NASA TECHNICAL MEMORANDUM

NASA TM X-3170

NASA TM X-3170

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

James A. Biaglow and Arthur M. Trout

Lewis Research Center

Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1975

1. Report No. NASA TM X-3170	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PERFORMANCE AND POLLUTION MEASUREMENTS OF TWO-ROW SWIRL-CAN COMBUSTOR HAVING 72 MODULES		5. Report Date January 1975
		6. Performing Organization Code
7. Author(s) James A. Biaglow, and Arthur M. Trout		8. Performing Organization Report No. E-8068
		10. Work Unit No. 501-24
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. 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.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Swirl-can combustor; Exhaust emissions	Unclassified - unlimited STAR category 45 (rev.)

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	28	$3.75

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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

by James A. Biaglow and Arthur M. Trout

Lewis Research Center

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/cm^2) and for simulated cruise (inlet-air temperature of 733 K, average exit temperature of 1488 K, inlet pressure of 62.0 N/cm^2). 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° 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 (NO_2)).

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:

$$\eta_{gs} = 100 - 0.1\ EI_{HC} - \frac{EI_{CO}}{42.7}$$

where EI_{HC} and EI_{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 $\overline{\delta}$, stator factor δ_{stator}, and rotor factor δ_{rotor}.

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

$$\overline{\delta} = \frac{T_{max} - T_{av}}{\Delta T_{av}} \tag{1}$$

where T_{max} is the maximum individual exit temperature, T_{av} is the mass-weighted average exit temperature, and ΔT_{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 δ_{stator} was defined as

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

To measure the magnitude of temperature nonuniformity which affects turbine rotor blades, a rotor factor δ_{rotor} was defined as

$$\delta_{rotor} = \frac{\left(T_{r,av} - T_{r,design}\right)_{max}}{\Delta T_{av}} \qquad (3)$$

In these equations, $T_{r,max}$ is an individual maximum radial temperature, and $T_{r,av}$ is an average radial temperature which, when compared with the corresponding design radial average temperature $T_{r,design}$, 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 climbout, 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 climbout, 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 maximum individual (local) temperatures at each radial position are also shown in this figure. 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 corresponded to a stator factor of 0.27. For the takeoff run (fig. 9(b)) the maximum average 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 produced a stotor 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 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 volume). 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 NO_2) varied from 4.84 grams of NO_2 per kilogram of fuel at an inlet-air temperature of 588 K and an average exit temperature of 1469 K to 14.2 grams of 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 reported 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 temperature 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 88.8 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 2.37×10^5 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 (2.46×10^5 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. 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,
501-24.

REFERENCES

1. Niedzwiecki, Richard W.; and Trout, Arthur M.: Performance of a Swirl-Can Combustor at Idle Conditions. NASA TM X-2578, 1972.
2. Niedzwiecki, Richard W.; and Jones, Robert E.: Pollution Measurements of a Swirl-Can Combustor. AIAA Paper 72-1201, Nov.-Dec. 1972.
3. Niedzwiecki, Richard W.; Juhasz, Albert J.; and Anderson, David N.: Performance of a Swirl-Can Primary Combustor to Outlet Temperatures of 3600° F (2256 K). NASA TM X-52902, 1970.
4. Niedzwiecki, Richard W.; and Jones, Robert E.: Parametric Test Results of a Swirl-Can Combustor. Presented at American Institute of Chemical Engineers 75th National Meeting, Detroit, Mich., June 4-6, 1973.
5. Humenik, Francis M.; and Biaglow, James A.: Evaluation of an Experimental Short-Length Annular Combustor: One-Side Entry Dilution Airflow Concept. NASA TN D-7225, 1973.
6. Adam, Paul W.; and Norris, James W.: Advanced Jet Engine Combustor Test Facility. NASA TN D-6030, 1970.
7. Rusnak, J. P.; and Shadowen, J. H.: Development of an Advanced Annular Combustor. (PWA-FR-2832, Pratt & Whitney Aircraft.) Available as NASA CR - 72453, 1969.
8. Glawe, George E.; Simmon, Frederick S.; and Stickey, Truman M.: Radiation and Recovery Corrections and Time Constants of Several Chromel-Alumel Thermocouple Probes in High-Temperature, High-Velocity Gas Streams. NACA TN 3766, 1956.
9. Procedure for the Continuous Sampling and Measurement of Gaseous Emissions From Aircraft Turbine Engines. Aerospace Recommended Practice 1256, SAE, Oct. 1, 1971.

TABLE I. - NOMINAL DESIGN CONDITIONS

[Combustor inlet pressure, 62.0 N/cm^2.]

Design condition	Combustor inlet-air temperature, K	Combustor reference velocity, m/sec
Takeoff, 12:1 engine	588	23 to 27
Cruise, 30:1 engine	733	27.0
Climbout, 30:1 engine	825	30 to 33.0
Takeoff, 30:1 engine	858	30 to 33.0

