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EXHAUST POLLUTANT EMISSIONS FROM SWIRL-CAN COMBUSTOR MODULE ARRAYS AT PARAMETRIC TEST CONDITIONS

Edward J. Mularz, Jerrold D. Wear, and Peter W. Verbulecz

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16. Abstract

Three improved designs of swirl-can combustor modules were tested using seven-module arrays in a combustor. The combustor was operated over a pressure range of 69 to 207 N/cm^2 (100 to 300 psia), a fuel-air ratio range of 0.015 to 0.046, at a constant inlet air temperature of 733 K (860° F), and at reference velocities of 23.9 and 30.6 m/sec (76 and 100 ft/sec). The three designs performed with high combustion efficiency at all conditions tested and exhibited oxides of nitrogen emissions substantially lower than that of conventional gas turbine combustors. However, a correlating parameter used to extrapolate oxides of nitrogen emissions to full power or takeoff conditions for large commercial turbofan engines predicts oxides of nitrogen emissions somewhat higher than those specified in the 1979 Environmental Protection Agency emissions standards.

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SUMMARY

Combustor tests were conducted to evaluate three improved designs of swirl-can combustor modules. The objective of the program was to demonstrate low levels of exhaust pollutants while maintaining high combustion efficiency at combustor operating conditions which exist in today's modern gas turbine engines. The combustor, composed of a seven-module array of swirl-cans, was operated over a range of test conditions using ASTM Jet-A fuel and the gaseous pollutants were sampled at the combustor exhaust for each of the swirl-can module array designs. The combustor was operated over a pressure range of 69 to 207 newtons per square centimeters (100 to 300 psia), a fuel-air ratio range of 0.015 to 0.046, at a constant inlet air temperature of 733 K (860° F), and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec). The emissions from the three combustor module arrays indicates that a sizable reduction in oxides of nitrogen over conventional combustors is possible while maintaining high combustion efficiency. The lowest value of oxides of nitrogen emission index at a NASA standard engine takeoff condition was calculated to be 21.2 using a correlating parameter to extrapolate the data. This combustor model had a combustion efficiency greater than 99 percent for practically all conditions tested. However, the oxides of nitrogen emissions from this swirl-can combustor model are greater than 13 which is estimated to be the maximum allowable value at full power takeoff to achieve the 1979 EPA standards for large turbofan engines.

INTRODUCTION

Combustor tests were conducted to evaluate three improved design swirl-can combustor modules in terms of minimum levels of exhaust pollutants and high combustion efficiency.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas turbine engines. Two general areas of concern have been expressed: urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons (HC) and carbon monoxide (CO) during idle and taxi, and oxides of nitrogen (NO_x) and smoke during takeoff and landing. Oxides of nitrogen are also considered to be the most predominant gaseous emission products formed during altitude cruise of aircraft. Improving gas turbine combustor designs to make substantial reductions in oxides of nitrogen will be an extremely difficult task (ref. 1). Oxides of nitrogen are formed during any combustion process involving air. The amount formed is reaction rate controlled and is a function of flame temperature, dwell time of the combustion gases at high temperatures, concentrations of nitrogen and oxygen present, and the combustor pressure. Flame temperatures increase as the combustor inlet temperature increases and as the primary zone fuel-air ratio approached stoichiometric values. Dwell time is affected by combustor primary zone length and reference velocity. Trends in combustor operating conditions indicate a steady increase in inlet temperature and pressure due to increasing compressor pressure ratios (ref. 2).

Lewis Research Center is engaged in research directed toward development of combustors with substantially reduced levels of oxides of nitrogen emissions. Combustors consisting of arrays of combustor modules constitute one phase of this research. Past studies of swirl-can modular combustors (refs. 3 to 9) indicated that this combustor type offers several inherent advantages for reducing oxides of nitrogen. These advantages include:

(1) Short combustor lengths with accompanying short recirculation zones are realized for burning and mixing. Thus dwell time is reduced.

(2) Quick mixing of burning gases and diluent air occurs inasmuch as swirl-can combustors pass nearly all of the air flow through the primary combustion zone. As a result, large interfacial mixing areas exist between combustion gases and airflow around the swirl-cans.

(3) A more uniform mixture of fuel and air is produced by the large number of fuel entry points, thereby reducing localized intense burning.

Most of the previous work was limited to pressures far below the levels which combustors encounter in most subsonic jet aircraft gas turbine engines. A number of swirl-can module designs were evaluated in reference 3 over wide ranges of pressure and fuel-air ratio. However, these tests were performed using a single swirl-can module and these results cannot be assumed to be representative of a large array of these modules since the modules interact with one another when clustered in an array. For this reason the present investigation was conducted, using a seven-module array of swirl-cans arranged in a hexagonal pattern in a circular duct. This arrangement still does not fully simulate an annular combustor since no air diffusion was present ahead of the array as would exist in an actual engine. However, it does give the effect of multiple module burning with a closely packed array of modules typical of the arrangement of an annular combustor.

The tests were performed using ASTM Jet-A fuel and operating conditions were: a combustor pressure range of 69 to 207 newtons per square centimeter (100 to 300 psia), a fuel-air ratio range of 0.015 to 0.046, a constant inlet air temperature of 733 K (860° F), and reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

APPARATUS AND PROCEDURE

Test Facility

The tests in this report were conducted in a closed-duct test facility in the Engine Research Building of the Lewis Research Center. This facility, shown in figure 1, has the capability for supplying air to a combustor at flow rates up to 15.9 kilograms per second (35 lb/sec) and at pressures up to 310 newtons per square centimeter (450 psia). This high pressure air may be indirectly heated to 733 K (860° F) in a counterflow U-tube heat exchanger using natural gas fired J-47 combustor cans as a heat source. In these tests, the hot exhaust gases from the combustor were cooled in a water-spray section before they entered the facility exhaust ducting. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

Test Combustor

The test combustor was designed for an array of seven swirl-can modules and is shown in figure 2. A swirl-can module was located in the center with six modules equally spaced around it. This enabled the modules to be closely packed together for high geometric blockage across the combustor. A fuel tube for each swirl-can was centered in each module and the fuel tubes and the swirl-can array were all attached to a separate flange for ease of removal and assembly. The combustor liner inside wall was hexagonal in shape at the downstream end of the swirl-can array and then became circular with an inside diameter of 20.7 centimeters (8.15 in.). The liner was 21.3 centimeters (8.5 in.) in length and was Rockide coated along the inside wall. The liner was provided with neither film nor convective air cooling, thus all of the combustor inlet air passed through the swirl-can array. A 20-joule ignitor plug was inserted through a hole in the liner adjacent to one of the swirl-can modules.

Swirl-Can Array Designs

A typical swirl-can module is shown schematically in figure 3. Each module consists of three components; a carburetor, an inner swirler, and a flame stabilizer. In operation, the module performs several functions. Each module mixes fuel with air, swirls the mixture, stabilizes combustion in its wake, and provides large interfacial mixing areas between the bypass air around the module and combustion gases in its wake.

Tests were performed on seven-module arrays of three swirl-can designs which are shown in figure 4. A description of the swirl-can design for each combustor model is found in table I. The three models are all characterized by fairly high blockage.

Combustor model A shown in figure 4(a) incorporated concentric swirlers for each module, with the air swirling in opposite directions from the two swirlers (counterswirl). Triangular pieces of 6.3 percent open area perforated plate were attached between the models to increase the blockage. The fuel was injected downstream of the swirlers by splashing against a 1.9-centimeter- (0.75-in. -) diameter disk attached to the inner swirler hub.

Combustor models B and C used only a single swirler per module with fuel splashing against the swirler hub, enabling a fuel and air mixture to emit from the inner swirler. A perforated plate provided the necessary blockage for model B (fig. 4(b)) with a hexagonal flat plate around each module providing flame stability. Combustor model C (fig. 4(c)) used a large hexagonal flat plate for each module to provide both blockage and flame stability. The small holes around the hexagonal flat plates of models B and C were for cooling purposes.

Exhaust Emissions

Concentrations of total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were determined with an online sampling system.

Gas sample probe. - The hot combustion gases exhausted into an instrumentation section in which were located two fixed water cooled gas sampling probes. The probes were located approximately 25 centimeters (9.9 in.) downstream of the flame stabilizers of the swirl-can array. This distance was fixed by the design of the instrumentation section and does not imply an optimum location for the combustor exhaust station. A photograph and a sketch of a gas sample probe is shown in figure 5. The probes had both water and steam cooling to ensure adequate quenching of the gas sample. Samples were obtained at three different radial positions for each probe at centers of equal areas. The hole size of these sample parts were 0.71 millimeter (0.028 in.) in diameter and the gas sample pressure inside the probe was kept below 38 newtons per square centimeter (55 psia) by venting excess sample gas when necessary. The gas sample temperature at the probe was also maintained between 394 to 616 K (250° to 650° F). These procedures were followed to ensure that the gas sample did not change in composition after it entered the probe. The gas samples from each probe were manifolded outside of the instrumentation housing to a common sample line for transmission to the gas analyzer system.

Gas analysis system. - A picture of the gas analysis instrumentation and a schematic of the system are shown in figures 6 and 7, respectively. The sample collected by the probes was transported through 0.63-centimeter (1/4-in.) stainless-steel line to the analytical instruments. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated. Sample line pressure was nominally maintained at 24 newtons per square centimeter (20 psig) at the instruments in order to supply sufficient pressure to operate the instruments. Excess sample was vented at the instruments.

The exhaust gas analysis system is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. The hydrocarbon content of the exhaust gas is determined by a Beckman Instruments Model 402 Hydrocarbon Analyzer. This instrument is of the flame ionization detector type.

The concentration of the oxides of nitrogen is determined by a Thermo Electron Corporation Model 10A Chemiluminescent Analyzer. The instrument includes a thermal reactor to reduce nitrogen dioxide to nitric oxide and was operated at 973 K (1290° F).

Both carbon monoxide (CO) and carbon dioxide (CO_2) analyzers are of the nondispersive infrared (NDIR) type (Beckman Instruments Model 315B). The CO analyzer has four ranges: 0 to 100 ppm, 0 to 1000 ppm, 0 to 1 percent, and 0 to 10 percent. These ranges of sensitivity are accomplished by using stacked cells of 0.64 centimeter (0.25 in.) and 34 centimeters (13.5 in.) in length. The carbon dioxide analyzer has two ranges: 0 to 5 percent and 0 to 15 percent, with a sample cell length of 0.32 centimeter (0.125 in.).

