(NASA-TM-X-2958) THE EFFECT OF WATER INJECTION ON NITRIC OXIDE EMISSIONS OF A GAS TURBINE COMBUSTOR BURNING ASTM JET-A FUEL (NASA) 24 p HC $2 75 CSCL 20M

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THE EFFECT OF WATER INJECTION ON NITRIC OXIDE EMISSIONS OF A GAS TURBINE COMBUSTOR BURNING ASTM JET-A FUEL

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SUMMARY

Tests were conducted to determine the effect of water injection on the formation of oxides of nitrogen (NO_x). A full annular, ram induction combustor was operated over a range of inlet-air temperatures, pressures, and reference Mach numbers to simulate sea-level takeoff and cruise conditions. The combustor was operated with ASTM Jet-A fuel at fuel-air ratios high enough to maintain an exit temperature of 1478 K (2200° F) with water injection. Water at ambient temperature was injected into the combustor primary zone at water-fuel ratios up to 2.

The effect of the water injection was to decrease the NO_x emission index and to increase the emission indexes of carbon monoxide and unburned hydrocarbons. On a water-fuel mass ratio basis, the greatest percent decrease in NO_x was at the lowest combustor inlet-air temperature tested, 589 K (600° F). At this condition the NO_x was reduced at a constant exponential rate: $NO_x = NO_{x_o} e^{-1.5 W/F}$ (where W/F is the water-fuel ratio and NO_{x_o} is the NO_x emission index with no water injection). Increasing combustor inlet-air temperature decreased the effect of the water injection, expecially at the lower water-fuel ratios. At an inlet-air temperature of 589 K (600° F) a 50-percent reduction in NO_x was accomplished with a water-fuel ratio of 0.46; at 894 K (1150° F) the same percent reduction in NO_x required a water-fuel ratio of 0.66. No substantial increase in carbon monoxide (CO) and unburned hydrocarbons (H/C) occurred at water-fuel ratios up to 0.5. At higher water-fuel ratios there were substantial increases in CO and H/C especially at the lower inlet-air temperature.

Operating conditions other than combustor inlet-air temperature did not appear to have a significant effect of NO_x reduction due to water injection. At two conditions where smoke data were taken, emissions were reduced with increasing water injection.

INTRODUCTION

The effect of direct water injection on the exhaust-gas emissions of a 107-centimeter (42-in.) diameter annular turbojet combustor burning ASTM Jet-A fuel was investigated. The measured pollutants included oxides of nitrogen (NO_x), unburned hydrocarbons (H/C), carbon monoxide (CO), and smoke.

The rate of formation of nitric oxide (NO) in combustion flames is strongly dependent on the flame temperature. Significant decreases in nitric oxide concentrations have been found by injecting water into the combustion zone. Hilt and Johnson (ref. 1) used up to 1 percent water injection (based on air flow) to lower the nitric oxide emissions of turbines used for stationary power. No significant increase in unburned hydrocarbons and carbon monoxide was noted in their tests. A reduction in smoke (ref. 2) has also been attributed to direct liquid water injection; although water injection as steam in the same tests did not reduce the smoke.

The use of water injection for abatement of nitric oxide emissions is important in that it lowers the flame temperature by evaporation and by the water vapor and air mixture having a higher specific heat. The amount of water vapor in the ambient air (humidity) has already been shown to have a significant effect on the formation of oxides of nitrogen (refs. 3 to 5), attributed to the specific heat difference alone.

For stationary power applications, it would be desirable to decrease the NO_x emissions as much as possible with water injection. A high rate of water injection, however, is responsible for an increase in the emissions of unburned hydrocarbons and carbon monoxide. Some methods of injecting the water appear to be more successful in maximizing the reduction in NO_x while minimizing the increase in the other pollutants (ref. 6).

The present investigation was conducted to determine the effect of combustor operating variables on the reduction of NO_x by water injection. The combustor used in these tests was designed for a duct burning turbofan engine having supersonic cruise capability. Tests were conducted over a range of inlet-air temperatures from 589 to 894 K (600° to 1150° F), pressures of 4 and 6 atmospheres, and reference Mach numbers from 0.065 to 0.078. Water at ambient temperature was injected into the combustor primary zone at water to fuel ratios from zero to 2.0. No attempt was made to vary the location or method of injecting the water. The combustor was operated at fuel to air ratios high enough to maintain an exhaust gas temperature of 1478 K (2200° F) with and without water injection.

Exhaust gas emissions data were taken at all test conditions. Smoke data were taken at two test conditions.

FACILITY

Testing was conducted in a closed-duct test facility at the Lewis Research Center. A schematic of this facility is shown in figure 1. A detailed description of the facility and instrumentation are contained in reference 7. All fluid flow rates and pressures are controlled remotely.

Test Combustor

The combustor tested was designed using the ram-induction approach and is described in reference 8. With this approach the compressor discharge air is diffused less than it is in conventional combustors. The relatively high velocity air is captured by scoops in the combustor liner and turned into the combustion and mixing zones. Vanes are used in the scoops to reduce pressure loss caused by the high-velocity turns. The high velocity and the steep angle of the entering air jets promote rapid mixing of both the fuel and air in the combustion zone and of the burned gases and air in the dilution zone. The potential result of rapid mixing is a shorter combustor or, alternatively, a better exit temperature profile in the same length.

A cross section of the combustor is shown in figure 2. The outside diameter is almost 1.07 meters (42 in.), and the length from compressor exit to turbine inlet is approximately 0.76 meter (30 in.). A snout of the combustor divides the diffuser into three concentric annular passages. The central passage conducts air to the combustor headplates and the inner and outer passages supply air to the combustor liners. There are five rows of scoops on each of the inner and outer liners to turn the air into the combustion and dilution zones.

Photographs of the snout and the combustor liners are shown in figure 3. Figure 3(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liner and the openings in the headplate for the fuel nozzles and swirlers can be seen. Figure 3(b) is a view of the snout and the upstream end of the combustor liner. The V-shaped cutouts in the snout fit around struts in the diffuser. The circular holes through the snout walls are for the fuel nozzle struts. Figure 3(c) gives a closer view of the liner and headplate showing the fuel nozzles and swirlers in place. There are 24 fuel nozzles in the combubster.

WATER INJECTION

Water was injected into the combustor at 24 locations upstream of the fuel spray nozzles. Figure 4 shows an exterior view of the combustor housing and shows the location of both water and fuel injection nozzles. A photograph of a water spray nozzle is shown in figure 5. The nozzle produces a flat fan spray into the center fuel-nozzle-snout volume. All the water passes into the combustion zone through the air swirlers and slots around the combustor headplate. Some of the water vaporizes due to atomization, the high inlet-air temperature, and impingement on the back of the combustor headplate. No attempt was made to calculate the percent of water that was vaporized before entering the combustor.

