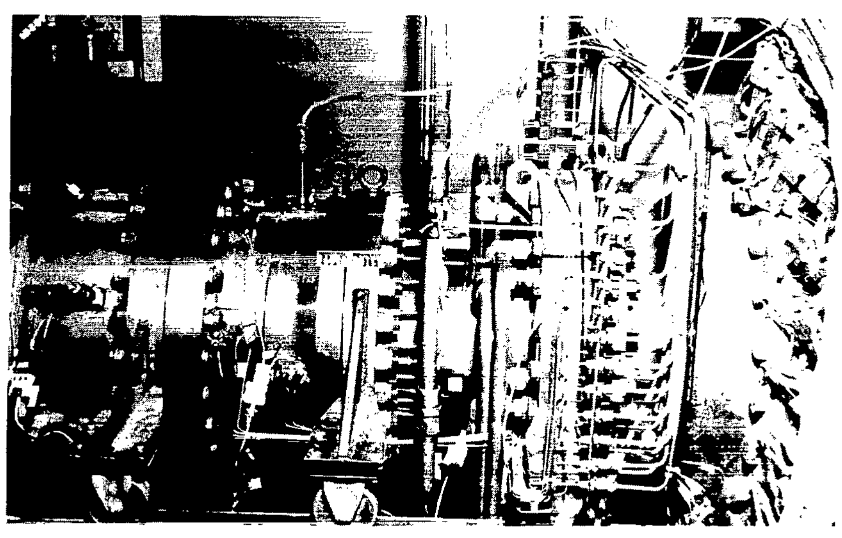
Figure 2. - Concluded.



(a) Aft view of combustor.



(b) Combustor liners.



(c) Housing.

Figure 3. - Reverse-flow combustor.