Analytical procedure. - All analyzers were checked for zero and span prior to the test. Solenoid switching within the console allows rapid selection of zero, span, or sample modes. Therefore, it was possible to perform frequent checks to ensure calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included both inlet-air humidity and water vapor from combustion. The equations used were obtained from reference 10.

The emission levels of all the constituents were converted to an emission index (EI) parameter. The EI was computed from the measured quantities as proposed in reference 10; this technique measures the fuel-air ratio from the total carbon atom content of the gas sample. An alternate procedure is to use a simplified equation and the metered fuel-air ratio when this is accurately known. When this latter scheme is used, the EI for any constituent X is given by

$$EI_X = \frac{M_x}{M_E} \frac{1 + f}{f} (X) \, 10^{-3}$$

where

EI_X emission

M_x molecular weight of X

M_E average molecular weight of exhaust gas

f metered fuel-air ratio, g of fuel/g of wet air

(X) measured concentration of X, ppm of exhaust gas

Both procedures yield identical results when the sample validity is good.

Test Conditions

The swirl-can arrays were each tested at the nominal test conditions shown in table II. The reference velocity was determined from a reference area taken as the cross-sectional area inside the combustor at the flame stabilizer axial position of the swirl-can modules. Not all of the models were tested over the complete spans of pressure and fuel-air ratio of the table, due to facility or gas sampling system limitations. These test conditions were selected to represent the full power operating condition of various gas turbine engines. With emissions data at these test conditions, emissions at actual engine operating conditions may be extrapolated using appropriate correlating parameters.

Units

The U.S. Customary system of units was used for primary measurements and calculations. Conversion of SI units (System International d'Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

RESULTS AND DISCUSSION

Results are presented next for the three swirl-can arrays. Pollutant emissions and combustion efficiency over ranges of pressure and fuel-air ratio and at two reference velocities are presented and discussed. The gas sample validity is also discussed. Finally, the NO_x emissions results are compared with the NO_x emissions of current engines with the use of a correlating parameter.

Combustor Performance

Pollutant emissions. - Combustor exhaust emission indices for swirl-can combustor models A, B, and C are shown in figures 8 to 10. Data are presented over a range of combustor pressures for a constant inlet-air temperature of 733 K (860° F), a fuel-air ratio of 0.02, and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec). In figures 8(c), 9(c), and 10(c) data are also presented over a range of fuel-air ratios for a constant inlet-air temperature of 733 K (860° F), a normalized combustor pressure δ of 13.6 atmospheres, and at a reference velocity of either 23.9 or 30.6 meters per second (76 or 100 ft/sec). The normalized combustor pressure δ is defined as the combustor pressure divided by the standard sea-level pressure of 10.13 newtons per square centimeter (14.696 psia). As expected, the NO_x emissions decreased with an increase in the reference velocity whereas the unburned hydrocarbons HC and carbon monoxide CO emissions increased with increased reference velocity. In addition, chemical kinetic theory predicts that NO_x emissions ought to increase with increasing pressure according to the following relation (ref. 11):

$$NO_x \sim P^{0.5}$$

The data presented here show a variation in the exponent on pressure from 0.13 to 0.59. However, other factors such as changing fuel differential pressure and swirl-can recirculation zone changes with pressure could explain the differences between the data and theory. Comparison of figures 8(a), 9(a), and 10(a) shows that combustor model B gave the lowest value of NO_x emission index whereas combustor model C gave the highest value for a fuel-air ratio of 0.02.

Combustion efficiency. - Unburned hydrocarbons and carbon monoxide emissions represent inefficient combustion. Therefore, combustion efficiencies may be calculated based on pollutant emissions by realizing that a HC emission index of 10 represents a 1 percent combustion inefficiency (assuming all the hydrocarbon emissions are of the form CH_2), and a CO emission index of 42.5 also represents 1 percent combustion inefficiency. Thus the combustion efficiency η_b is calculated using the following equation:

$$\eta_b = 100 - \frac{HC_{EI}}{10} - \frac{CO_{EI}}{42.5} \quad \text{percent}$$

The combustion efficiencies for swirl-can cluster models A, B, and C are shown in figure 11(a) based on the emissions data of figures 8(b), 9(b), and 10(b). All three models had combustion efficiencies close to 100 percent for all conditions tested. Therefore, the NO_x emissions were achieved with combustion efficiencies comparable to the levels required in an engine. The combustion efficiencies generally increased with increasing pressure. Figure 11(b) which is based on data from figures 8(c), 9(c), and 10(c) shows that as the fuel-air ratio is increased, the combustion efficiency first increased and then began to fall off. This decrease in combustion efficiency at the higher fuel-air ratios is the result of an increase in CO emissions. As more and more fuel is introduced into the same combustor volume, eventually the fuel cannot find sufficient oxygen to complete the combustion process in the given combustor length, thus CO emissions increase. If the combustor were lengthened the CO emissions would probably be proportionally lower. The combustion efficiency of model B which gave the lowest NO_x emissions is lower than that of models A and C; however, it is still greater than 99 percent at practically all conditions tested. This lower combustion efficiency is attributed to a lower primary zone equivalence ratio than that of the other two models. Almost all of the air that bypassed the swirl-can modules was forced through narrow annular slots between the perforated plate and each module can. The air then passed around the hexagonal flame stabilizers and was entrained into the module wakes to a greater degree than with the other two models. This leaner burning in the primary zone would also explain why the maximum combustion efficiency of model B occurred at a much higher fuel-air ratio than the other two models.

Gas sample validity. - Because two fixed gas sampling probes were used to measure the gaseous pollutants in the exhaust of the combustor, some assurance is needed that the gas samples are representative of the entire combustor exhaust. Comparing the calculated fuel-air ratio from gas sampling with the actual metered fuel-air ratio is one means of determining how closely the gas sample represents the average combustor exhaust. The fuel-air ratio is calculated from the gas sample by a carbon atom count using the emission levels of unburned hydrocarbons, carbon monoxide, and carbon dioxide. The ratio of the gas sampling fuel-air ratio to the metered fuel-air ratio (FARR) for all the gas analysis data above is shown in figure 12. Ideally, all the data should have FARR values of 1.0. The spread of FARR values from 0.8 to 1.0 for these data is considered as acceptable accuracy for the purposes of this investigation.

Comparison of NO_x Emissions With Emissions From Current Engines

In order to relate the NO_x emissions of the three swirl-can combustor models with emissions from current gas turbine engines, the emissions of the swirl-can models must be compared at the operating conditions of the various combustors of these gas turbine engines. Since the full power operating condition or takeoff condition is different for each gas turbine combustor, and since data could not be obtained at exactly each combustor's full power operating condition, a correlating parameter has been formulated and is used to extrapolate the data. Previous correlating parameters have been proposed (refs. 5, 12, and 13). The correlating parameter used for this report is

$$\mathrm{C.P.} = \frac{\delta^{0.5} e^{T_{in}/T_d}}{V_{ref}} \left(\frac{T_{ex} - T_{in}}{T_d}\right)^{1.5}$$

where

δ combustor inlet pressure normalized to standard sea-level pressure of 10.13 N/cm^2 (14.696 psia)

T_{in} combustor inlet air temperature, K

T_d constant normalizing factor taken to be 288 K

T_{ex} combustor exhaust gas temperature, K

V_{ref} combustor reference velocity, m/sec

This correlating parameter has the same functional form for inlet pressure, inlet air temperature, and reference velocity as the correlating parameter of reference 5. The combustor temperature rise term

$$\left(\frac{T_{ex} - T_{in}}{T_d}\right)^{1.5}$$

is similar to the correlating parameter of reference 13 which used instead fuel-air ratio to the 1.5 power. The exponent on the normalized pressure was held constant at 0.5 in spite of the variation in this exponent indicated in the NO_x emission data. With models A and C the exponent on normalized pressure was determined to be less than 0.5; therefore, the use of this correlating parameter is more pessimistic than if the experimentally determined pressure exponent were used.

The NO_x exhaust emissions data from figures 8 to 10 for the three swirl-can combustor models are presented as functions of the previous correlating parameter in figure 13. A linear curvefit of the data for each model has been drawn and extrapolated to a correlating parameter value of 17.7. The NO_x data follow the linear curvefits as well as expected considering the fact that gas sampling was confined to two locations of the combustor exhaust. Model B, in fact, shows very good NO_x emission linearity with the correlating parameter over a wide range.

These linear curvefits of the NO_x exhaust emissions as a function of correlating parameter are also shown in figure 14 for each model with data points removed for clarity. As mentioned, these lines were extrapolated to a correlating parameter value of 17.7 which represents the full power condition of the computed NASA standard engine model. This engine, whose characteristics are shown in table III, is assumed to be typical of an advanced CTOL engine for use as a power plant for the large commercial jet transports. Comparing the three swirl-can combustors at the NASA standard engine condition, models A and B are quite close to one another with NO_x emission indices of 21.2 and 23.2. Model C is substantially higher with a NO_x emission index of 30.8.

Also shown in figure 14 are the measured NO_x emissions from four current gas turbine engines plotted at correlating parameter values which correspond to the full power takeoff condition of these engines. The JT8D and JT3D are much lower pressure ratio engines than the JT9D and CF6-50 engines and therefore have correspondingly lower correlating parameter values. The high pressure ratio engines (JT9D and CF6-50) exhibit substantially higher NO_x emission indices than the three swirl-can combustor models, particularly models A and B. There is also a considerable improvement in NO_x emissions between the swirl-can combustors and the lower pressure-ratio JT8D and JT3D engines.

The Environmental Protection Agency standards for class T_2 engines (ref. 14) will require a NO_x emission index value at the 100 percent full power takeoff condition to be no larger than about 13 (ref. 15). However, these swirl-can combustor models have NO_x emission indices higher than 13 at correlating parameter values representing the JT9D, the CF6-50, or the NASA standard engine takeoff conditions. Thus the three swirl-can combustor models exhibited NO_x emissions substantially below those of current large engines but not sufficiently low to meet the 1979 EPA requirements.