TABLE II. - COMBUSTOR PERFORMANCE DATA

Design condition	Total pressure, P_3, N/cm^2	Average inlet temperature, T_3, K	Airflow, W, kg/sec	Diffuser inlet Mach number, M_3	Reference velocity, V_{ref}, m/sec	Measured fuel-air ratio, $(f/a)_m$	Mass-weighted average exit temperature, K	Pattern factor, $\bar{\delta}$	Stator factor, δ_{stator}	Rotor factor, δ_{rotor}	Nominal combustor fuel flow split, Percent to outer row / Percent to inner row	Combustor pressure $(\Delta P/P)\times 100$, percent	Combustor thermocouple efficiency, η, percent
Takeoff, 12:1 engine	62.40	586	34.46	0.166	23.34	------	----	----	----	----	-----	3.41	------
	62.87	584	34.34	.164	23.04	0.0151	1134	0.31	0.34	0.07	55/45	3.81	101.00
	62.22	584	35.03	.164	23.05	.0183	1252	.31	.33	.04	↓	4.05	101.92
	62.50	592	34.22	.165	23.27	.0212	1340	.30	.34	.03		4.01	101.80
	62.53	592	34.64	.165	23.29	.0212	1344	.29	.32	.02		4.05	101.48
	62.64	593	34.11	.164	23.27	.0232	1412	.30	.35	.04		4.00	101.11
	62.58	593	34.02	.165	23.29	.0252	1462	.31	.36	.06		4.02	100.70
	62.60	594	33.67	.165	23.32	.0252	1464	.31	.34	.06		3.98	100.92
	61.85	588	38.82	.193	27.10	.0155	1147	.31	.33	.06		5.28	100.31
	62.87	591	38.72	.190	26.68	.0184	1245	.31	.33	.04		5.12	100.57
	62.37	584	39.43	.191	26.70	.0214	1338	.30	.32	.03		5.36	100.79
	61.07	585	40.69	.196	27.31	.0234	1400	.30	.31	.04		5.79	100.74
	61.30	586	39.65	.195	27.16	.0257	1469	.31	.30	.06		5.61	100.19
	61.67	587	39.73	.195	27.33	.0254	1461	.31	.29	.06		5.62	100.50
	61.99	585	38.84	.195	27.21	.0256	1460	.31	.27	.09	↓	5.46	99.88
Cruise, 30:1 engine	62.71	734	31.85	0.173	26.98	0.0145	1244	0.28	0.28	0.07	55/45	4.27	101.19
	61.80	738	32.07	.179	28.00	.0181	1366	.29	.28	.05	55/45	4.56	101.05
	61.55	739	31.53	.179	27.95	.0233	1492	.29	.29	.03	55/45	4.51	100.35
	61.84	740	32.24	.179	27.97	.0222	1488	.27	.27	.05	60/40	4.58	100.22
Climbout, 30:1 engine	61.80	838	31.29	0.191	31.63	0.0155	1363	0.31	0.38	0.06	55/45	4.93	99.61
	63.72	829	31.83	.182	30.02	.0187	1457	.32	.31	.06	55/45	4.70	100.53
	61.93	828	32.32	.188	31.07	.0187	1458	.28	.27	.02	60/40	4.91	100.39
Takeoff, 30:1 engine	62.92	859	37.02	0.197	29.20	0.0151	1375	0.27	0.34	0.08	60/40	5.21	100.89
	63.18	857	32.57	.196	32.74	.0182	1465	.27	.27	.02	60/40	5.05	99.92
	62.14	860	28.87	.177	29.71	.0192	1501	.29	.29	.02	60/40	4.11	100.23
	61.68	859	28.97	.179	30.13	------	----	----	----	----	-----	3.77	------

TABLE III. - COMBUSTOR GASEOUS EMISSION DATA

Design condition	Oxides of nitrogen, $NO_x = NO + NO_2$		Nitric oxide		Unburned hydrocarbons		Carbon monoxide		Carbon dioxide		Ratio of gas sample to measured fuel-air ratio, $\frac{(f/a)_{gs}}{(f/a)_m}$	Combustor gas analysis efficiency, η_{gs}, percent
	ppm	$\frac{g\ NO_2}{kg\ fuel}$	ppm	$\frac{g\ NO}{kg\ fuel}$	ppm	$\frac{g\ CH_2}{kg\ fuel}$	ppm	$\frac{g\ CO}{kg\ fuel}$	ppm	$\frac{g\ CO_2}{kg\ fuel}$		
Takeoff, 12:1 engine	25.7	2.76	8.0	0.06	316.6	10.36	1114	72.8	27 132	2786	0.93	97.30
	43.6	3.86	20.0	1.78	130.5	3.50	953	51.4	32 589	2763	.90	98.90
	65.1	5.00	43.0	3.30	38.6	.90	640	30.0	37 523	2763	.89	99.20
	63.1	4.85	41.0	3.10	44.7	1.00	709	33.2	38 481	2830	.91	99.10
	73.6	5.18	55.0	3.86	23.3	.50	455	19.5	42 925	2892	.92	99.49
	85.8	5.57	68.0	4.42	11.2	.20	304	12.0	45 468	2825	.90	99.70
	86.3	5.61	68.0	4.42	10.4	.20	290	11.5	45 381	2821	.90	99.70
	32.7	3.42	8.0	.92	398.0	12.60	1393	88.8	26 784	2683	.91	96.66
	41.0	3.63	13.0	1.16	207.0	5.55	1284	69.2	32 253	2731	.90	97.82
	55.0	4.19	41.0	3.12	100.7	2.32	950	49.1	38 032	2771	.90	98.74
	64.5	4.51	56.0	3.93	50.8	1.07	739	31.4	41 458	2770	.89	99.16
	76.1	4.84	53.0	3.14	30.1	.58	498	19.3	45 785	2784	.89	99.49
	74.0	4.77	53.0	3.42	27.0	.53	464	20.6	45 119	2784	.89	99.51
	73.7	4.72	54.0	3.37	30.7	.60	491	19.1	45 575	2791	.89	99.49
Cruise, 30:1 engine	65.0	7.26	40.0	4.46	21.4	0.72	457	31.1	45 986	2776	0.89	99.20
	93.7	8.41	80.0	7.19	5.2	.14	170	9.3	32 766	2811	.89	99.77
	123.0	8.98	112.0	8.15	4.1	.09	56	2.5	39 937	2790	.88	99.93
	123.3	9.05	112.0	8.17	3.6	.08	50	2.2	40 372	2836	.89	99.94
Climbout, 30:1 engine	103.5	10.78	87.0	9.30	4.3	0.14	277	17.6	29 210	3126	0.93	99.20
	135.5	11.81	127.0	11.08	4.1	.11	80	4.2	34 672	2889	.92	99.89
	133.0	11.54	127.0	11.00	4.3	.11	116	6.1	34 313	2847	.90	99.84
Takeoff, 30:1 engine	110.9	11.88	100.0	10.70	4.0	0.13	82	5.9	27 759	2845	0.90	99.86
	143.4	12.78	135.0	12.02	4.0	.11	32	1.7	33 535	2859	.90	99.95
	168.1	14.20	154.0	13.00	4.1	.10	23	1.2	34 498	2788	.88	99.96