All the water used in these tests was demineralized by a chemical process. This was necessary to prevent a gradual buildup of scale on the combustor. Such scale could potentially seal many small air entry holes and slots.

TEST CONDITIONS

Tests were conducted at simulated sea-level takeoff and cruise conditions. The nominal test conditions are listed in table I. Conditions A to D were run at 6 atmospheres pressure and at a constant reference Mach number of 0.064 over a range of inlet-air temperatures from 589 to 838 K (600° to 1050° F). Condition E is the same as condition C with the exception that the reference Mach number is 0.072. Conditions E and F simulate supersonic flight cruise conditions with combustor inlet-air temperatures of 838 and 895 K (1050° and 1150° F) and combustor pressures of 4 and 6 atmospheres, respectively.[1] The inlet-air temperatures simulate the temperature coming from an engine's compressor and before the water addition.

For most of the test conditions, the combustor fuel-air ratio was held constant at a value which would give a combustor exit temperature of 1478 K (2200° F) without water injection. Since the exhaust gas temperature is lowered by the addition of water, additional data were taken at the maximum water injection rate and at a higher fuel-air ratio to give the 1478 K (2200° F) exit temperature. For maximum thrust an engine would be operated at its maximum allowable combustor exit temperature (turbine inlet temperature).

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[1]From payload considerations it may not be practical to use water injection at cruise conditions. Nevertheless, tests were conducted at the high-inlet-temperature conditions (even though pressures were low) to also simulate present-day high-pressure-ratio turbofan engines combustor inlet temperatures at near takeoff conditions.

INSTRUMENTATION

Exhaust Gas Temperatures

Combustor exhaust gas temperatures were measured at 3° increments around the circumference with three five-point aspirated thermocouples probes which traverse circumferentially in the exit plane. Five hundred eight-five individual exit temperatures were used in each mass-weighted average exit temperature calculation. The exhaust gas temperature was used only as a check on combustion efficiency, which was primarily measured by gas sampling.

Exhaust Gas Sampling

Concentrations of nitric oxide, total oxides of nitrogen, carbon monoxide, unburned hydrocarbons, and carbon dioxide were obtained with an on-line system. The samples were drawn at the combustor exit from two circumferential locations and at five radial positions through water-cooled stainless-steel probes. The exit instrumentation plane is shown in figure 2. A photograph of the sample probe is pictured in figure 6.

Gas sample system. - The samples collected by the two sample probes were formed into one sample line. Approximately 9 meters (30 ft) of 0.95-centimeter (3/8-in.) stainless-steel line was used to transport the sample to the analytical instruments. A photograph of the instruments and a schematic of the system are shown in figures 7 and 8, respectively. In order to prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated to 420 K (310° F). Sample line pressure at the inlet to the instruments was maintained at 6.9 newtons per square centimeter (10 psig) in order to supply sufficient pressure to operate the instruments. Sufficient sample is vented at the instruments to provide a line residence time of about 2 seconds.

The exhaust gas analysis system shown in figure 7 is a packaged unit consisting of four commercially available instruments along with associated peripheral equipment necessary for sample conditioning and instrument calibration. In addition to visual readout, electrical inputs are provided to an IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas was 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 was determined by a Thermo Electron Corporation Model 10A Chemiluminescent Analyzer. The instrument includes a thermal convertor to reduce NO_2 to NO and was operated at 973 K (1290° F).

Both carbon monoxide and carbon dioxide 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. This range of sensitivity is accomplished by using stacked cells of 0.64 centimeter (0.25 in.) and 33 centimeters (13.5 in.) length. The CO_2 analyzer has two ranges, 0-5 percent and 0-10 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 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 testing.

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

The emission levels of all the constituents in parts per million (ppm) were converted to an emission index (EI) parameter. The EI may be computed from the measured quantities as (proposed in ref. 9) or from metered fuel-air ratio when this is accurately known. Using the latter scheme 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 grams 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 fuel/g wet air
(X)	measured concentration of X in ppm

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

Correlating parameters. - The exhaust gas pollutant data correlate with emission index (g/kg fuel) and with water-fuel mass ratio (g H_2O/g fuel). The emission index parameter correlates the first-order variations in pollutants with the fuel flow. The water-fuel ratio correlates the variation in fuel flow required to maintain constant combustor exit temperature when the water flow is changed.

Smoke Number Measurement

The smoke sampling procedure as recommended in reference 10 was followed as closely as possible. The samples were drawn at the combustor exit plane (fig. 2) from one circumferential location at three radial positions through a water-cooled stainless-steel probe similar to that shown in figure 6 except for the number of holes. The sample was transported to the filtering material (Whatman No. 4 filter paper) through approximately 4.5 meters (15 ft) of stainless-steel line. The sample rate through the filter was 2.36×10^{-4} cubic meter per second (0.50 ft^3/min). The filter was placed on a black background tile to measure comparative reflectance using a Welch Densichron and Reflection unit (3832 A). A Welch Gray Scale (catalog No. 3827T) was used as a calibration reference.

RESULTS AND DISCUSSION

Exhaust Gas Pollutants

The effect of water injection on the exhaust gas emissions at all test conditions is shown in figure 9. The data are plotted on semilog coordinates because the NO_x emission index was found to vary exponentially with humidity in a previously reported effort (ref. 3). The trends in the emission index data are the same for all test conditions. The effect of increasing water injection is to decrease the NO_x emission index and to increase the emission indexes of carbon monoxide and unburned hydrocarbons. The increase in carbon monoxide and unburned hydrocarbons is insignificant in terms of combustion inefficiency at low water-fuel ratios (less than 0.5 g H_2O/g fuel), especially at the higher inlet-air temperatures. The overall level of carbon monoxide and unburned hydrocarbons is, as expected, lower at the higher inlet-air temperatures.

A significant amount of carbon monoxide and unburned hydrocarbons appear at the 589 K (600° F) inlet-air temperature condition. At this condition and at a water-fuel ratio of unity, combustion inefficiency is over 1 percent and is increasing rapidly. The amount of carbon monoxide and unburned hydrocarbons is not as great at the higher inlet-air temperatures, but both pollutants increase rapidly at higher water-fuel ratios.

The slopes of the emission index against water-fuel ratio curves for each pollutant appear to be similar over all the test conditions. This indicates that the injected water affects the combustion process in a similar manner regardless of inlet-air temperature and pressure.