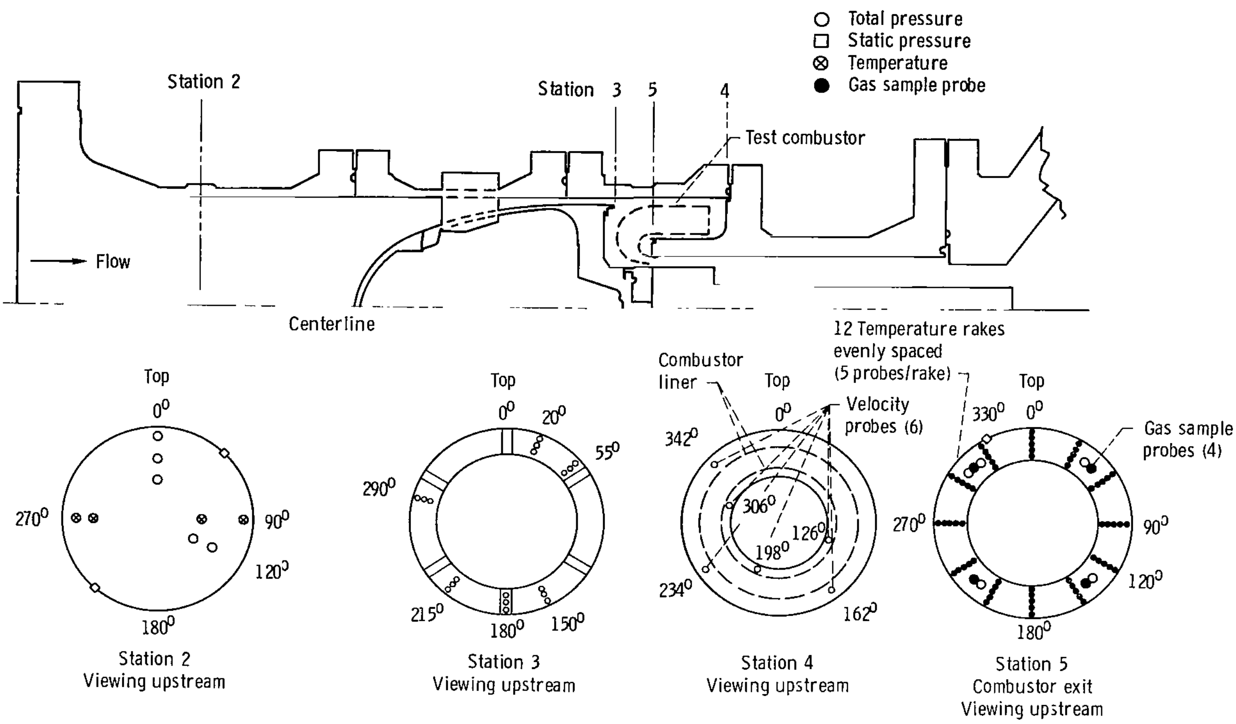
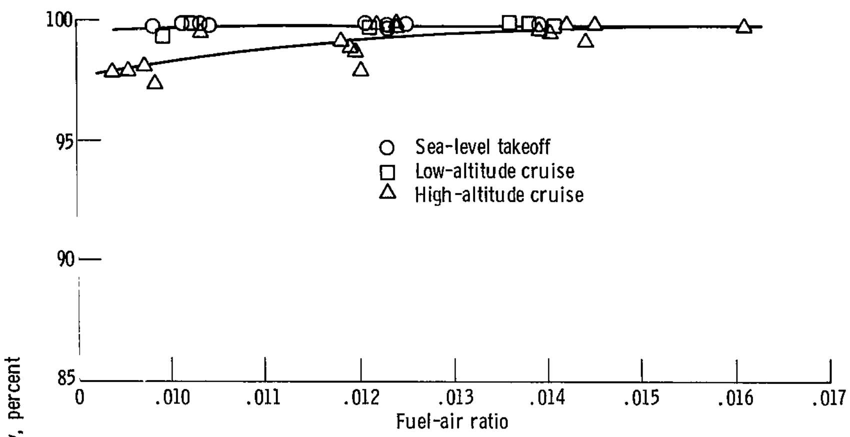
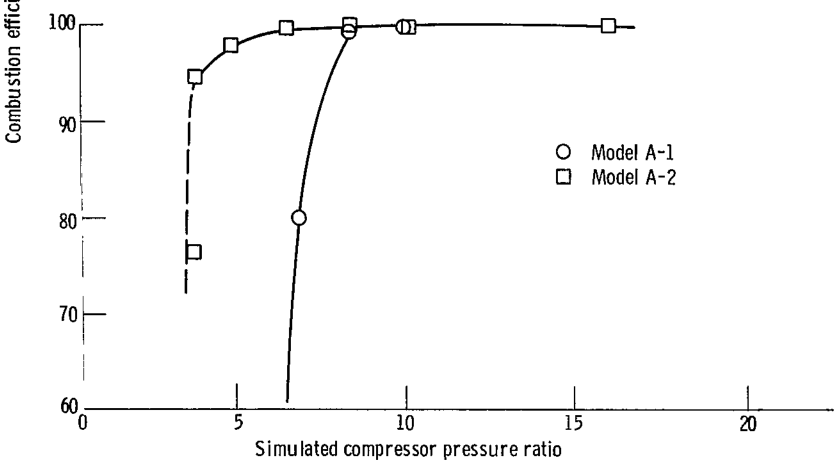


Figure 4. - Research instrumentation.



(a) Effect of fuel-air ratio for combustor model A-1.



(b) Effect of reduced power conditions. Fuel-air ratio, 0.014.

Figure 5. - Combustion efficiency obtained with reverse-flow combustor operating with simplex fuel injectors at simulated inlet flight conditions with Jet A fuel.

