PERFORMANCE AND POLLUTION MEASUREMENTS OF TWO-ROW SWIRL-CAN COMBUSTOR HAVING 72 MODULES

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Abstract
A test program was conducted to evaluate the performance and gaseous-pollutant levels of an experimental full-annulus 72-module swirl-can combustor. A comparison of data with those for a 120-module swirl-can combustor showed no significant difference in performance or levels of gaseous pollutants. In addition, oxides of nitrogen were correlated for the 72- and 120-swirl-can combustors by using a previously developed parameter.
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SUMMARY

A test program was conducted to evaluate the performance and gaseous-pollutant levels of an experimental full-annulus 72-swirl-can combustor. Data were compared with those for a previously tested 120-module swirl-can combustor. No significant difference in performance or levels of gaseous pollutants was detected. In addition, oxides of nitrogen were correlated for the 72- and 120-swirl-can combustors by using a previously developed parameter.

The combustor average exit temperature pattern factors were 0.27 for simulated takeoff (inlet-air temperature of 855 K, average exit temperature of 1465 K, and inlet pressure of 62.0 N/cm²) and for simulated cruise (inlet-air temperature of 733 K, average exit temperature of 1488 K, inlet pressure of 62.0 N/cm²). The emission index for oxides of nitrogen was 12.2 grams per kilogram of fuel at simulated takeoff and 8.17 grams per kilogram of fuel at simulated cruise. Unburned-hydrocarbon and carbon monoxide levels were compatible with the combustion efficiencies, which were nominally 100 percent.

INTRODUCTION

This report presents performance and pollution data for a full-annulus two-row swirl-can combustor having 72 swirl-can modules. Previous test results for a three-row swirl-can combustor having 120 modules (refs. 1 to 3) have shown a good potential for reducing levels of combustor exhaust gas pollutants. In particular, emission-index levels for oxides of nitrogen were 4.5 and 13.6 grams of nitrogen oxide per kilogram of fuel at inlet temperatures of 588 and 839 K, respectively. The fuel-air ratio was 0.025 with a nominal combustor inlet pressure of 62 newtons per square centimeter. Previous work has also shown that emissions depend on the number of active modules and on the
geometry of the flame stabilizer (ref. 2).

Combustors for many future gas turbine engine cycles may not be as large in diameter or hydraulic radius as those tested in previous work. The present investigation was conducted, therefore, on a combustor having fewer modules and a smaller hydraulic radius in order to evaluate what difference might be expected when the number of modules and the combustor size are changed. The annular height required for the modules of the three-row 120-swirl-can combustor was 16.0 centimeters compared with 11.3 centimeters for the two-row test combustor. The two-row 72-swirl-can combustor tests thus provided information on whether combustor performance values and gaseous emission levels are comparable with those obtained for the previously tested combustors. At the same time data were obtained to check a correlating parameter developed in reference 4 for extrapolating the levels of oxides of nitrogen for swirl-can combustors to different operating conditions. Also obtained was some design information regarding what type of swirl-can blockage is required and whether fuel scheduling to the two combustor rows can be effectively utilized.

Test conditions for the 72-swirl-can combustors included simulated cruise and takeoff conditions for a range of fuel-air ratios at inlet total pressures of 62 newtons per square centimeter and inlet-air temperatures from 588 to 858 K. The design average exit temperature was 1477 K. All tests were performed with ASTM Jet A fuel.

APPARATUS

Combustor Design

The two-row 72-swirl-can test combustor is shown in figures 1 and 2. It is a modification of a previously tested 120-swirl-can combustor (ref. 1). The modification to the 120-swirl-can design was achieved by the insertion of a new outer annulus liner that eliminated 48 swirl cans from the burning zone. To minimize any distortion of airflow to the outer liner cooling holes, the 48 fuel tubes, swirlers, and flame stabilizers were removed. The resulting test combustor was a two-row design, having 40 swirl cans in its outer row and 32 swirl cans in its inner row. The combustor was evaluated in the same housing as that of the 120-swirl-can combustor. The combustor housing had an outer diameter of 1.067 meters and an inner diameter of 0.54 meter and was 0.514 meter long. The inlet diffuser passage was 12.95 centimeters long and had an exit to inlet area ratio of 1.2. Immediately downstream of the diffuser there was a sudden dump region in which the ratio of the annular flow area at the inlet plane of the swirl cans to the diffuser exit area was 2.75.
Module Design

