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POLLUTION EMISSIONS FROM SINGLE SWIRL-CAN COMBUSTOR MODULES AT PARAMETRIC TEST CONDITIONS

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16. Abstract

Exhaust pollutant emissions were measured from single swirl-can combustor modules operating over a pressure range of 69 to 276 N/cm^2 (100 to 400 psia), over a fuel-air ratio range of 0.01 to 0.04, at an inlet air temperature of 733 K (860° F), and at a constant reference velocity of 23.2 m/sec (76 ft/sec). Many swirl-can module designs were evaluated; the 11 most promising designs exhibited oxides of nitrogen emission levels lower than that from conventional gas-turbine combustors. In addition, the dependence of the oxides of nitrogen emissions on normalized combustor pressure δ was δ^x. The exponent x was a different value for each module design, varying from 0.27 to 0.74. Although these single module test results are not necessarily indicative of the performance characteristics of a large array of modules, the results are very promixing and offer a number of module designs that should be tested in a full combustor.

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SUMMARY

Tests were conducted to evaluate a number of swirl-can combustor module designs for oxides of nitrogen emissions at simulated full-power gas-turbine operation. Exhaust pollutants were measured from single swirl-can modules burning Jet A fuel and operating over a pressure range of 69 to 276 newtons per square centimeter (100 to 400 psia), a fuel-air ratio range of 0.01 to 0.04, at an inlet air temperature of 733 K (860° F), and at a constant reference velocity of 23.3 meters per second (76 ft/sec). Eleven swirl-can models exhibited oxides of nitrogen emission levels lower than that from conventional gas turbine combustors. Also, higher pressure drop module designs may further reduce these oxides of nitrogen concentrations based on the trends of the test results. In addition, the oxides of nitrogen emissions varied with normalized combustor pressure δ, according to the expression δ^x, where the value of x was different for each model and varied from 0.27 to 0.74. Because the emissions from a single swirl-can module may not be representative of a large array installed in a complete combustor, tests on arrays of the most promising swirl-can models are necessary to verify these test findings.

INTRODUCTION

Tests were conducted to evaluate a number of single swirl-can combustor module designs for oxides of nitrogen emissions at simulated full-power gas turbine operation. Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by gas-turbine engines. The two general areas of concern are urban pollution in the vicinity of airports and pollution of the stratosphere. The principal urban pollutants are unburned hydrocarbons and carbon monoxide during idle and taxi, and oxides of nitrogen (NO_x) and smoke during take-off and landing. Oxides of nitrogen are also considered to be the most predominant gaseous emission products formed during high altitude cruise.

Altering gas turbine combustor designs to make substantial reductions in the emission of oxides of nitrogen is a difficult task (ref. 1). Oxides of nitrogen are formed during any combustion process involving air. The amount formed is controlled by the reaction rate 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 approaches 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 is engaged in research directed toward the development of combustors with substantially reduced oxides of nitrogen emissions. Combustors consisting of arrays of swirl-can combustor modules constitute one phase of this research. Past studies of these swirl-can modular combustors (refs. 3 to 8) indicate 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 airflow through the primary combustion zone, and 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.

However, these past studies were limited in pressure, up to 62 newtons per square centimeter (90 psia), and the large number of modules in one combustor array made changing module hardware quite time consuming.

For these reasons, a variety of swirl-can designs were tested in a high pressure, single module combustor facility using Jet A fuel to evaluate design changes in terms of oxides of nitrogen emissions. The most promising of the swirl-can models and their test results are described in this report. Combustor inlet pressures were varied from 69 to 276 newtons per square centimeter (100 to 400 psia), and fuel-air ratios were varied from 0.01 to 0.04. Combustor inlet temperature and reference velocity were held nominally constant at 733 K (860° F) and 23.2 meters per second (76 ft/sec), respectively, resulting in airflow rates from 0.29 to 1.2 kilograms per second (0.63 to 2.6 lb/sec).

The U. S. Customary system of units was used for primary measurements and calculations. Conversion to 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.

APPARATUS AND PROCEDURE

Test Facility

The tests in this report were conducted in a closed-duct test facility in the Engine Research Building at Lewis. This facility, (fig. 1) is capable of 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 gasoline fired J-47 combustor cans as the 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 (fig. 2) was designed for a single swirl-can module. The fuel tube for each swirl-can was centered in the combustor housing and passed out of the combustor through an upstream flange. The combustor liner was 6.90 centimeters (2.72 in.) in diameter and was convectively cooled only. Combustion air was not used to cool this liner, but instead a small amount of additional air was injected between the liner and the combustor housing, as required. Each swirl-can module was centered in the liner near its downstream end; that is, the distance between the downstream end of the swirl-can module and the downstream end of the liner was approximately 5.2 centimeters (2.06 in.). A 20-joule ignitor plug was inserted into the adapter flange and was located adjacent to the swirl-can module. The hot combustion gases exhausted into an instrumentation section with a water-cooled liner 16.1 centimeters (6.36 in.) in diameter. It was assumed that the combustion gases act as a jet and diffuse to a 7.63 centimeter (3.0 in.) diameter jet at the gas sample probe location. This design enabled wall quenching effects to be minimized and was less severe on the combustor rig than a constant area combustion zone would have been.

Swirl-Can Module 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 the combustion gases in its wake.

Pollutant emission measurements were made on 20 swirl-can module designs. Of these, the 11 most promising were selected for discussion in this report. A description of these 11 models are presented in table I. The remaining nine swirl-can models were judged less promising and are briefly described in table II and will not be discussed further.

The differences in the 11 models are in the projected flow area blockage, the degree of swirl, and the method of fuel injection. The blockage, which is related to pressure drop, varied from 43.3 to 60.3 percent. In calculating the percent blockage, the swirler discharge coefficient was assumed equal to 1. The swirl was varied by changing the inner swirler open area and by adding another swirler of opposite sense from the inner swirler outside of the carburetor can as part of the flame stabilizer portion of the swirl-can module. The standard method of fuel injection was to splash a stream of fuel against the hub of the inner swirler; a mixture of fuel and air then passes through the inner swirler. Another method was to spray the fuel upstream of the inner swirler using a simplex pressure atomizing nozzle. It was expected that this would promote a more uniform fuel and air mixture emerging from the inner swirler. A third method was to splash a stream of fuel against a disk mounted just downstream of the inner swirler; the fuel is then sheared off the disk by the air emerging from the inner swirler. It was expected that this method would better confine the fuel to the recirculation zone of the swirl-can module, and would eliminate any possible autoignition upstream of the module wake.

Exhaust Emissions

Concentrations of total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were obtained with an online sampling system. The gas sample was drawn at the axial location shown in figure 2, which is approximately 11.7 centimeters (4.59 in.) from the downstream end of the swirl-can module.

Gas sample probe. - The gas sample probe (fig. 4) was inserted across the diameter of the exhaust instrumentation section and had four sampling ports located at centers of equal area within a 7.63-centimeter (3.0-in.) diameter circle. The hole size of these sample ports could be varied to ensure that the gas sample pressure inside the probe was kept below 31 newtons per square centimeters (45 psia): The gas sample temperature at the probe was also maintained between 394 to 616 K (250° to 650° F). These procedures were followed to insure that the gas sample did not change in composition after it entered the probe.

Gas sample system. - A picture of the gas analysis instrumentation and a schematic of the system are shown in figures 5 and 6. The sample collected by the probe was transported through 0.63-centimeter (1/4-in.) diameter stainless steel line to the analytical instruments. In order to prevent the condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated. Sample line pressure was nominally 25 newtons per square centimeters (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 and the associated 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 the carbon monoxide (CO) and the carbon dioxide (CO_2) analyzers are of the nondispersive infrared (NDIR) type (Beckman Instruments Model 315B). The CO analyzer had 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 0.64- and 34-centimeter (0.25- and 13.5-in.) long stacked cells. 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 before 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 insure calibration accuracy without disrupting the test.

Where appropriate, the measured quantities were corrected for the amount of water vapor removed. The correction included both inlet-air humidity and water vapor from combustion. The equations used were obtained from reference 9.

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 9; this technique measures the fuel-air ratio from the total carbon atom content of the gas sample. An alternative procedure is to use a simplified equation and the metered fuel-air ratio when this is accurately known. When this 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 index in g of X per kg of fuel burned

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 in ppm of exhaust gas

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

Test Conditions

Each of the swirl-can modules was tested at the nominal test conditions shown in table III. The combustor inlet air pressure, when normalized to the standard sea-level pressure of 10.13 newton per square centimeter (14.696 psia), is expressed as δ and the ranges of δ are also shown. Not all of the models were tested over the complete spans of pressure and fuel-air ratio of the table because of 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.

RESULTS AND DISCUSSION

The exhaust pollutant emissions were measured on 20 swirl-can module designs operating over a range of pressures and fuel-air ratios using Jet A fuel. The inlet air temperature was held constant at 733 K (860° F) and the reference velocity remained at 23.2 meters per second (76 ft/sec) for all the tests. The test results of the 11 most promising swirl-can module designs are presented in the following section.

Combustor Exhaust Emissions

Exhaust emissions as functions of pressure. - Data of total oxides of nitrogen, total hydrocarbons, and carbon monoxide concentrations as functions of normalized combustor inlet air pressure δ are presented in figure 7 for the 11 swirl-can models described in table I at a constant fuel-air ratio of 0.02. The data are presented as values of emission index and were converted from parts per million values using the method proposed in reference 9. This method uses a calculated fuel-air ratio based on the gas analysis sample. Combustion efficiency at any pressure can easily be calculated from the data of total hydrocarbons and carbon monoxide concentrations by recalling that a hydrocarbon emission index of 10 represents 1 percent combustion inefficiency, (assuming all the hydrocarbon emissions are of the form CH_2) and a carbon monoxide emission index of 42.5 also represents 1 percent combustion inefficiency.

Exhaust emissions functions of fuel-air ratio. - Data of total oxides of nitrogen, total hydrocarbons, and carbon monoxide concentrations as functions of fuel-air ratio are presented in figure 8 at a normalized combustor inlet air pressure of 13.6 (200 psia) for models 3 to 6 and 10 and at a normalized combustor inlet air pressure of 27.2 (400 psia) for models 2 and 10. The fuel-air ratio on the abscissa of the figures is based on metered fuel and airflow rates. However, the emission index values were again converted from parts per million values using a calculated fuel-air ratio based on the gas analysis sample.

Sample validity. - 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. A comparison of gas sampling fuel-air ratios with metered fuel-air ratios for all the preceding data is shown in figure 9. The data show a wide variation because the sampling was limited to one fixed circumferential position, and the gas sample probe was located close to the burning zone where the combustion gases may not have sufficiently mixed with the diluent air to a uniform composition. An interesting point is that most of the data show a gas sample to metered fuel-air ratio greater than unity. This indicates that the gas sample was withdrawn from a region of higher temperature than the average temperature of the entire combustion gas cross section, since its fuel-air ratio was greater than the average fuel-air ratio. And since the oxides of nitrogen formation rate is temperature rise dependent, this suggests that the reported oxides of nitrogen data, if in error due to gas sampling, are higher than they would be if the gas sample were more representative of the entire combustion cross-section. Therefore, even though the gas sampling is not very satisfactory, the results of exhaust emissions concentrations are nevertheless valid, and better gas sampling might have resulted in even lower oxides of nitrogen values.