Oxides of nitrogen. - The NO_x emission indexes decrease almost exponentially with increasing water-fuel ratio, especially at the inlet-air temperature conditions of 589 and

672 K (600° and 750° F). Figure 10 shows the effect of the water injection on NO_x emission index (normalized to the value at zero water injection) for all the test conditions. The maximum percent NO_x reduction occurs at the lowest inlet-air temperature condition of 589 K (600° F). At this condition the NO_x is reduced exponentially:

$$\frac{NO_x}{NO_{x_o}} = e^{-1.5\,W/F} \tag{1}$$

where W/F is the water-fuel ratio and NO_{x_o} is the value of NO_x at zero water injection.

The effect of water injection decreases with increasing inlet-air temperature. Especially at low quantities of water flow. This phenomena is probably due to the preheating and vaporizing of the water by the higher inlet-air temperatures and hotter combustor hardware, especially at the lower water flow rates. Preheating and vaporizing of the water lowers its effectiveness in cooling the primary zone flame temperature. A 50-percent reduction in the NO_x emission index is accomplished with a water-fuel ratio of 0.46 at 589 K (600° F). The same percent reduction in NO_x required a water-fuel ratio of 0.66 at an inlet-air temperature of 894 K (1150° F).

Inlet-air humidity. - Inlet-air humidity H was measured near the air orifice and was was 0.0056±0.0006 gram water per gram dry air over the period that test were conducted. The effect of inlet-air humidity is to decrease the NO_x emission index with increasing humidity

$$NO_x = NO_{x_o} e^{-19H}$$

(where the subscript o indicates the value at zero humidity)(ref. 3). The NO_x emission index values shown in this report are the measured values. If the tests were conducted at another significantly different value of inlet-air humidity, the NO_x emission index values would be affected. However, the normalized relations shown in figure 10 would not be affected.

Oxides of nitrogen and carbon monoxide. - As previously mentioned, no significant increase in carbon monoxide occurred at water-fuel ratios less than 0.5 for all the conditions tested. However, at higher water-fuel ratios the similarity in trends between decreasing NO_x and increasing CO is significant.

Figure 11 shows the relation between NO_x and CO emissions. The data are the same as from figure 9. The solid symbols indicate water- fuel ratios less than 0.5. The relation shows that, for this combustor and water injection method, at water-fuel ratios greater than 0.5 a reduction of the NO_x is not independent of an increase in the formation of CO. This result was previously noted in the discussion of figure 9. If low levels of

CO emission index are required, water injection as a method to reduce NO_x may be restricted to low water-fuel ratios and high inlet-air temperatures.

Nitric oxide. - Nitric oxide (NO) made up approximately 91 percent of NO_x emission index. This is the same percent found in previous work with this combustor (ref. 3). Figure 12 shows the variation in NO with NO_x (expressed as ppm) for all test conditions. The water injection had no significant effect on the percent NO in NO_x.

Effect of water injection on smoke formation. - Smoke samples were taken at two test conditions, with an inlet-air temperature of 589 K (600° F) and 755 K (900° F). The combustor pressure and reference Mach number were held constant at 6 atmospheres and 0.065, respectively. The data are shown in figure 13.

Smoke levels were below the visible limit at all test conditions sampled. With no water injection, the smoke number at 755 K (900° F) was lower than the smoke number at 589 K (600° F) as expected. With increasing water injection, the smoke numbers were reduced for both conditions. Although the combustion inefficiency increased dramatically with the higher water-fuel ratios, there was no similar dramatic increase in smoke number.

Sample Validity

A comparison of a gas sample to metered fuel-air ratio for all the data is shown in figure 14 plotted against water-fuel ratio. Most of the data exhibit a scatter of ±6 percent about a mean value of 1.02. The fact that the mean value is 2 percent high is most probably due to the location of the two gas sample probes. (Additional data taken with multiple probes and different probe placement support this conclusion.) Some decrease in fuel-air-ratio ratio is apparent with increasing inlet-air temperature. This decrease is probably related to probe locations and to the decreasing fuel-air ratio required at the higher inlet-air temperatures to reach an exit temperature of 1478 K (2200° F).

SUMMARY OF RESULTS

The effect of direct water injection on the exhaust gas emissions of a full annular, ran induction turbojet combustor burning ASTM Jet-A fuel was investigated. The following results were obtained:

1. Increasing water injection decreased the oxides of nitrogen (NO_x) emission index and increased the emissions of carbon monoxide (CO) and unburned hydrocarbons (H/C). On a water-fuel mass ratio basis, the greatest percentage decrease in NO_x was at the lowest inlet-air temperature tested, 589 K (600° F). At this temperature, the NO_x was

was reduced at a constant exponential rate:

$$NO_x = NO_{x_0} e^{-1.5 W/F}$$

(where W/F is the water-fuel ratio and NO_{x_0} is the NO_x emission index with no water injection).

2. The effect of water injection on exhaust emissions appeared to be similar over all test conditions. The effect of increasing inlet-air temperature was to decrease the effect of the water injection, especially at the lower water-fuel ratios. At an inlet-air temperature of 589 K (600° F) a 50-percent reduction in NO_x was accomplished with a water-fuel ratio of 0.46; at 894 K (1150° F) the same percent reduction in NO_x required a water-fuel ratio of 0.66.

3. No substantial increase in carbon monoxide and unburned hydrocarbons emissions occurred at water-fuel ratios up to 0.5. At higher water-fuel ratios, significant increases in carbon monoxide occurred. A correlation of the NO_x and CO emissions (at the higher water-fuel ratios) indicates that a decrease in NO_x due to water injection has a corresponding increase in CO.

4. At the two conditions where data were taken, smoke emissions were reduced with increasing water injection. At high water injection rates where a rapid increase in combustion inefficiency occurs with increasing water injection, no increase in the smoke number was observed.

5. Operating conditions other than combustor inlet-air temperature did not appear to have a significant effect on the rate of NO_x reduction due to water injection.

6. Nitric oxide made up 91 percent of the NO_x exhaust gas emission index over all test conditions.

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TABLE I. - COMBUSTOR NOMINAL TEST CONDITIONS

Condition	Combustor pressure, atm	Inlet-air temperature, K	Inlet-air temperature, °F	Reference Mach number	Dry fuel-air ratio[a]
A	6	589	600	0.064	0.0257
B	6	672	750	.064	.0234
C	6	755	900	.064	.0211
D	6	838	1050	.064	.0185
E	6	755	900	.072	.0211
F	4	838	1050	.078	.0185
G	6	894	1150	.078	.0170

[a]Fuel-air ratios are for a combustor exit temperature of 1478 K (2200° F) without water injection.