The combustor module design is shown in figure 3. Each module premixes fuel with air in the carburetor, swirls the mixture, stabilizes combustion in its wake, and provides an interfacial mixing region between the bypass air through the array and the hot gases in the wake of the module. Two flame-stabilizer designs were used in order to provide equal blockage to the inner and outer rows of swirl cans. The design blockage was 67.3 percent. The open area of the swirler was 1.81 square centimeters.

Figure 4 shows a typical mounting strut used to hold the swirl-can array in position. Fuel was injected into the swirl cans by means of 0.475-centimeter-diameter fuel tubes. The fuel tubes entered the swirl cans from the upstream side and terminated approximately 0.63 centimeter from the face of the swirlers.

Test Facility

The annular two-row 72-module swirl-can combustor was tested in a connected-duct test facility. A line diagram of this facility and an isometric sketch of a typical combustor installation are shown in reference 5. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. A more complete description of the test facility is included in reference 6.

Instrumentation

Combustor inlet pressures and temperatures were measured at the locations shown in figure 5. Combustor exit total pressures and temperatures were measured in the exit plane, at station 5, at $3^\circ$ circumferential increments by equally spaced five-point rotatable probes. Airflow rates were measured with an orifice installed with flange taps according to ASME specifications. Fuel-flow rates were measured with turbine flowmeters. Detailed descriptions of the traversing combustor exit probe and of the data acquisition and recording system are contained in references 6 and 7. The combustor exit thermocouples were high-recovery aspirating platinum-13-percent-rhodium-platinum thermocouples (ref. 8, type 6).

Combustor exhaust gas samples were also obtained by using four fixed five-point sampling probes, such as the one shown in figure 6(a). Figure 6(b) shows the circumferential probe positions in the exit gas sample plane, at station 6. Facility limitations prevented positioning the probes in four equal sectors of the exit plane. The exhaust gas samples from the fixed probes were collected in a common line which was maintained at a minimum temperature of $422 \, K$. The sample line was connected to an
automated gas analyzing system (fig. 7). This system consisted of four separate instruments that measured concentrations of unburned hydrocarbons, carbon monoxide, carbon dioxide, and oxides of nitrogen. Figure 8 shows a schematic diagram of the gas analysis system. The unburned-hydrocarbon content of the gas sample was measured by a flame ionization detector, while carbon monoxide and carbon dioxide concentrations were determined by two nondispersive infrared analyzers. Oxides of nitrogen were measured by a chemiluminescent analyzer. This instrument was capable of providing separate measurements of nitric oxide (NO) and total oxides of nitrogen (NO plus nitrogen dioxide (NO₂)).

PROCEDURE

Test Conditions

Tests were conducted over a range of fuel-air ratios at combustor inlet temperatures simulating takeoff for a 12:1-pressure-ratio turbofan engine and at climbout, takeoff, and cruise conditions for a high-pressure-ratio (30:1) turbofan engine. Combustor design and operating conditions are listed in table I.

For all design conditions, the combustor inlet total pressure was scaled down, because of facility limitations, to one-half of that required for a 12:1-pressure-ratio engine and one-fifth of that required for a high-pressure-ratio (30:1) engine. However, combustor inlet-air temperatures were maintained at the required condition while reference velocity was maintained at sufficiently high levels to produce a minimum combustor total-pressure loss of 4.0 percent. The combustor design average exit temperature was 1477 K.

Calculations

Combustion efficiency from exit temperature. - Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. The exit temperatures were mass weighted for the efficiency calculation by the procedure given in reference 7. In each mass-weighted average, 585 individual exit temperatures were used.