Discussion of Exhaust Emission Results

Examination of the exhaust emissions data for the 11 swirl-can models (figs. 7 and 8) lead to the following observations:

All 11 models exhibited oxides of nitrogen emission levels lower than conventional gas turbine combustors at a similar operating condition. All models except models 4 to 6 operated at combustion efficiencies greater than 99 percent. The lower efficiencies were mainly due to the carbon monoxide concentrations in the exhaust of models 4 to 6. Since the gas sampling probe was quite close to the burning zone, the carbon monoxide reaction may not have been complete in some cases. In an engine application the combustor length would be greater than that in this test rig, and combustion efficiencies would be expected to improve substantially.

Swirl-can models 2, 8, and 9 produced the lowest levels of oxides of nitrogen while maintaining high combustion efficiency (greater than 99.5 percent) over their entire range of operation. However, these levels are not yet low enough to achieve the 1979 Environmental Protection Agency emission standards (ref. 10). For example, the oxides of nitrogen emission index for model 2 at a normalized combustor inlet air pressure of 27.2 atmospheres and a fuel-air ratio of 0.03 is approximately 15 (see fig. 8(f)). The value of emission index for this model when operating at a condition typical of an advanced turbofan engine may be predicted by using the oxides of nitrogen correlating parameter of reference 4,

$$\frac{\delta^{1/2} e^{T_{in}/T_d} T_{exit}}{V_{ref} W}$$

where

$\delta^{1/2}$	normalized combustor inlet air pressure in atmospheres
T_{in}	combustor inlet air temperature, K
T_d	constant correlating factor evaluated to be 288 K
T_{exit}	combustor average exit temperature, K
V_{ref}	combustor reference velocity, m/sec
W	combustor module wetted perimeter

For a normalized combustor inlet air pressure of 29.1 atmospheres, a combustor inlet air temperature of 858 K (1085° F), a combustor exit temperature of 1659 K (2527° F), and a reference velocity of 26.5 meters per second (87 ft/sec), the oxides of nitrogen emission index would be 17. A conventional combustor operating at these conditions produces an oxides of nitrogen emission index of about 36. The oxides of nitrogen emission index level at full power necessary to achieve the 1979 EPA emission standards is approximately 13 for an advanced turbofan engine.

The trend in the oxides of nitrogen emission levels indicates that swirl-can module designs similar to models 2, 8, and 9 with even higher pressure drop (i.e., higher blockage) might result in further reductions in oxides of nitrogen concentrations. For models 1, 7, and 2, as the blockage or pressure drop increased, the oxides of nitrogen emissions decreased for any particular combustor pressure.

The influence of pressure on the oxides of nitrogen emissions varied from model to model. Assuming the dependence on combustor inlet air pressure is δ^x, where δ is the normalized pressure as defined above, the values of x are simply the slopes of the oxides of nitrogen against pressure curves of figures 7. The pressure dependence for each model is shown in table IV. As is shown, the exponent on pressure was different for each model and varied from 0.27 to 0.74. On the other hand, theoretical considerations based on chemical kinetics indicate that the oxides of nitrogen emissions vary as the square root of combustor inlet air pressure (ref. 11). The wide variation of the pressure dependence of the data indicates that gas dynamics and combustor geometry may strongly influence the oxides of nitrogen emissions.

These tests were performed to screen a large number of swirl-can designs in a short time. The conditions of the tests cannot completely simulate the conditions inside an engine with a combustor made up of a large array of these swirl-cans. An uneven distribution of air to the swirl-can array, and the interaction of the swirl-can array itself cannot be simulated. Further tests of these swirl-can models in an array is necessary to validate the results of these tests. However, these results do indicate several promising designs which may achieve low emissions when used in a complete combustor.

SUMMARY OF RESULTS

Exhaust pollutant emission measurements of 11 single swirl-can combustor module designs operating over a pressure range of 69 to 276 newtons per square centimeter (100 to 400 psia), a fuel-air ratio range of 0.01 to 0.04, an inlet air temperature of 733 K (860° F), and a constant reference velocity of 23.2 meters per second (76 ft/sec) produced the following results.

1. Each of the 11 models exhibited oxides of nitrogen emission levels lower than conventional combustor emissions for similar operating conditions.

2. Swirl-can models 2, 8, and 9 produced the lowest levels of oxides of nitrogen, although these values are not low enough to meet the 1979 EPA emission standards.

3. Further reductions in the oxides of nitrogen concentrations may be realized with swirl-can module designs similar to models 2, 8, and 9 but with even greater pressure drop (higher blockage).

4. The oxides of nitrogen emissions (NO_x) varied with pressure according to the expression $NO_x \approx \delta^x$, where δ is the normalized combustor inlet air pressure, and where the value of x was different for each model and varied from 0.27 to 0.74.

Further tests of these models, arranged to simulate an actual gas turbine engine combustor, are necessary to reinforce the results of these tests.

Lewis Research Center,
National Aeronautics and Space Administration,
and
U. S. Army Air Mobility R&D Laboratory,
Cleveland, Ohio, August 30, 1974,
501-24.

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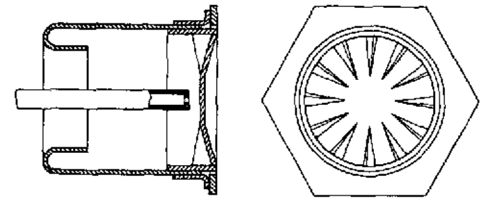
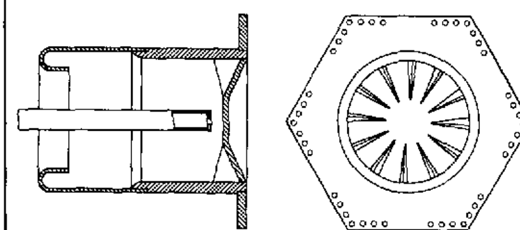
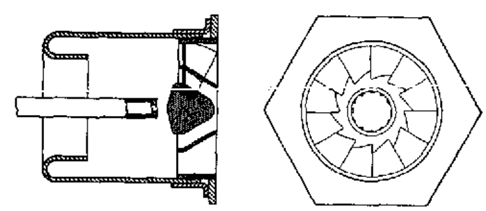
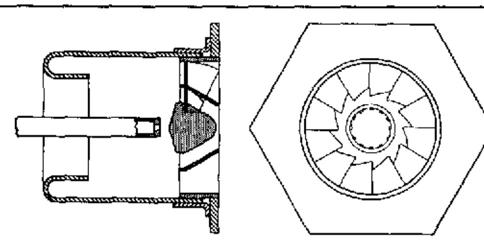
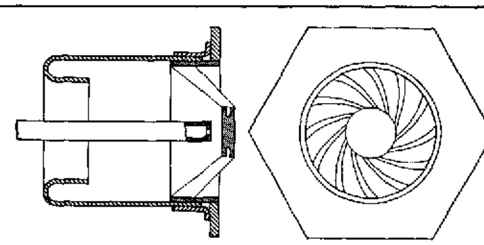
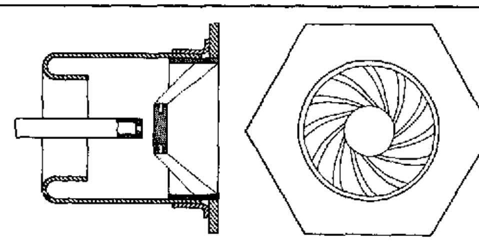
TABLE I. - DESCRIPTION OF ELEVEN

Model number	Sketch of swirl can Cross section / View looking upstream	Percent blockage in 6.9-cm (2.72-in.) diameter duct
1		47.8
2		60.3
3		43.3
4		56.4
5		50.8
6		50.8

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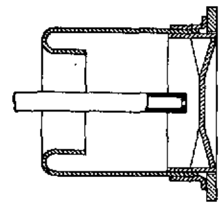
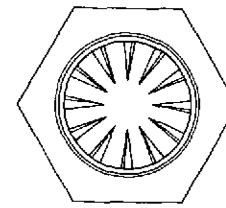
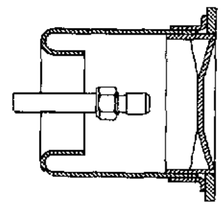
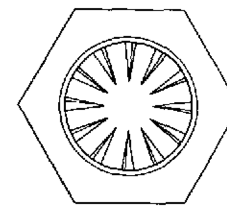
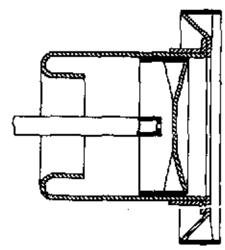
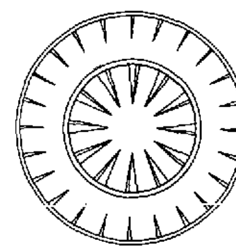
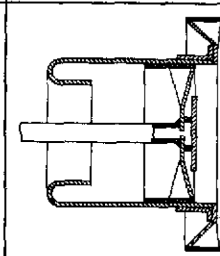
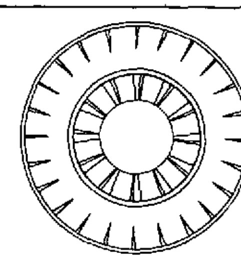
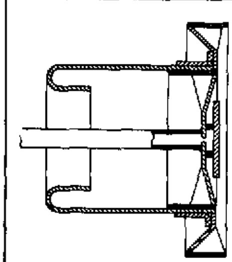
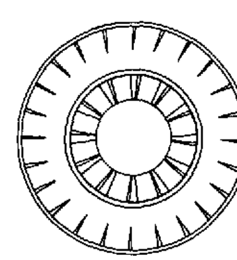
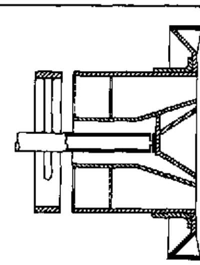
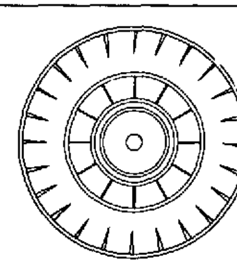
BEST SWIRL-CAN COMBUSTOR MODULES

