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HIGH-PRESSURE COMBUSTOR EXHAUST EMISSIONS WITH IMPROVED AIR-ATOMIZING AND CONVENTIONAL PRESSURE-ATOMIZING FUEL NOZZLES

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16. Abstract

A high-pressure combustor segment 0.456 meter (18 in.) long with a maximum cross section of 0.153 by 0.305 meter (6 by 12 in.) was tested with specially designed air-atomizing and conventional pressure-atomizing fuel nozzles at inlet-air temperatures of 340 to 755 K (610° to 1360° R), reference velocities of 12.4 to 26.1 meters per second (41 to 86 ft/sec), and fuel-air ratios of 0.008 to 0.020. Increasing inlet-air pressure from 4 to 20 atmospheres generally increased smoke number and nitric oxide, but decreased carbon monoxide and unburned hydrocarbon concentrations with air-atomizing and pressure-atomizing nozzles. Emission indexes for carbon monoxide and unburned hydrocarbons were lower at 4, 10, and 20 atmospheres, and nitric oxide emission indexes were lower at 10 and 20 atmospheres with air-atomizing than with pressure-atomizing nozzles.

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HIGH-PRESSURE COMBUSTOR EXHAUST EMISSIONS WITH IMPROVED AIR-ATOMIZING AND CONVENTIONAL PRESSURE-ATOMIZING FUEL NOZZLES

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SUMMARY

In order to compare exhaust pollutant emissions and performance characteristics obtained with air-atomizing and pressure-atomizing fuel nozzles, a high pressure combustor was tested by burning ASTM A-1 fuel at inlet-air pressures up to 20 atmospheres. The rectangular combustor segment has a cross section of 0.053 by 0.305 meter (2.1 by 12 in.) at the diffuser inlet, 0.051 by 0.305 meter (2 by 12 in.) at the combustor exit, and a maximum combustor cross section of 0.153 by 0.305 meter (6 by 12). The combustor length was 0.456 meter (18 in.), which included the diffuser. A snout open area of 40 percent of the combustor inlet area was used to admit air into the combustor primary zone.

Increasing the inlet-air pressure from 4 to 20 atmospheres generally increased smoke number and the nitric oxide emission index, but decreased the carbon monoxide and unburned hydrocarbon concentrations for both air-atomizing splash-cone nozzles and pressure-atomizing nozzles. Emission indexes for carbon monoxide and unburned hydrocarbons were lower at 4, 10, and 20 atmospheres, and nitric oxide emission indexes were lower at 10 and 20 atmospheres with air-atomizing than with pressure-atomizing nozzles. Exhaust smoke numbers were near the visible limit (25±5) with air-atomizing splash-cone and pressure-atomizing nozzles at an inlet-air temperature of 590 K (1060° R). This temperature was considerably below 755 K (1360° R), the design takeoff inlet-air temperature, which would tend to give even lower smoke numbers.

Data were obtained over a fuel-air ratio range of 0.008 to 0.020, inlet-air temperatures of 340 to 755 K (610° to 1360° R), and reference velocities of 12.4 to 26.1 meters per second (41 to 86 ft/sec). Combustion efficiencies were approximately 100 percent for both the improved air-atomizing and the conventional pressure-atomizing fuel nozzles. Air-atomizing nozzles were tested under ambient flow conditions in a full-scale Lucite model of the combustor to determine spray patterns produced by water injection. Photographs taken at several water-air ratios and reference velocities showed that a splash-cone type of air-atomizing nozzle gave a better distribution of liquid and a finer spray of water droplets than that obtained with a radial-jet type of air atomizer. Thus, only a limited number of combustor tests were made with radial-jet nozzles since it was found that smoke numbers were relatively high compared with splash-cone nozzles, as expected from the water spray tests.

INTRODUCTION

High-pressure combustor tests were made to determine pollutant emissions and performance characteristics obtained with low-fuel-pressure-drop air-atomizing fuel nozzles designed to utilize the air-stream momentum in atomizing ASTM A-1 fuel. Similar tests were made with pressure-atomizing fuel nozzles for comparison.

With the present trend in development toward advanced turbojet engines with high compressor-pressure ratios (ref. 1), the problem of developing low pollutant combustors has become more difficult at the resulting high levels of inlet-air pressure and temperature. High inlet-air temperature produces high concentrations of nitric oxide due to high primary-zone flame temperature. Also, theory predicts a marked increase in nitric oxide concentration with increasing combustor pressure, particularly when the equivalence ratio is near unity in the primary zone (ref. 2).

Experimental studies with gas-turbine engines have demonstrated that high engine pressure ratios produce high nitric oxide concentrations (ref. 3). In addition the problem of high exhaust smoke concentrations produced at high combustor pressures was demonstrated recently with the use of pressure-atomizing fuel nozzles (ref. 4). Thus, similar studies are needed with air-atomizing fuel nozzles or other types that might give lower concentrations of pollutants at high combustor pressures and temperatures. Preliminary studies with low pressure-drop fuel nozzles in swirl-can combustor modules have shown considerable promise in giving low pollutants at a combustor pressure of 4 atmospheres and high inlet-air temperatures (ref. 3).

One of the main advantages of air-atomizing fuel nozzles is their flexibility in design in producing fuel sprays that spread out fairly uniformly across the airstream. With improved atomization and mixing obtained from air-atomizing fuel nozzles, it would be expected that nitric oxide concentrations could be reduced (ref. 5). Besides being relatively simple in design and fabrication, air-atomizing fuel nozzles are less susceptible to fuel fouling at high inlet-air temperatures as compared with the pressure-atomizing type.

To evaluate performance and pollutant emissions, the following combustor characteristics were determined: combustion efficiency, total pressure loss, emission indexes for nitric oxide, carbon monoxide, and unburned hydrocarbons, exhaust smoke number, liner temperature, and blowout data. Other factors considered were the effect of inlet-air total pressure and temperature and fuel-air ratio on combustor characteristics. Test conditions included a fuel-air ratio range of 0.008 to 0.020 at inlet-air total pressures of 4 to 20 atmospheres, inlet-air temperatures of 340 to 755 K (610° to 1360° R), and reference velocities of 12.4 to 26.1 meters per second (41 to 86 ft/sec). Performance and emission characteristics obtained with the splash-cone air-atomizing nozzle configuration are described in detail and compared with results obtained with pressure-atomizing fuel nozzles. Limited data were obtained with radial-jet air-atomizing fuel nozzles in order to select the better of the two air-atomizing nozzle designs.

APPARATUS AND PROCEDURE

Test Facility

The test combustor mounted in the closed-duct test facility shown in figure 1 is described in more detail in reference 4. The combustor was tested at inlet-air pressures up to 20 atmospheres and temperatures up to 755 K (1360° R). Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to 700 K (1260° R) in a counterflow U-tube heat exchanger.

The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of bypassed air. To obtain an air temperature of 755 K (1360° R), the air was further heated with a natural gas vitiating heater mounted downstream of the heat exchanger. Airflow through the heat exchanger and bypass flow system and the combustor inlet-air pressure were regulated by remote control valves.

Test Section

The combustor was mounted in the counterflow high-pressure test section shown in figure 1. As a safety precaution in the event of a fuel leak, the counterflow arrangement prevented an accumulation of fuel in the housing. Combustion air flowed through the outer annular passage, reversing its flow direction through the inner annular passage surrounding the combustor, and was finally deflected by the dome into the diffuser. The bellmouth upstream of the combustor gave a uniform airflow distribution at the diffuser inlet.

Test Combustor

The test combustor shown in detail in figure 2 was a rectangular segment which simulated an annular combustor design. The overall combustor length of 0.456 meter (18 in.) included a diffuser length of 0.140 meter (5.5 in.) and a burner length of 0.316 meter (12.5 in.). The cross section of the combustor measured to be 0.053 by 0.305

meter (2.1 by 12 in.) at the diffuser inlet, 0.051 by 0.305 meter (2 by 12 in.) at the combustor exit, and 0.153 by 0.305 meter (6 by 12 in.) at the midsection of the combustor. The inlet snout open area was 40 percent of the combustor inlet area. A detailed description of airflow in the primary and secondary mixing zones of the combustor is given in the discussion of combustor model 3 in reference 4.

A jet fuel conforming to ASTM A-1 specifications was used in all of the tests. The fuel had an average hydrogen to carbon ratio of 0.161 and a lower heating value of 43 000 joules per gram (18 600 Btu/lb). Ignition was obtained with a capacitor ignitor with a maximum energy of 12 joules.