Combustion efficiency from gas analysis. - Efficiency was determined from gas analysis by using the following equation:

$$\eta_{gs} = 100 - 0.1 \frac{EI_{HC}}{42.7} - \frac{EICO}{42.7}$$
where $\text{EI}_{\text{HC}}$ and $\text{EI}_{\text{CO}}$ are the emission indices in grams per kilogram of fuel for unburned hydrocarbons and carbon monoxide, respectively.

**Reference velocity and Mach number.** - Reference conditions were based on the total airflow, the inlet-air density at the total pressure and temperature at the diffuser inlet, and the reference area of 3992 square centimeters. The reference area was measured at the point of maximum difference in diameters between the outer and inner cooling liner.

**Total-pressure loss.** - Combustor total-pressure loss was calculated as the difference between 40 mass-averaged total pressures measured upstream of the diffuser inlet and 585 mass-averaged total pressures measured at the combustor exit divided by the mass-averaged upstream total pressure. Therefore, the combustor total-pressure loss includes the diffuser loss.

**Diffuser inlet Mach number.** - Diffuser inlet static pressure and total temperature, total airflow, and inlet annulus area (1182 cm$^2$) were used for calculating the inlet Mach number.

**Radial profile factors.** - The radial profile of exit temperature was established from the circumferential average of the temperature at each radial position and was plotted as a deviation from the average exit temperature as a function of radial position. To detect temperature nonuniformities which may not be evident in the average radial profile, three temperature profile quality factors were calculated: exit temperature pattern factor $\delta$, stator factor $\delta_{\text{stator}}$, and rotor factor $\delta_{\text{rotor}}$.

The exit temperature pattern factor $\delta$ was used to reflect the magnitude of nonuniformity caused by the maximum local temperature. This factor was defined as

$$\delta = \frac{T_{\text{max}} - T_{\text{av}}}{\Delta T_{\text{av}}} \quad (1)$$

where $T_{\text{max}}$ is the maximum individual exit temperature, $T_{\text{av}}$ is the mass-weighted average exit temperature, and $\Delta T_{\text{av}}$ is the temperature difference between the mass-weighted average exit temperature and the average inlet temperature. To measure the magnitude of temperature nonuniformity which affects turbine stator vanes, a stator factor $\delta_{\text{stator}}$ was defined as

$$\delta_{\text{stator}} = \frac{(T_{r,\text{max}} - T_{r,\text{design}})_{\text{max}}}{\Delta T_{\text{av}}} \quad (2)$$

To measure the magnitude of temperature nonuniformity which affects turbine rotor blades, a rotor factor $\delta_{\text{rotor}}$ was defined as
\[ \delta_{\text{rotor}} = \frac{(T_{r,\text{av}} - T_{r,\text{design}})_{\text{max}}}{\Delta T_{\text{av}}} \] 

In these equations, \( T_{r,\text{max}} \) is an individual maximum radial temperature, and \( T_{r,\text{av}} \) is an average radial temperature which, when compared with the corresponding design radial average temperature \( T_{r,\text{design}} \) yields the maximum positive temperature difference and the largest radial profile factor.

**Exhaust gas concentration.** - The concentrations of measured exhaust gases in parts per million (ppm) were converted to a wet basis, as proposed in reference 9, and recorded in terms of an emission index parameter \( EI \). The emission index was determined from the following equation:

\[ EI_x = \frac{m_x}{m_E} \frac{1 + f}{f} X \times 10^{-3} \]

where

- \( EI_x \) emission index, g/kg of fuel burned
- \( m_x \) molecular weight of \( x \)
- \( m_E \) average molecular weight of exhaust gas
- \( f \) metered fuel-air ratio
- \( X \) measured concentration of \( x \), ppm

In addition to determining the emission index, a ratio of gas sample fuel-air ratio (as determined by concentrations of carbon monoxide and unburned hydrocarbons) to measured fuel-air ratio was calculated as a check of sample validity.