Inner swirl description	Flame stabilizer description	Fuel injection description	Overall description
Stamped; 12 blades; 45° angle at tips; tip diam, 3.25 cm (1.28 in.); hub diam, 1.59 cm (0.625 in.); open area, 2.36 cm^2 (0.366 $in.^2$); flush with flame stabilizer	Hexagon of side length, 2.8 cm (1.1 in.); full area, 20.2 cm^2 (3.14 $in.^2$)	Fuel tube centered in can, 0.13 cm (0.05 in.) diam orifice at end of tube, 0.32 cm (0.125 in.) upstream of inner swirler hub; fuel sprayed through inner swirler	Baseline model
Same as model 1	Hexagon of side length, 3.11 cm (1.22 in.); 7 holes, 0.11 cm (0.042 in.) diam at each corner; hexagon full area, 25.2 cm^2 (3.90 $in.^2$)	Same as model 1	Larger hexagonal flame stabilizer than model 1 for more intense mixing, holes in hexagon for durability
2 concentric full-bladed swirlers; 12 blades each, 45° angle blades; both counterclockwise swirlers; Inner: tip diam, 2.03 cm (0.801 in.) hub diam, 1.27 cm (0.500 in.) open area, 1.03 cm^2 (0.160 $in.^2$) Outer: tip diam, 3.34 cm (1.32 in.) hub diam, 2.19 cm (0.863 in.) open area, 3.00 cm^2 (0.466 $in.^2$)	Same as model 1	Same as model 1, except fuel sprayed through both inner swirlers	Open area of inner swirlers larger than that of model 1 for leaner burning in primary zone
Same as model 3	Hexagon of side length, 3.11 cm (1.22 in.); full area, 25.2 cm^2 (3.90 $in.^2$)	Same as model 3	Open area of inner swirlers larger than that of model 2 for leaner burning in primary zone
Full-bladed, 45° conical swirler, with swirler hub extending downstream; 12 blades, 45° angle; tip diam, 3.34 cm (1.32 in.); hub diam, 1.27 cm (0.500 in.); open area, 6.14 cm^2 (0.951 $in.^2$)	Same as model 4	Same as model 1	Open area of inner swirler much larger than that of model 2 for leaner burning in primary zone; fuel sprayed radially through conical swirler for more homogeneous distribution
Same as model 5 except swirler hub extends upstream	Same as model.4	Same as model 1	Open area of inner swirler much larger than that of model 2 for leaner burning in primary zone; radial inflow of fuel/air through conical swirler for confined burning

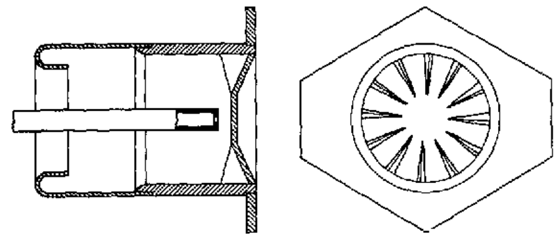
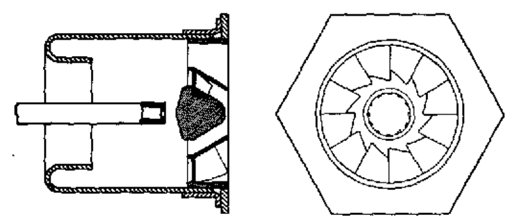
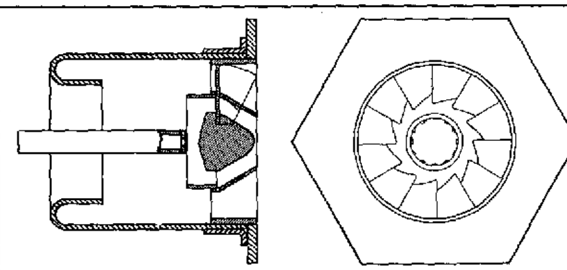
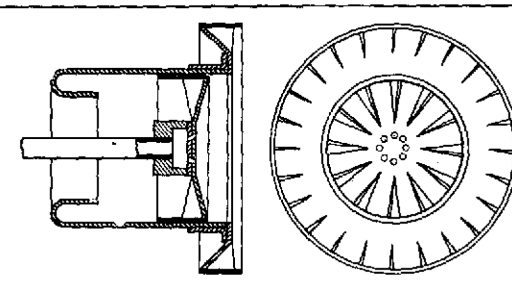
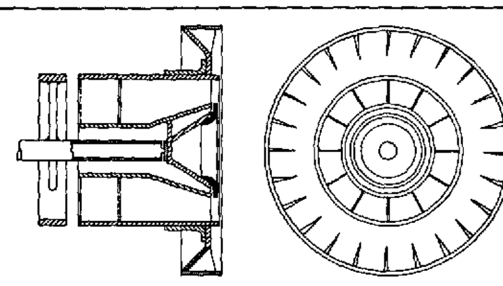
TABLE I. - Concluded. DESCRIPTION OF

Model number	Sketch of swirl can		Percent blockage in 6.9-cm (2.72-in.) diameter duct
	Cross section	View looking upstream	
7A			51.2
7B			51.2
8			60.3
9			60.3
10			60.3
11			51.1

ELEVEN BEST SWIRL-CAN COMBUSTOR MODULES

Inner swirler description	Flame stabilizer description	Fuel injection description	Overall description
Stamped, 12 blades, 45° angle at tips; tip diam, 3.34 cm (1.31 in.); hub diam, 1.90 cm (0.750 in.); open area, 2.30 cm^2 (0.357 in.^{2})	Irregular hexagon, 4 sides length, 2.92 cm (1.15 in.); 2 sides length, 2.78 cm (1.10 in.); full area, 21.5 cm^2 (3.33 in.^{2})	Same as model 1	Flame stabilizer size and blockage between those of models 1 and 2 for different mixing intensity
Same as model 7A	Same as model 7A	Fuel tube centered in can; simplex nozzle (60° spray angle) at end of tube 1.4 cm (0.55 in.) upstream of inner swirler hub; fuel sprayed through inner swirler	Simplex nozzle to more finely atomize fuel than model 7A
Stamped, 12 blades, 45° angle at tips; swirler face recessed 0.56 cm (0.22 in.) from flame stabilizer; tip diam, 3.34 cm (1.31 in.); hub diam, 1.90 cm (0.750 in.); open area, 2.30 cm^2 (0.357 in.^{2})	Stamped swirler, 24 blades, 45° angle at tips; this swirler of opposite rotation from inner swirler; tip diam, 5.79 cm (2.28 in.); hub diam, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 in.^{2}); swirler shroud diam, 5.94 cm (2.34 in.)	Same as model 1	Contraswirl design for better mixing than that of model 2
Same as model 8	Same as model 8	Fuel tube attached to center of inner swirler hub; 0.13-cm (0.05-in.) diam orifice through hub; fuel passes through orifice and splashes against 1.9-cm (0.75-in.) diam disk mounted 0.15 cm (0.062 in.) from inner swirler hub	Fuel injection downstream of inner swirler to confine fuel to recirculation zone better than model 8
Stamped swirler, 12 blades 45° angle at tips; swirler face flush with flame stabilizer; tip diam, 3.34 cm (1.31 in.); hub diam, 1.90 cm (0.750 in.); open area, 2.30 cm^2 (0.357 in.^{2})	Same as model 8	Same as model 9	Same as model 9 except that inner swirler made flush with flame stabilizer for improved durability
Full-bladed swirler mounted at upstream end of can; 12 blades, 45° angle blades; tip diam, 3.51 cm (1.38 in.); hub diam, 1.27 cm (0.50 in.); open area, 5.06 cm^2 (0.784 in.)^2	Same as model 8	Fuel tube centered in can; 0.051 cm (0.020 in.) circumferential slot at end of tube; fuel sprayed through slot into air stream; fuel/air mixture exits can through annular slot of open area, 0.70 cm^2 (0.11 in.^{2})	Fuel/air premixing prior to ignition: fuel well confined to recirculation zone

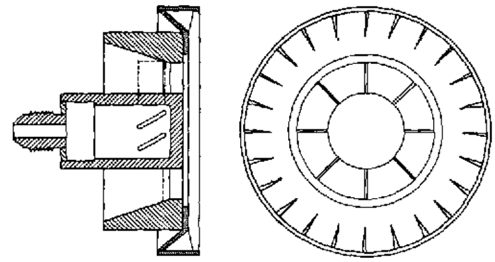
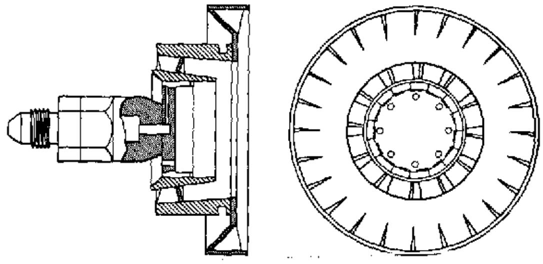
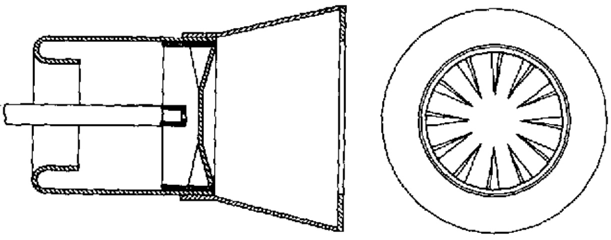
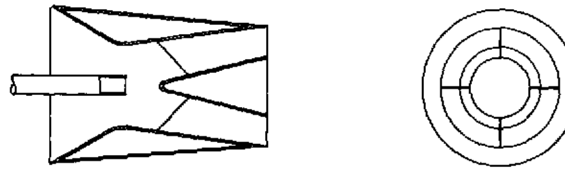
TABLE II. - DESCRIPTION OF SWIRL-CAN COMBUSTOR

Model number	Sketch of swirl can Cross section / View looking upstream	Percent blockage in 6.9-cm (2.72-in.) diameter duct
12		51.5
13		43.3
14		56.4
15		60.3
16		51.1

MODULES WHICH WERE TESTED BUT ARE NOT OTHERWISE DISCUSSED IN THIS REPORT

Inner swirler description	Flame stabilizer description	Fuel injection description	Test results
Stamped; 12 blades; 45° angle at tips; flush with flame stabilizer; tip diam, 3.25 cm (1.28 in.); hub diam, 1.59 cm (0.625 in.); open area, 2.36 cm^2 (0.366 $in.^2$)	Irregular hexagon: 4 sides length, 3.48 cm (1.37 in.); 2 sides length, 1.84 cm (0.726 in.); full area, 21.6 cm^2 (3.36 $in.^2$)	Fuel tube centered in can; 0.13-cm (0.05-in.) diam orifice at end of tube 0.32 cm (0.125 in.) upstream of inner swirler hub; fuel sprayed through inner swirler	Pollutant emissions similar to model 7; irregular hexagon to fit in double annular combustor design with model 7
2 concentric full-bladed swirlers, 12 blades each, 45° angle blades flush with flame stabilizer; inner swirler counterclockwise, outer swirler clockwise; Inner: tip diam, 2.03 cm (0.801 in.); hub diam, 1.27 cm (0.500 in.); open area, 1.03 cm^2 (0.160 $in.^2$) Outer: tip diam. 3.34 cm (1.32 in.); hub diam, 2.19 cm (0.863 in.); open area, 3.00 cm^2 (0.466 $in.^2$)	Hexagon of side length, 2.8 cm (1.1 in.); full area, 20.2 cm^2 (3.14 $in.^2$)	Same as model 12, except fuel sprayed through both inner swirlers	Combustion efficiency good; oxides of nitrogen emissions higher than that of model 3; which differs from this model only in inner swirler directions
Same as model 13 except both swirlers counterclockwise and 0.63 cm (0.25 in.) ridge between swirlers on upstream face	Hexagon of side length, 3.11 cm (1.22 in.); full area, 25.2 cm^2 (3.90 $in.^2$)	Same as model 12 except fuel sprayed through innermost swirler only	Poor combustion efficiency compared with model 4
Stamped swirler, 12 blades, 45° angle at tips; swirler face recessed 0.56 cm (0.22 in.) from flame stabilizer; tip diam, 3.34 cm (1.31 in.); hub diam, 1.90 cm (0.750 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Stamped swirler, 24 blades, 45° angle at tips; this swirler of opposite rotation from inner swirler; tip diam, 5.79 cm (2.28 in.); hub diam, 4.57 cm (1.80 in.); open area, 2.90 cm^2 (0.450 $in.^2$); swirler shroud diam, 5.94 cm (2.34 in.)	Fuel tube attached to center of inner swirler hub; 8 fuel orifices of 0.13-cm (0.05-in.) diam through hub and equally spaced on 0.63 cm (0.25 in.) diam circle; fuel sprays directly into wake of module	Longer primary combustion zone than first 11 models resulting in higher oxides of nitrogen emissions
Full-bladed swirler mounted at upstream end of can; 12 blades, 45° angle blades; tip diam, 3.51 cm (1.38 in.); hub diam, 1.27 cm (0.50 in.); open area, 5.06 cm^2 (0.784 $in.^2$)	Same as model 15	Fuel tube centered in can; 0.051 cm (0.020 in.) circumferential slot at end of tube; fuel sprayed through slot into air stream; fuel/air mixture exits can through 1.0-mm (0.04-in.) radial slot entering inner swirler air passage	Improved combustion efficiency from similar model 11; oxides of nitrogen values higher than model 11, however