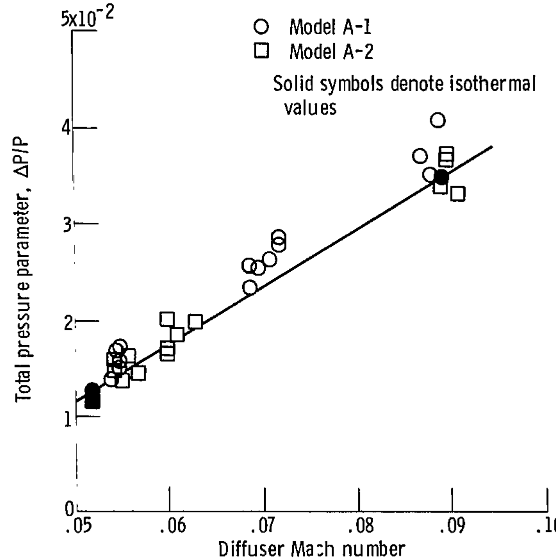
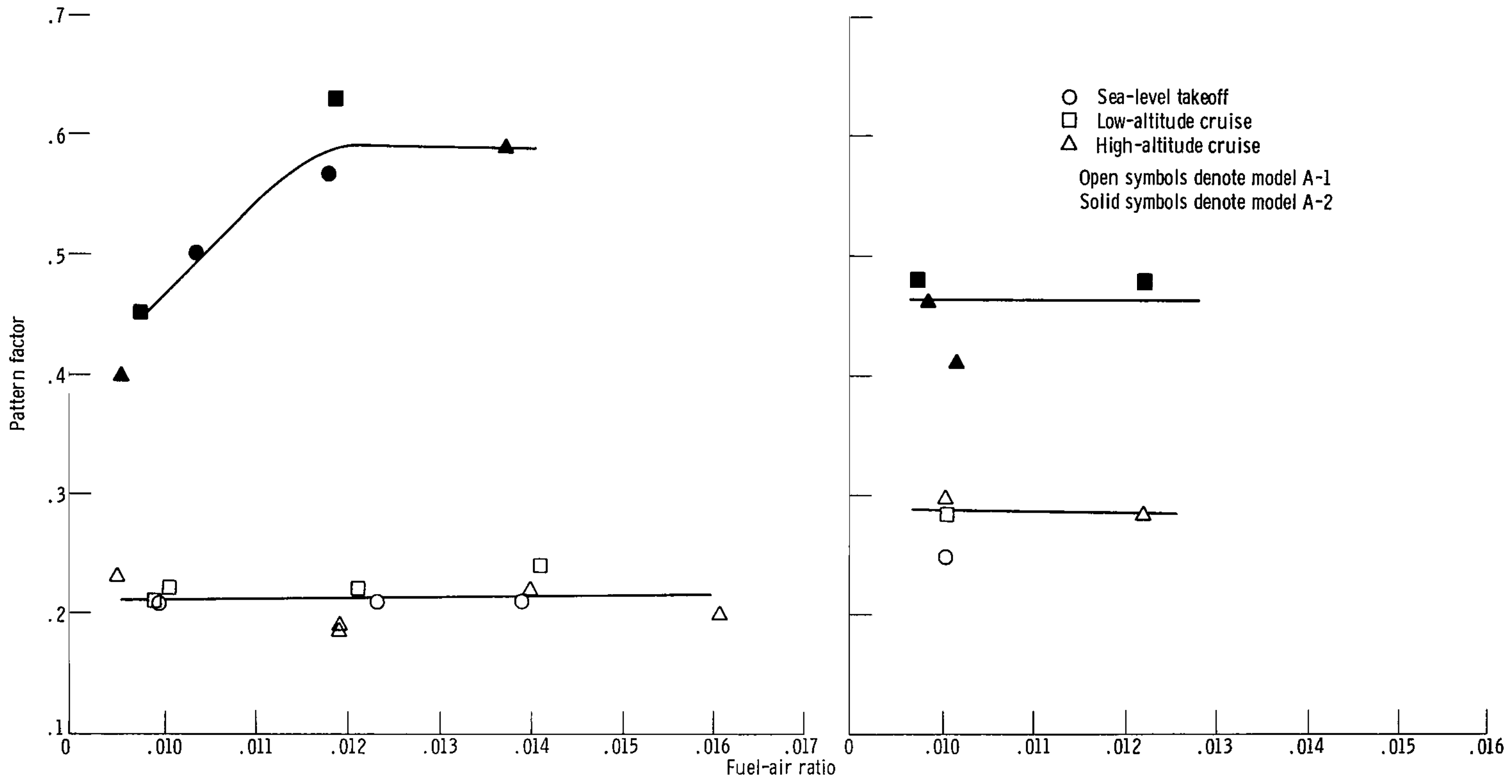


Figure 6. - Reverse-flow combustor total pressure loss over a range of inlet diffuser Mach numbers.



(a) Reference velocity, 5.5 meters per second.

(b) Reference velocity, 9.1 meters per second.