Fuel atomizers. - A specially designed air-atomizing splash-cone nozzle configuration shown in figure 3(a) was used in most of the combustor tests. Fuel was injected through four equally spaced orifices (0.16-cm (0.063-in.) diam) and splashed against the curved base of a stainless-steel conical plug mounted on the end of the fuel tube. This tended to break up the jets into sheets of fuel that were then atomized by the swirling airstream passing through the air swirler and accelerating through the snout nozzle adjacent to the atomizer. An air-atomizing radial jet nozzle configuration shown in figure 3(b) was used in ambient airflow water-spray tests and smoke tests for comparison with splash-cone nozzles.

Two simplex pressure-atomizing fuel nozzles (fig. 3(c)) were used in combustor tests for comparison with the splash-cone nozzles. Pressure-atomizing nozzle 2 was similar to that used in reference 4. It was considerably smaller than nozzle 1 and had a lower pressure-drop fuel-swirler design. However, both gave a spray angle of approximately 90°. Variation in flow rate with fuel pressure drop is given in table I for the air-atomizing splash-cone nozzle and both types of pressure-atomizing nozzles.

Instrumentation and data acquisition. - Combustor instrumentation stations are shown schematically in figure 2, and detailed locations are given in reference 4. Inlet-air total temperature and pressure were measured at station 1 in the diffuser inlet with four stationary rakes consisting of two chromel-alumel thermocouples and three total pressure tubes, respectively, in each rake. Wall static-pressure taps were centrally located in the top and bottom of the diffuser. Combustor exhaust temperature and pressure measurements and smoke samples were obtained with the probe by traversing the combustor exit at station 2. The probe consisted of 12 elements: five aspirating platinum/platinum - 13-percent-rhodium total temperature thermocouples, five total pressure tubes, and two wedge-shaped static pressure tubes. Smoke samples were withdrawn through the aspirating thermocouple lines. A detailed description of the probe is given in reference 4. The incremental travel and dwell time of the probe were controlled by automatic adjustable counters. Combustor outlet temperature and pressures were taken for every 1.27 centimeters (0.50 in.) of travel for 23 locations across the combustor exhaust.

Combustion air flow was measured with sharp-edged orifices, installed according to ASME specifications. ASTM A-1 fuel flows were measured with two turbine flowmeters connected in series. Redundancy in measurement permitted a crosscheck on flowmeter accuracy. Three sets of flowmeters were required to cover the fuel flow range. All data were recorded on a punched paper tape and processed by the Lewis data processing system.

Smoke measurement. - Exhaust smoke numbers were determined with the smoke meter shown in figure 4 in accordance with SAE Aerospace Recommended Practice (ARP 1179 (ref. 6)). Exhaust gas samples were withdrawn through the movable exhaust probe which traversed the combustor exit at station 2 as shown in figure 2. The gas flow rate at standard conditions was 2.36×10^{-4} cubic meter per second (0.50 ft^3/min), and four smoke samples were obtained at each test condition for a time duration of 12, 22, 36, and 72 seconds, respectively. From a plot of smoke number against weight of gas samples per square centimeter of filter, the smoke number at 1.623 grams of gas per square centimeter of filter (0.0230 lb of gas/$in.^2$ of filter) was determined.

Exhaust pollutant measurement. - Exhaust pollutant concentrations of nitric oxide, carbon monoxide, and unburned hydrocarbons were determined with the gas-anslysis equipment shown in figure 5 in accordance with Aerospace Recommended Practice (ARP 1256 (ref. 7)). Exhaust gas samples were withdrawn through the air-cooled stationary sampling probe shown in figure 6, which was mounted approximately 0.92 meter (3 ft) downstream of the traversing probe and in the center of the exhaust gas stream as shown in figure 1. The traversing probe used in smoke sampling was not used in this case because its platinum construction would affect the reliability of the determinations of nitric oxide concentrations. Gas samples at a pressure of approximately 2 atmospheres were passed through an electrically heated sampling line at a temperature of approximately 450 K (810° R) to the gas analyzer. Most of the sample flow passed through the analyzer oven while excess flow was bypassed to the exhaust system. To prevent fuel accumulation in the sample line, a nitrogen purge was used just before and during combustor ignition.

Sample flow leaving the analyzer oven was divided into three parts and analyzed accordingly. Concentrations of nitric oxide, carbon monoxide, and unburned hydrocarbon were measured by the chemiluminescence, nondispersed infrared, and flame ionization methods, respectively. In the first portion of this study nitric oxide concentrations were determined by means of a nondispersed infrared technique before converting to the chemiluminescence method. Concentrations were reported on a dry basis for nitric oxide and carbon monoxide, and on a wet basis for unburned hydrocarbon. Also, nitric oxide emission indexes were expressed as grams of nitrogen oxide (NO_2) per kilogram of fuel.

Flame radiance. - Total flame radiance in the primary zone was determined with an infrared radiometer at the station shown in figure 1. This instrument and methods of calculating radiance are described in reference 8.

Calculations

The customary English system of units was used in primary measurements. Conversions to SI units (Systems International d'Unites) were made for reporting purposes, only. In making the conversion, consideration is given to implied accuracy and generally result in rounding off the values expressed in SI units.

Combustion efficiency. - The combustion efficiency, defined as the ratio of actual to theoretical temperature rise, was calculated from the inlet-air temperature and the average mass-weighted exit temperature obtained from the total number of temperature readings taken at the combustor exit plane.

Reference velocity and Mach number. - Combustor reference velocity was computed from the measured total airflow, the maximum cross-sectional area of the combustor (0.047 m^2 (72 $in.^2$)), and the air density based on the total pressure and temperature at the diffuser inlet. The diffuser inlet Mach number was determined from the measured total airflow, and the static pressure at the diffuser inlet.

Total pressure loss. - Combustor total pressure loss, $\Delta P/P$ includes the diffuser pressure loss and is defined as follows:

$$\frac{\Delta P}{P} = \frac{(\text{Average diffuser inlet total pressure}) - (\text{Average combustor exit total pressure})}{\text{Average diffuser inlet total pressure}}$$

Smoke number. - Smoke spots on the filter tape were analyzed with a reflective densitometer calibrated with a Welsh Gray scale. Smoke numbers, as defined in ARP 1179 (ref. 6) were determined from the following expression:

$$\text{Smoke number} = 100(1 - r)$$

where r is the ratio of the percent of absolute reflectivity of the smoke spot to that of the clean filter tape.

Liner temperature. - Nine chromel-alumel thermocouples were installed in the combustor liner walls. The 0.15-centimeter (0.06-in.) diameter thermocouple sheaths were imbedded in liner-wall grooves, and thermocouple junctions were filled with high-temperature braze. Figure 2 shows the location of three thermocouples in the top and three in the bottom liner. The remaining three were located in the top liner in the same distance downstream of the fuel nozzles, but were displaced 0.095 meter (3.75 in.) to the left of the combustor centerline looking downstream. The three thermocouples located 0.051 meter (2 in.) downstream of the fuel nozzles were arithmetically averaged to obtain the average liner temperature at that station.

RESULTS AND DISCUSSION

To determine performance characteristics and exhaust pollutant emissions with air-atomizing and pressure-atomizing fuel nozzles, the combustor was tested over a range of inlet-air pressures and temperatures by burning ASTM A-1 fuel over a range of fuel-air ratios. The test conditions are given in table II. The combustor reference velocity was 21.3 meters per second (70 ft/sec) except when it was varied from 12.4 to 26.1 meters per second (41 to 86 ft/sec) for blowout data. From the combustor tests with air-atomizing and pressure-atomizing fuel nozzles, the following combustor characteristics were compared: combustion efficiency, total-pressure loss, emission indexes for nitric oxide, carbon monoxide, and unburned hydrocarbons, exhaust smoke number, liner temperature, and blowout data.

Initially, two types of air-atomizing nozzles were tested under ambient flow conditions in a full-scale Lucite model of the combustor to determine water-spray patterns. The series of four photographs in figure 7 were taken at simulated fuel-air ratios of 0.004 and 0.025 and reference velocities of 30.5 and 76.3 meters per second (100 and 250 ft/sec). These photographs indicated that increasing airstream momentum and fuel flow rate considerably improved atomization and fuel spreading. Also, the splash-cone air-atomizing nozzle gave a much better spray distribution of fine water droplets than that observed with the radial-jet air atomizer. Thus, the splash-cone air-atomizing nozzle was chosen for most combustor tests.

Combustor Performance Characteristics

Combustion efficiency. - As shown in figure 8 there was no appreciable difference between combustion efficiencies obtained with the splash-cone air-atomizing and pressure-atomizing nozzles 1 and 2. Except for radial-jet fuel nozzles, all combustion efficiencies were near 100 percent over the range of fuel-air ratios at inlet-air pressures of 10 and 20 atmospheres and an inlet-air temperatures of 590 K (1060° R). Radial-jet nozzles gave the lowest combustion efficiencies.