TABLE II. - Concluded. DESCRIPTION OF SWIRL-CAN COMBUSTOR

Model number	Sketch of swirl can: Cross section / View looking upstream	Percent blockage in 6.9-cm (2.72-in.) diameter duct
17		59.2
18		52.2
19		57.9
20		41.4

MODULES WHICH WERE TESTED BUT ARE NOT OTHERWISE DISCUSSED IN THIS REPORT

Inner swirler description	Flame stabilizer description	Fuel injection description	Test results
Full-bladed swirler, eight 45^0 angle blades; swirler face recessed 0.32 cm (0.125 in.) from flame stabilizer; tip diam, 3.30 cm (1.30 in.); hub diam, 1.80 cm (0.71 in.); open area, 2.73 cm^2 (0.432 $in.^2$)	Same as model 15	Fuel injected directly into wake of module by being emitted through slots in downstream edge of 4 inner swirler blades, slot dimensions: tapered width, 0.025 to 0.051 cm (0.01 to 0.02 in.); length, 0.63 cm (0.25 in.)	Low combustion efficiency, probably due to poor fuel atomization
Full-bladed swirler, 12 45^0 angle blades; swirler face recessed 0.79 cm (0.31 in.) from flame stabilizer; tip diam, 3.44 cm (1.36 in.); hub diam, 2.69 cm (1.06 in.); swirler open area, 4.68 cm^2 (0.726 $in.^2$); in hub: 8 holes 0.15 cm (0.06 in.) diam total hole open area, 0.14 cm^2 (0.023 $in.^2$), 16 slots in circular ring; total slot open area, 0.52 cm^2 (0.08 $in.^2$)	Same as model 15	Fuel injected into 16 slots in hub of inner swirler through passages in hub; fuel atomized with air going through slots and passes into module wake	Good combustion efficiency; oxides of nitrogen emissions similar to model 11; design much more complicated than models with similar emissions
Stamped swirler, 12 blades 45^0 angle at tips; tip diam, 3.34 cm (1.31 in.); hub diam, 1.90 cm (0.750 in.); open area, 2.30 cm^2 (0.357 $in.^2$)	Truncated cone with annular ring at end; cone length (inner swirler to cone base), 3.05 cm (1.2 in.); cone base and outside diam of ring; 5.53 cm (2.17 in.); inside diam of ring, 3.71 cm (1.46 in.); cone full area, 24.0 cm^2 (3.71 $in.^2$)	Same as model 12	Low combustion efficiency, oxides of nitrogen emissions higher than first 11 models
Full-bladed swirler, four 45^0 angle helical blades; end of swirler flush with downstream end of can; tip diam, 3.81 cm (1.50 in.); hub diam, 1.90 cm (0.75 in.); open area, 4.75 cm^2 (0.737 $in.^2$)	No flame stabilizer as such; can is inverted cone with respect to airflow; maximum full swirl-can area, 20.2 cm^2 (3.14 $in.^2$)	Fuel tube centered in can ending at throat of venturi; fuel and air premix as they pass through swirler; small amount of fuel is injected inside hub of swirler to provide pilot flame	Low combustion efficiency

TABLE III. - NOMINAL TEST CONDITIONS FOR SINGLE MODULE

SWIRL-CAN COMBUSTOR EVALUATION

[Fuel temperature, ambient; reference velocity, 23.2 m/sec (76 ft/sec); liner diameter, 6.9 cm (2.72 in.).]

Inlet air pressure		Normalized combustor inlet air pressure, δ	Inlet air temperature		Fuel-air ratio
N/cm^2	psia		K	^oF	
69 to 276	100 to 400	6.8 to 27.2	733	860	0.02
138	200	13.6	733	860	.01 to 0.04
276	400	27.2	733	860	.02 to .03

TABLE IV. - MEASURED FUNCTIONAL DEPENDENCE OF OXIDES OF NITROGEN EMISSIONS ON PRESSURE ($NO_x \sim \delta^x$) FOR SWIRL-CAN MODELS 1 to 11

Model	Value of x	Model	Value of x
1	0.48	7	0.27
2	.61	8	.37
3	.50	9	.74
4	.60	10	.66
5	.62	11	.70
6	.39		

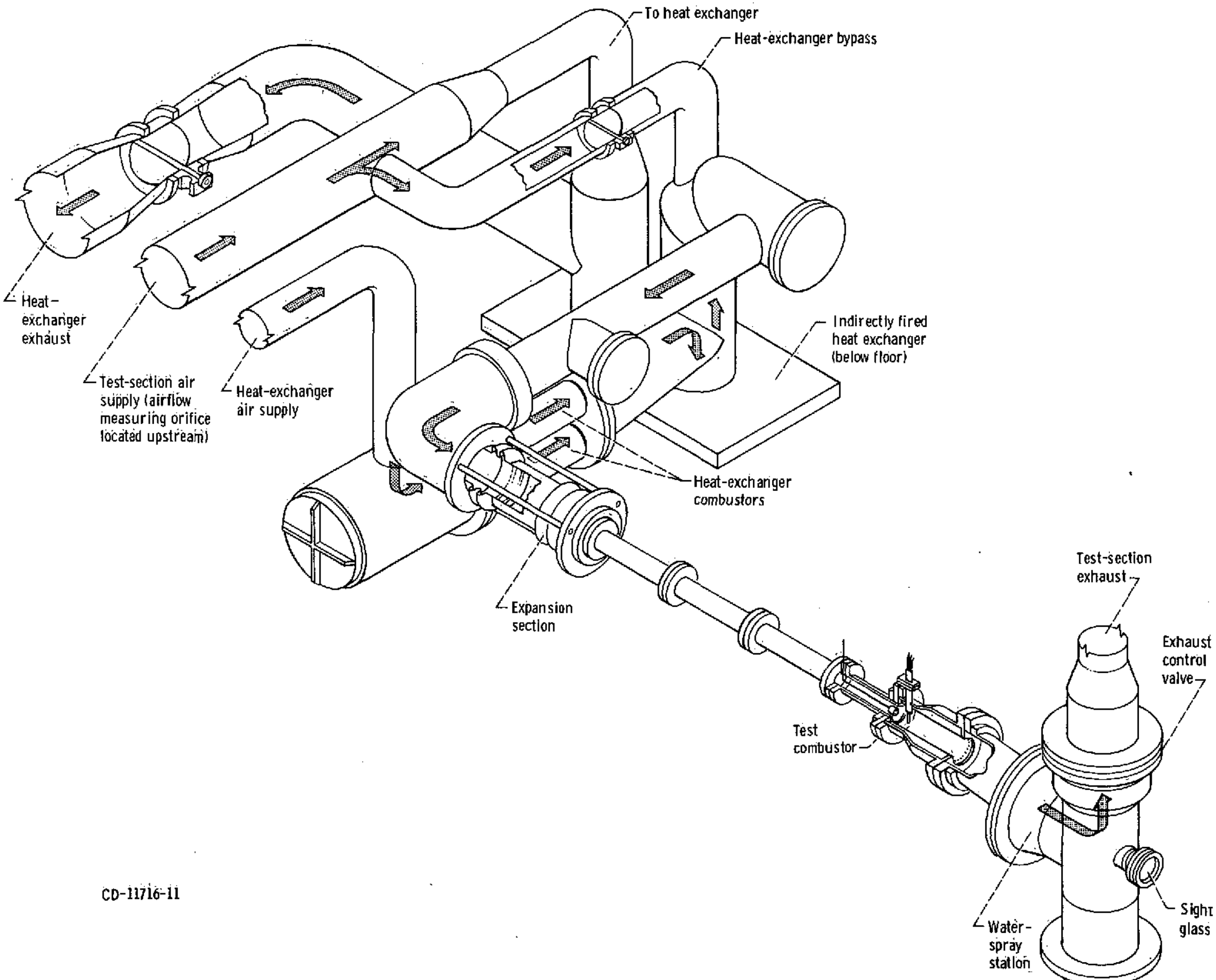


Figure 1. - High pressure test facility.

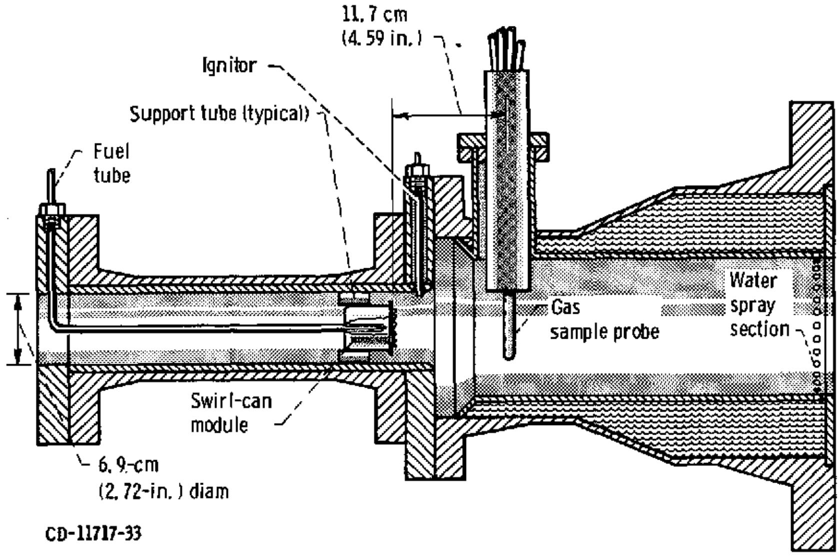


Figure 2. - Combustor test section for single swirl-can module tests.