CONCLUDING REMARKS

A further reduction in oxides of nitrogen emissions is possible by using the previously described swirl-can designs in the design of the main stage of a two-stage combustor. This might enable the swirl-can modules to be run only during high power operation such as takeoff and cruise, at operating conditions which would result in lower values of the correlating parameter and therefore lower NO_x. This could be accomplished by operating the main stage combustor with a higher reference velocity or with a lower fuel-air ratio. For example, if swirl-can combustor model B were used as the main stage of a staged combustor for the JT9D engine, then from figure 14 a NO_x emission index of 13 could be realized for the main stage at the takeoff operating condition by reducing its correlating parameter from 11.7 to 10. This could be achieved by increasing the main stage reference velocity by 17 percent. The change in combustion efficiency would be slight based on data of this model. However, this type of combustor concept is much more complex than conventional combustors and would require substantial development.

SUMMARY OF RESULTS

A program was conducted to evaluate three swirl-can combustor module designs. The results of this program are the following:

1. The seven-module combustor arrays performed with high combustion efficiencies (>99 percent) at all conditions tested.

2. Using an oxides of nitrogen correlating parameter, the predicted emissions of NO_x for the three swirl-can combustor models when operating at the full power or takeoff condition of various current gas turbine engines was substantially lower than the current emissions from these engines. However, the NO_x emissions from the swirl-can combustor models are still higher than the maximum allowable level of 13 which is needed to achieve the 1979 EPA emissions standards for class T_2 engines.

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National Aeronautics and Space Administration,
and
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Cleveland, Ohio, January 31, 1975,
505-04.

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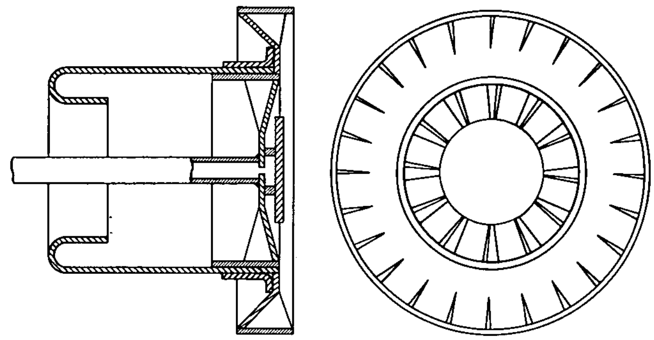
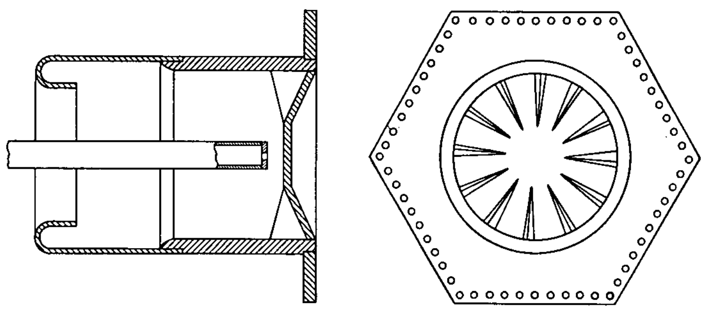
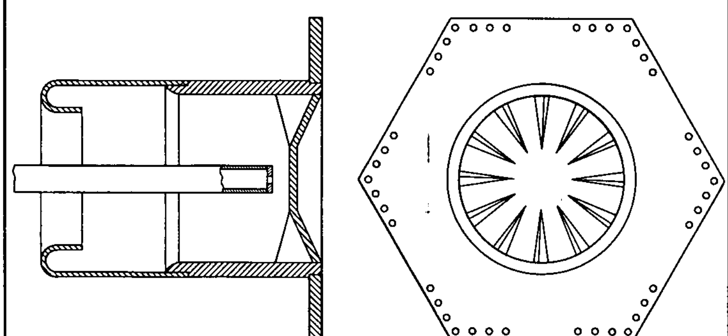
TABLE I. - DESCRIPTION OF COMPONENTS OF SWIRL

Model	Sketch of one swirl-can module Cross section — View looking upstream	Percent blockage inside hexagonal liner of 286-cm^2 (44.27-$in.^2$) cross-sectional area
A		74.4
B		72.3
C		71.0

AN MODULES FOR COMBUSTOR MODELS INDICATED

Inner swirler description	Flame stabilizer description	Fuel injection description	Note
tamped swirler, 2 blades, 45° ngle at tips; wirler face flush ith flame stabi- izer; tip diame- er, 3.34 cm 1.31 in.); hub iameter, 1.90 cm 0.750 in.); open rea, 2.30 cm^2 0.357 in.^{2})	Stamped swirler, 24 blades, 45° angle at tips; swirler blades of opposite rotation from inner swirler; tip diameter, 5.79 cm (2.28 in.); hub diameter, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 in.^{2}); swirler shroud diameter, 5.94 cm (2.34 in.); perforated plate, 0.157-cm- (0.062-in.-) diameter holes 6.3 percent open, attached to shrouds of cans to provide additional blockage	Fuel tube attached to center of inner swirler hub; 0.13-cm- (0.05-in.-); diameter orifice through hub; fuel passes through orifice and splashed against 1.9-cm- (0.75-in.-) diameter disk mounted 0.15 cm (0.062 in.) downstream from inner swirler hub	Same as model 10 of ref. 3
tamped swirler, 2 blades, 45° an- le at tips; swirler ce flush with ame stabilizer; p diameter, 3.25 m (1.28 in.); hub iameter, 1.59 cm).625 in.); open rea, 2.36 cm^2).366 in.^{2})	Hexagon of side L = 3.11 cm (1.22 in.); sixty 0.11-cm- (0.042-in.-) diameter holes around plate; perforated plate, 0.157-cm-(0.062-in.-) diameter holes, 6.3 percent open located 0.63 cm (0.25 in.) upstream of hexagonal flame stabilizer to provide indicated blockage	Fuel tube centered in can; 0.13-cm- (0.05-in.-) diameter orifice at end of tube 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed against swirler hub and ejected through inner swirler	Same as model 2 of ref. 3 except in number of holes in hexagonal flame stabilizer
Stamped swirler, 2 blades, 45° ngle at tips; swirler face flush with flame stabi- izer; tip diame- er, 3.25 cm 1.28 in.); hub diameter, 1.59 cm 0.625 in.); open rea, 2.36 cm^2 0.366 in.^{2})	Hexagon of side L = 3.48 cm (1.37 in.); seven 0.11-cm- (0.042-in.-) diameter holes at each corner hexagon; full area, 31.0 cm^2 (4.88 in.^{2})	Fuel tube centered in can; 0.13-cm- (0.05-in.-) diameter orifice at end of tube 0.32 cm (0.125 in.) upstream of inner swirler; fuel sprayed against swirler hub and ejected through inner swirler	---------

TABLE II. - SEVEN-MODULE SWIRL-CAN COMBUSTOR OPERATING CONDITIONS

[Combustor inlet air temperature, 733 K (860° F).]

Combustor inlet pressure, N/cm^2 (psia)	69 - 207 (100 - 300)
Normalized combustor inlet pressure, δ	6.8 - 20.4
Reference velocity (A_{REF} = 285 cm^2 or 44.27 $in.^2$), m/sec (ft/sec)	23.9, 30.6 (76, 100)
Fuel-air ratio	0.015 - 0.046

TABLE III. - NASA STANDARD ENGINE

[At 100 percent power sea-level takeoff.]

Thrust, N (lb)	222 000 (50 000)
Pressure ratio	30 to 1
Combustor inlet pressure, N/cm^2 (psia)	303 (440)
Combustor inlet temperature, K (°F)	826 (1028)
Combustor exhaust temperature, K (°F)	1644 (2500)
Fuel-air ratio	0.0249 (Jet-A Fuel)
Reference velocity (typical), m/sec (ft/sec)	25.9 (85)