Figure 7. - Outlet pattern factor over range of fuel-air ratios for simulated inlet flight conditions with Jet A fuel.

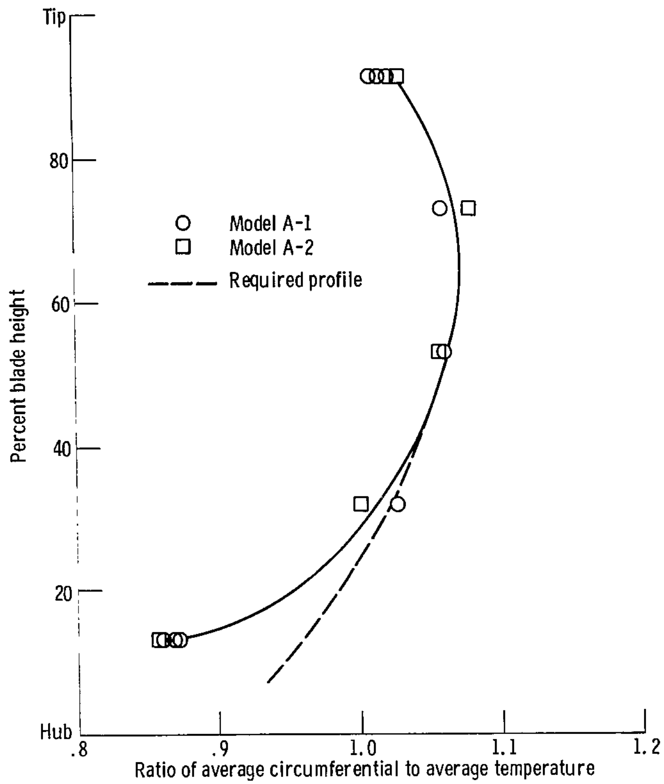


Figure 8. - Outlet radial profile for simulated sea-level takeoff inlet condition. Overall fuel-air ratio, 0.014 with Jet A fuel.