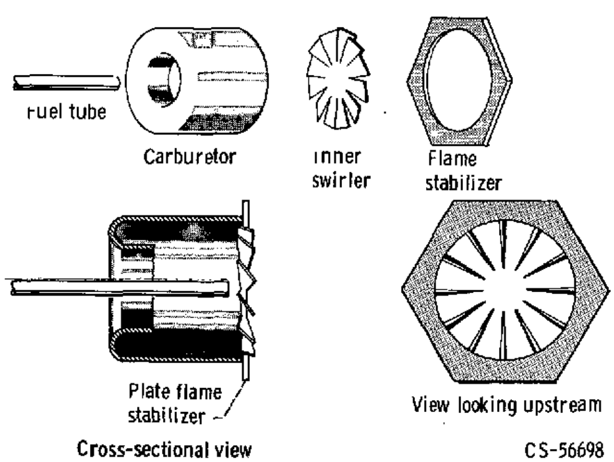
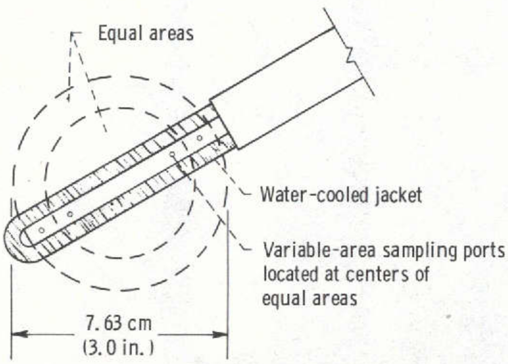
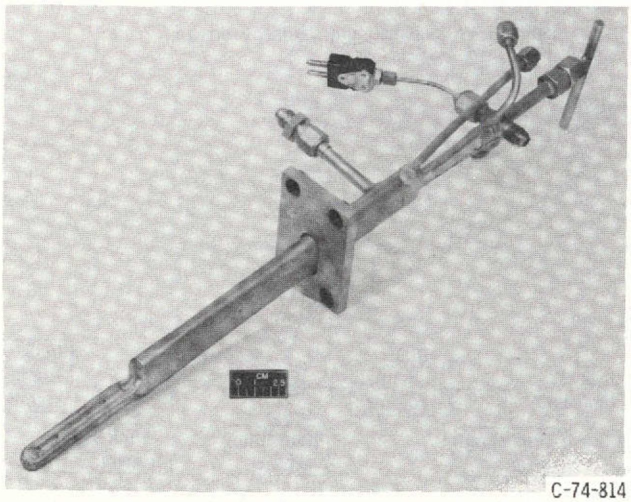


Figure 3. - Typical swirl-can combustor module details.





C-74-814

Figure 4. - Variable flow gas sample probe.

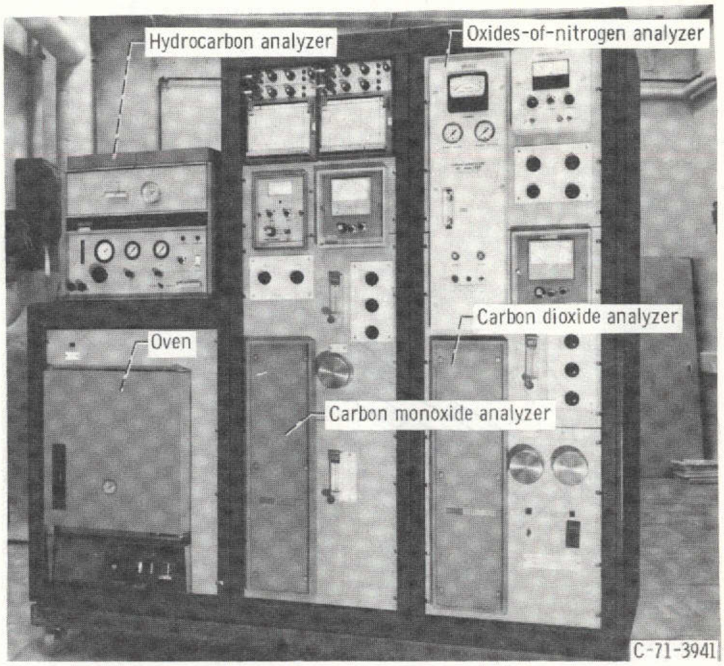


Figure 5. - Gas sampling instrument console.

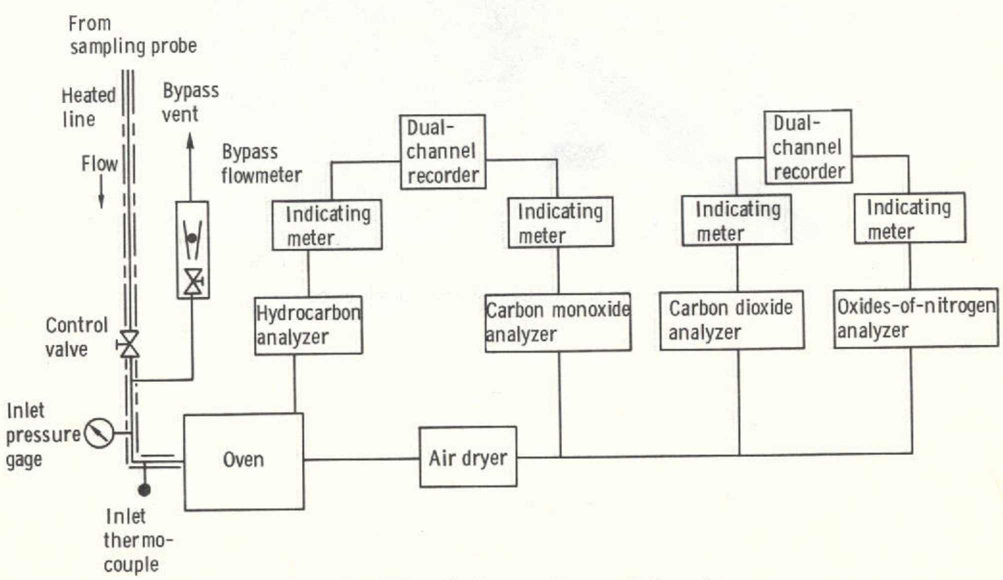
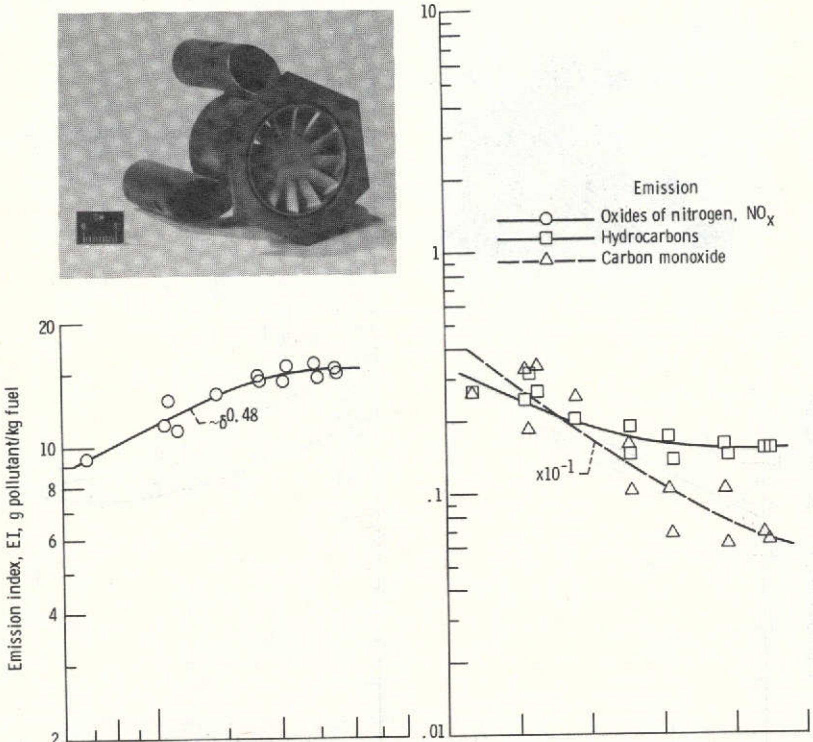
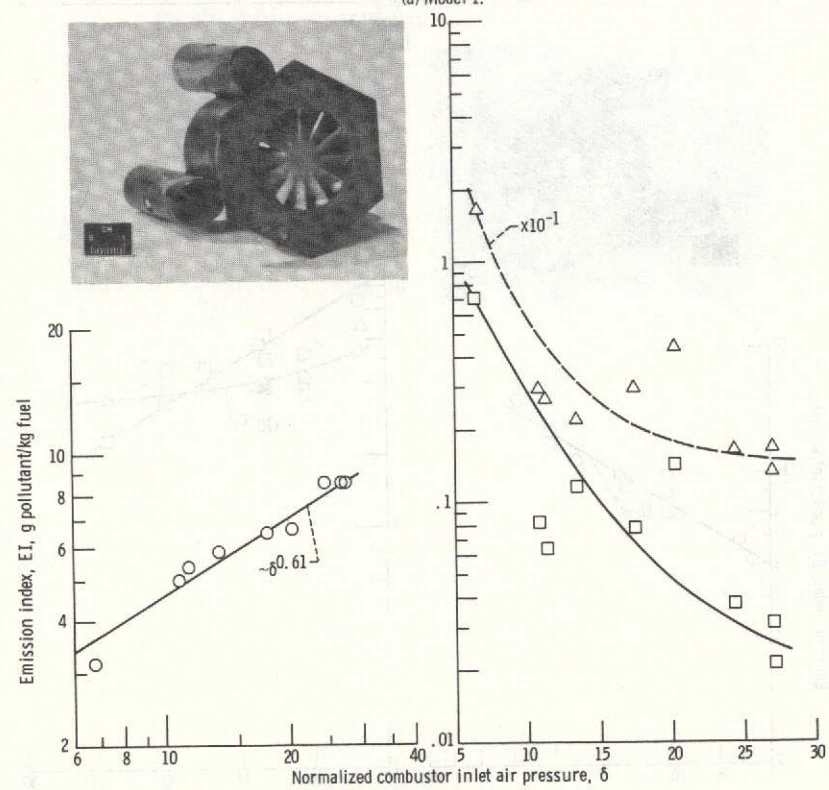


Figure 6. - Schematic diagram of gas analysis system.

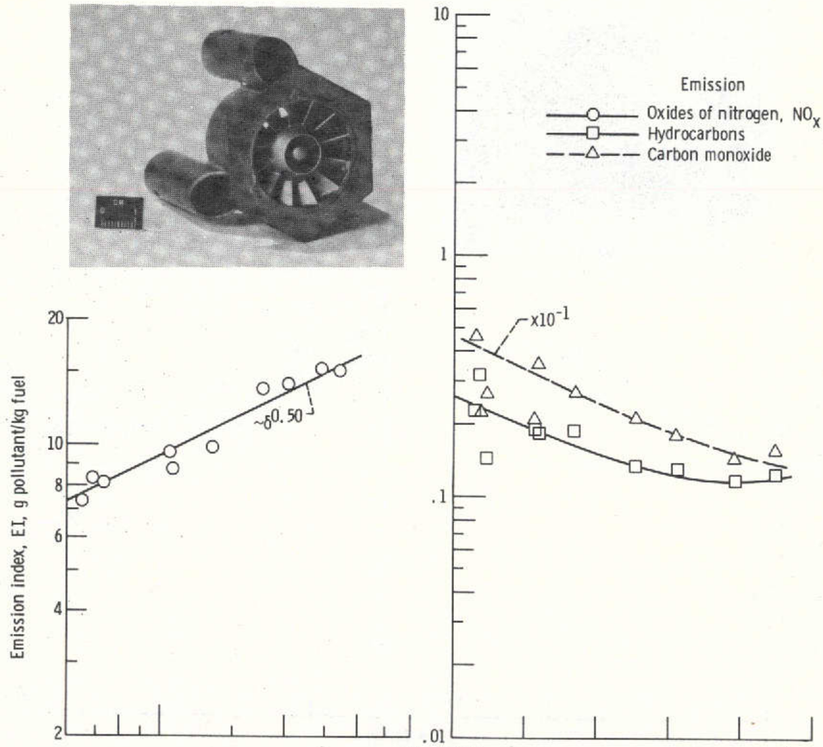


(a) Model 1.