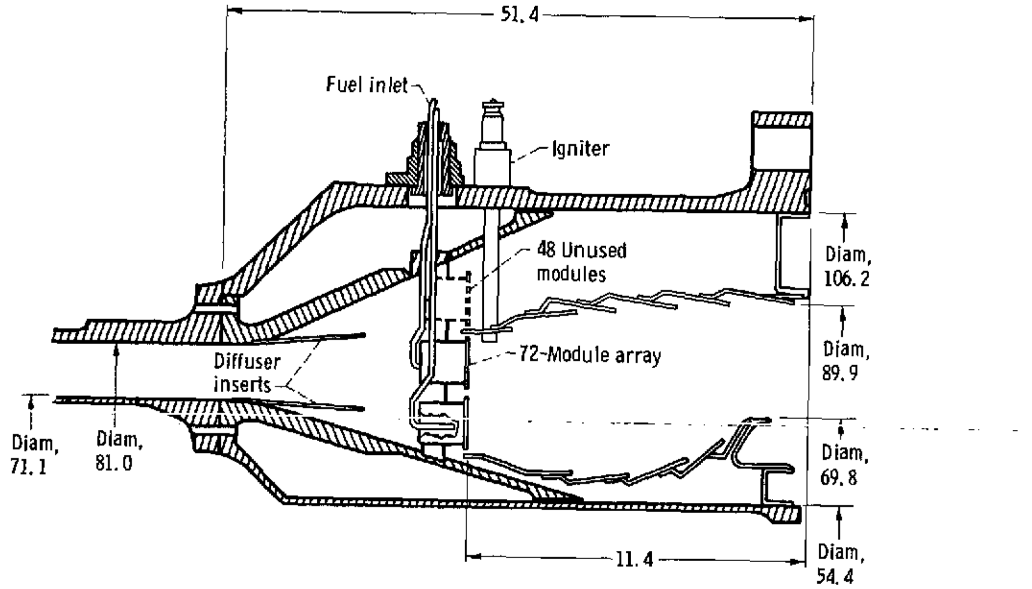
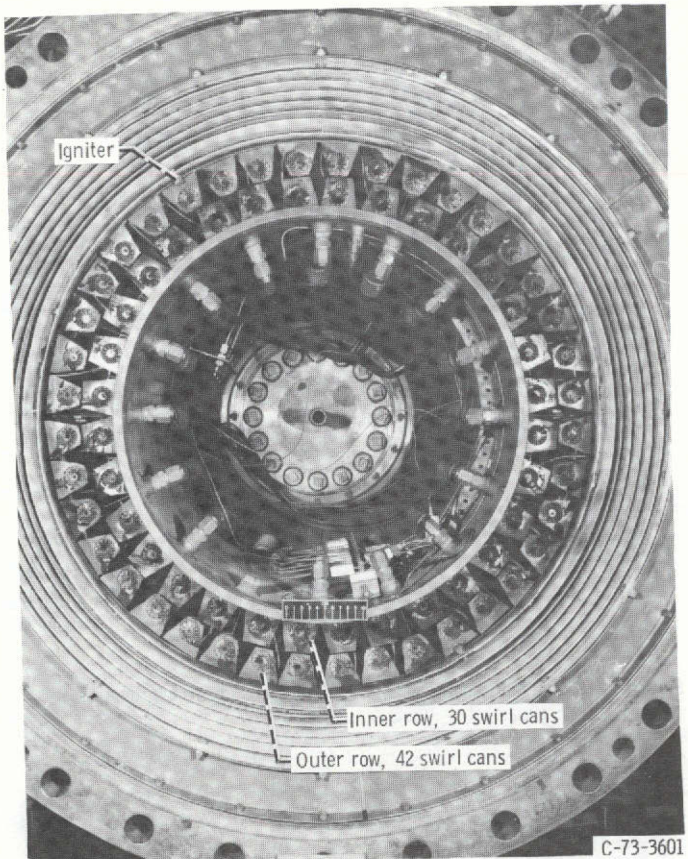
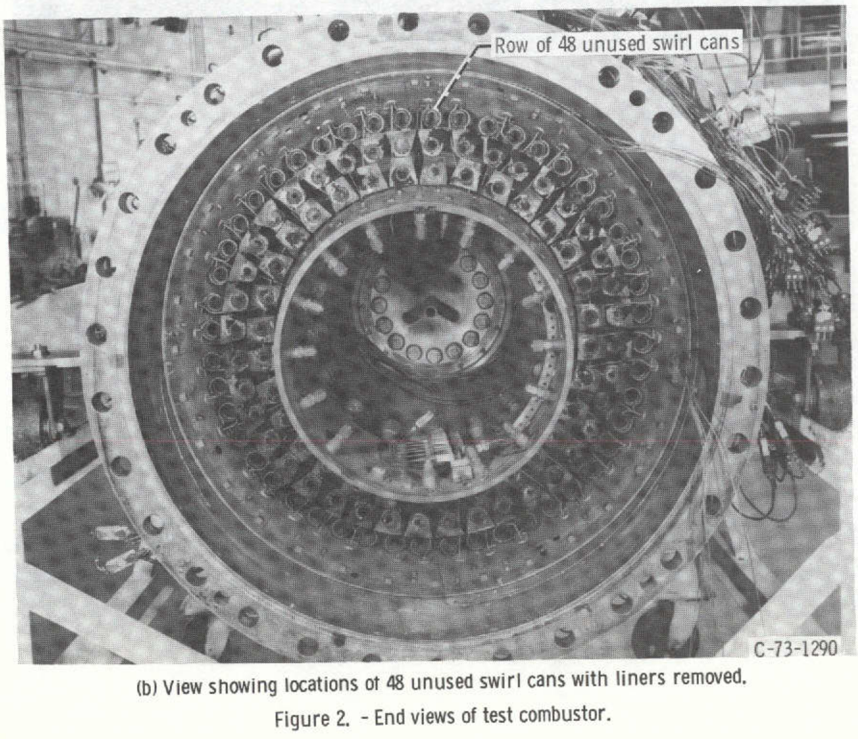


Figure 1. - Cross section of two-row 72-swirl-can combustor. (Dimensions are in centimeters.)



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



(b) View showing locations of 48 unused swirl cans with liners removed.

Figure 2. - End views of test combustor.

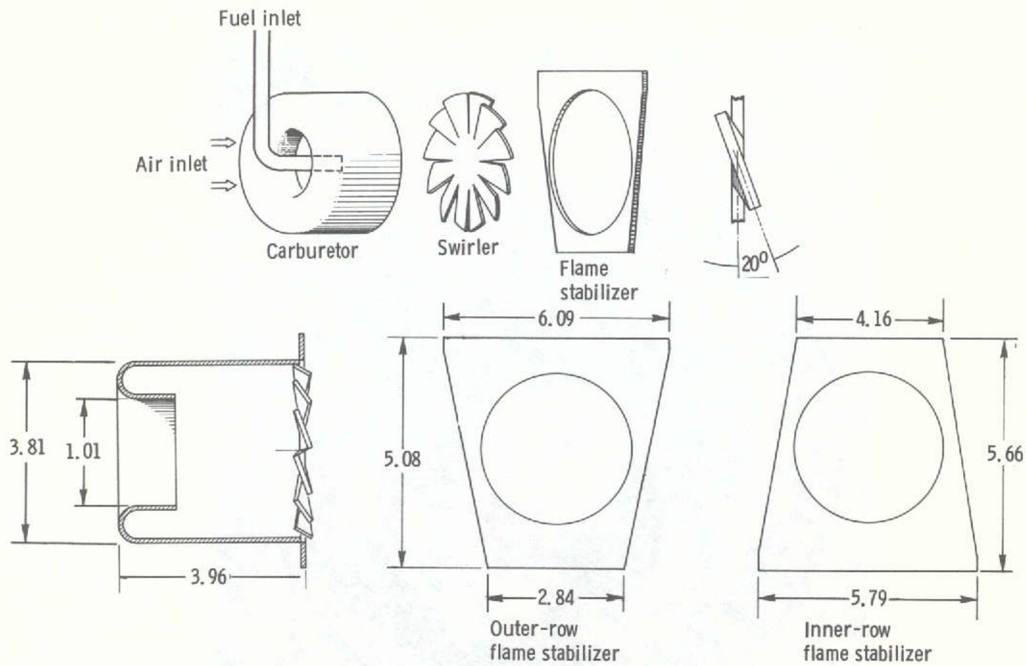


Figure 3. - Combustor module details. (Dimensions are in centimeters.)