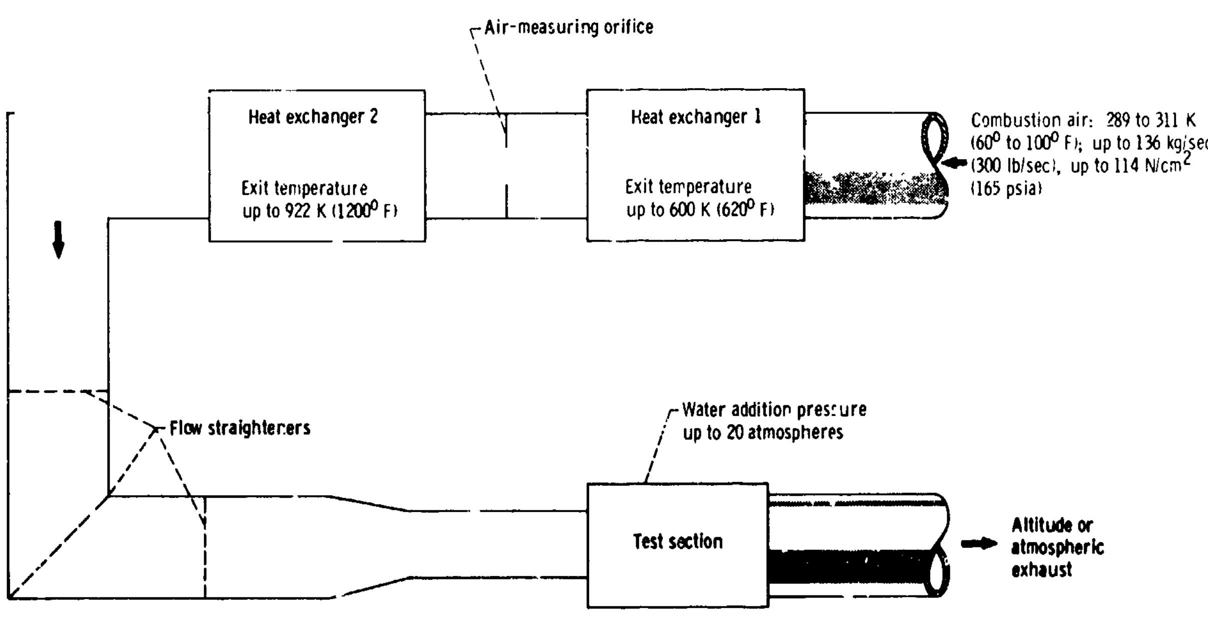


Figure 1. - Schematic of test facility.

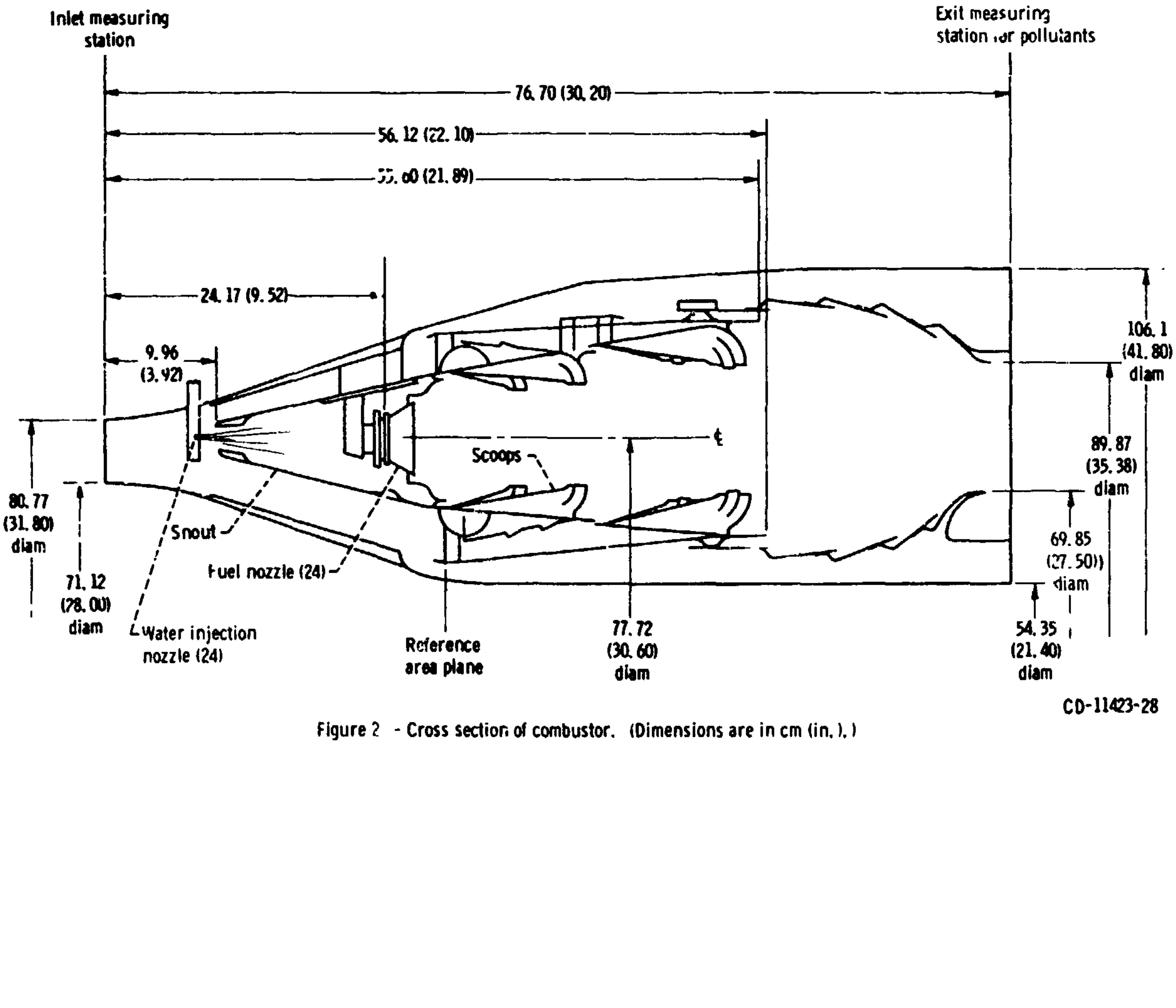
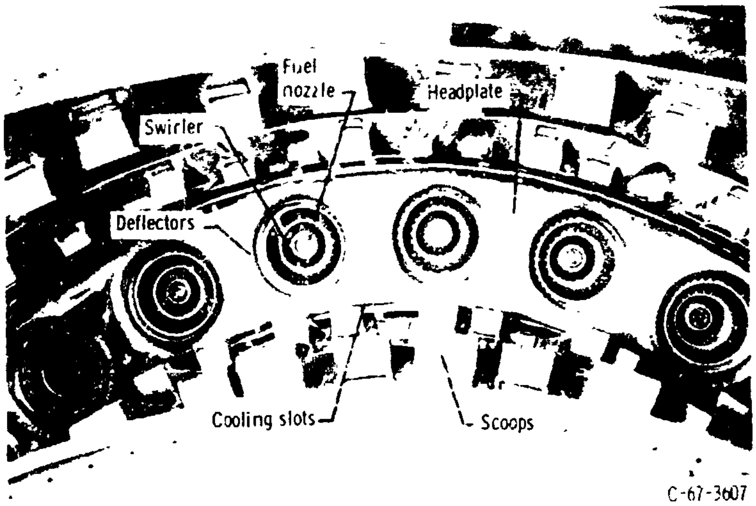


Figure 2. - Cross section of combustor. (Dimensions are in cm (in.).)