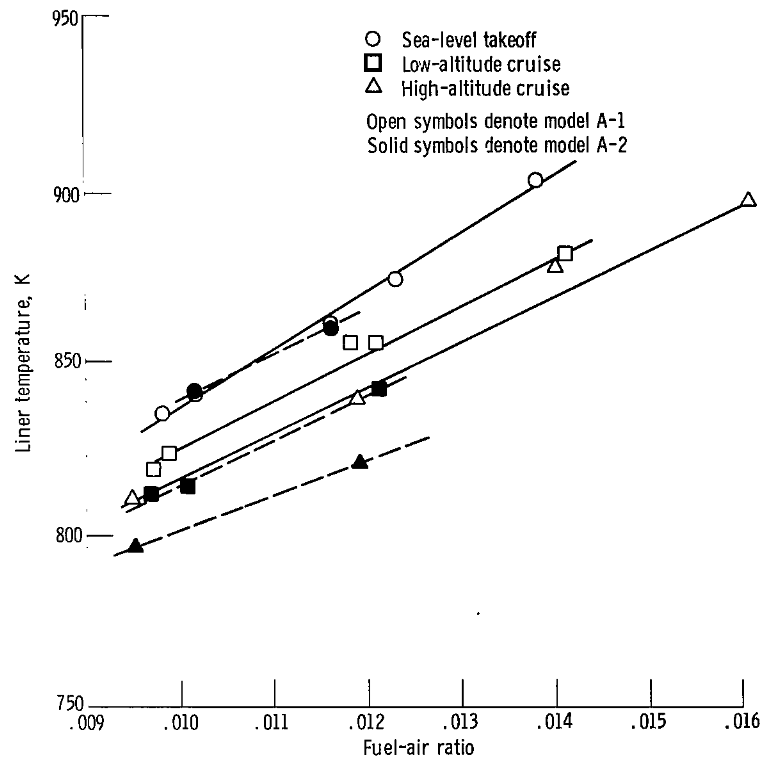
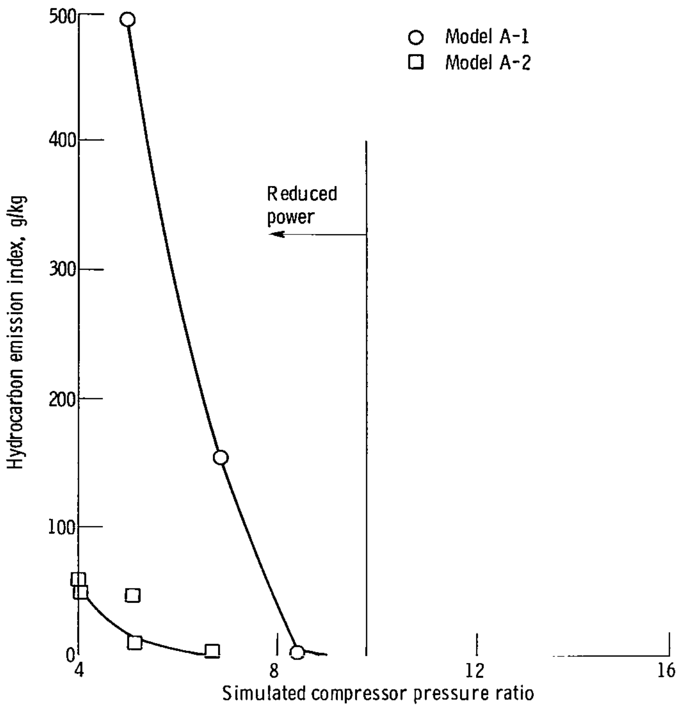
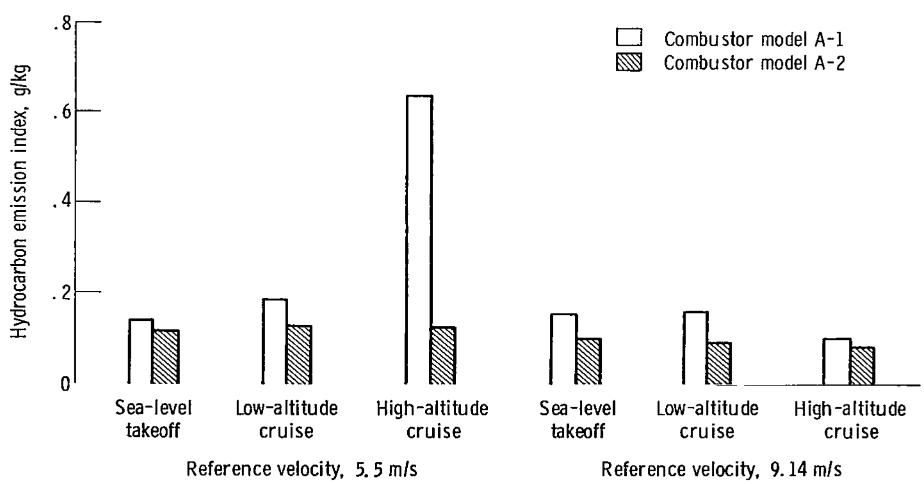


Figure 9. - Liner temperature on inner turn of a reverse-flow combustor for simulated inlet flight conditions over range of fuel-air ratios with Jet A fuel.