Combustor total pressure loss. - No appreciable difference in the air flow isothermal total-pressure loss is shown (fig. 9) for the air-atomizing and pressure-atomizing nozzles. No attempt was made to reduce the combustor total pressure loss which, it should be noted, includes that of the diffuser.

Exhaust Pollutant Emissions

Combustion efficiencies, as discussed in the previous section, agreed within 10 percent of calculated values based on the unburned hydrocarbon and carbon monoxide concentrations determined in the gas samples. Also, carbon dioxide concentrations were determined in the gas samples, and fuel-air ratios were calculated that agreed to within 15 percent of experimental values. Thus, the gas sampling technique appeared to give fairly representative samples of the exhaust gas.

Nitric oxide. - Nitric oxide emission data were obtained with the splash-cone air-atomizing and the pressure-atomizing nozzle 2. These data are shown in figure 10 as a function of fuel-air ratio at inlet-air pressures of 4, 10, and 20 atmospheres and an inlet-air temperature of 590 K (1060° R), which was the maximum temperature obtained with the indirect fired heater at 20 atmospheres pressure. Emission indexes did not show any appreciable or consistent trend with fuel-air ratio. However, at 10 atmospheres, a considerable increase in emission index was obtained by increasing inlet-air temperature from 590 to 700 K (1060° to 1260° R; see fig. 10(b)). Tests were not made with splash-cone nozzles at the higher inlet-air temperature. No nitric oxide data were obtained while using the vitiating heater.

In order to compare the results obtained with splash-cone and pressure-atomizing nozzles, a cross plot of the data at a fuel-air ratio of 0.015 was made as shown in figure 11. Emission index generally increased with increasing inlet-air pressure. However, there was a considerable drop in emission index with the splash-cone nozzle when inlet-air pressure was increased from 10 to 20 atmospheres. This was attributed to improved atomization of the fuel, which was demonstrated in figure 7 when airstream momentum was increased by increasing airstream velocity. In this case, momentum was increased by increasing the airstream density. Thus, at an inlet-air pressure of 20 atmospheres, the nitrogen-oxide emission index was considerably lower with the splash-cone air-atomizing nozzle than with the pressure-atomizing nozzle 2. Also, in this comparison, inlet-air temperature was somewhat below the design takeoff condition of 20 atmospheres and 755 K (1360° R) because of the limitations of the direct-fired heater. Thus, emission indexes are below what might be expected at actual takeoff conditions. A theoretical curve from reference 2 is included in figure 11 for comparison (primary-zone equivalence ratio, 1.50). The shape of this curve is quite similar to that of the pressure-atomizing nozzle 2. However, the values of nitric oxide emission index can not be compared directly because an inlet-air temperature of 460 K (830° R) was used in reference 2.

Exhaust smoke number. - Increasing the fuel-air ratio increased exhaust smoke number with the splash-cone air-atomizing nozzle and pressure-atomizing nozzle 2 (figs. 12(a) and (d)) but decreased the exhaust smoke number with the radial-jet nozzle and the pressure-atomizing nozzle 1 (figs. 12(b) and (c)). However, increasing inlet-air temperature consistently decreased exhaust smoke number.

A cross plot of the data as a function of inlet-air pressure, at a fuel-air ratio of 0.015, is shown in figure 13 for comparison. Increasing inlet-air pressure from 4 to 10 atmospheres increased exhaust smoke numbers for all of the fuel nozzles. However, smoke number decreased slightly with the splash-cone nozzle when inlet-air pressure was increased from 10 to 20 atmospheres. As previously mentioned, the nitric oxide emission index decreased in a similar manner. This was attributed to improved fuel atomization when airstream momentum was increased. Thus, with the air-atomizing splash-cone nozzle, an improvement in fuel atomization at high inlet-air pressure tended to counteract the general tendency of smoke number to increase with increasing inlet-air pressure. However, at 20 atmospheres inlet-air pressures, the splash-cone nozzle gave smoke numbers somewhat higher than pressure-atomizing nozzle 2 but lower than that of nozzle 1. Also, it should be noted that inlet-air temperature was somewhat below the design takeoff condition of 20 atmospheres and 755 K (1360° R). Thus, smoke numbers are somewhat higher than might be expected at the design takeoff condition.

An increase in exhaust smoke number gives a corresponding increase in the total radiance of the flame (fig. 14) with the splash-cone air-atomizing and the pressure-atomizing nozzles. Results are comparable with those given in reference 4 for pressure-atomizing nozzles. Thus, the effect of primary zone smoke concentration on the total radiance with splash-cone air-atomizing nozzles is quite similar to that obtained with pressure-atomizing nozzles.

Carbon monoxide and unburned hydrocarbons. - As shown in figures 15 and 16, increasing either inlet-air pressure or temperature decreased carbon monoxide and unburned hydrocarbon emission indexes with the splash-cone and the pressure-atomizing nozzle 2. Data of this type were not obtained with the pressure-atomizing nozzle 1. The comparison between the splash-cone and the pressure-atomizing nozzle 2 shows that both carbon monoxide and unburned hydrocarbons were lower with splash-cone nozzles at an inlet-air temperature of 589 K (1060° R).

Additional Combustor Performance Tests

Blowout tests. - The minimum inlet-air total pressure at which steady combustion could be maintained in the combustor with air-atomizing splash-cone fuel nozzles is shown in figure 17 at a fuel-air ratio of 0.020, an inlet-air total temperature of 339 K (610° R), and two different airflow rates. Although direct comparison can not be made with the pressure-atomizing nozzles used in reference 4, figure 17 shows that similar blowout limits were obtained with swirl-cone nozzles (approximately 0.85 atm at a reference velocity of 16 m/sec (51 ft/sec)). No attempt was made to further improve blowout limits.

Combustor liner temperature. - With splash-cone and pressure-atomizing fuel nozzles, liner temperature decreased with increasing inlet-air pressure (fig. 18). This effect was attributed to increased convective cooling of the liner wall at higher pressures.

SUMMARY OF RESULTS

Performance characteristics and exhaust pollutants for a high-pressure combustor segment using air-atomizing and pressure-atomizing fuel nozzles were compared by burning ASTM A-1 fuel at inlet-air pressures up to 20 atmospheres. Combustion efficiency, total pressure loss, liner temperature, exhaust smoke number, and exhaust emission indexes for nitric oxide, carbon monoxide, and unburned hydrocarbons were determined for comparison. Test conditions included a fuel-air ratio range of 0.008 to 0.020 at inlet-air total pressures of 4, 10, and 20 atmospheres, inlet-air total temperatures of 340 to 755 K (610° to 1360° R), and reference velocities of 12.4 to 26.1 meters per second (41 to 86 ft/sec). The test results are as follows:

1. Combustion efficiencies of nearly 100 percent were obtained with the splash-cone air-atomizing and the conventional pressure-atomizing fuel nozzles. Thus, combustion efficiency was not impaired with the improved air-atomizing fuel nozzles.

2. At an inlet-air pressure of 20 atmospheres, exhaust emission indexes for nitric oxide, carbon monoxide and unburned hydrocarbons were lower with the splash-cone air-atomizing than with pressure-atomizing nozzles. This was attributed to improved fuel atomization and spreading with splash-cone nozzles when inlet-air pressure was increased from 10 to 20 atmospheres.

3. Exhaust smoke numbers were near the visible limit (25±5) with splash-cone air-atomizing and pressure-atomizing nozzles at an inlet-air temperature of 589 K (1060° R). This temperature was considerably below 755 K (1360° R), the design takeoff inlet-air temperature, which would tend to give even lower smoke numbers.

4. Isothermal total pressure loss was nearly the same for air-atomizing and pressure-atomizing nozzles; approximately 4.7 percent at a diffuser inlet Mach number of 0.26. Thus, the use of air-atomizing fuel nozzle configurations did not give excessive flow blockage or appreciably affect isothermal total pressure loss.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 13, 1972,
501-24.