**Units**

The U.S. customary system of units was used for primary measurements and calculations. Values were converted to SI units (Systeme International d'Unites) for reporting purposes only. When the conversions were made, consideration was given to implied accuracy, so that some of the values expressed in SI units were rounded off.
RESULTS AND DISCUSSION

The two-row 72-swirl-can combustor performance data, including exit temperature, pressure loss, combustion efficiency determined on the basis of temperature rise, and pattern factor, are presented in table II. Concentrations of exhaust emissions and combustion efficiency based on exhaust gas analysis are presented in table III. Significant performance characteristics of this combustor are discussed in this section.

Combustion Efficiency

Good agreement was obtained between the combustion efficiencies determined by exit thermocouple measurements and exhaust gas analysis. Differences between the two efficiencies did not exceed 4 percent. However, the combustion efficiency based on exhaust concentrations of carbon monoxide and hydrocarbons was considered to be more accurate, and this efficiency is therefore used throughout the report. The combustion efficiency data at an inlet pressure of 62 newtons per square centimeter and inlet-air temperatures of 588, 733, 825, and 858 K were all nominally 100 percent.

Total-Pressure Loss

Combustor total-pressure loss, over a range of fuel-air ratios, varied from a low of 3.81 percent at a fuel-air ratio of 0.015 to a high of 5.79 percent at a fuel-air ratio of 0.0234 at an inlet-air temperature of 588 K and reference velocities between 23.0 and 27.3 meters per second. The isothermal total-pressure loss was 3.41 percent at an inlet-air temperature of 588 K and a reference velocity of 23.3 meters per second.

Exit Temperature Distribution

The combustor exit temperature distribution pattern factor for the simulated climb-out, takeoff, and cruise conditions for the 30:1-pressure-ratio engine was nominally 0.27 at an average exit temperature of 1477 K. The pattern factor for simulated takeoff (588 K inlet-air temperature) for the 12:1-pressure-ratio engine was nominally 0.31. The slightly lower pattern factor for the 30:1-pressure-ratio engine at simulated climb-out, cruise, and takeoff conditions was achieved by providing 5 percent more fuel flow to the outer row of swirl cans. This fuel staggering reduced the hub temperatures and produced a better average radial exit temperature profile. As an example of the typical average radial exit temperature profiles obtained for all design conditions, the average
radial temperature profiles for a simulated cruise and a simulated takeoff run of the
30:1-pressure-ratio engine are plotted against a desired profile in figure 9. The maxi-
mum individual (local) temperatures at each radial position are also shown in this fig-
ure. Agreement between the actual and desired radial profiles was good. For the
cruise run (fig. 9(a)) the maximum average radial profile temperature difference from
the design profile was 35 K and corresponded to a rotor factor of 0.05. The maximum
individual (local) temperature difference from the desired profile was 201 K and cor-
responded to a stator factor of 0.27. For the takeoff run (fig. 9(b)) the maximum aver-
age radial profile temperature difference was 15 K, which produced a rotor factor of
0.02. The maximum individual (local) temperature difference was 162 K, which pro-
duced a stator factor of 0.27.

Exhaust Emissions

A summary of the combustor exhaust gas emissions is presented in table III. The
data cover a variety of exit temperatures for inlet-air temperatures from 588 to 858 K.
The gaseous exhaust emissions for nitric oxide, total oxides of nitrogen (NO plus \(\text{NO}_2\)),
unburned hydrocarbons, carbon monoxide, and carbon dioxide are presented in terms
of an emission index (grams of pollutant per kilogram of fuel) and parts per million by vol-}
ume). Included in the table as a check of sample validity are ratios of the fuel-air ratios
as determined from exhaust emissions and as determined from separately measured
flow rates of air and fuel.

**Oxides of nitrogen.** - The measured values of emission index for oxides of nitrogen
(NO plus \(\text{NO}_2\)) varied from 4.84 grams of \(\text{NO}_2\) per kilogram of fuel at an inlet-air tem-
perature of 588 K and an average exit temperature of 1469 K to 14.2 grams of \(\text{NO}_2\) per
kilogram of fuel at an inlet-air temperature of 859 K and an average exit temperature of
1501 K. Figure 10 shows the effect of increasing fuel-air ratio on the oxides-of-nitrogen
emission index at various inlet-air temperatures and reference velocities. The trends
of emission index values decreasing at higher reference velocities for a given inlet-air
temperature and increasing at higher inlet-air temperatures agree with previously re-
ported trends (refs. 2 and 5).