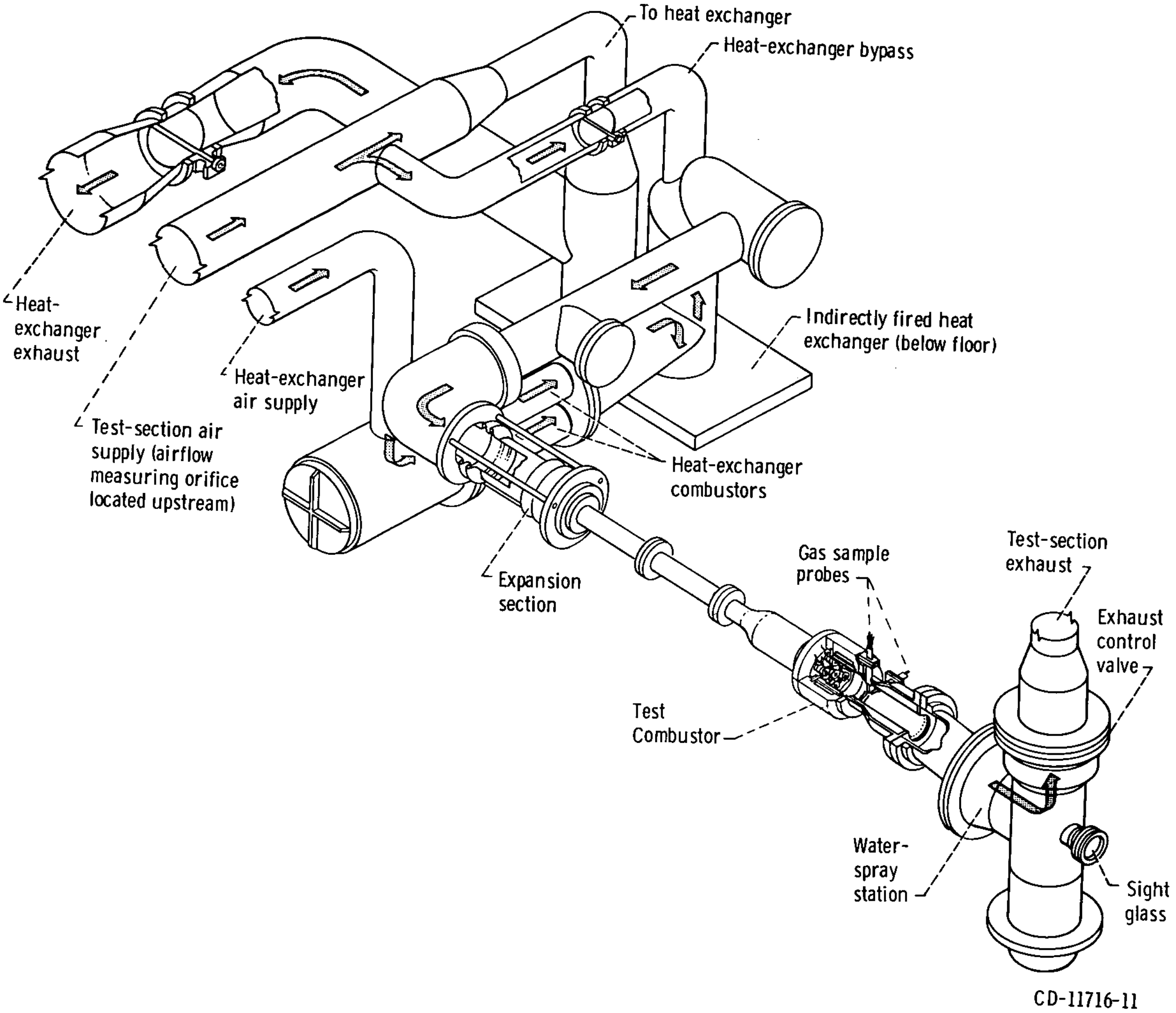


Figure 1. - Test facility.

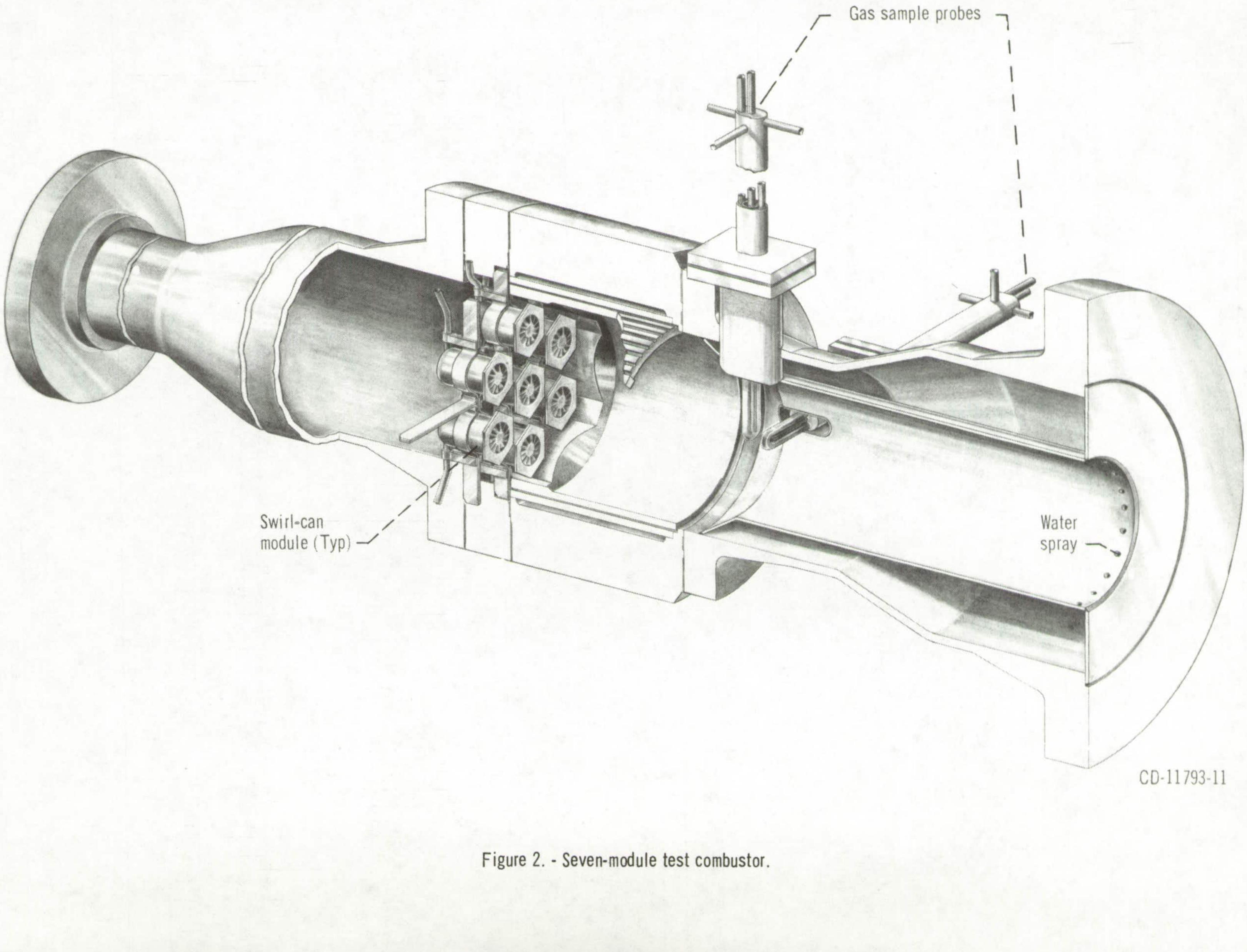


Figure 2. - Seven-module test combustor.

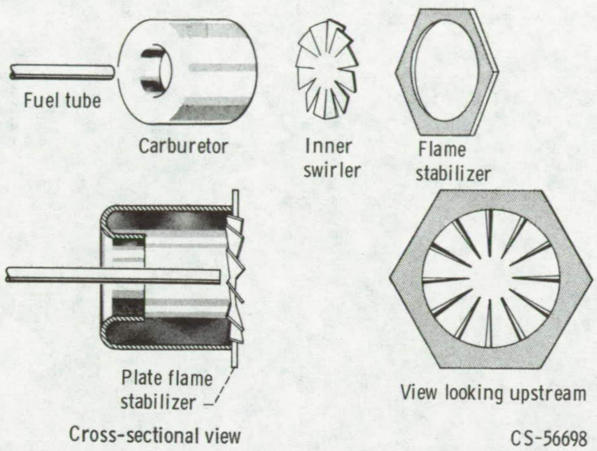
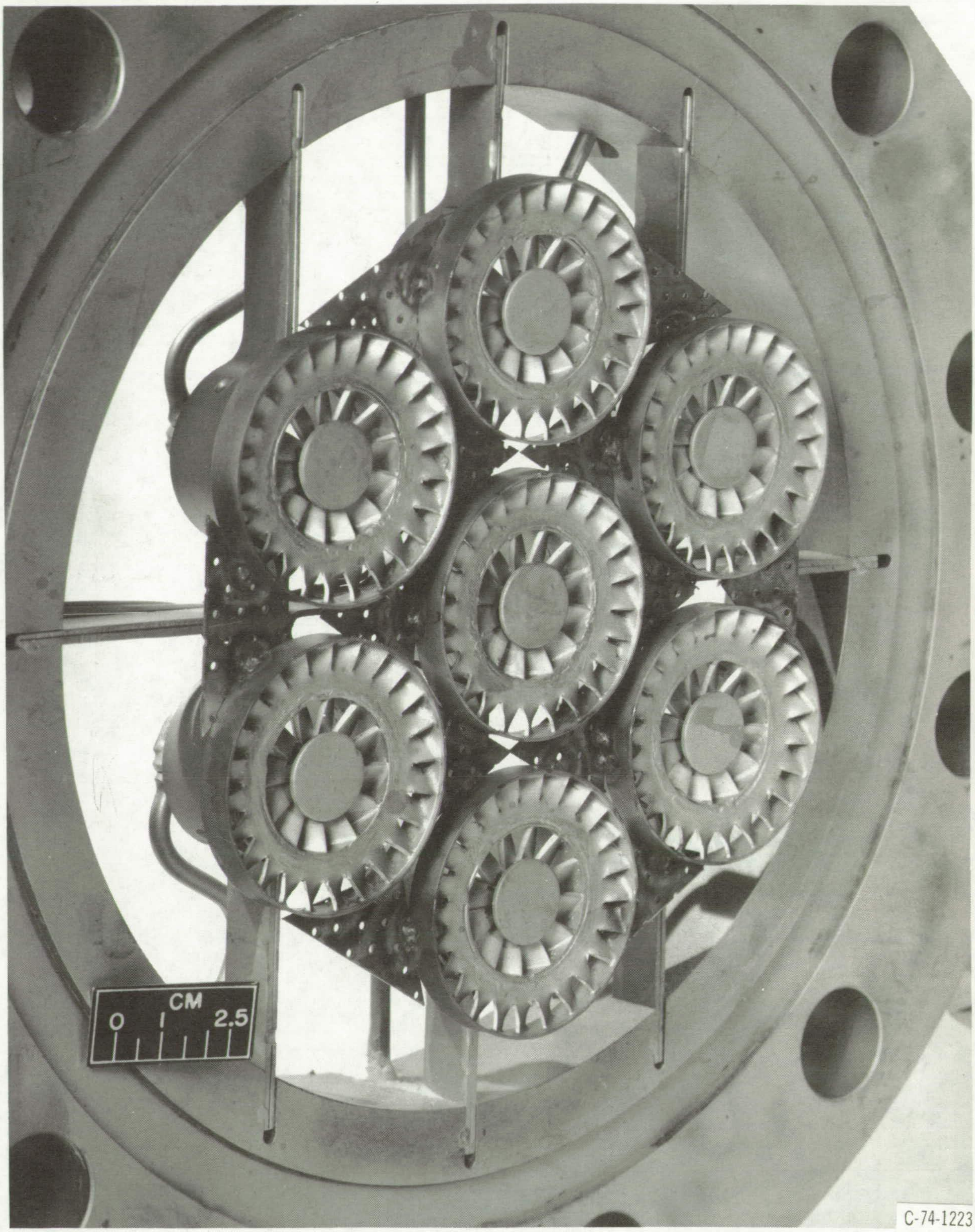
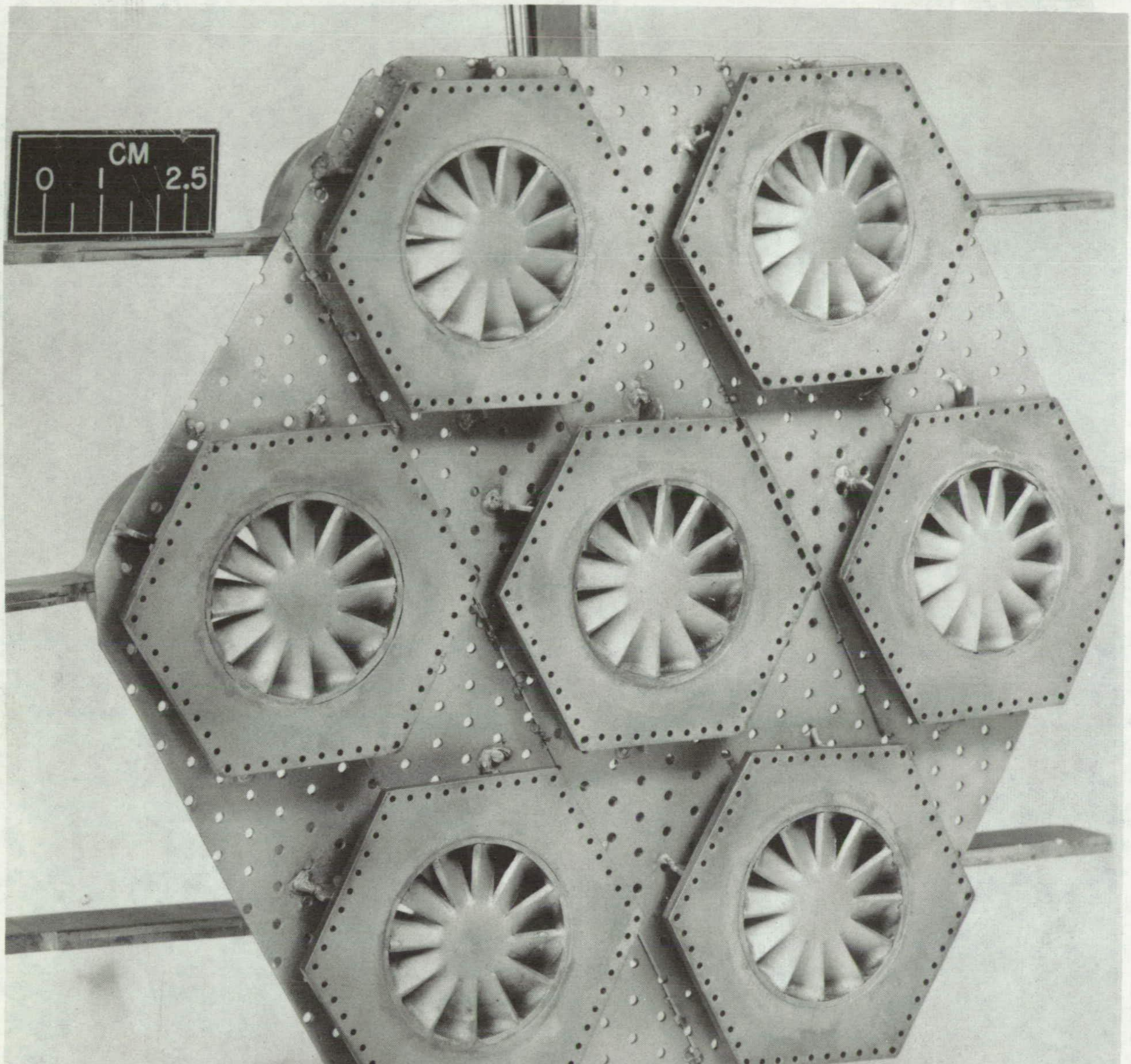