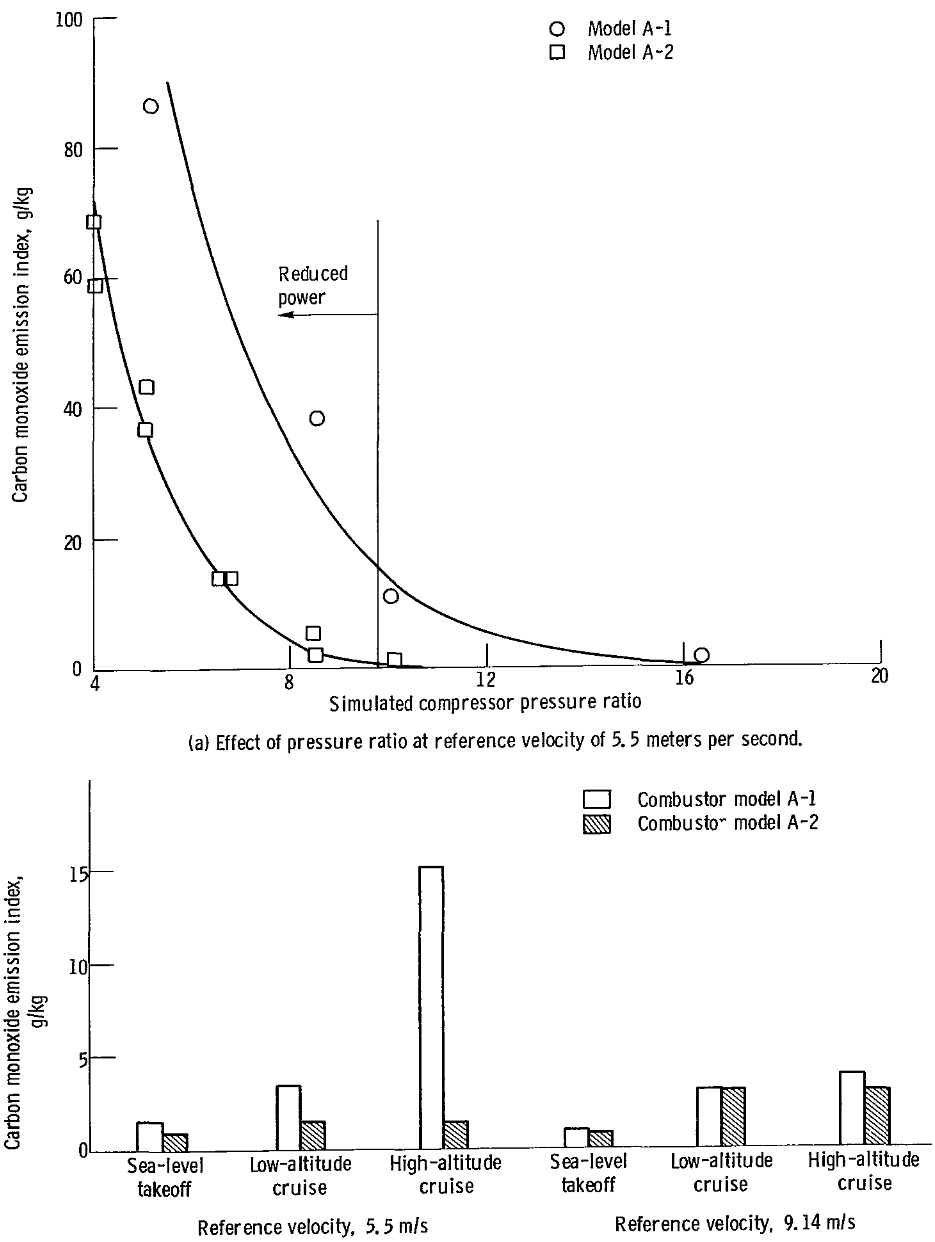


(a) Effect of pressure ratio at reference velocity of 5.5 meters per second.



(b) Effect of velocity.