(c) Closeup view from downstream end.

Figure 3. - Concluded.

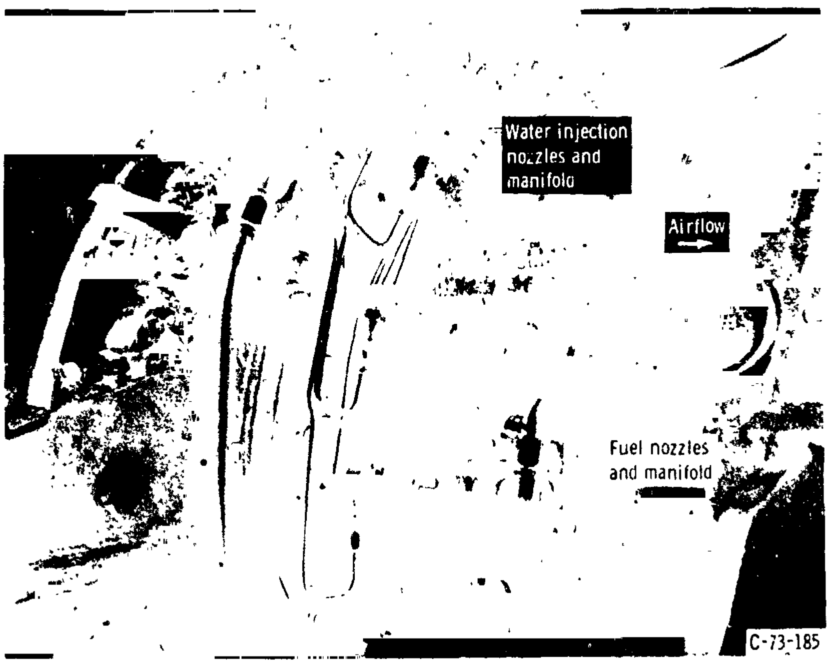
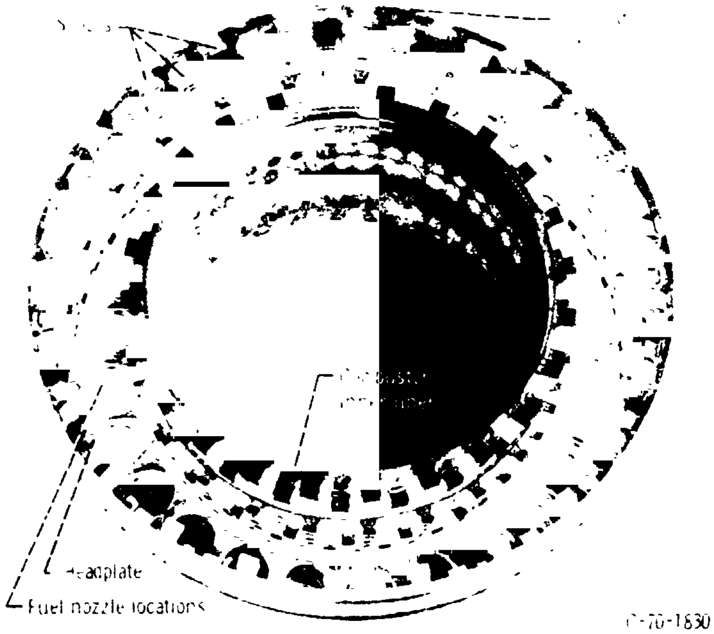
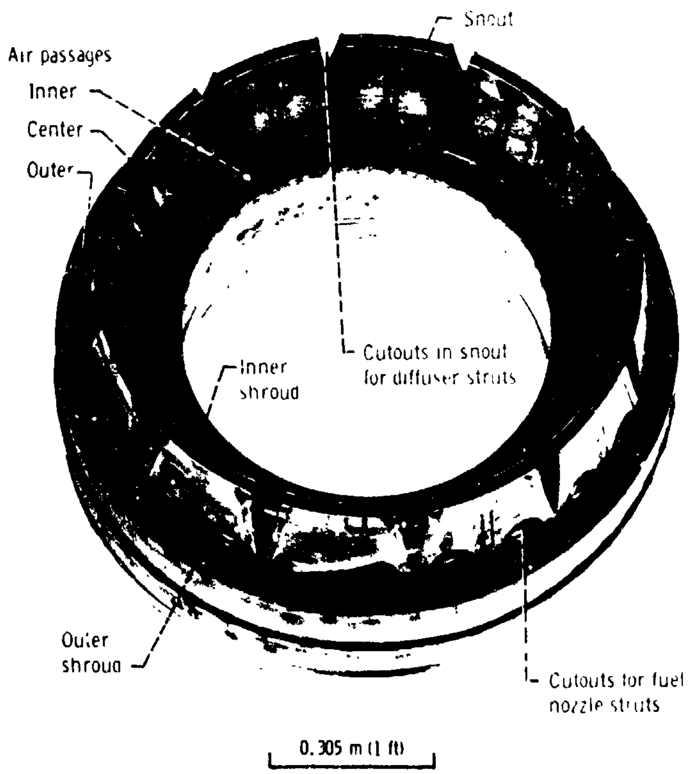


Figure 4. - Exterior of combustor housing showing location of fuel and water injection nozzles.



(a) View from downstream end.



(b) View from upstream end.

Figure 3. - Annular ram-induction combustor.

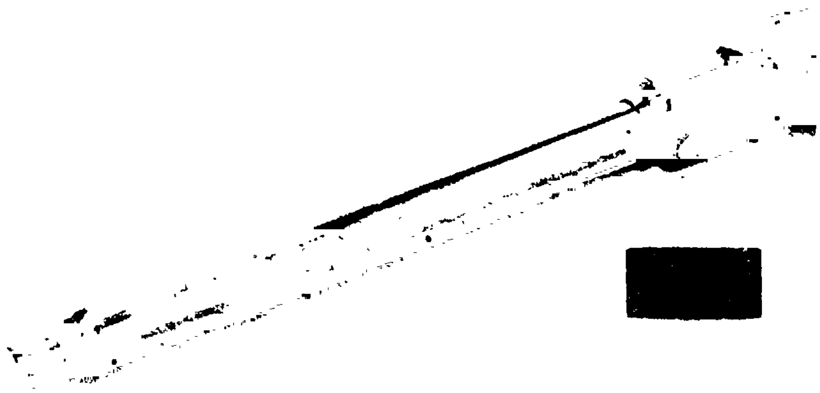


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Figure 5. - Water injection nozzle.