Figure 3. - Typical swirl-can combustor module details.



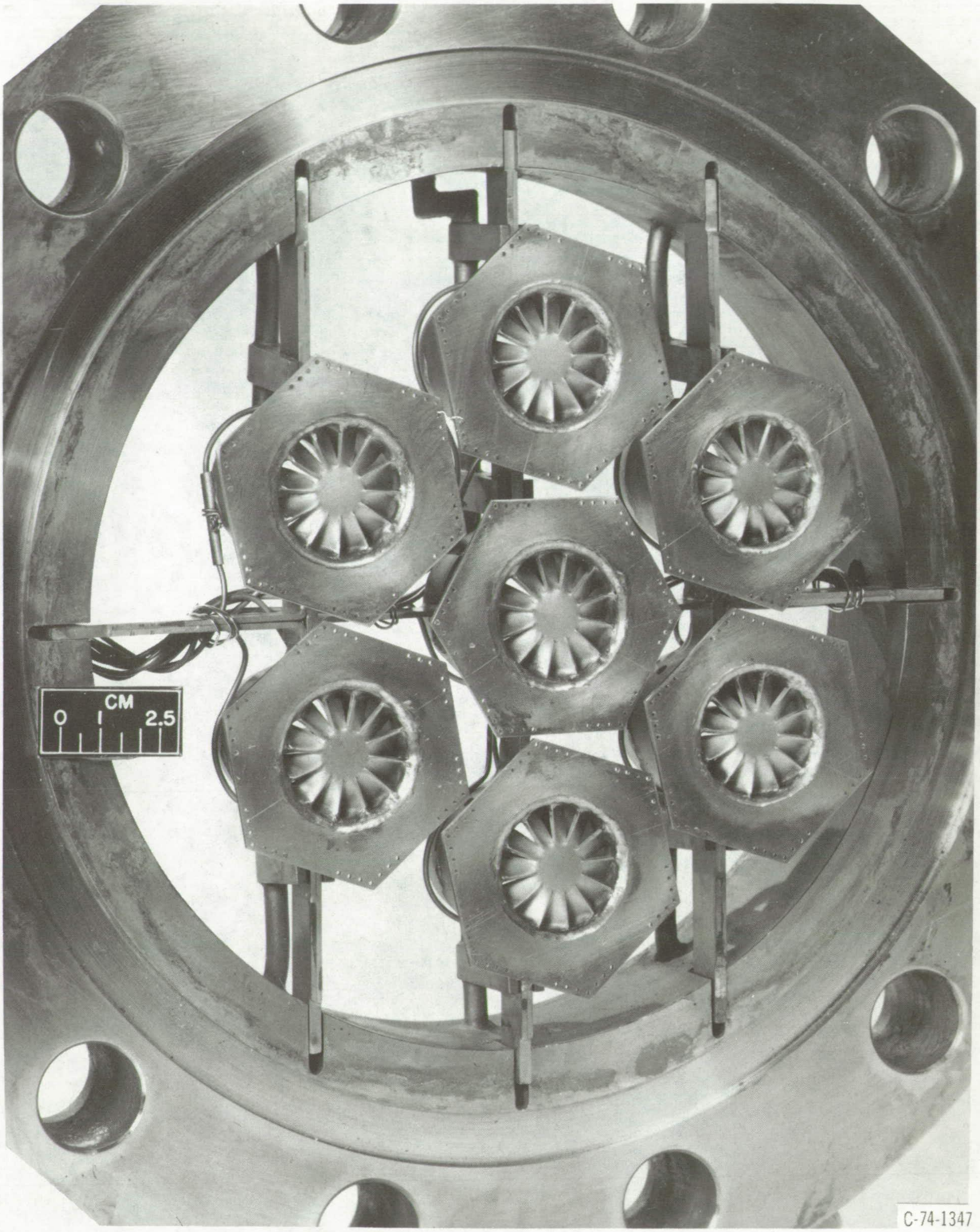
(a) Model A.

Figure 4. - Photographs looking upstream of three swirl-can combustor arrays with combustor liner removed for clarity.



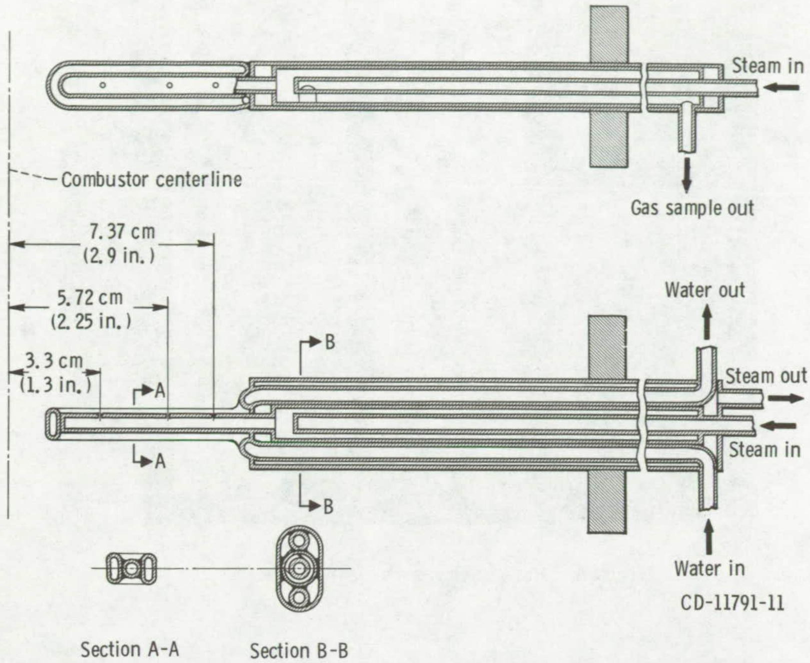
(b) Model B.

Figure 4. - Continued.



(c) Model C.

Figure 4. - Concluded.