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TABLE I. - FUEL NOZZLE FLOW RATE VARIATION

WITH PRESSURE-DROP

Flow rate		Pressure-atomizing nozzles		Air atomizing splash-cone nozzle
kg/hr	lb/hr	1	2	
		Fuel pressure-drop, atm		
174	382	39.5	16.3	2.5
54.5	120	4	1.7	.2

TABLE II. - COMBUSTOR NOMINAL

TEST CONDITIONS

Inlet-air total pressure, atm					
4		10		20	
Inlet-air total temperature					
K	^{o}R	K	^{o}R	K	^{o}R
422	760	422	760	422	760
589	1060	589	1060	589	1060
756	1360	700	1260	756	1360
		756	1360		

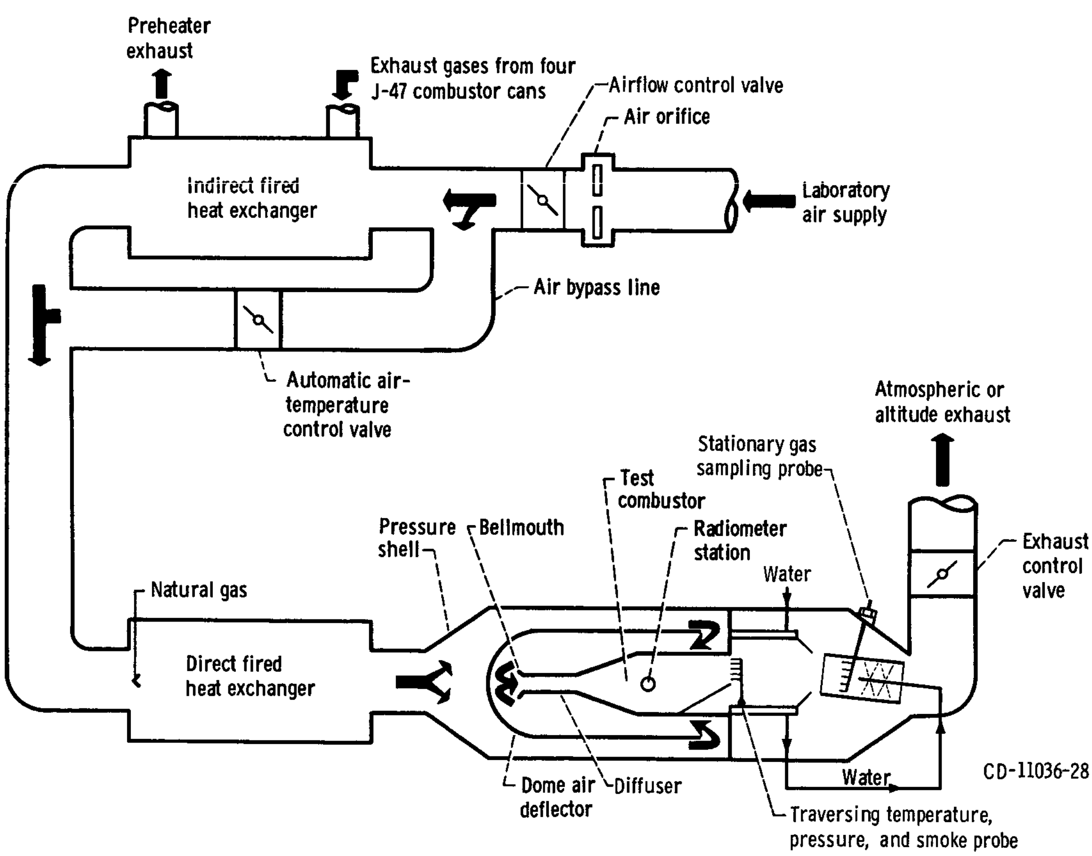
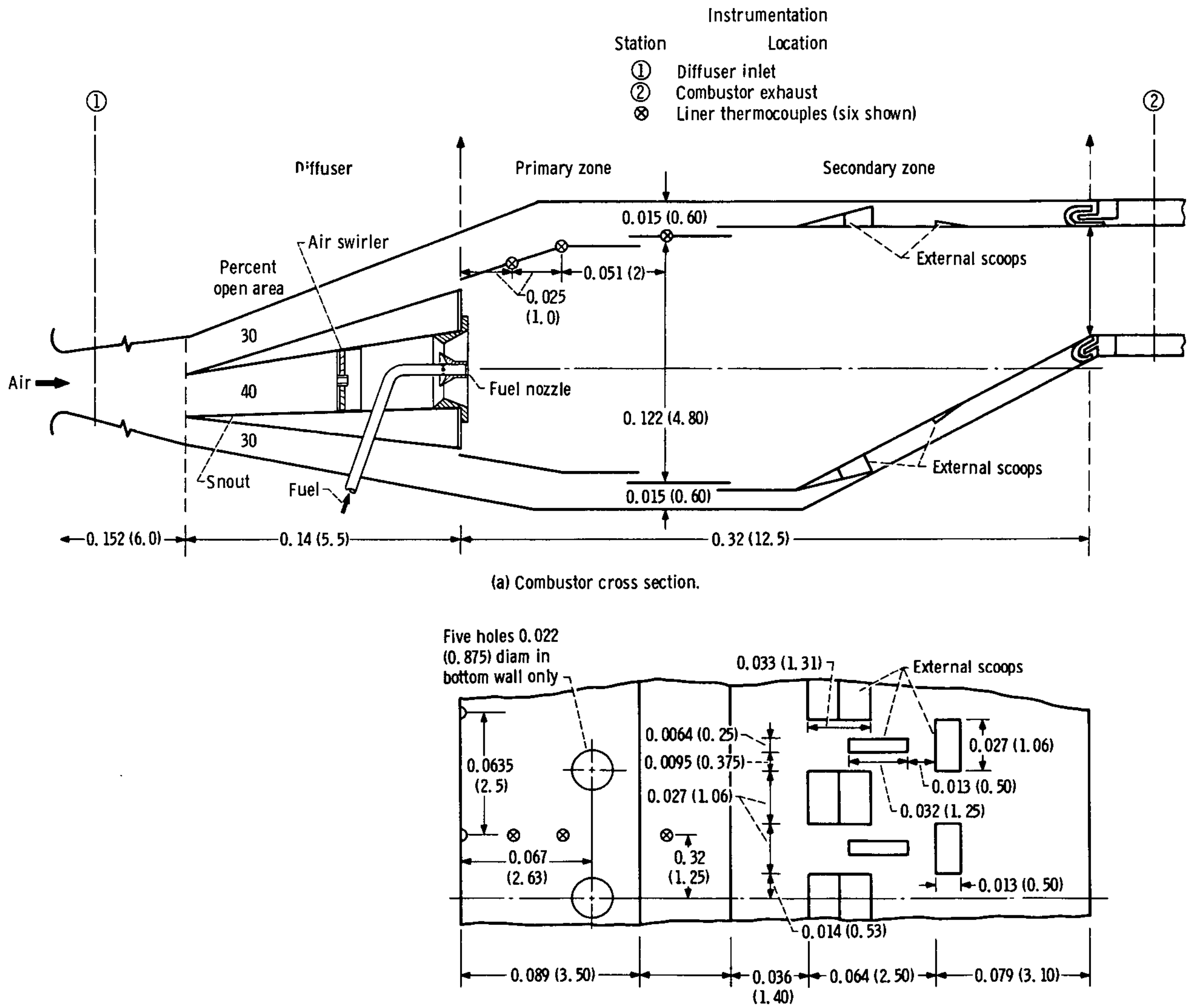


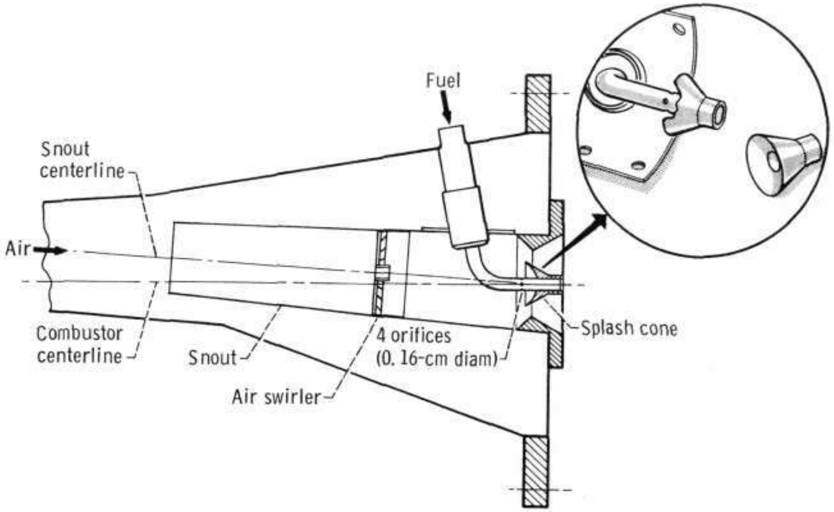
Figure 1. - Test facility and auxiliary equipment.