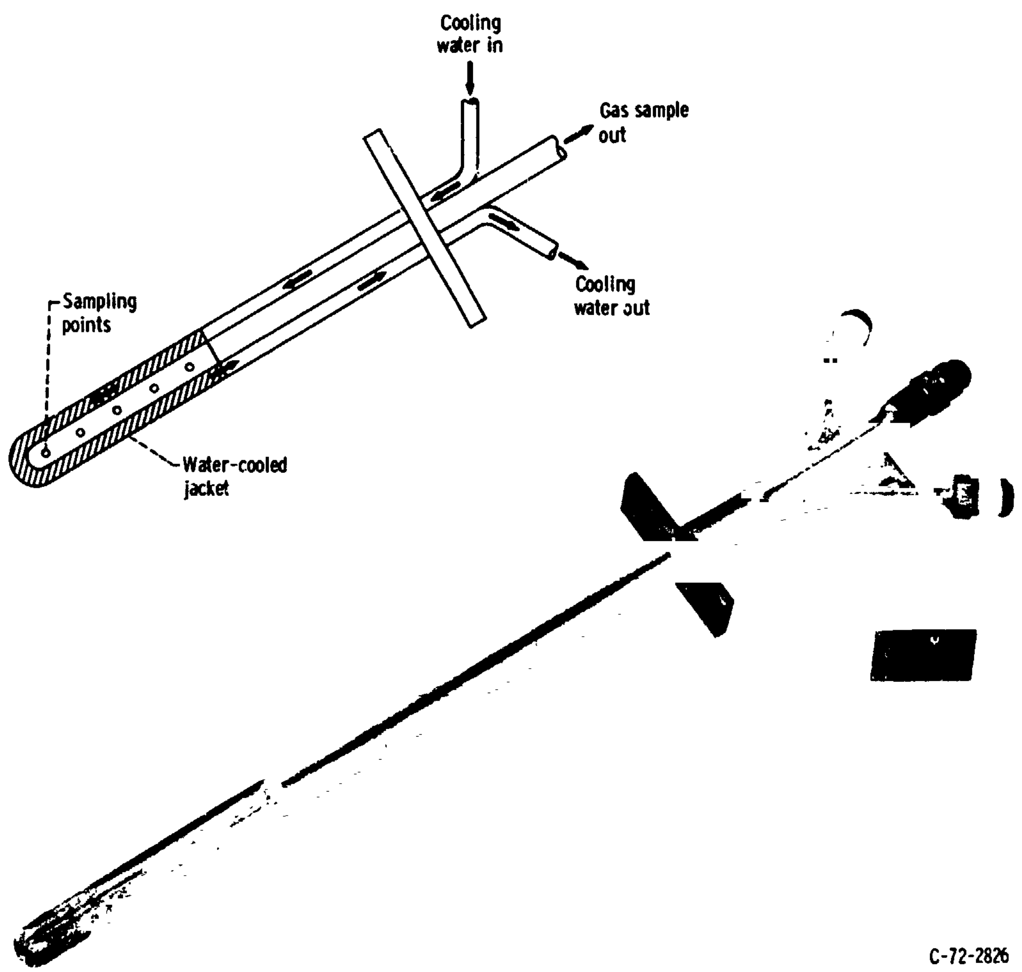


Figure 6. - Gas sampling probe.

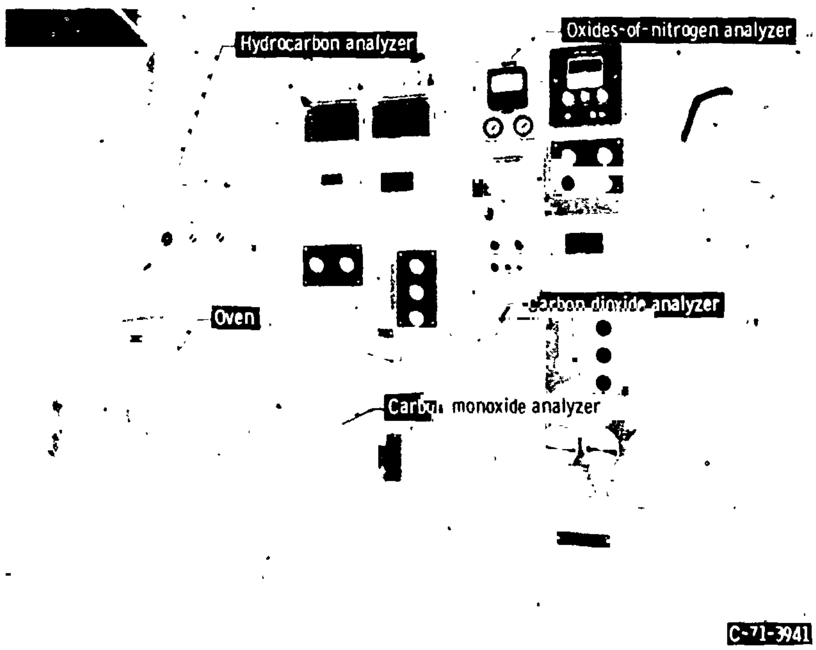


Figure 7. - Gas sampling instrument console.