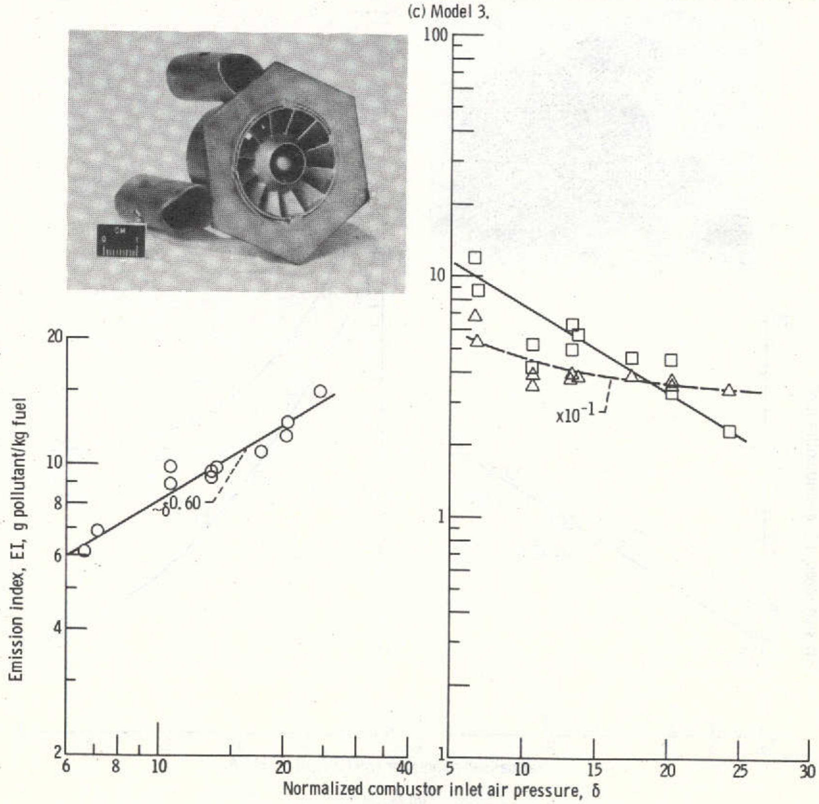


(b) Model 2.

Figure 7. - Exhaust emissions as functions of pressure. Inlet temperature, 733 K (860° F); reference velocity, 23.2 meters per second (76 ft/sec); fuel-air ratio, 0.02. (The NO_x pollutant is represented as grams of NO_2, and the hydrocarbon pollutant is represented as grams of CH_2.)

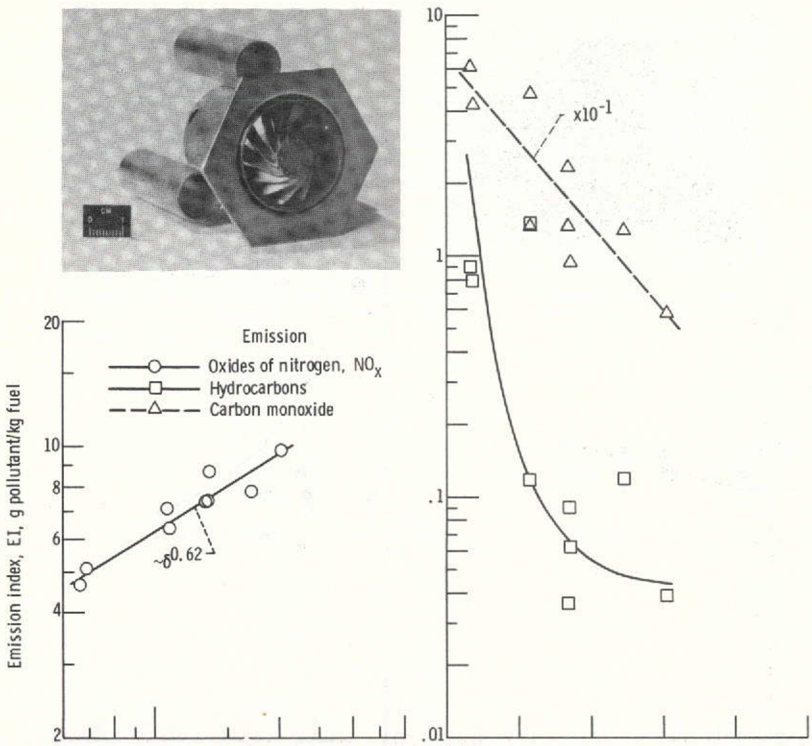


(c) Model 3.

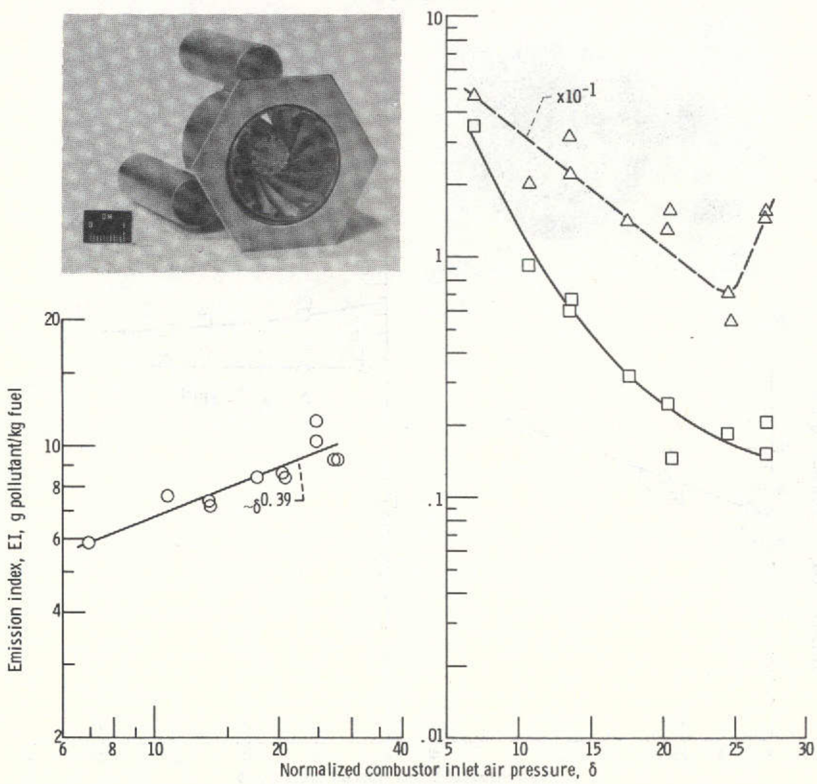


(d) Model 4.

Figure 7. - Continued.

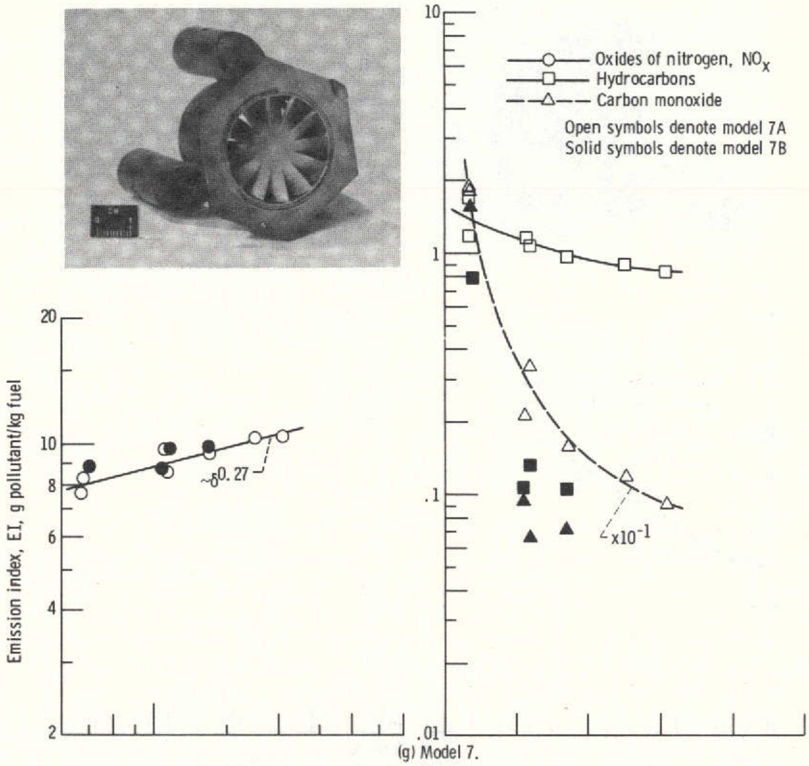


(e) Model 5.

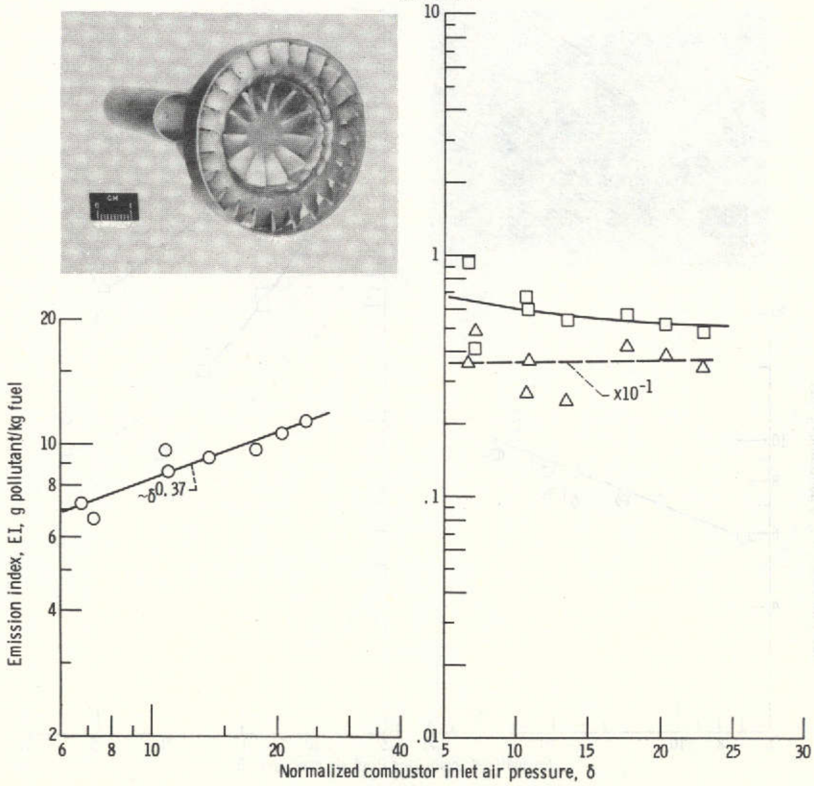


(f) Model 6.

Figure 7. - Continued.