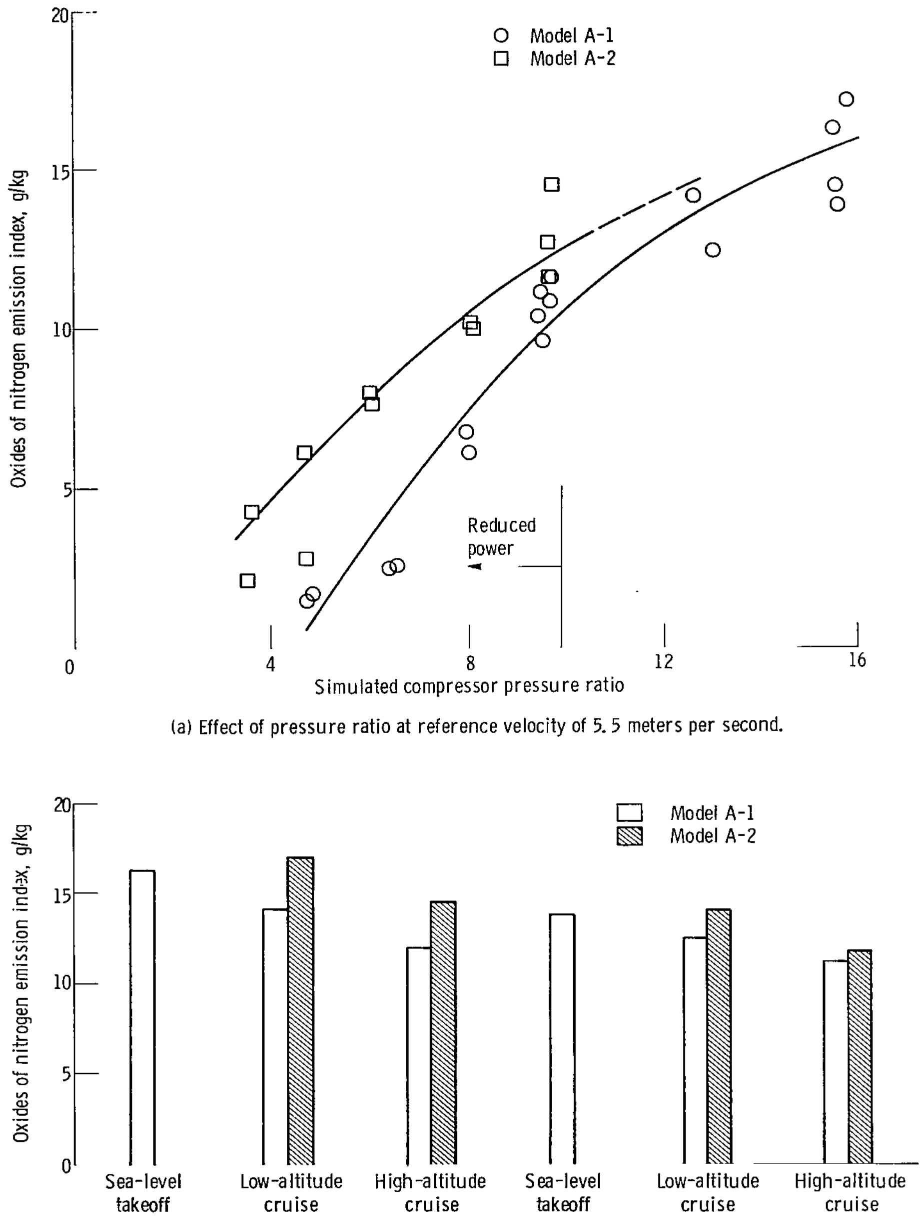
Figure 10. - Emission index of unburned hydrocarbons in reverse-flow combustor for constant fuel-air ratio of 0.014 with Jet A fuel.



(a) Effect of pressure ratio at reference velocity of 5.5 meters per second.

(b) Effect of velocity.

Figure 11. - Emission index of carbon monoxide in reverse-flow combustor for constant fuel-air ratio of 0.014 with Jet A fuel.



(a) Effect of pressure ratio at reference velocity of 5.5 meters per second.

(b) Effect of velocity.

Figure 12. - Emission of oxides of nitrogen in reverse-flow combustor for constant fuel-air ratio of 0.014 with Jet A fuel.