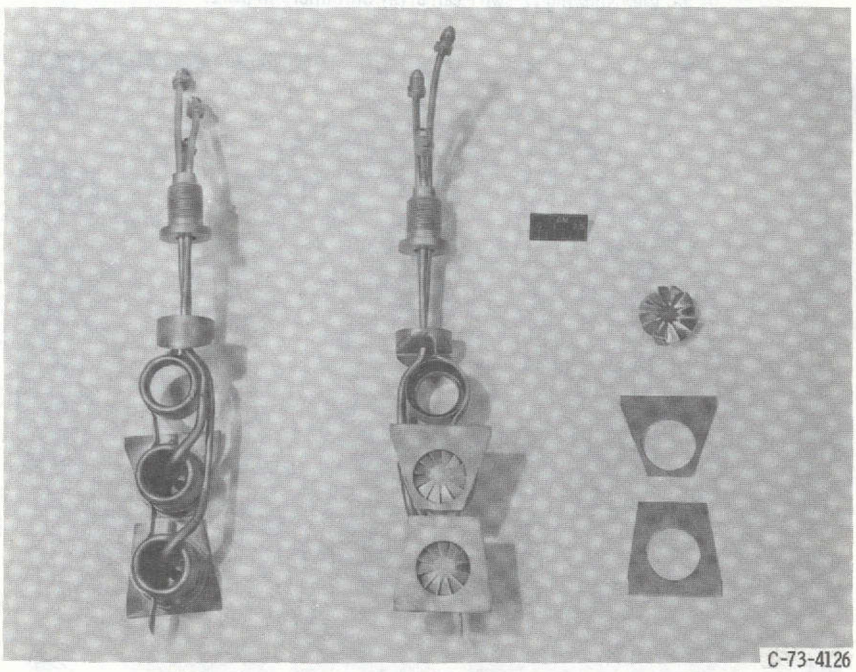


Figure 4. - Typical mounting strut and fuel injection lines.

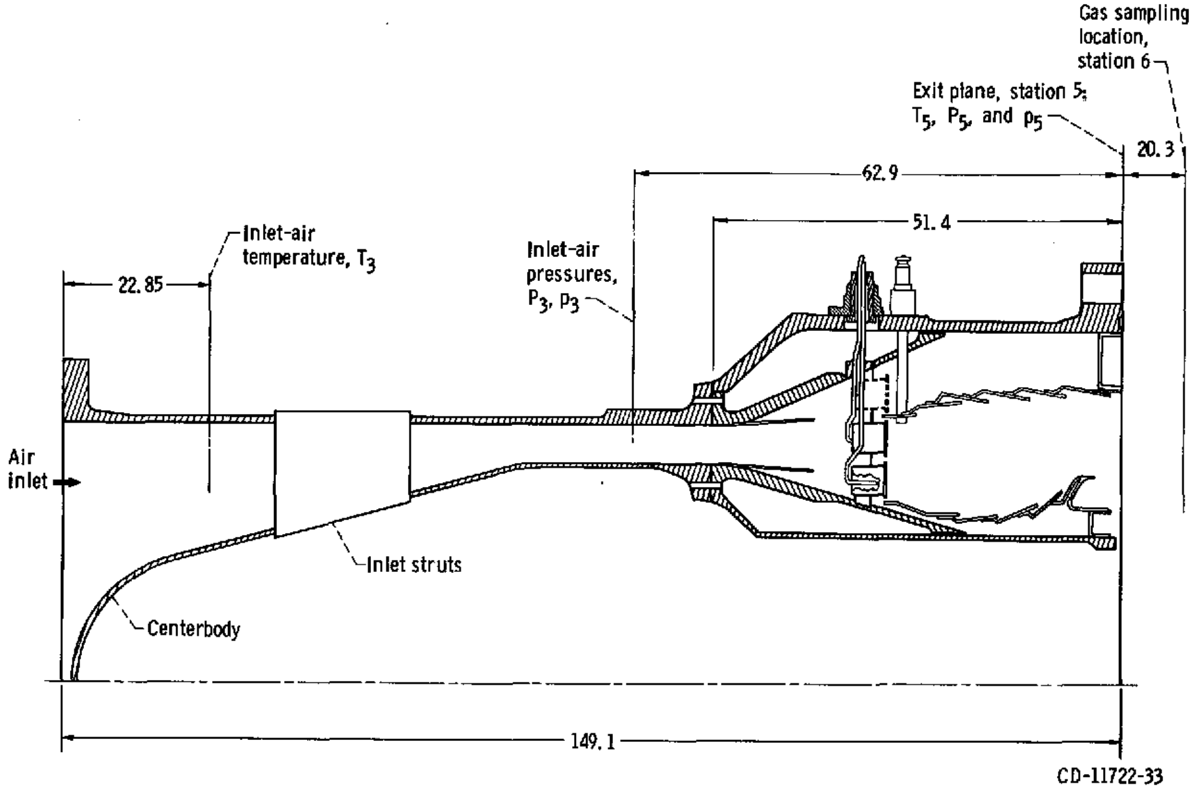
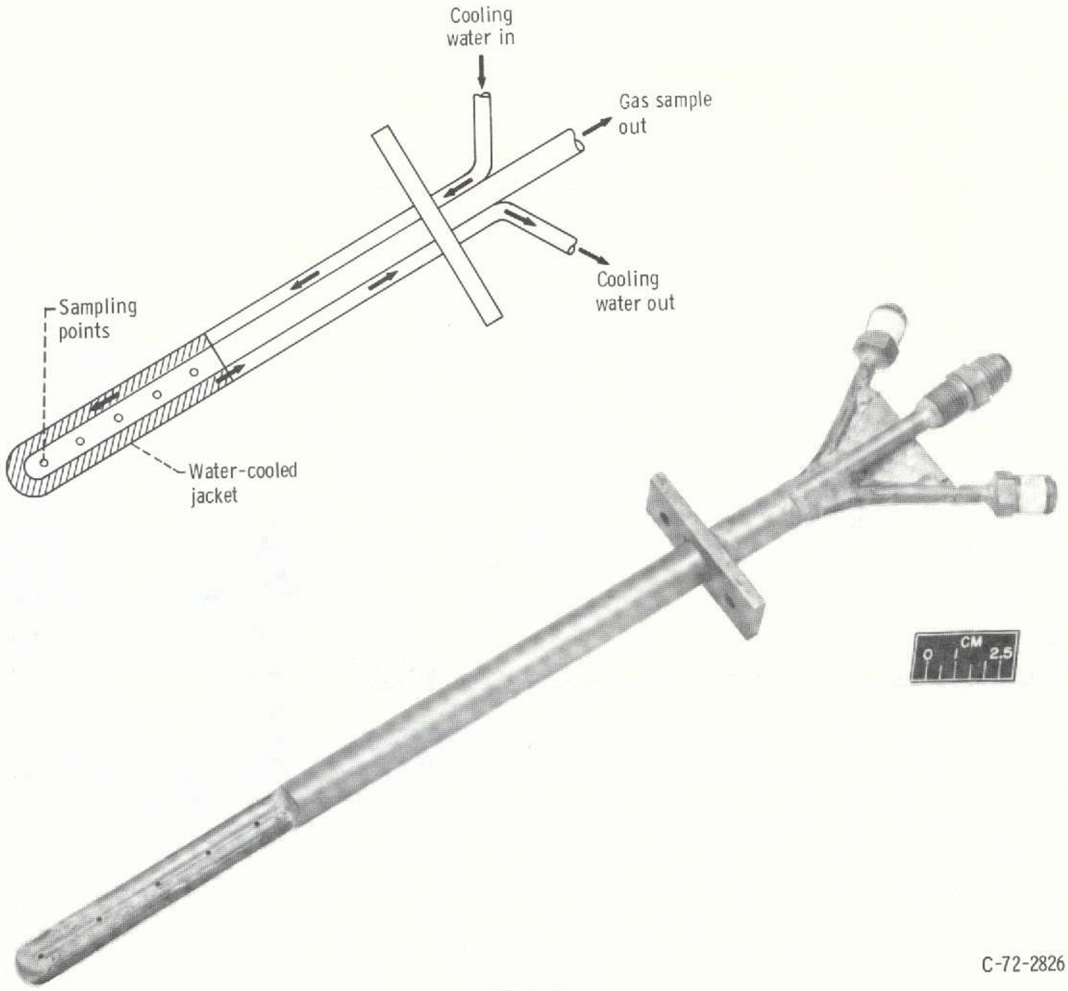
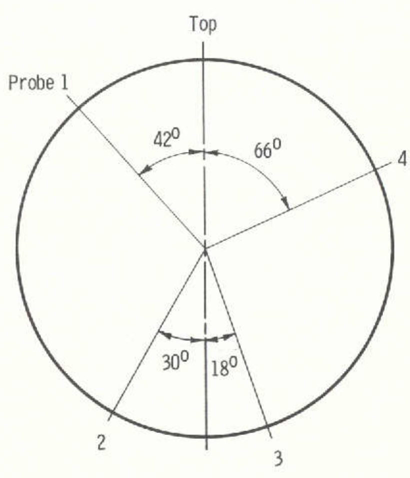