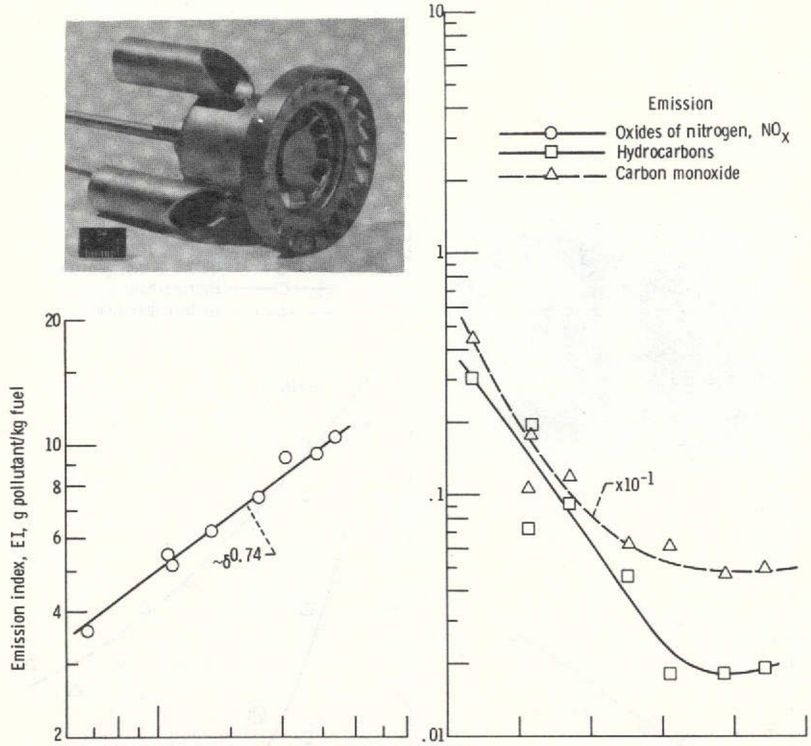


(g) Model 7.

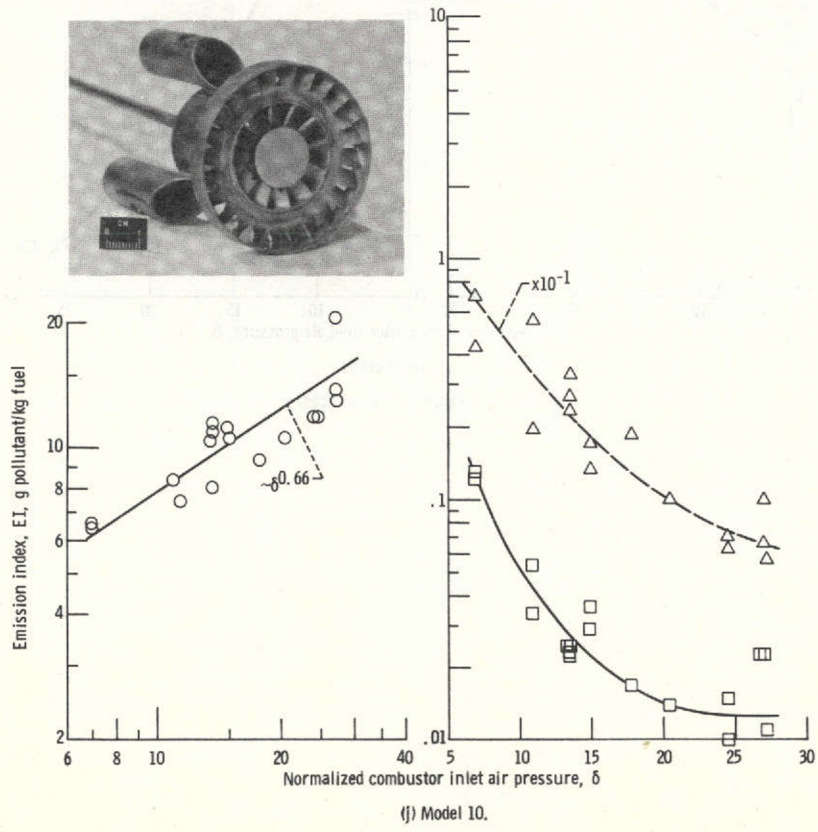


(h) Model 8.

Figure 7. - Continued.

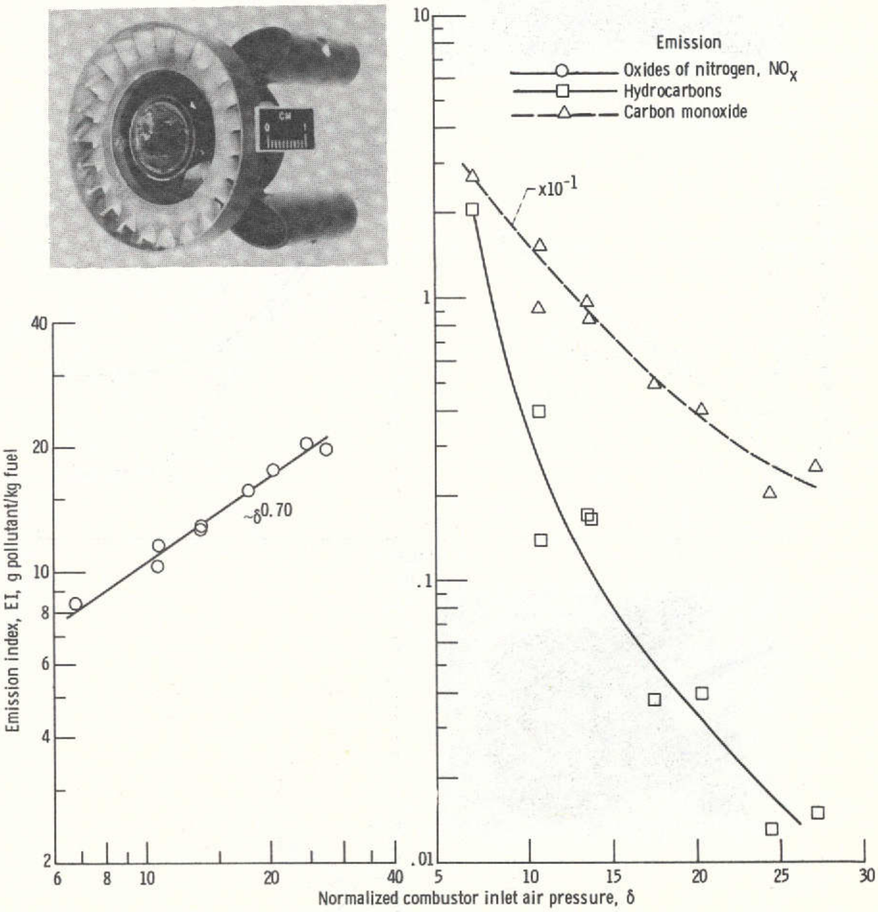


(i) Model 9.



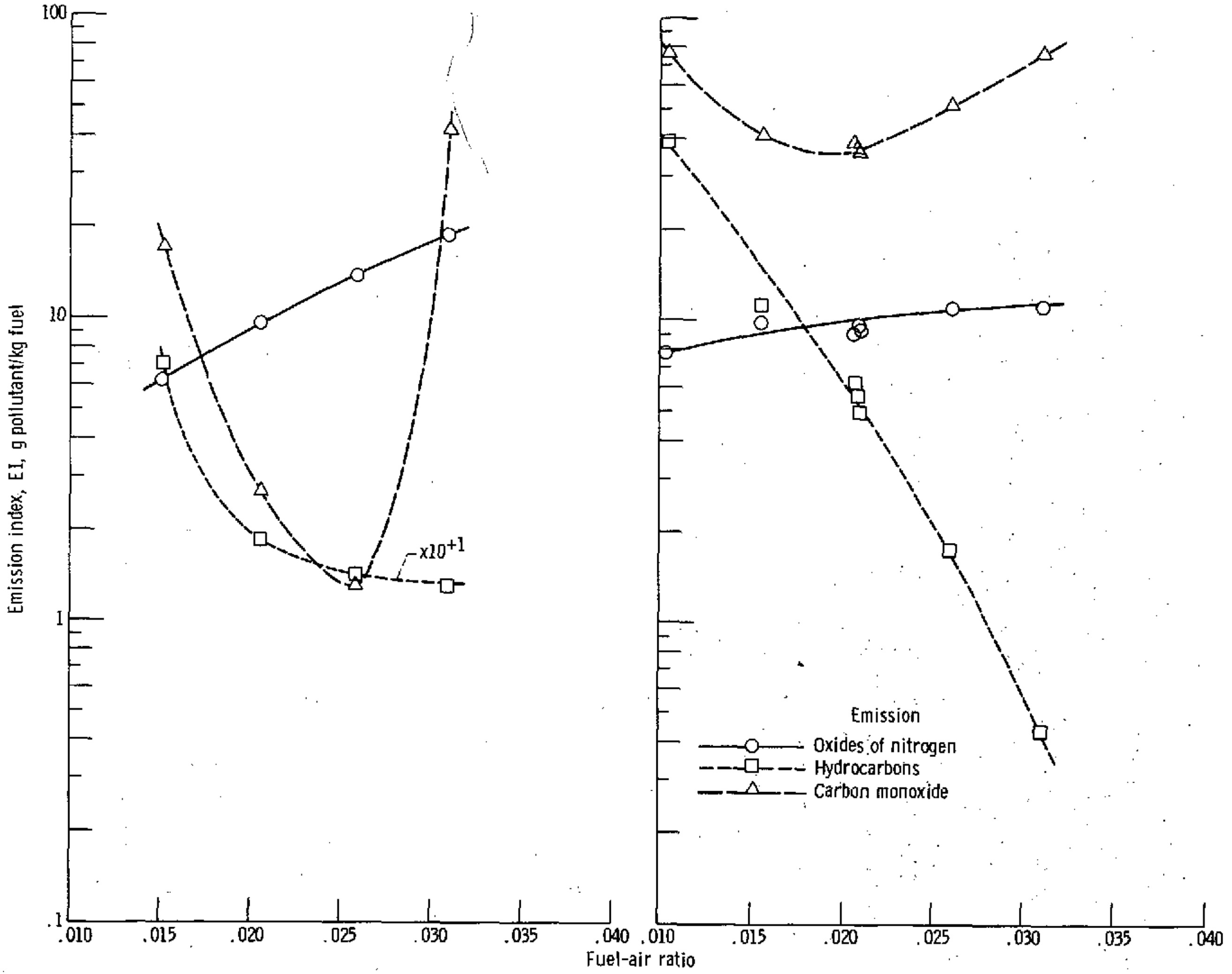
(j) Model 10.

Figure 7. - Continued.



(k) Model 11.