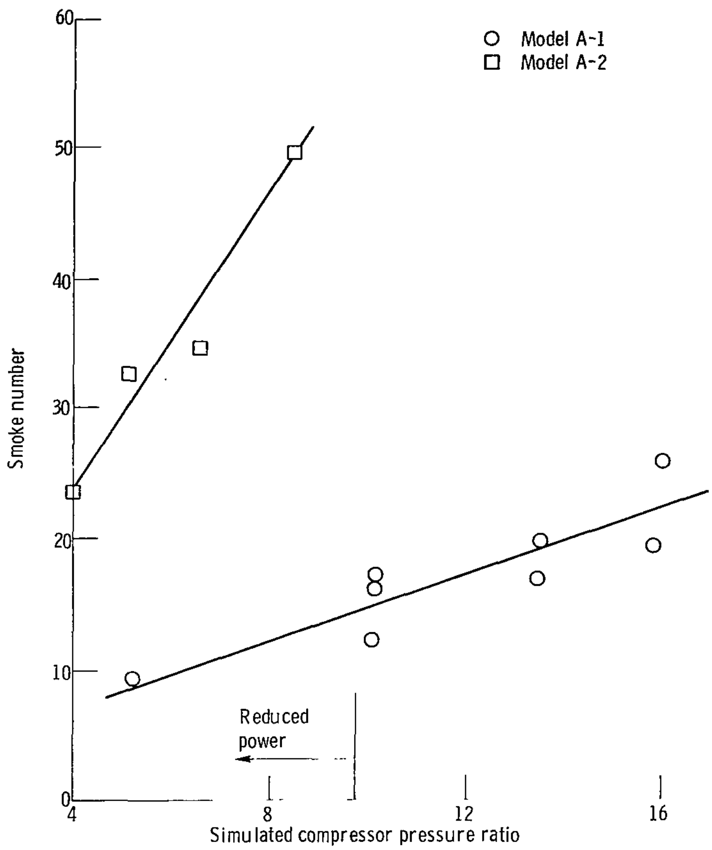


Figure 13. - Smoke number obtained with reverse-flow combustor for constant fuel-air ratio of 0.014 with Jet A fuel.

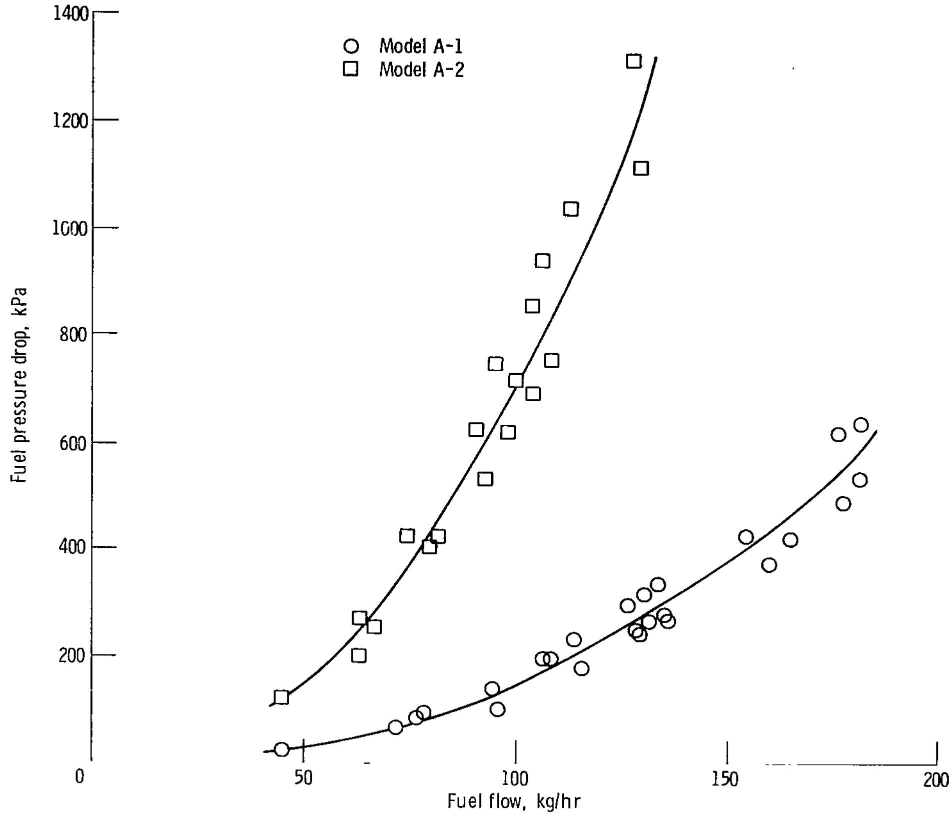


Figure 14. - Simplex pressure-atomizing fuel injector pressure drop over range of fuel flows with Jet A fuel.

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16. Abstract

A reverse-flow combustor suitable for a small gas turbine (2 to 3 kg/s mass flow) was used to evaluate the effect of pressure-atomizing fuel injectors on combustor performance. In these tests an experimental combustor was designed to operate with 18 simplex pressure-atomizing fuel injectors at sea-level takeoff conditions. To improve performance at low-power conditions, fuel was redistributed so that only every other injector was operational. Combustor performance, emissions, and liner temperature are compared over a range of pressure and inlet-air temperatures corresponding to simulated idle, cruise, and takeoff conditions typical of a 16 to 1 pressure ratio turbine engine.

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