Figure 5. - Combustor housing, test section, and axial locations of instrumentation. (Dimensions are in centimeters.)



(a) Probe.



(b) Fixed probe positions.

Figure 6. - Gas sampling probe and positions in combustor.

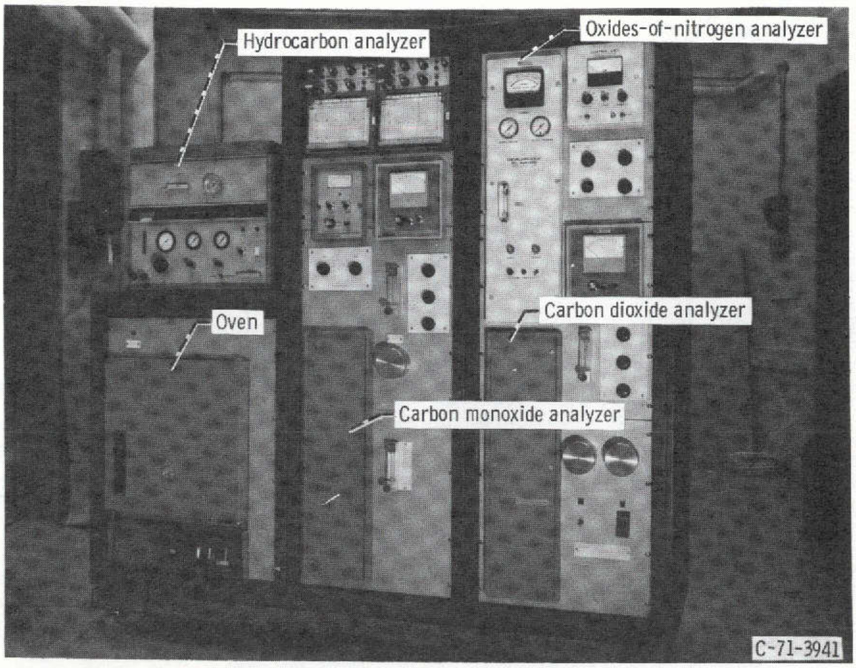


Figure 7. - Gas sampling instrument console.