**Unburned hydrocarbons.** - The emission index for unburned hydrocarbons is plotted
in figure 11 for inlet-air temperatures of 588 and 733 K. The emission index varied
from a high of 12.5 grams per kilogram of fuel at an inlet-air temperature of 588 K and
a fuel-air ratio of 0.0155 to a low of 0.08 gram per kilogram of fuel at an inlet-air tem-
perature of 733 K and a fuel-air ratio of 0.0222. Emission-index data for inlet-air
temperatures of 825 and 858 K are listed in table III and did not exceed 0.14 gram per
kilogram of fuel. The concentrations of unburned hydrocarbons followed the trends of
previous swirl-can data (ref. 2). They increased with increasing reference velocity and
decreased with increasing fuel-air ratio and inlet-air temperature.

Carbon monoxide. - The emission index for carbon monoxide is shown in figure 12. The data followed the same trend as those for unburned hydrocarbons: values increased with reference velocity and decreased with fuel-air ratio and inlet-air temperature. The highest emission-index value for carbon monoxide was 88.6 grams per kilogram of fuel, at a fuel-air ratio of 0.0155 and an inlet-air temperature of 588 K. The lowest emission-index value was 1.2 grams per kilogram of fuel at a fuel-air ratio of 0.0192 and an inlet-air temperature of 859 K.

Sample validity. - Measured values of carbon monoxide, carbon dioxide, and unburned hydrocarbons were used to determine a gas sample fuel-air ratio \( f/a \) \(_{gs} \). These values were compared with fuel-air ratios determined from measured flow rates of fuel and air. Agreement between the two fuel-air ratios would indicate how well the gas sampling probe was obtaining a representative sample of exhaust products. The four fixed sample probes yielded gas sample fuel-air ratios 7 to 12 percent less than the measured fuel-air ratios.

Comparison With Previous Work

Combustor design. - The two-row 72-swirl-can combustor, besides having 48 fewer modules than the 120-swirl-can combustor, contained two other major design differences: (1) the combustor length-diameter ratio was increased from 1.80 to 2.55, and there was a corresponding decrease in combustor volume from 0.122 to 0.094 cubic meter; and (2) the flame-stabilizer plates were changed from star-shaped and hexagonal to trapezoidal.

The effect of reducing number of modules and combustor volume mainly influenced the required fuel flow per module and the combustor space rates. For example, for the 72-module combustor the fuel flow rate per module was 4.36 kilograms per hour and the space rate was \( 2.37 \times 10^5 \) J/(hr)(cm)(atm) at design conditions (inlet total pressure of 62 N/cm\(^2\), inlet-air temperature of 588 K, reference velocity of 24.6 m/sec, and fuel-air ratio of 0.026). For the 120-module combustor the fuel flow rate per module was 23 percent lower (3.54 kg/hr) and the space rate was 4.1 percent higher (\( 2.46 \times 10^5 \) J/(hr)(cm)(atm)) at the same conditions. In order to compensate for the larger module fuel flows required by the test combustor, the flame-stabilizer area was increased to provide 67.3 percent blockage. Flame-stabilizer blockage for the 120-swirl-can combustor varied from 47.8 to 63.5 percent. The larger blockage would force more air through the module swirlers and compensate for their higher fuel flows while producing better mixing. The nominal difference in space rates between the combustors was not expected to affect the performance of the test combustor greatly, and no change was made to compensate for it. The trapezoidal shape of the flame stabilizers was chosen to provide
a better controlled blockage arrangement and to prevent excessive airflow to the hub and tip regions of the combustor.