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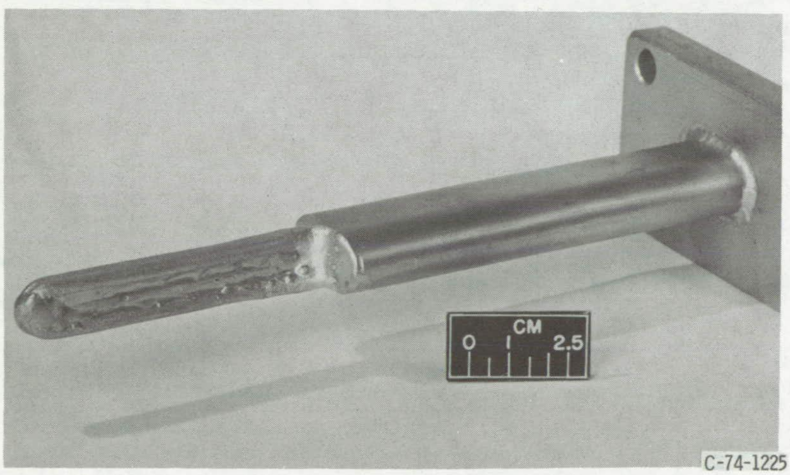


C-74-1225

Figure 5. - Gas sampling probe.

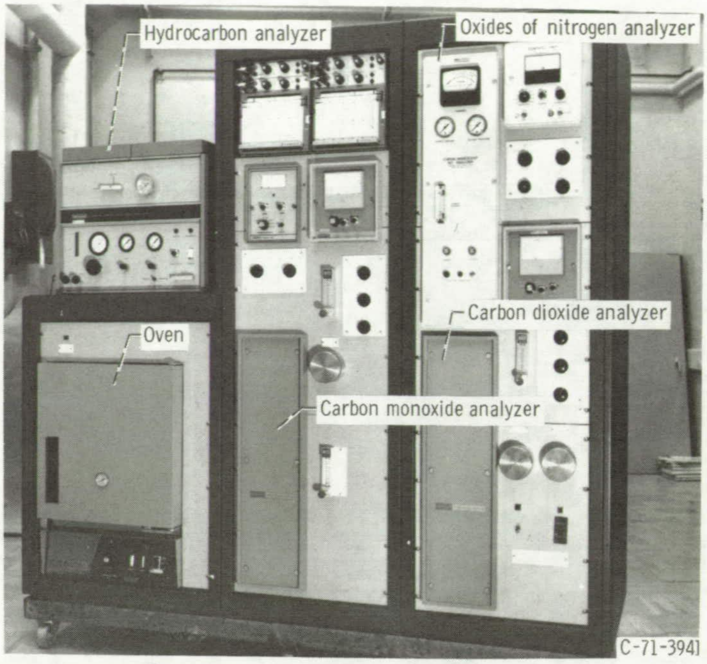


Figure 6. - Gas sampling instrument console.

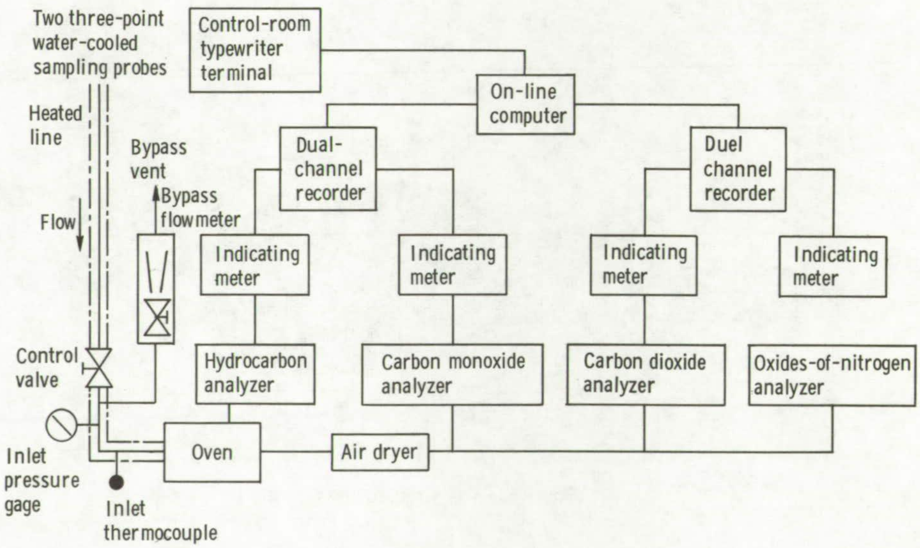
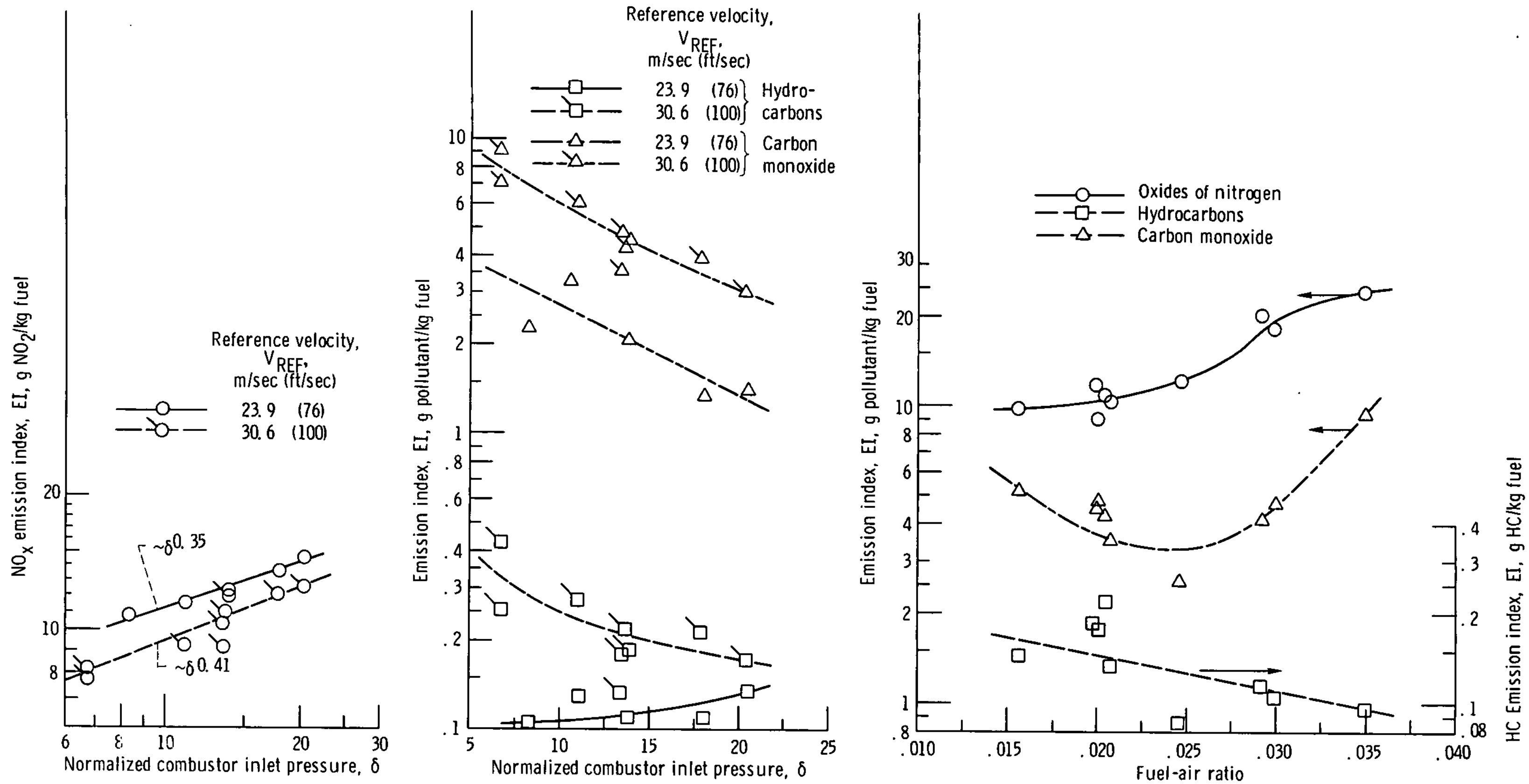


Figure 7. - Schematic diagram of gas analysis system.