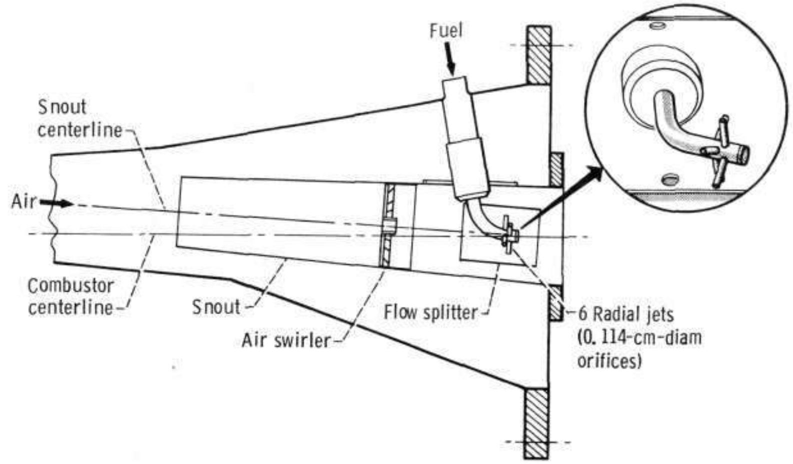
(a) Combustor cross section.

(b) Liner wall.

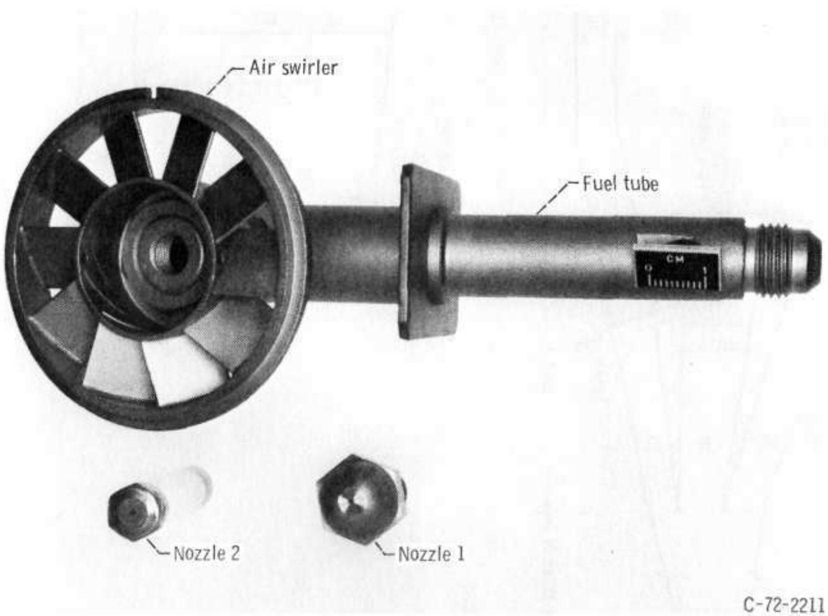
Figure 2. - High-pressure test combustor. (Dimensions are in meters (in.)).



(a) Air-atomizing splash cone.

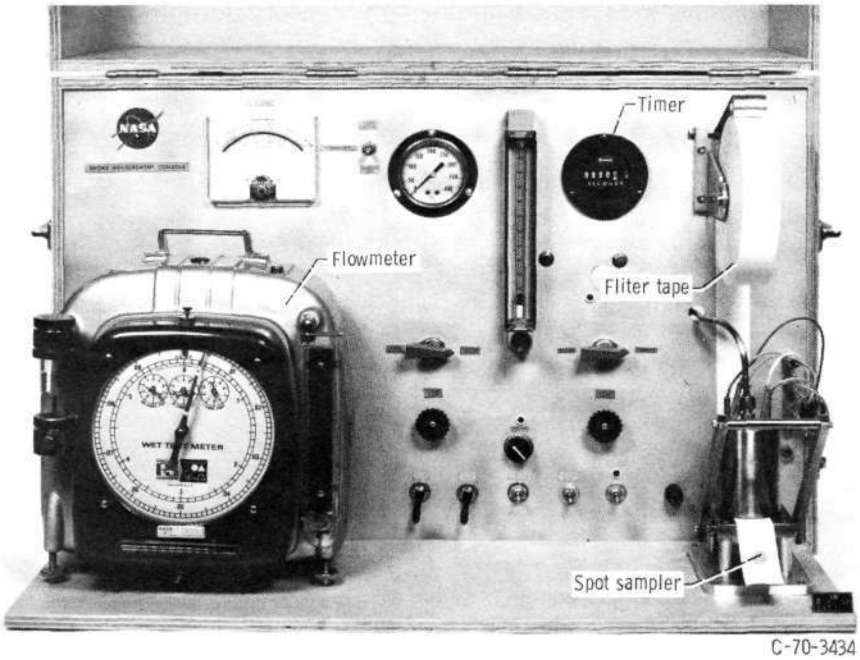


(b) Air-atomizing radial jets.

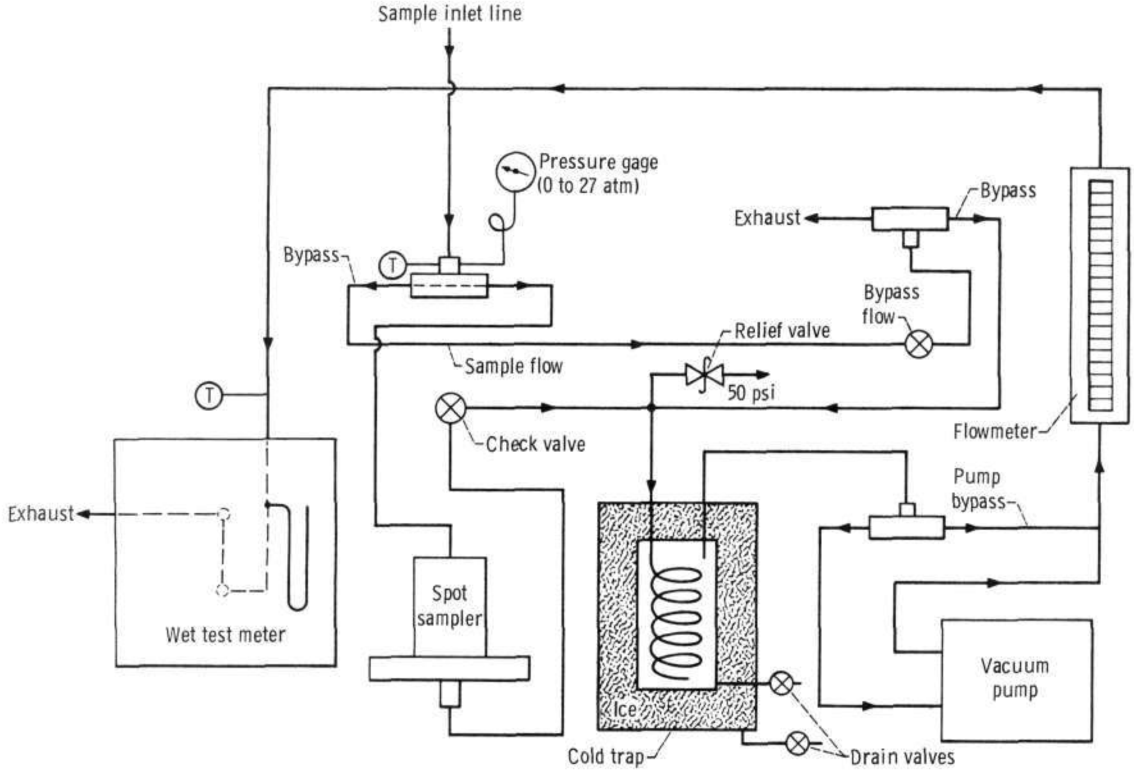


(c) Pressure-atomizing nozzles with air swirler and fuel tube.

Figure 3. - Fuel nozzles



(a) Photograph of smoke meter.



(b) Gas-sample flow diagram.

Figure 4. - Smoke meter.