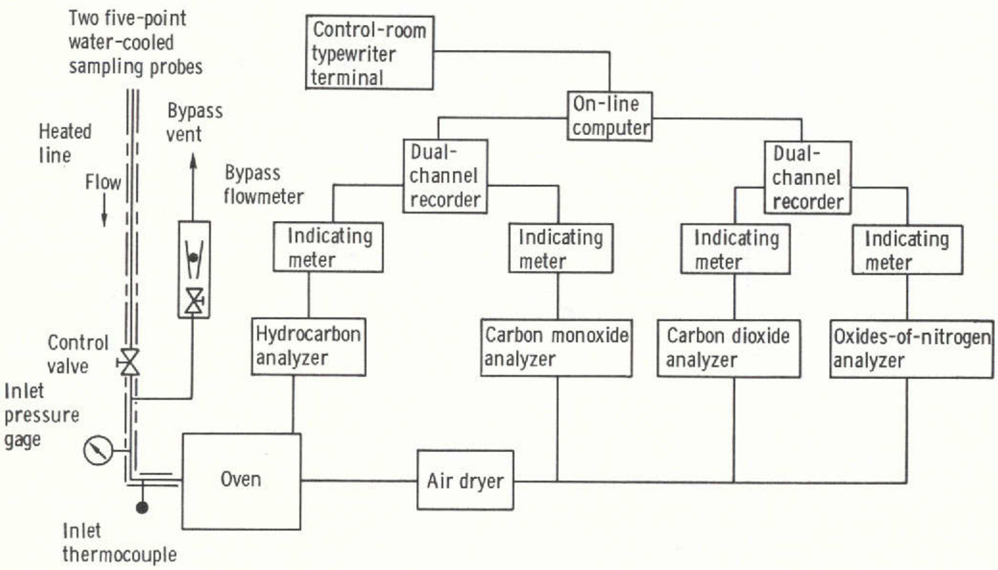
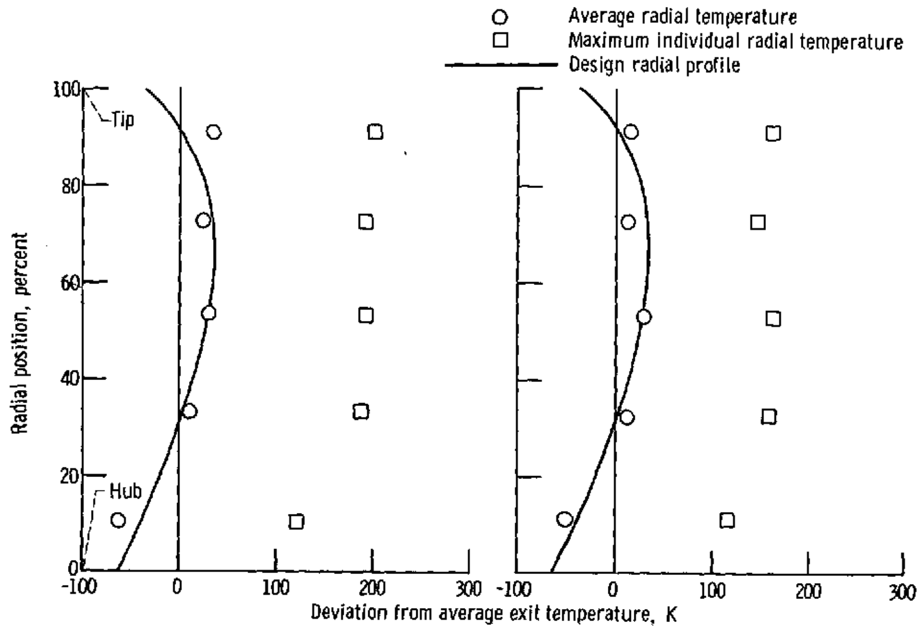


Figure 8. - Schematic diagram of gas analysis system.



(a) Simulated cruise condition; inlet-air temperature, 733 K; average exit temperature, 1488 K; reference velocity, 31.4 meters per second.

(b) Simulated takeoff condition; inlet-air temperature, 860 K; average exit temperature, 1465 K; reference velocity, 33.3 meters per second.

Figure 9. - Typical radial exit temperature profile characteristics. Inlet total pressure, 62.0 newtons per square centimeter.

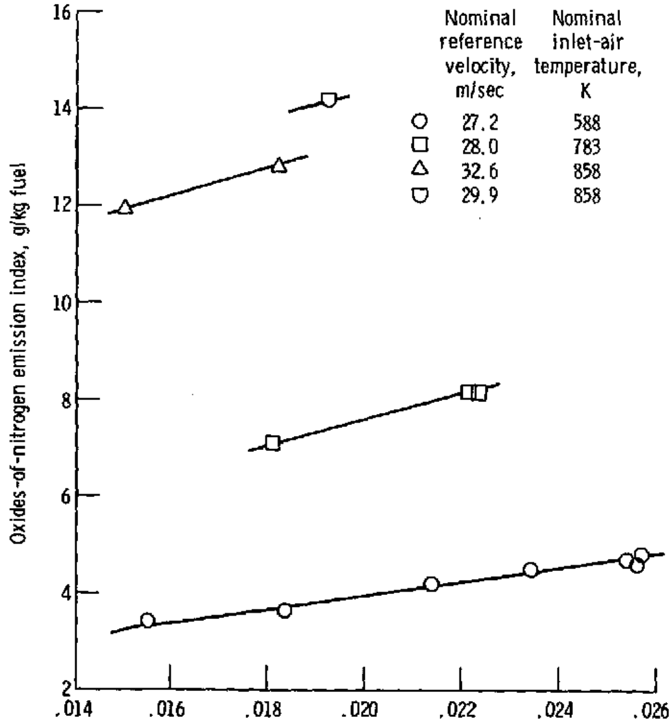


Figure 10. - Effect of fuel-air ratio on oxides of nitrogen at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.

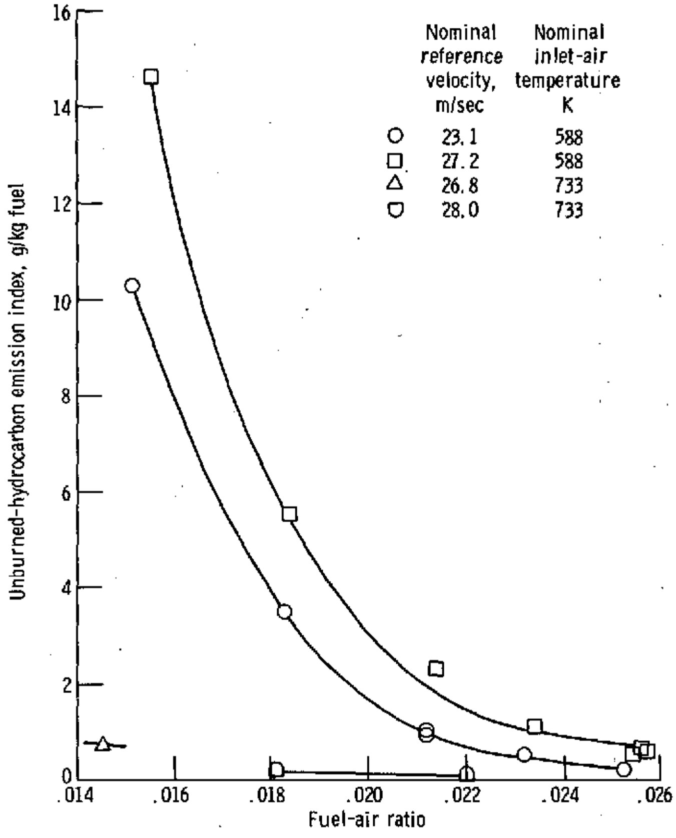


Figure 11. - Effect of fuel-air ratio on unburned-hydrocarbon emissions at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.