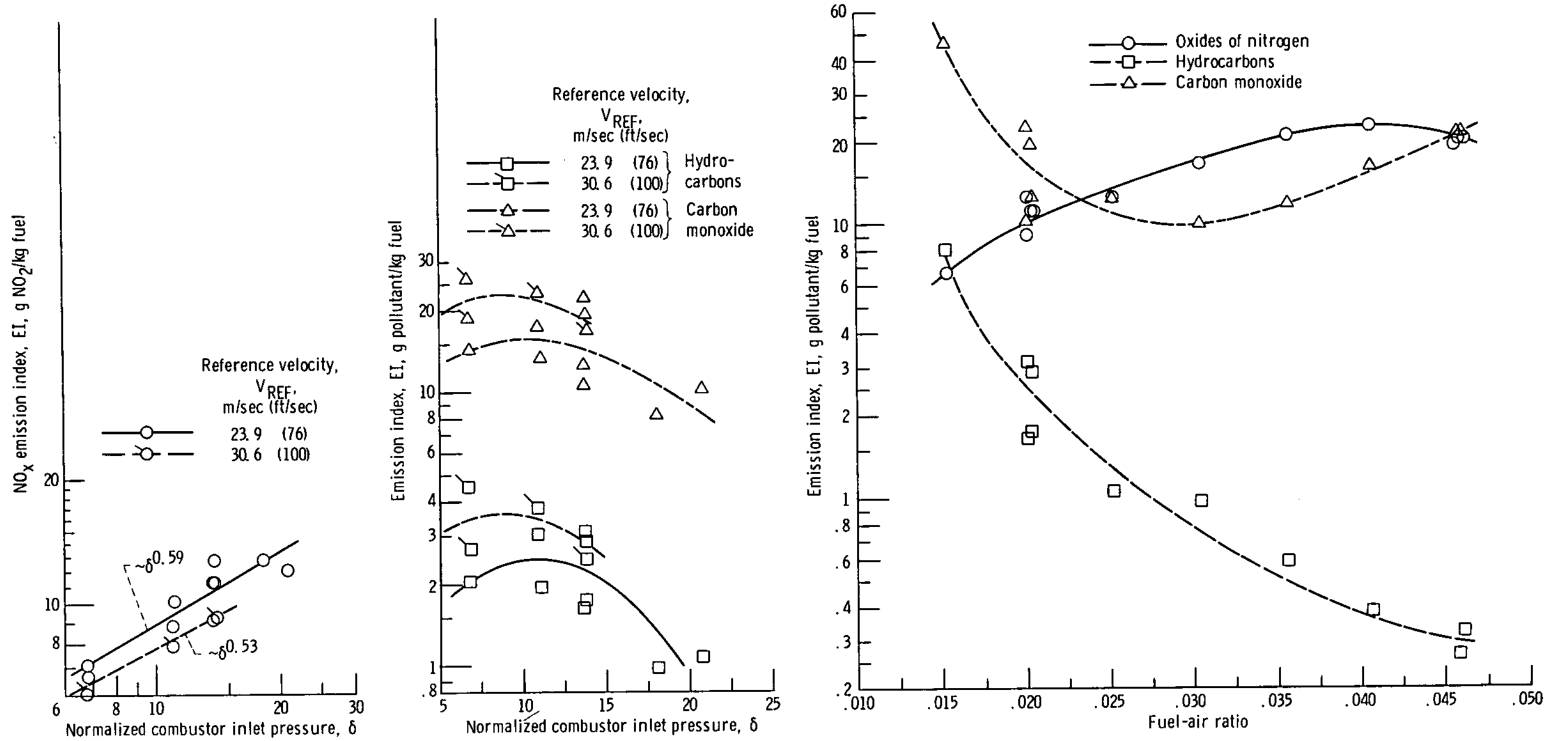


(a) Oxides of nitrogen as function of pressure at fuel-air ratio of 0.02 and at referference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(b) Unburned hydrocarbons and carbon monoxide emissions as function of pressure at fuel-air ratio of 0.02 and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(c) Oxides of nitrogen, unburned hydrocarbons, and carbon monoxide as function of fuel-air ratio at normalized combustor inlet pressure of 13.6 atmospheres (200 psia) and reference velocity of 30.6 meters per second (100 ft/sec).

Figure 8. - Pollutant emissions from a combustor of seven swirl-can modules. Swirl-can cluster model A; combustor inlet air temperture, 733 K (860° F).

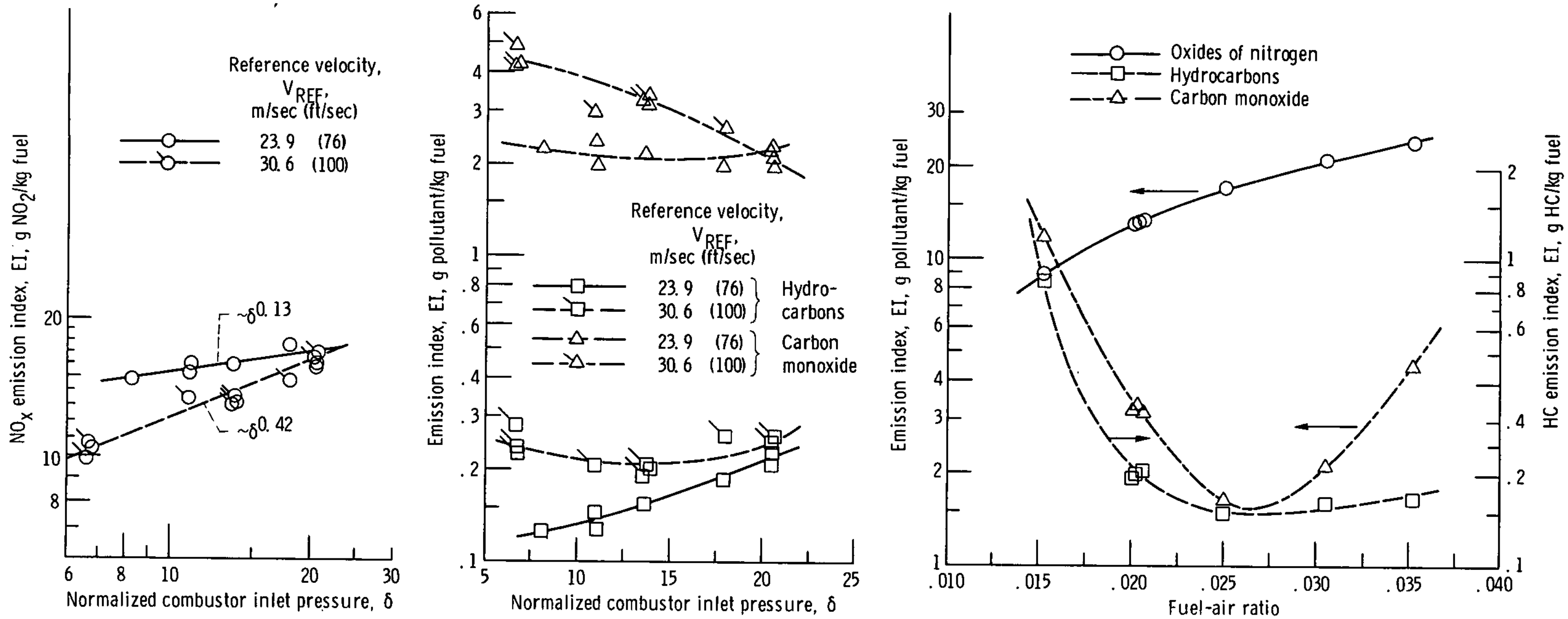


(a) Oxides of nitrogen as function of pressure at fuel-air ratio of 0.02 and and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(b) Unburned hydrocarbons and carbon monoxide emissions as function of pressure at fuel-air ratio of 0.02 and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(c) Oxides of nitrogen, unburned hydrocarbons, and carbon monoxide as function of fuel-air ratio at normalized combustor inlet pressure of 13.6 atmospheres (200 psia) and reference velocity of 23.9 meters per second (76 ft/sec).

Figure 9. - Pollutant emissions from combustor of seven swirl-can modules. Swirl-can cluster model B; combustor inlet air temperature 733 K (860° F).

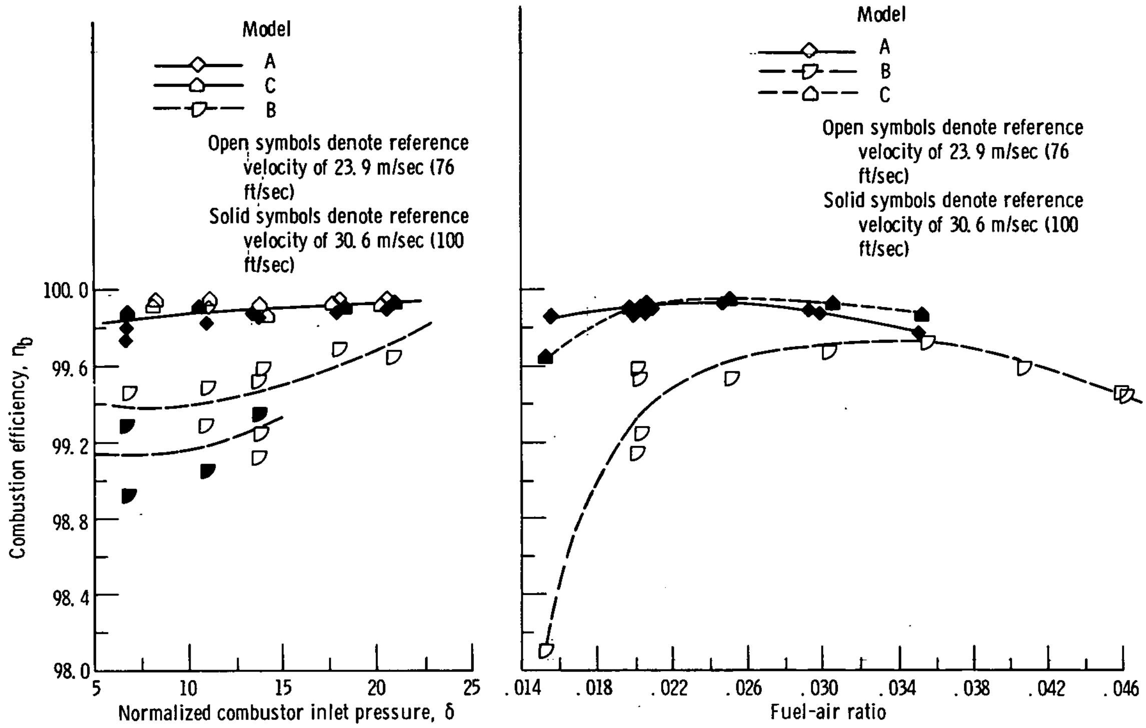


(a) Oxides of nitrogen as function of pressure at fuel-air ratio of 0.02 and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(b) Unburned hydrocarbons and carbon monoxide emissions as function of pressure at fuel-air ratio of 0.02 and at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec).

(c) Oxides of nitrogen, unburned hydrocarbons, and carbon monoxide as functions of fuel-air ratio at normalized combustor inlet pressure of 13.6 atmospheres (200 psia) and reference velocity of 30.6 meters per second (100 ft/sec).