**Combustor performance.** The test combustor produced results similar to those obtained with the 120-module combustor. An exception was combustor total-pressure loss. The isothermal pressure loss for the test combustor is shown in figure 13. The high losses were expected because of the larger blockage area of the test combustor. Combustion efficiencies for the range of test conditions for the 72- and 120-module combustors were nominally 100 percent. The pattern factor for the 72-module swirl-can combustor ranged from 0.27 to 0.32. The pattern factor for the 120-module swirl-can combustor varied from 0.25 to 0.32. The slightly higher pattern factors for the 72-module combustor were attributed to the module number and spacing irregularities between the two combustor rows. There were 40 modules in the outer row and 32 in the inner row. These irregularities made it difficult for modules in line and out of line with each other to receive the same mixing and airflow distribution. Elimination of these irregularities by using a more uniform module distribution per row should help in achieving even better pattern factors.

**Combustor emissions.** Combustor emissions for the 72- and 120-swirl-can combustors at similar inlet conditions and reference velocities are compared in figure 14. The emission index for unburned hydrocarbons, carbon monoxide, and oxides of nitrogen is plotted against combustor average exit temperature. The emission-index values for unburned hydrocarbons in figure 14(a) show a decrease as the number of modules is reduced from 120 to 72, particularly at high exit temperatures. For a combustor exit temperature of 1400 K the emission index for the 72-module combustor is 1.05 grams per kilogram of fuel compared with 3.15 grams per kilogram of fuel for the 120-module combustor. However, when the 72-module combustor is compared with the 120-module combustor with only 104 of its modules lit, there is little difference in hydrocarbon emission index. The lack of any difference may be attributed to higher fuel-flow rates to the 104 modules which produce the same overall fuel-air ratio as obtained when 120 modules are used. Reducing the number of modules below a certain level will not necessarily reduce the unburned hydrocarbons if the flame-stabilizer geometry is optimized for a given fuel-air ratio. This may explain why there was no further reduction in unburned-hydrocarbon emissions with the 72-module combustor.

The emission index for carbon monoxide is plotted in figure 14(b). There does not seem to be as significant an effect of number of modules as in the hydrocarbon data. However, whether it was a number of modules of a flame-stabilizer effect, the differences between unburned-hydrocarbon and carbon monoxide emissions for the 120- and 72-module combustors did not produce more than a 0.5-percent change in combustor efficiency.

The oxides-of-nitrogen emission-index values for the 72-module combustor are plotted in figure 14(c) along with values obtained at similar conditions for the 120-module combustor.
combustor. No significant differences are noted in the emission-index values for either combustor. However, the reference velocities of the 72-module combustor are slightly higher than those of the 120-module combustor. Since increasing reference velocity is known to decrease the oxides of nitrogen, the actual values at identical conditions would be slightly higher for the 72-module swirl-can combustor.

**Oxides of nitrogen correlating parameter.** - The oxides-of-nitrogen emission-index values for the 72-module combustor are plotted in figure 15 against the correlating parameters of reference 4. Included in this figure are the 120-module data from figure 14 obtained at similar inlet test conditions. These data also fit the correlation reasonably well.

**SUMMARY OF RESULTS**

An annular 72-module swirl-can combustor was evaluated with ASTM Jet A fuel. Pollution and performance data were obtained at inlet-air temperatures corresponding to takeoff and cruise for 30:1-pressure-ratio engines and takeoff for 12:1-pressure-ratio engines. All tests were conducted at inlet total pressures of 62.0 newtons per square centimeter. Data were compared with those for a previously tested 120-swirl-can combustor. The following results were obtained:

1. For simulated takeoff and cruise conditions the pattern factor for average exit temperatures of 1465 to 1488 K was 0.27.
2. Radial average exit temperature profiles for simulated takeoff and cruise were within 15 to 38 K of the desired profile.
3. Computed combustion efficiencies, obtained from exhaust gas analyses, were nominally 100 percent.
4. At simulated takeoff (inlet temperature for 30:1-pressure-ratio engine) the maximum oxides-of-nitrogen emission index was 12.2 grams per kilogram of fuel at an average exit temperature of 1465 K. At simulated cruise (inlet temperature for 30:1-pressure-ratio engine) the maximum oxides-of-nitrogen emission index was 8.17 grams per kilogram of fuel at an exit temperature of 1488 K.
5. Comparison of emission-index values for carbon monoxide and unburned hydrocarbons with values for the 120-module combustor showed a nominal increase of up to 0.5 percent in combustion efficiency for the 72-module test combustor. Oxides of nitrogen showed no significant change.
6. Oxides of nitrogen for the 72- and 120-swirl-can combustors were correlated by using a previously developed parameter.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 19, 1974,