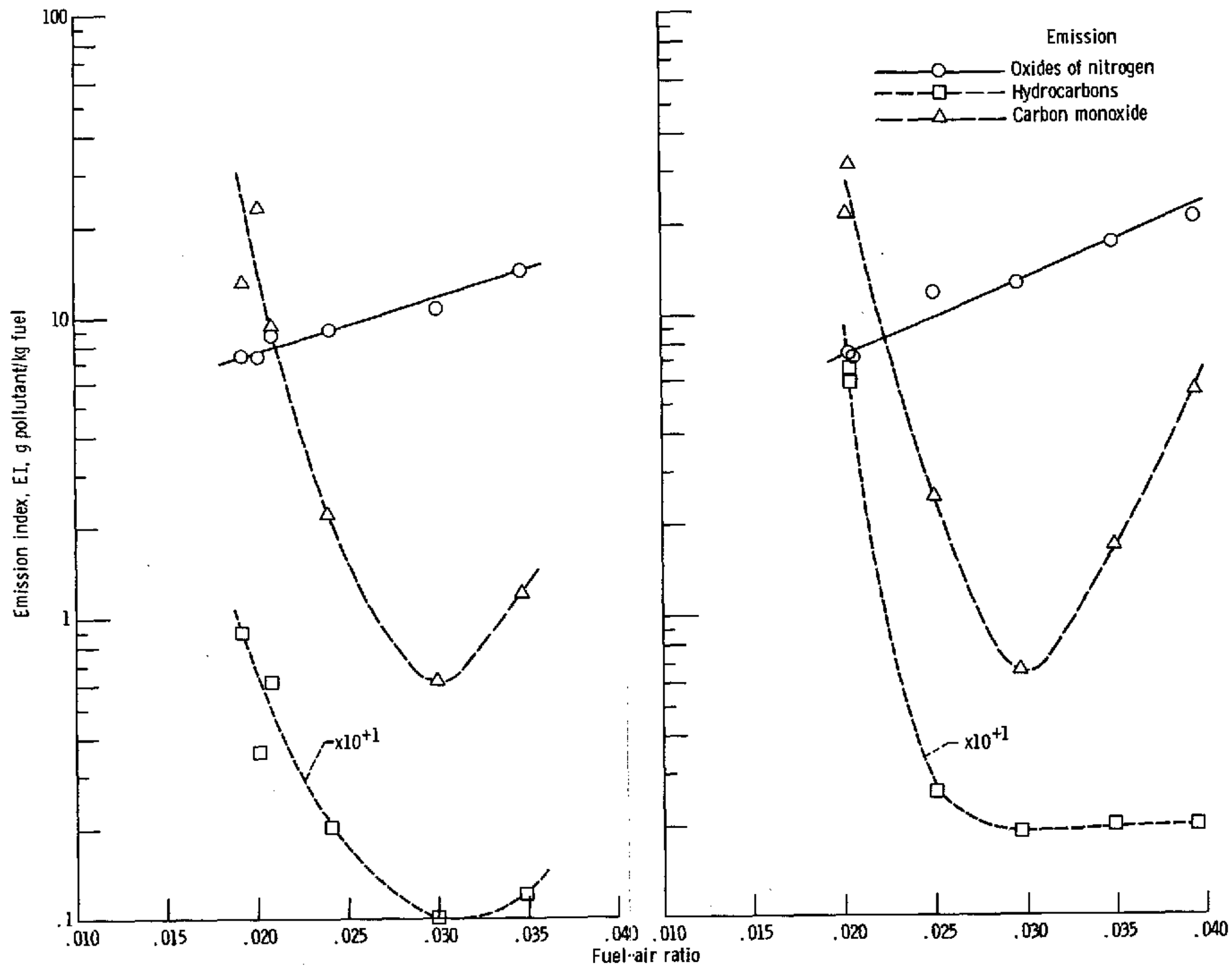
Figure 7. - Concluded.



(a) Model 3; combustor inlet air pressure, 138 newtons per square centimeter (200 psia; δ = 13.6).

(b) Model 4; combustor inlet air pressure, 138 newtons per square centimeter (200 psia; δ = 13.6).

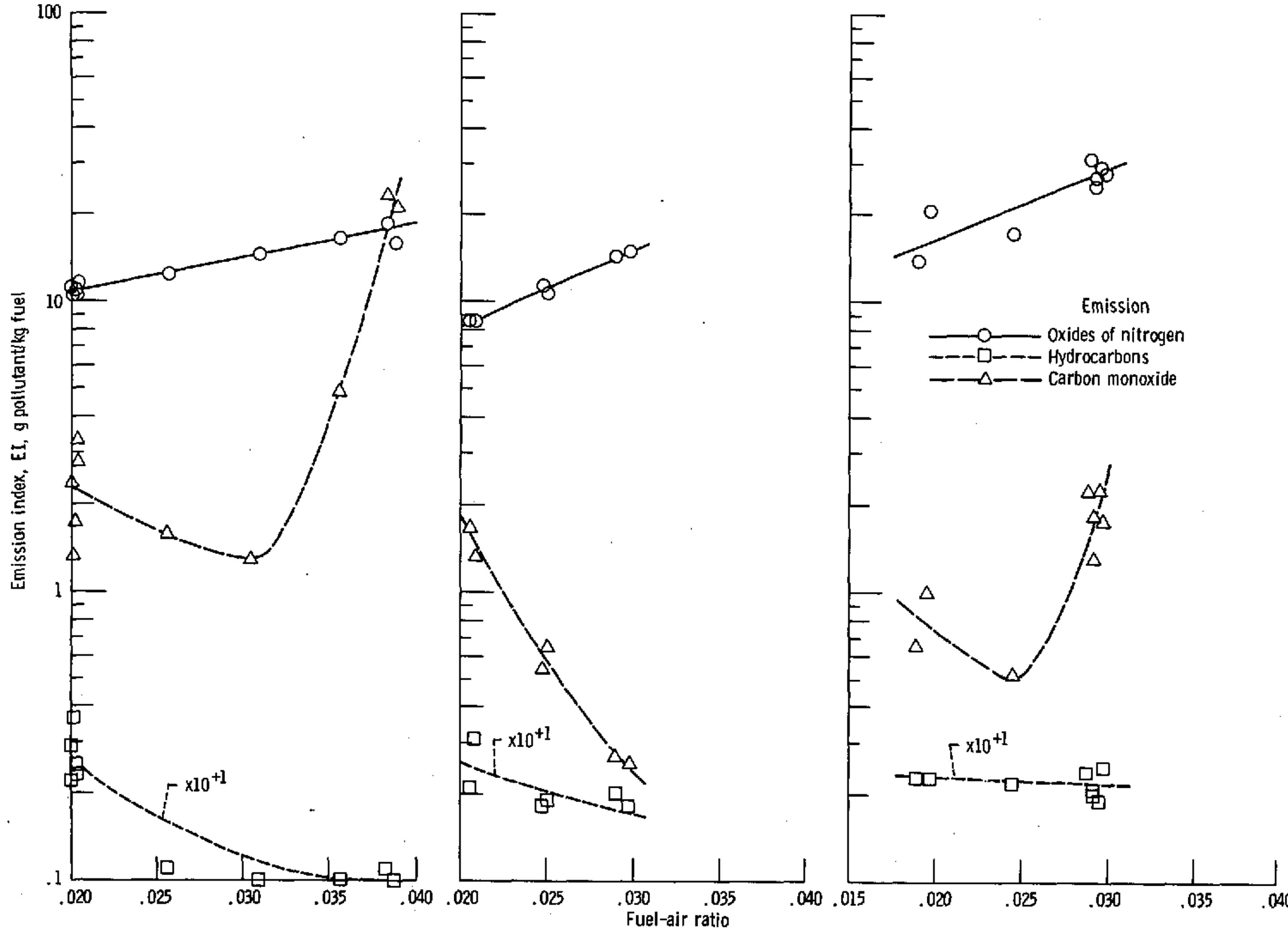
Figure 8. - Exhaust emissions as function of metered fuel-air ratio. Temperature, 733 K (860° F); reference velocity, 23.2 meters per second (76 ft/sec).



(c) Model 5; combustor inlet air pressure, 138 newtons per square centimeter (200 psia; δ = 13.6).

(d) Model 6; combustor inlet air pressure, 138 newtons per square centimeter (200 psia; δ = 13.6).

Figure 8. - Continued.

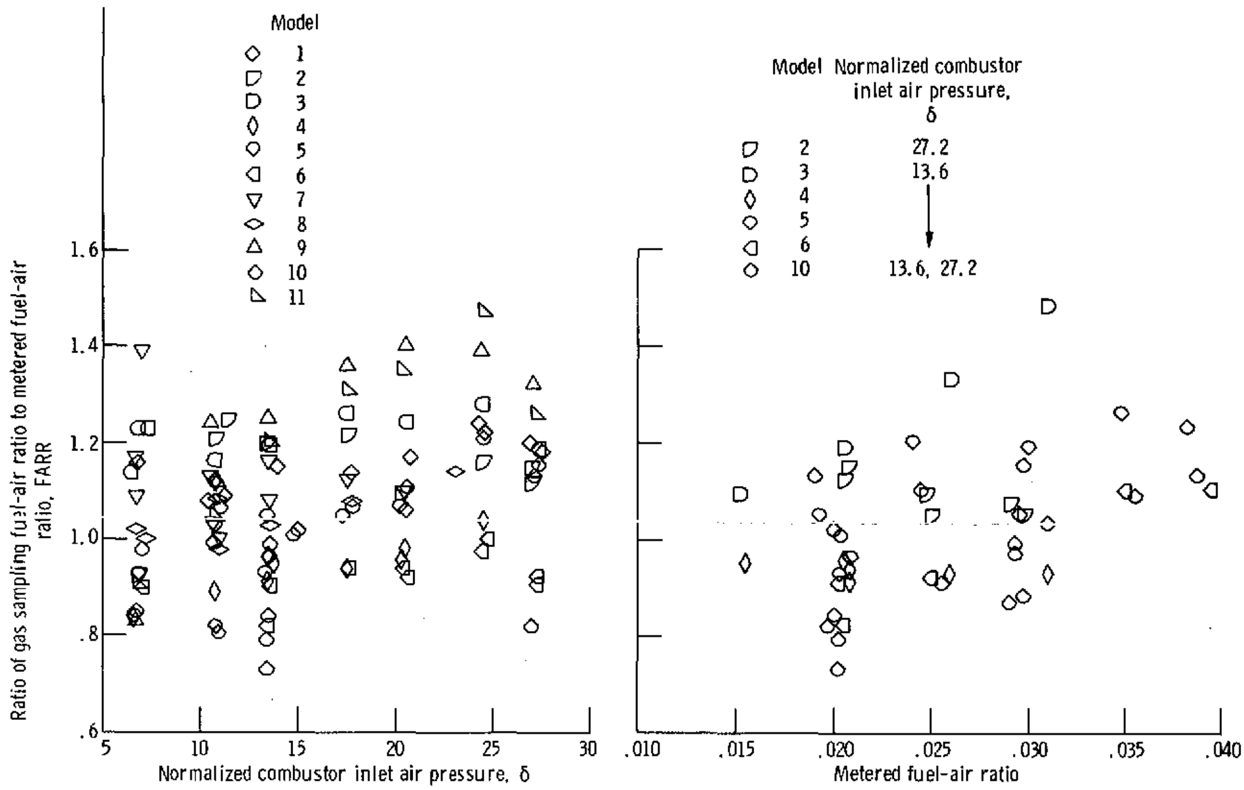


(e) Model 10; combustor inlet air pressure, 138 newtons per square centimeter (200 psia; δ = 13.6).

(f) Model 2; combustor inlet air pressure, 276 newtons per square centimeter (400 psia; δ = 27.2).

(g) Model 10; combustor inlet air pressure, 276 newtons per square centimeter (400 psia; δ = 27.2).

Figure 8. - Concluded.



(a) FARR as function of pressure; metered fuel-air ratio, 0.02.

(b) FARR as function of metered fuel-air ratio.

Figure 9. - Ratio of gas sampling fuel-air ratio to metered fuel-air ratio (FARR) for emissions data. Inlet temperature, 733 K (860° F); reference velocity, 23.2 meters per second (76 ft/sec).

NASA-Langley, 1975 E-8017