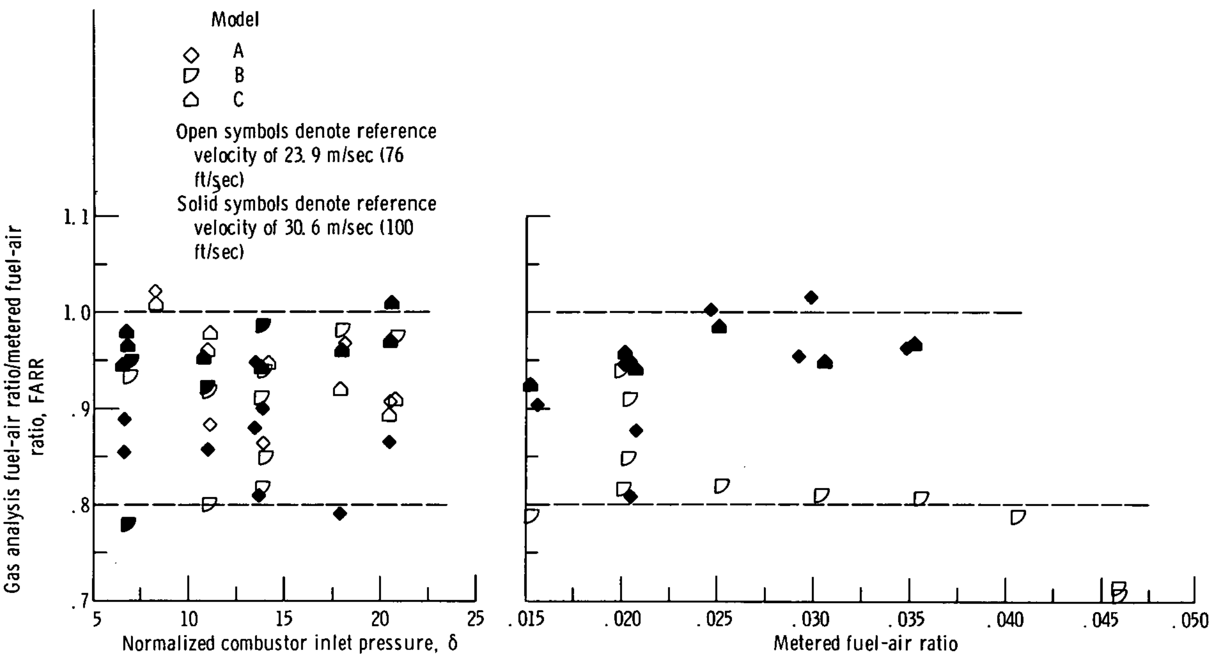
Figure 10. - Pollutant emissions from a combustor of seven swirl-can modules. Swirl-can cluster model C; combustor inlet air temperature, 733 K (860° F).



(a) Combustion efficiency as function of normalized pressure at fuel-air ratio of 0.02.

(b) Combustion efficiency as function of fuel-air ratio at normalized combustor inlet pressure of 13.6 atmospheres (200 psia).

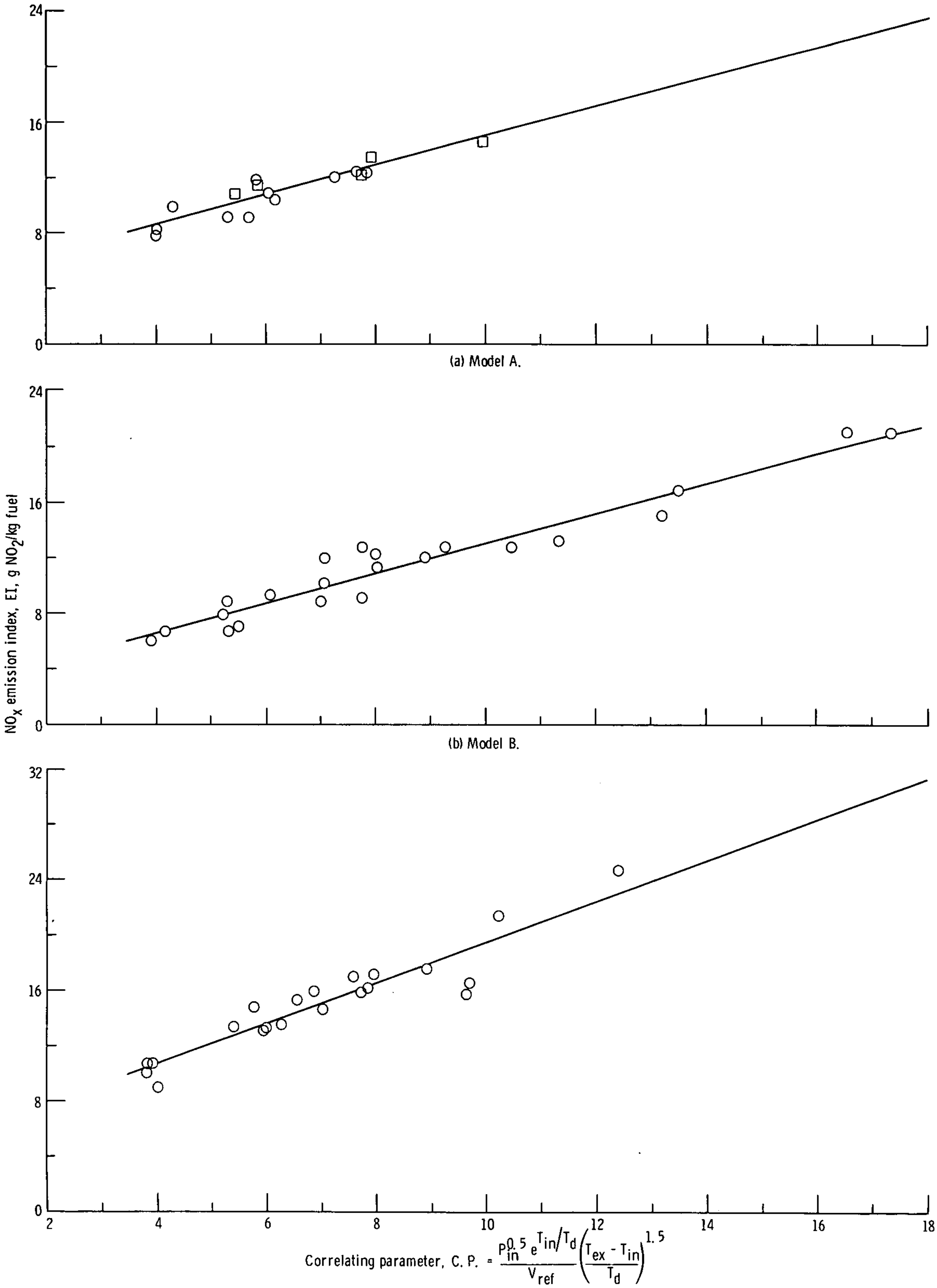
Figure 11. - Combustion efficiency as function of pressure and fuel-air ratio for combustor models, A, B, and C at reference velocities of 23.9 and 30.6 meters per second (76 and 100 ft/sec) and combustor inlet air temperature of 733 K (860° F).



(a) Fuel-air ratio ratio (FARR) over all combustor pressures tested.

(b) Fuel-air ratio ratio (FARR) over all metered fuel-air ratios tested.

Figure 12. - Fuel-air ratio caluclated from gas analysis sample divided by fuel-air ratio obtained from metered values of fuel and air for all gas analysis data for combustor models A, B, and C.



(c) Model C.

Figure 13. - NO_x emission data of figures 8 to 10 as functions of correlating parameter for swirl-can combustor models A, B, and C.

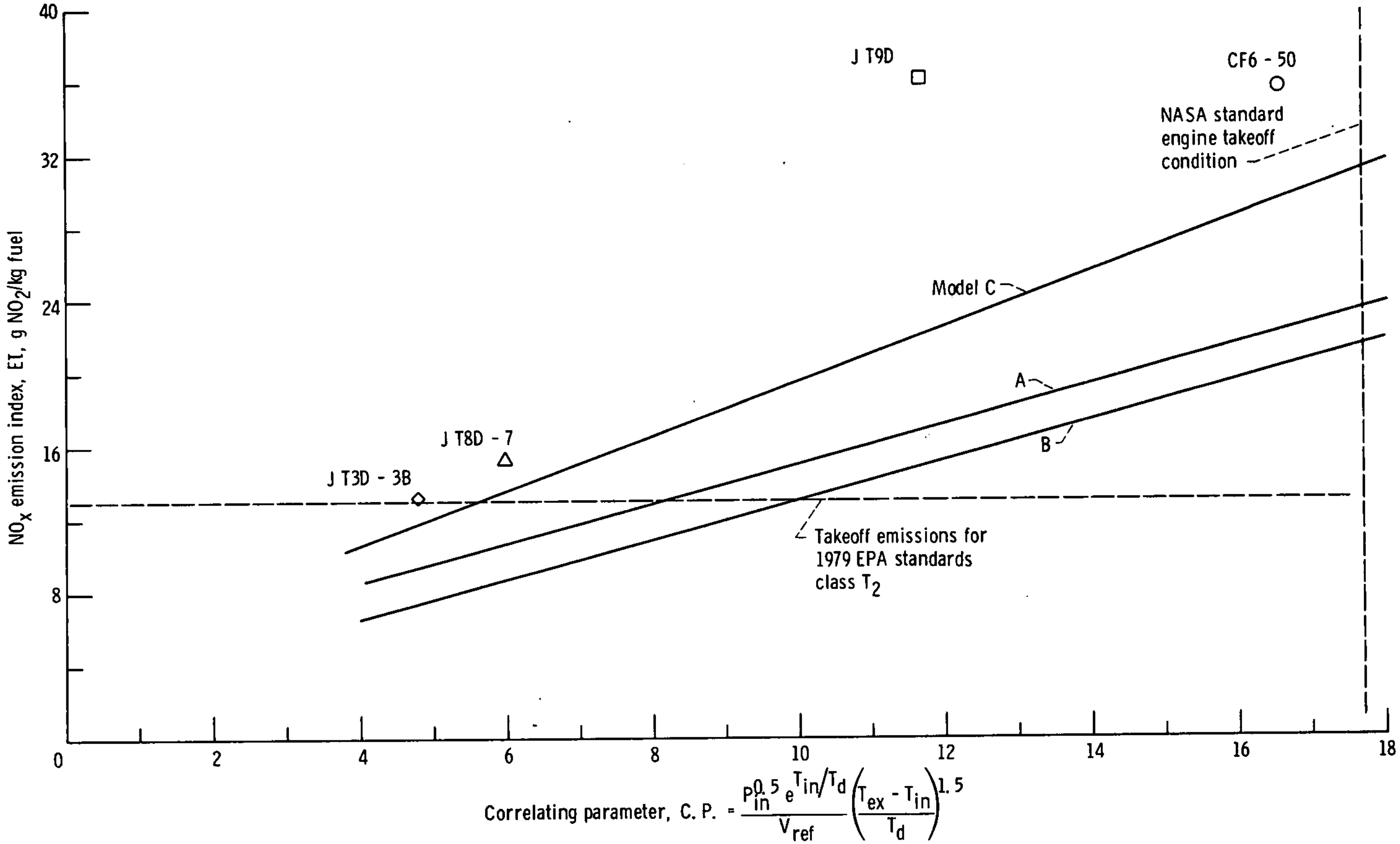


Figure 14. - Comparison of oxides of nitrogen emissions for current engines operating at takeoff and various swirl-can combustor models using oxides of nitrogen correlating parameter.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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