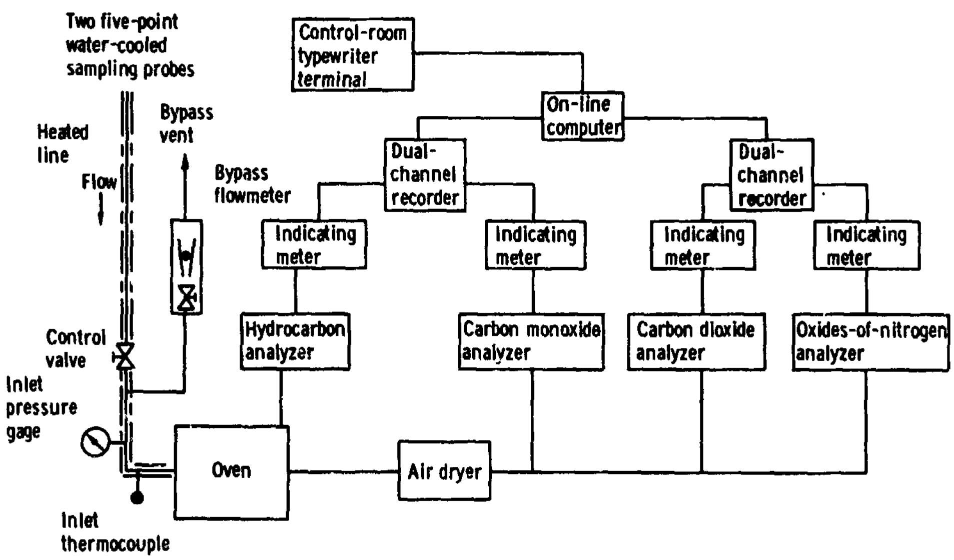
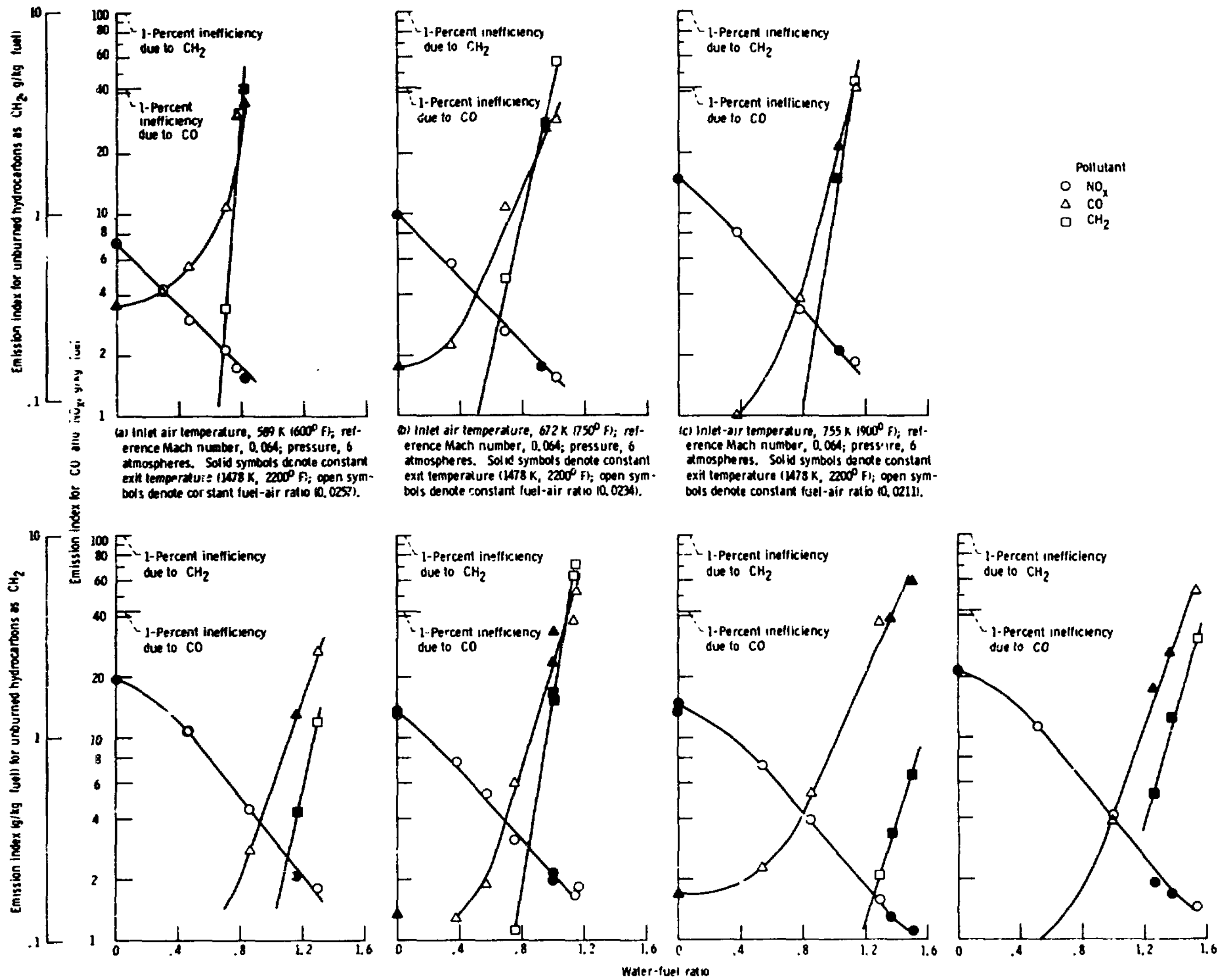


Figure 8. - Schematic diagram of gas analysis system.



(a) Inlet air temperature, 589 K (600° F); reference Mach number, 0.064; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1478 K, 2200° F); open symbols denote constant fuel-air ratio (0.0257).

(b) Inlet air temperature, 672 K (750° F); reference Mach number, 0.064; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1478 K, 2200° F); open symbols denote constant fuel-air ratio (0.0234).

(c) Inlet-air temperature, 755 K (900° F); reference Mach number, 0.064; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1478 K, 2200° F); open symbols denote constant fuel-air ratio (0.0211).

(d) Inlet-air temperature, 838 K (1050° F); reference Mach number, 0.064; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1478 K, 2200° F), open symbols denote constant fuel-air ratio (0.0185).

(e) Inlet-air temperature, 755 K (900° F), reference Mach number, 0.072; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1473 K, 2200° F), open symbols denote constant fuel-air ratio (0.0211).

(f) Inlet-air temperature, 838 K (1050° F), reference Mach number, 0.078; pressure, 4 atmospheres. Solid symbols denote constant exit temperature (1478 K; 2200° F); open symbols denote constant fuel-air ratio (0.0185).

(g) Inlet-air temperature, 894 K (1150° F), reference Mach number, 0.078; pressure, 6 atmospheres. Solid symbols denote constant exit temperature (1478 K, 2200° F), open symbols denote constant fuel-air ratio (0.0170).

Figure 9. - Effect of water injection on emission indexes.