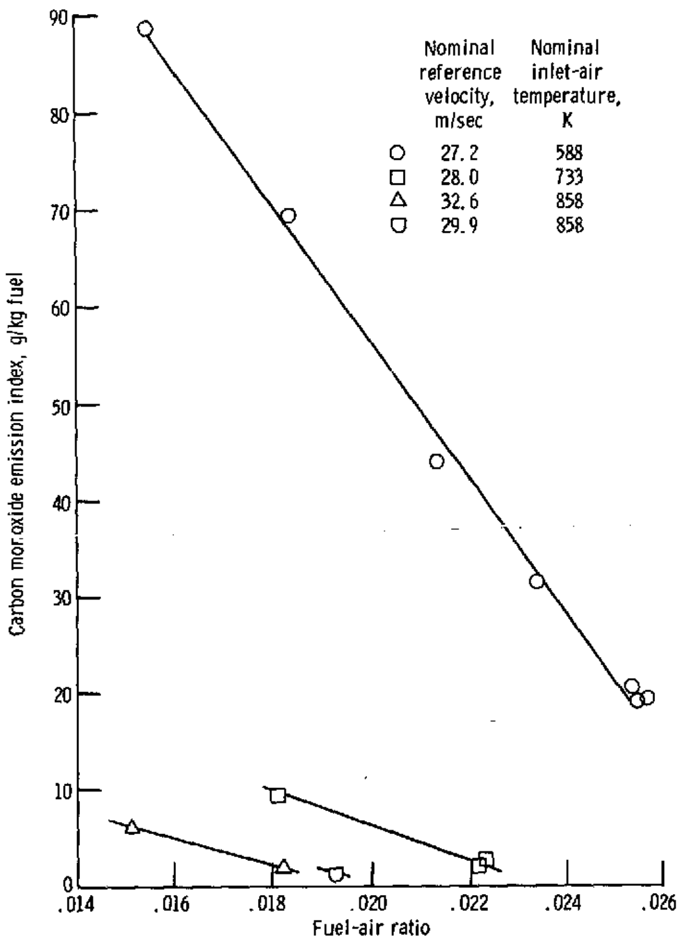


Figure 12. - Effect of fuel-air ratio on carbon monoxide emissions at various inlet-air temperatures and reference velocities. Nominal inlet total pressure, 62.0 newtons per square centimeter.

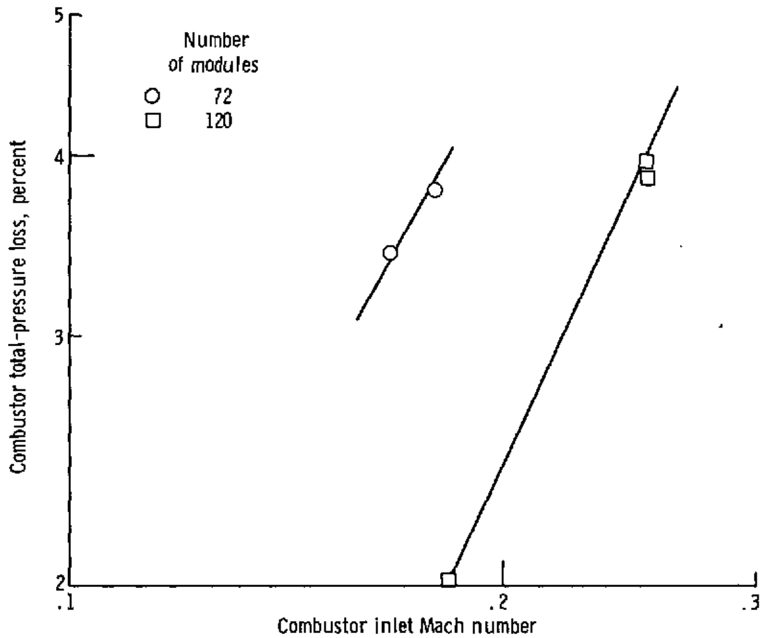
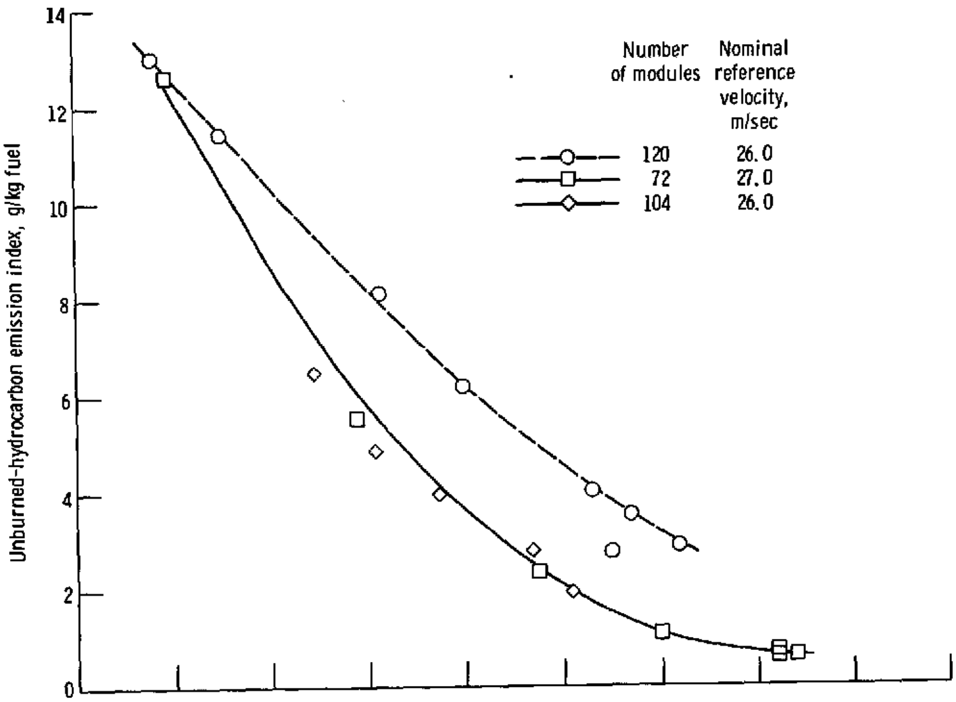
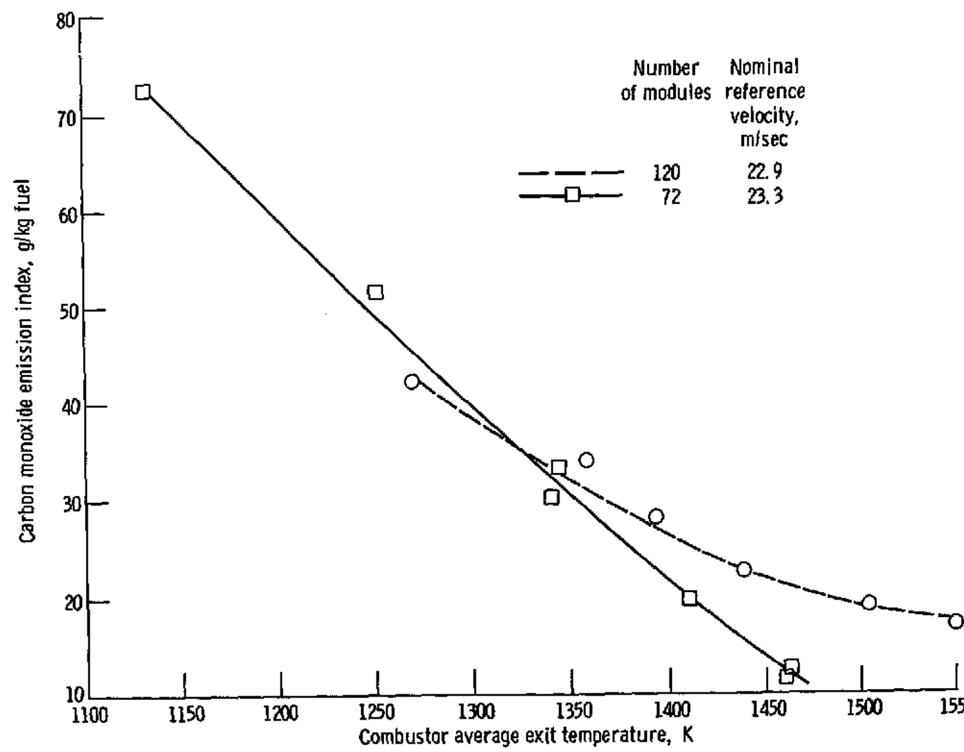