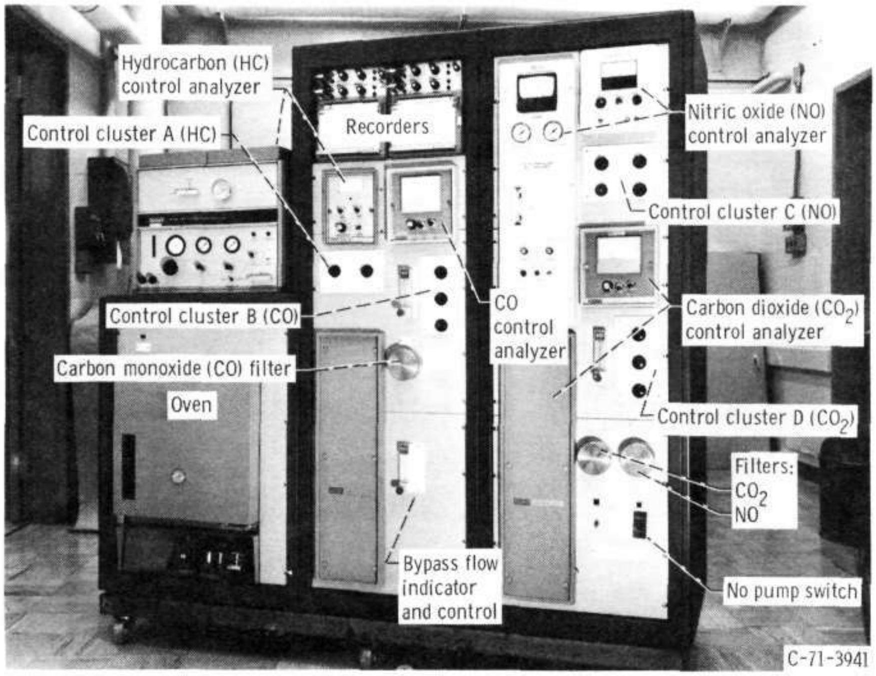


Figure 5. - Gas analysis equipment.

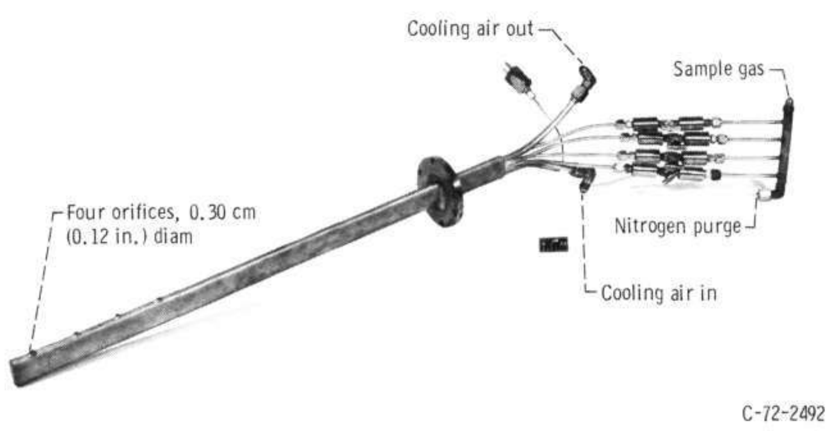
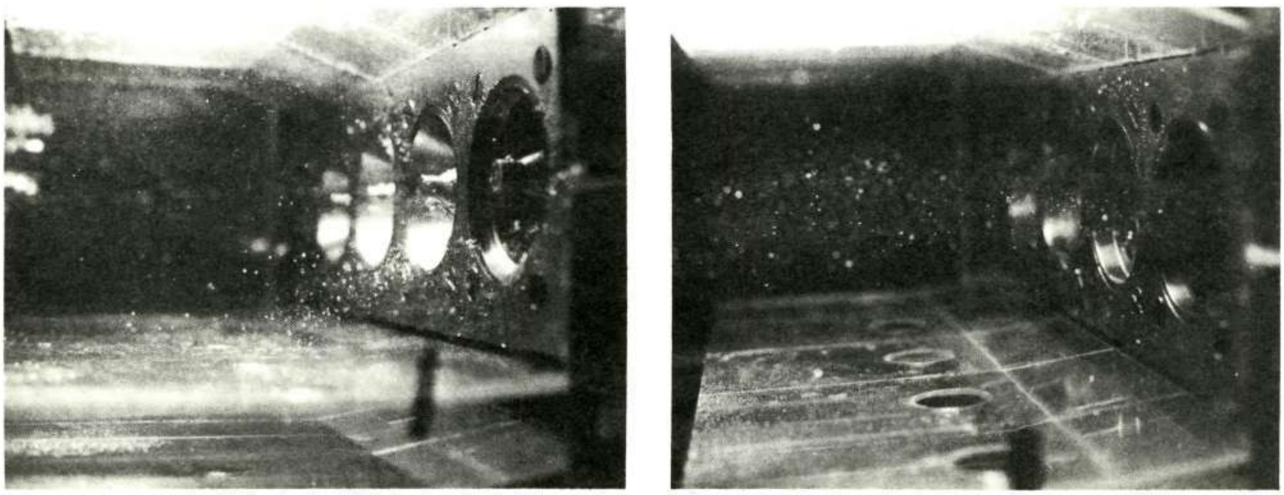
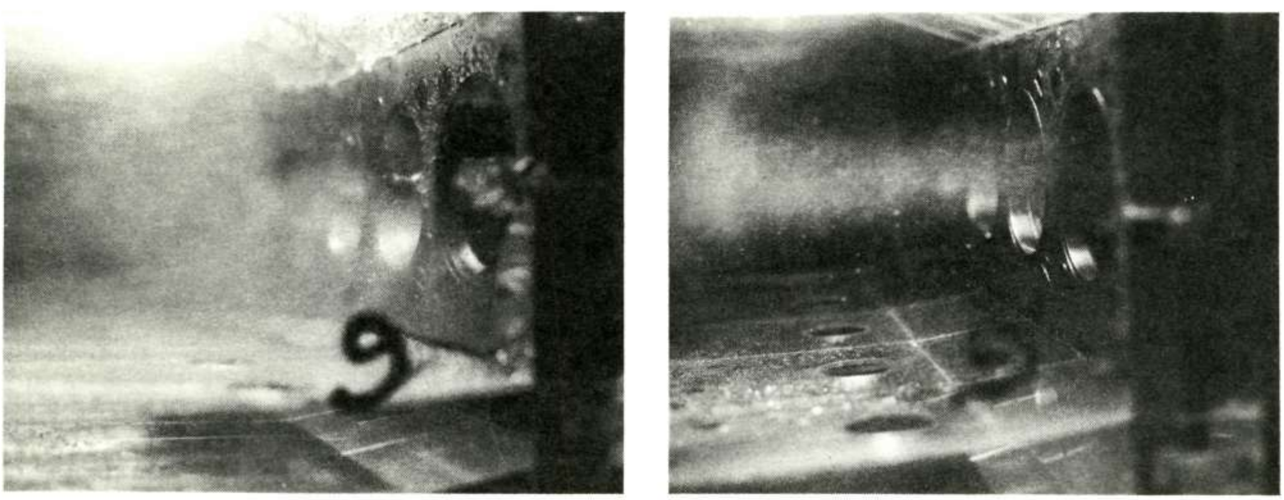


Figure 6. - Stationary gas sampling probe.

Splash cones | Radial jets



Simulated fuel-air ratio, 0.004; inlet-air velocity, 30.5 meters per second (100 ft/sec)



Simulated fuel-air ratio, 0.025; inlet-air velocity, 76.3 meters per second (250 ft/sec)

Figure 7. - Water-spray patterns for air-atomizing nozzles.

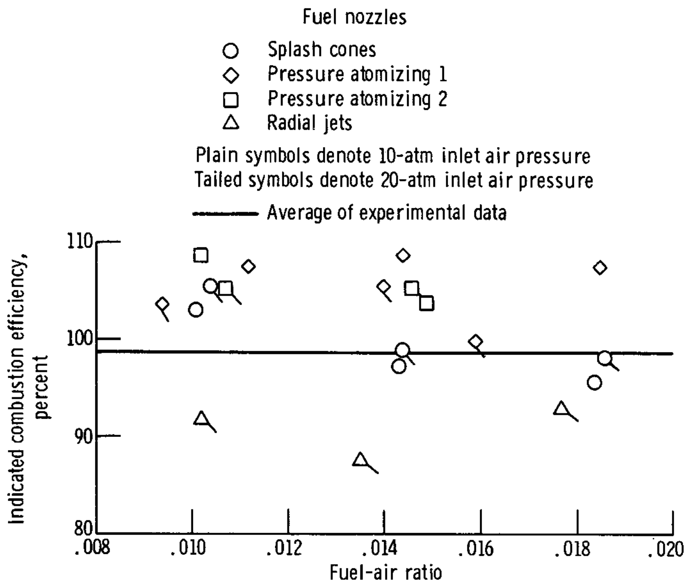


Figure 8. - Comparison of combustion efficiency of air-atomizing and pressure-atomizing fuel nozzles. Inlet-air temperature, 589 K (1060° R).