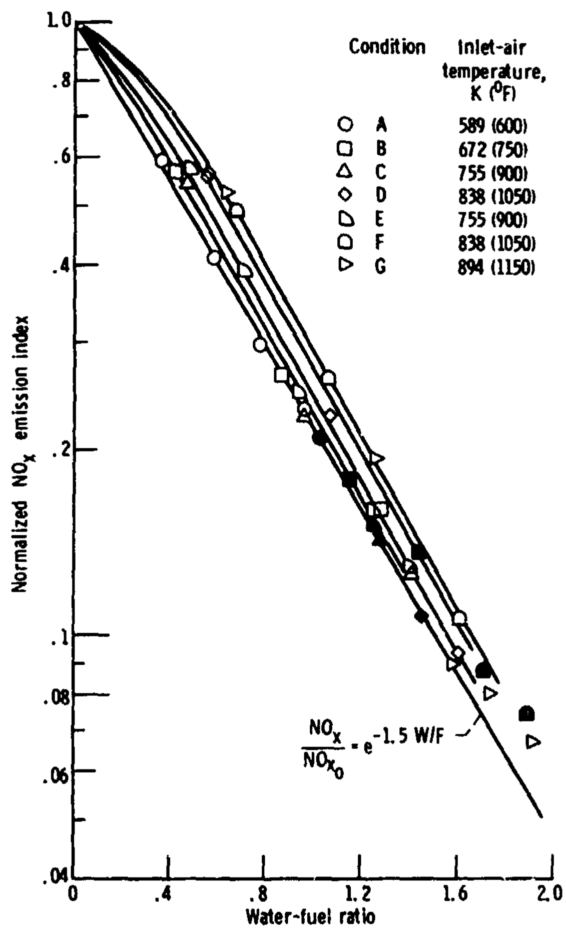


Figure 10. - Effect of water-fuel ratio on normalized NO_x emission index. Solid symbols denote constant nominal exhaust gas temperature (1478 K, 2200° F); open symbols denote constant fuel-air ratio (same value as with zero water injection).

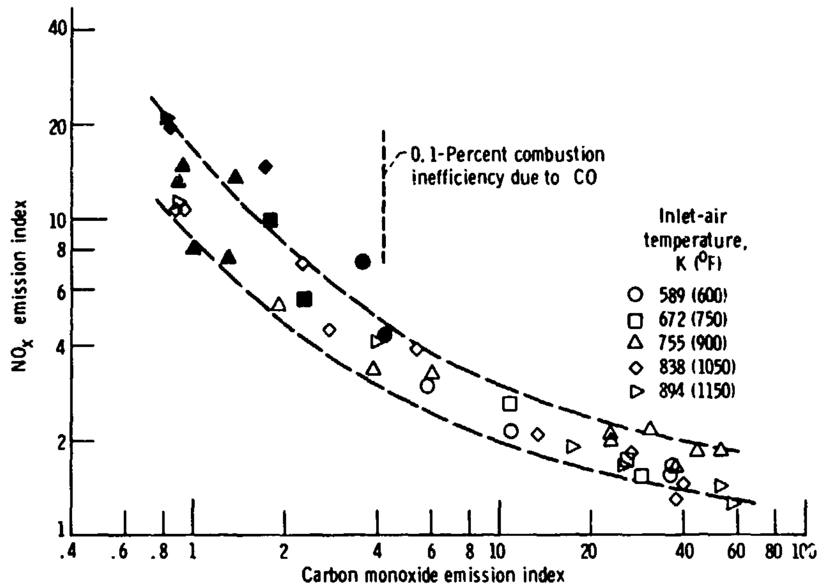


Figure 11. - Emission index as function of carbon monoxide emission index. Solid symbols are for water-fuel ratios less than 0.5.

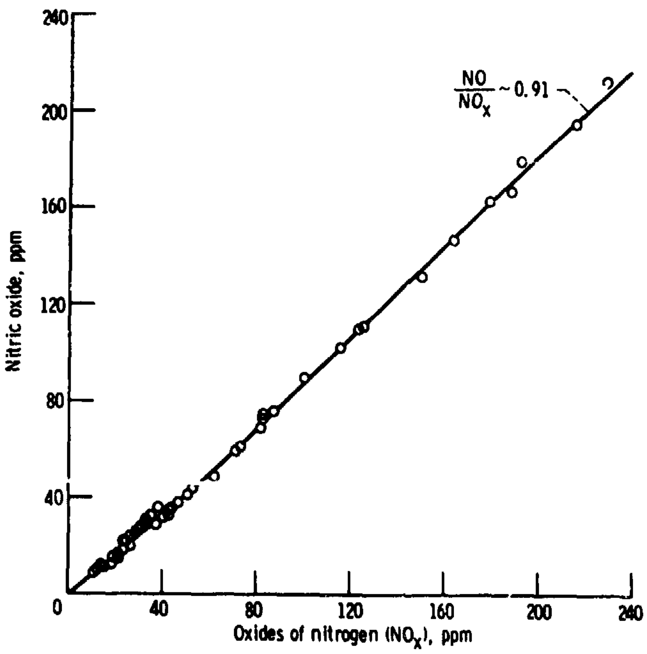


Figure 12. - Nitric oxide in NO_x emissions.

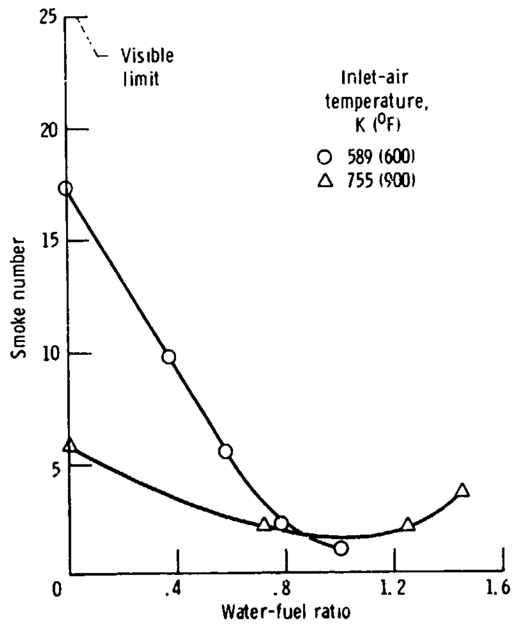


Figure 13. - Effect of water injection on smoke formation. Combustor pressure, 6 atmospheres; reference Mach number, 0.065.

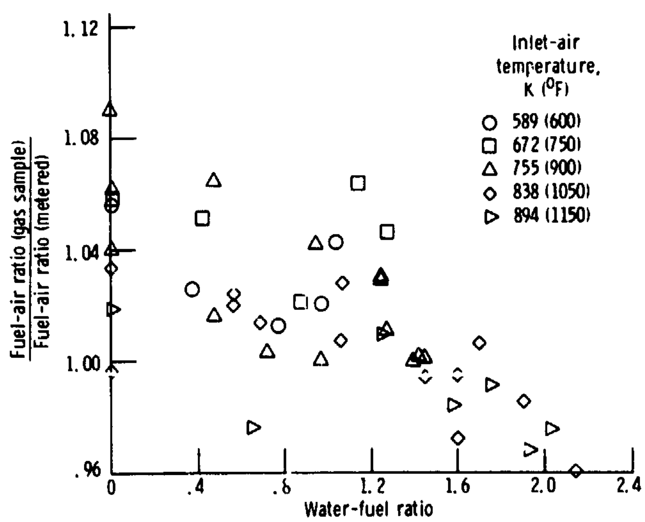


Figure 14. - Fuel-air-ratio ratio as function of water-fuel ratio.

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