Figure 13. - Isothermal pressure loss at various inlet Mach numbers. Inlet-air temperature, 584 K; inlet total pressure, 62.5 newtons per square centimeter.

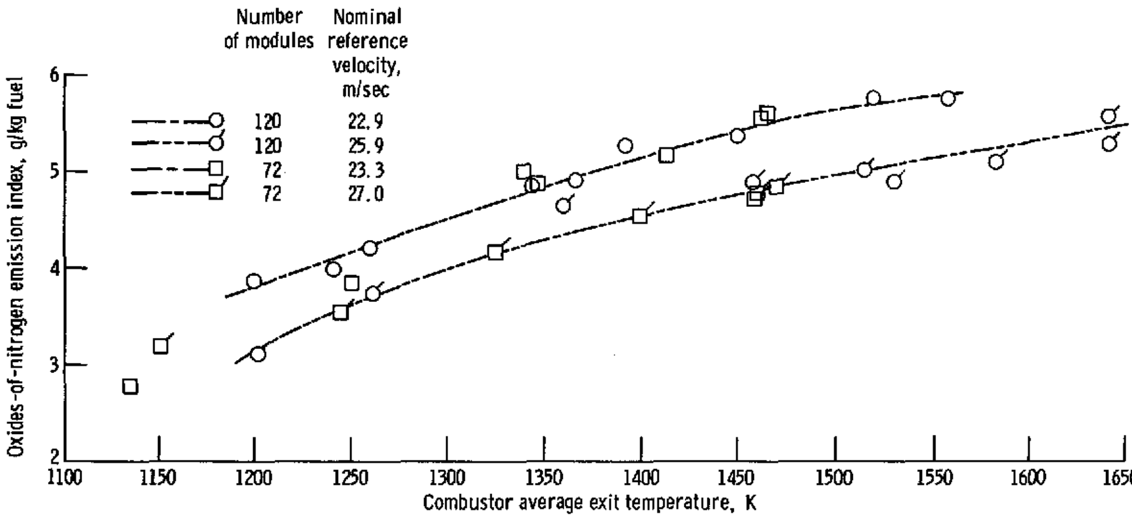


(a) Unburned hydrocarbons.



(b) Carbon monoxide.

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.



(c) Oxides of nitrogen.

Figure 14. - Concluded.

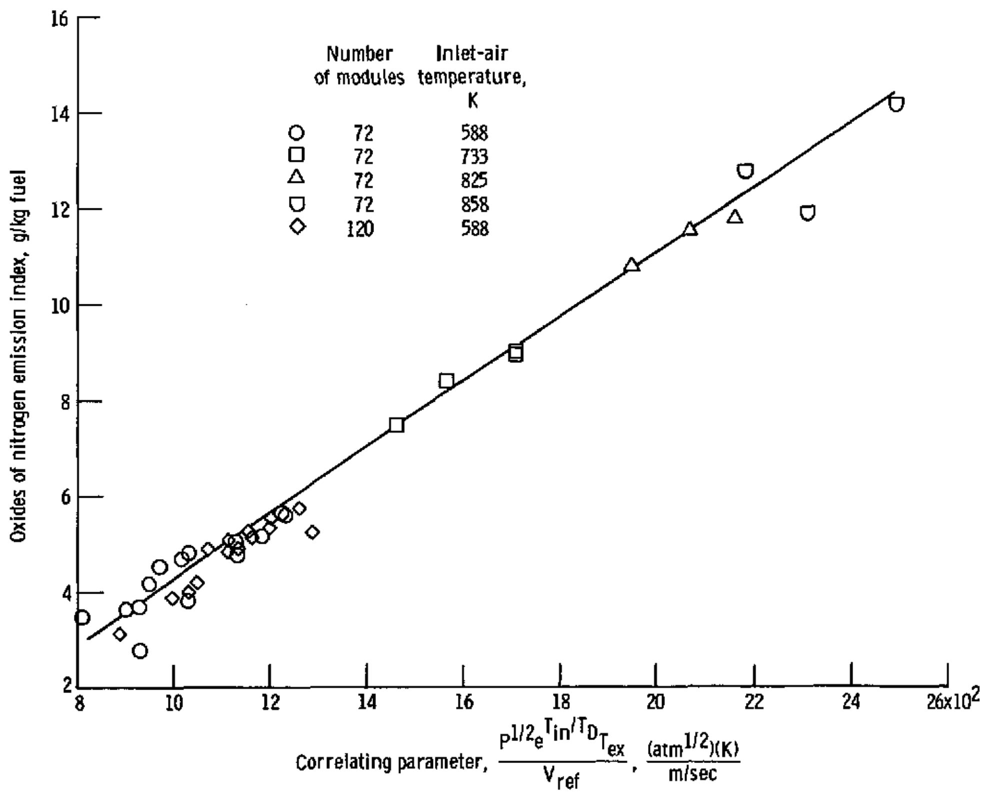


Figure 15. - Oxides-of-nitrogen correlation by parameter from reference 4.