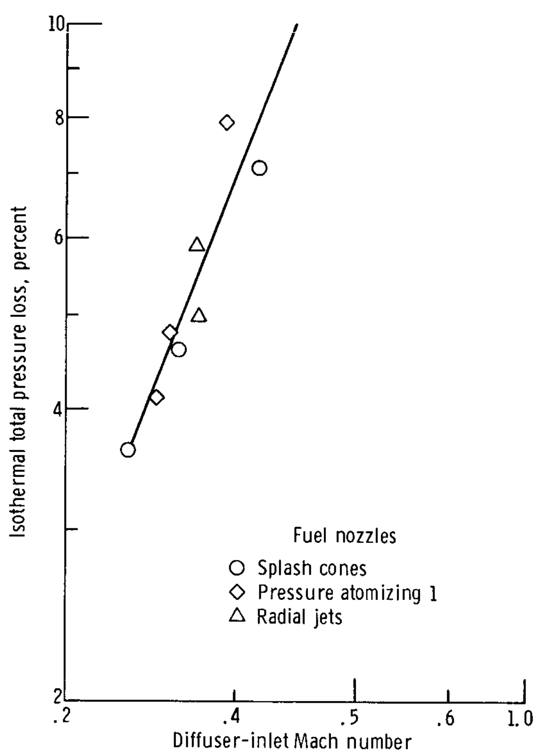


Figure 9. - Isothermal total pressure loss with air-atomizing and pressure-atomizing fuel nozzles, for range of diffuser-inlet Mach numbers.

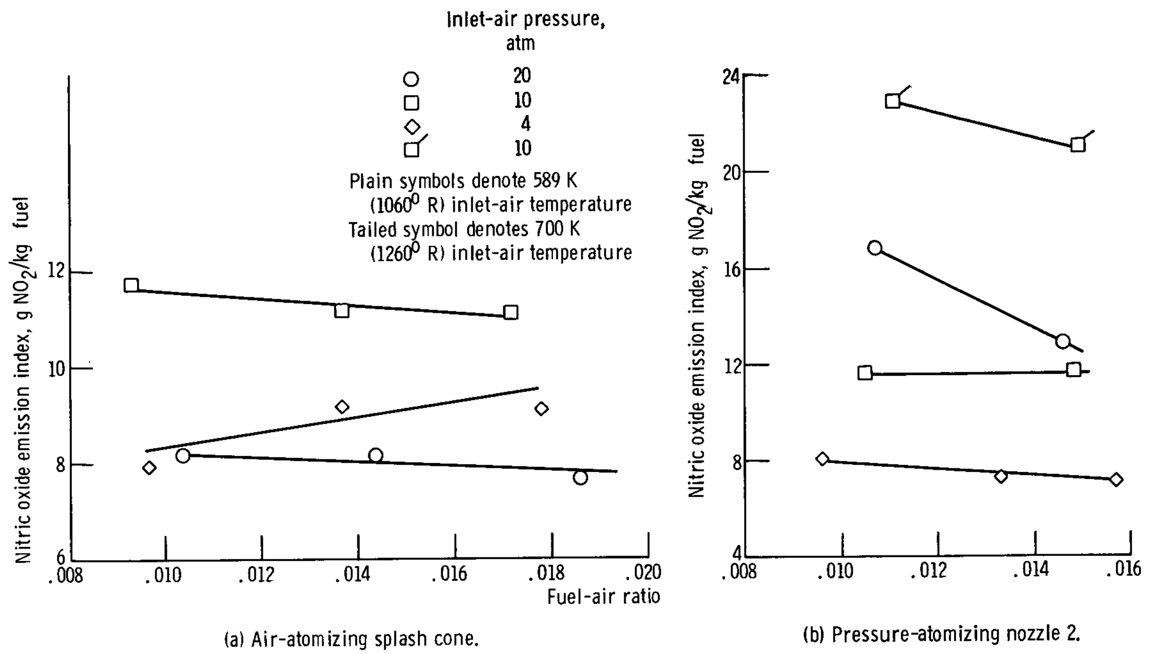


Figure 10. - Effect of fuel-air ratio on nitric oxide emission index.

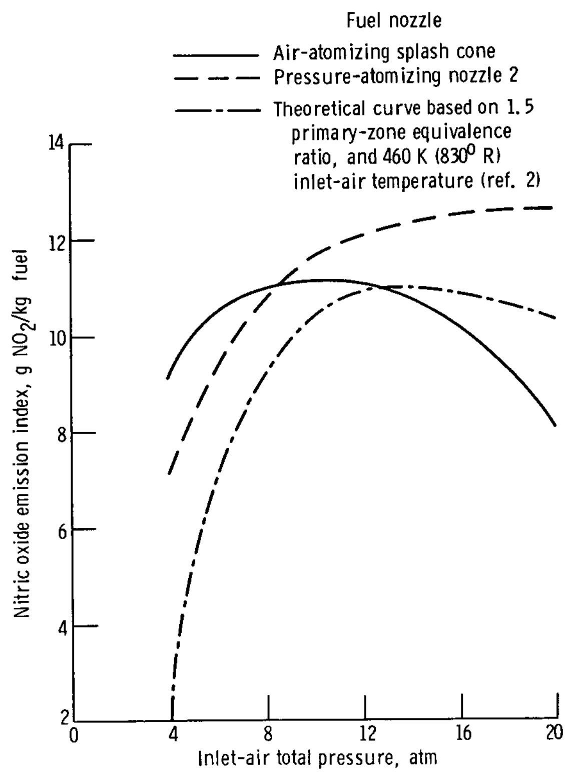
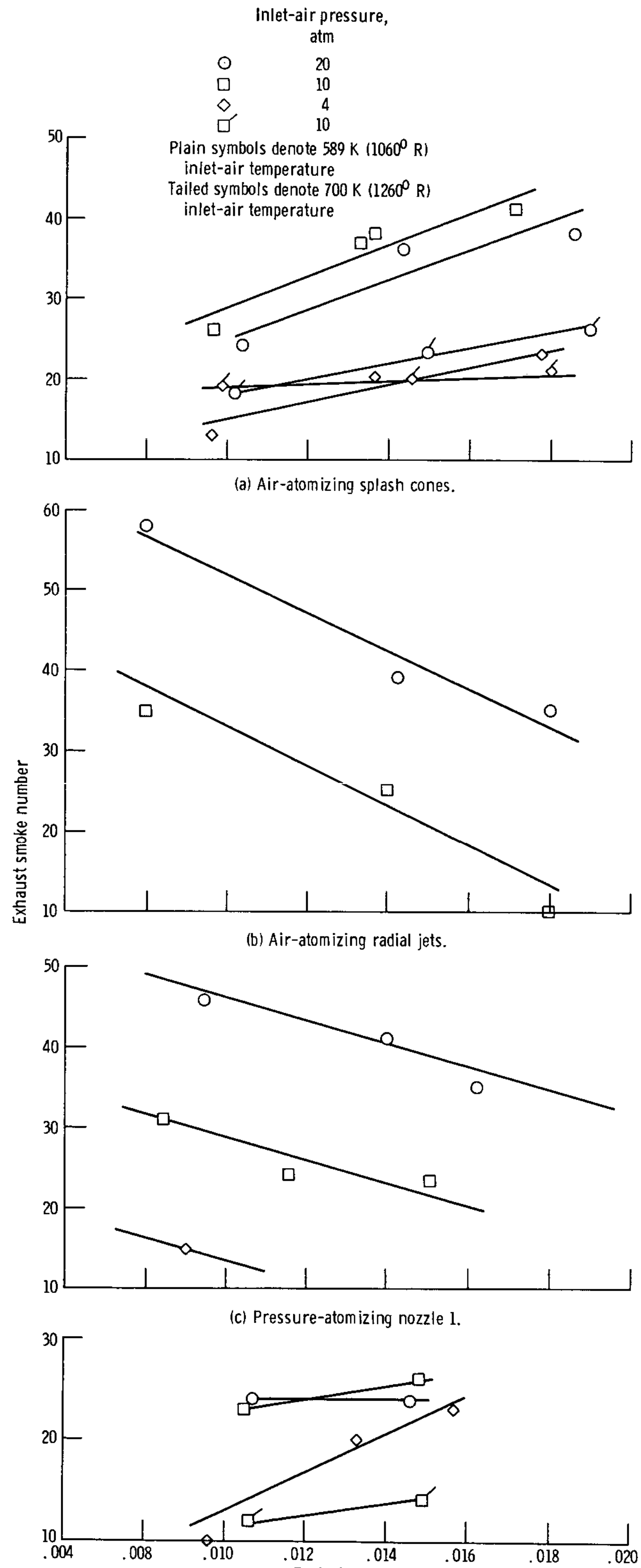


Figure 11. - Effect of combustor pressure on nitric-oxide emission index with air-atomizing and pressure-atomizing nozzles. Inlet-air temperature, 589 K (1060° R); fuel-air ratio, 0.015.



(d) Pressure-atomizing nozzle 2.