REFERENCES


<table>
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<tr>
<th>Design condition</th>
<th>Combustor inlet air temperature, K</th>
<th>Combustor reference velocity, m/sec</th>
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<tr>
<td>Takeoff, 12:1 engine</td>
<td>588</td>
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<td>Cruise, 30:1 engine</td>
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<td>Takeoff, 30:1 engine</td>
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<tr>
<td>Design condition</td>
<td>Total pressure, $P_3$, N/cm$^2$</td>
<td>Average inlet temperature, $T_3$, K</td>
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### TABLE III. COMBUSTOR GASEOUS EMISSION DATA

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<th>Design condition</th>
<th>Oxides of nitrogen, NO\textsubscript{x} = NO + NO\textsubscript{2} ppm</th>
<th>Nitric oxide ppm</th>
<th>Unburned hydrocarbons ppm</th>
<th>Carbon monoxide ppm</th>
<th>Carbon dioxide ppm</th>
<th>g CO\textsubscript{2} / kg fuel</th>
<th>Ratio of gas sample to measured fuel-air ratio, (t/a)\textsubscript{gs} / (t/a)\textsubscript{m}</th>
<th>Combustor gas analysis efficiency, η\textsubscript{gs} percent</th>
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Figure 1. - Cross section of two-row 72-swirl-can combustor. (Dimensions are in centimeters.)
Figure 2. - End views of test combustor.

(a) View showing 72-swirl-can array with liners in place.

(b) View showing locations of 48 unused swirl cans with liners removed.
Figure 3. - Combustor module details. (Dimensions are in centimeters.)

Figure 4. - Typical mounting strut and fuel injection lines.
Gas sampling location, station 6;
Exit plane, station 5,
T_5, P_5, and P_6.

Figure 5. - Combustor housing, test section, and axial locations of instrumentation. (Dimensions are in centimeters.)
Cooling water in Gas sample out
Cooling water out
Sampling points
Water-cooled jacket

(a) Probe.

(b) Fixed probe positions.

Figure 6. Gas sampling probe and positions in combustor.
Carbon monoxide analyzer

Figure 7. - Gas sampling instrument console.

Two five-point water-cooled typewriter sampling probes

Bypass vent

Heated line

Flow

Bypass flowmeter

Control-room typewriter terminal

On-line computer

Dual-channel recorder

Indicating meter

Hydrocarbon analyzer

Indicating meter

Carbon monoxide analyzer

Indicating meter

Carbon dioxide analyzer

Indicating meter

Oxides-of-nitrogen analyzer

Dual-channel recorder

Indicating meter

Figure 8. - Schematic diagram of gas analysis system.
Figure 9. - Typical radial exit temperature profile characteristics. Nominal inlet total pressure, 62.0 newtons per square centimeter.

Figure 10. - Effect of fuel-air ratio on oxides of nitrogen at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.
Figure 11. Effect of fuel-air ratio on unburned-hydrocarbon emissions at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.
Figure 12. - Effect of fuel-air ratio on carbon monoxide emissions at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.
Figure 13. Isothermal pressure loss at various inlet Mach numbers. Inlet-air temperature, 584 K; inlet total pressure, 62.5 newtons per square centimeter.
Figure 14. — Comparison of emission data for two-row swirl-can combustor with previously obtained data for three-row swirl-can combustor. Inlet-air temperature, 588 K; inlet total pressure, 62.0 newtons per square centimeter.
Figure 14. - Concluded.

Figure 15. - Oxides-of-nitrogen correlation by parameter from reference 4.