Figure 12. - Effect of fuel-air ratio on exhaust smoke number.

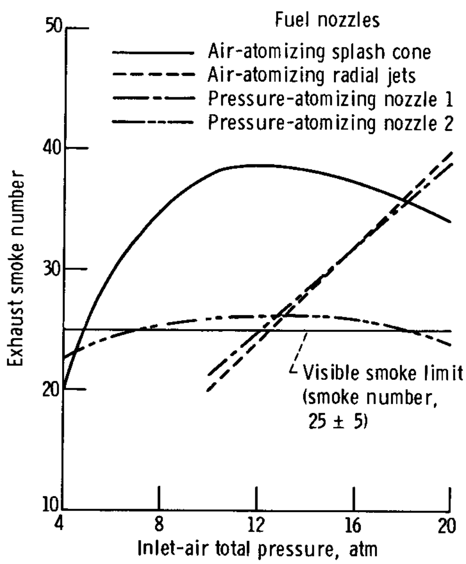


Figure 13. - Effect of combustor pressure on exhaust smoke number. Inlet-air temperature, 589 K (1060° R); fuel-air ratio, 0.015.

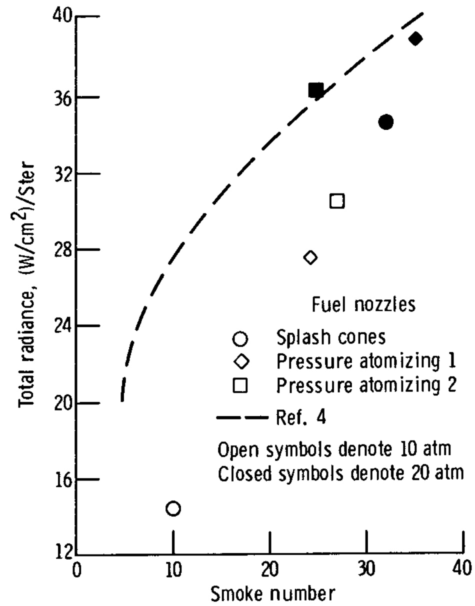


Figure 14. - Relation between exhaust smoke number and radiance for each nozzle. Inlet-air temperature, 589 K (1060° R); fuel-air ratio, 0.015.

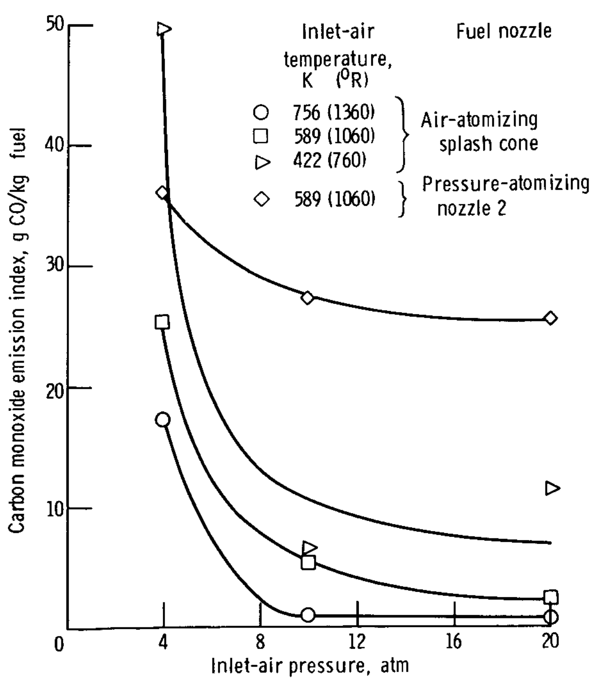


Figure 15. - Effect of combustor pressure on carbon monoxide emission index. Fuel-air ratio, 0.010.

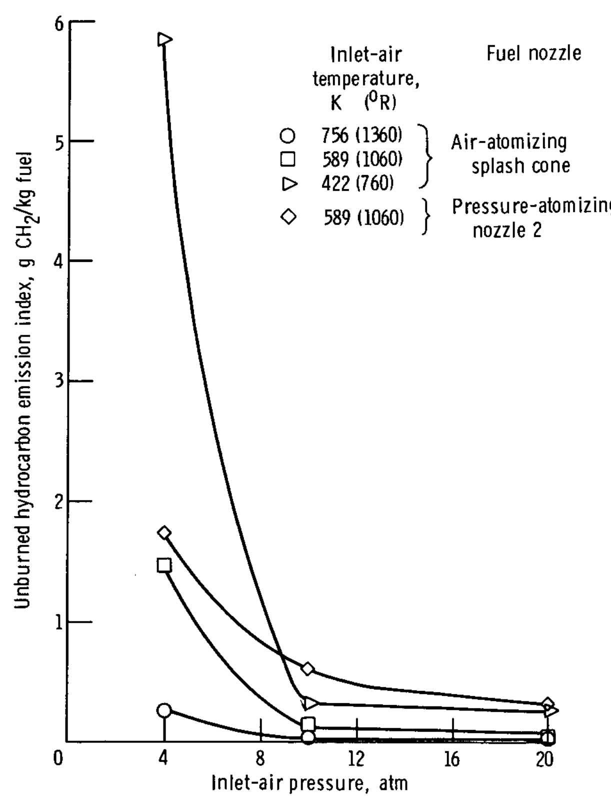


Figure 16. - Effect of combustor pressure on unburned hydrocarbons emission index. Fuel-air ratio, 0.010.

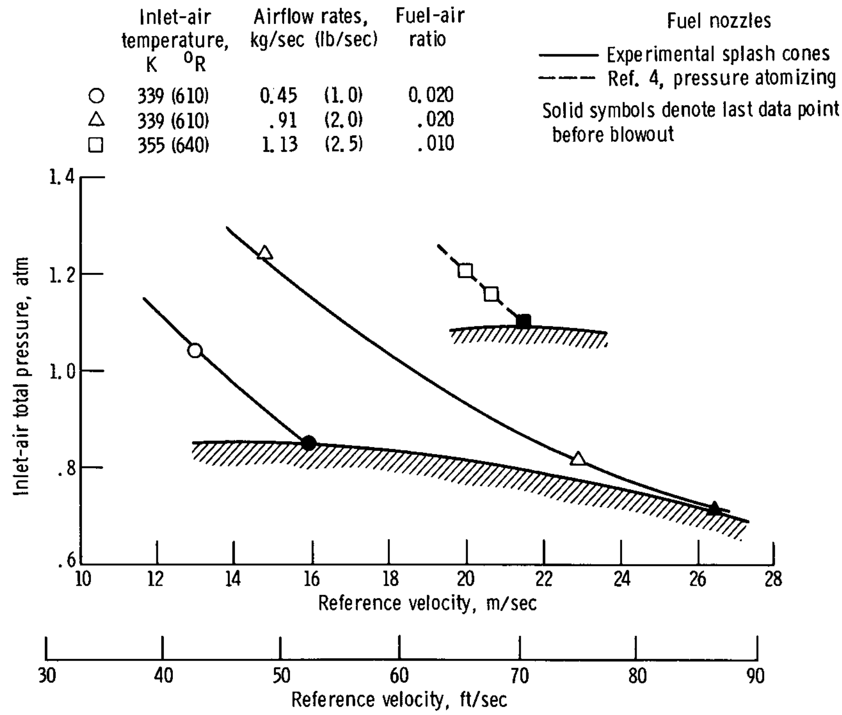


Figure 17. - Comparison of combustor blowout conditions with air-atomizing splash-cones and pressure-atomizing fuel nozzles.

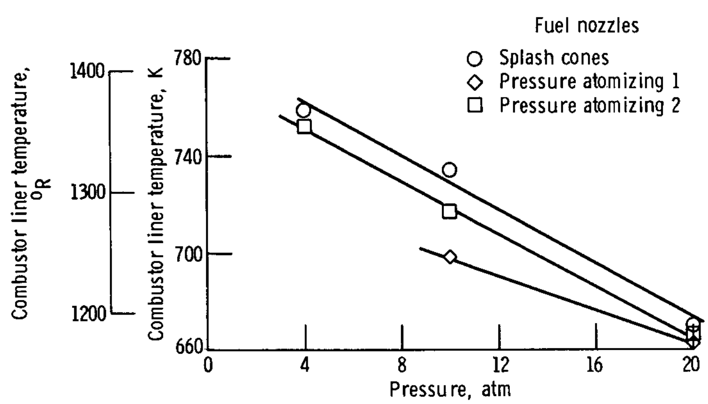


Figure 18. - Effect of inlet-air pressure on combustor liner temperature. Inlet-air temperature, 589 K (1060° R); fuel-air ratio, 0.015.

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