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EFFECT OF INLET-AIR HUMIDITY ON THE FORMATION OF OXIDES OF NITROGEN IN A GAS-TURBINE COMBUSTOR

by Nicholas R. Marchionna
Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

Tests were conducted to determine the effect of inlet-air humidity on the formation of oxides of nitrogen from a gas-turbine combustor. Combustor inlet-air temperature ranged from 506 K (450° F) to 838 K (1050° F). The tests were run at a constant pressure of 6 atmospheres and reference Mach number of 0.065. The NO_x emission index was found to decrease with increasing inlet-air humidity at a constant exponential rate of 19 percent per mass percent water vapor in the air. This decrease of NO_x emission index with increasing humidity was found to be independent of inlet-air temperature.

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EFFECT OF INLET-AIR HUMIDITY ON THE FORMATION OF OXIDES OF NITROGEN IN A GAS-TURBINE COMBUSTOR

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SUMMARY

Tests were conducted to determine the effect of inlet-air humidity on the formation of oxides of nitrogen from gas-turbine combustors. Combustor inlet-air temperature ranged from 506 K (450° F) to 838 K (1050° F). Tests were run at a constant pressure of 6 atmospheres and reference Mach number of 0.065.

The NO_x emission index decreased with increasing humidity at a constant exponential rate of 19 percent per mass percent water vapor in the air. The effect of inlet-air humidity on NO_x emissions was found to be independent of the combustor inlet-air temperature over the range of temperatures tested.

Combustion efficiency was close to 100 percent at all test conditions and deviated only slightly from 100 percent at the lowest inlet-air temperature tested (506 K (450° F)).

INTRODUCTION

The purpose of this report is to provide information concerning the effect of inlet-air humidity on the exhaust gas emissions of oxides of nitrogen for gas-turbine combustors.

Seasonal and geographic variations provide a wide variation in the amount of water vapor in the ambient air. These variations are encountered by gas-turbine engines for aircraft use and by stationary ground equipment. The water vapor affects the formation of nitric oxide (NO) because it reduces the flame temperature upon which the formation of NO is strongly dependent. Moore (ref. 1) has made theoretical estimates of the effect of water vapor on NO formation at 1 atmosphere pressure and concluded that the effect was a 25 percent reduction for each mass percent of water vapor in the air.

Analyzing the data from many experimental tests, Lipfert (ref. 2) inferred that the effect of water vapor was to reduce the NO_x 20 percent for each mass percent water vapor in the air. Correcting this data to a constant value of water vapor he was able to demonstrate a marked reduction in the apparent scatter of the NO_x data. He suggested that all future NO_x data be corrected to a constant value of water vapor.

No systematic experimental study has been undertaken to determine the effect of humidity on NO_x. This information is needed before an exhaust-gas emission standard can be established for pollution control.

SCOPE

The combustor used in these tests were designed for a T3 class engine. It was operated at a constant pressure of six atmospheres and reference Mach number of 0.065. Water was added to the air supply system in order to vary the inlet-air humidity up to a value of at least 0.043 grams of water per gram of dry air. The inlet-air temperature was varied between 506 K (450° F) and 838 K (1050° F) in order to determine whether the effect of humidity on NO_x formation was dependent on temperature. The combustor was operated at a constant fuel-air ratio to give an exhaust-gas temperature of 1478 K (2200° F) with zero humidity.

FACILITY AND INSTRUMENTATION

Testing was conducted in a closed-duct test facility of the Engine Components Research Laboratory of the Lewis Research Center. A diagram of this facility is shown in figure 1. A detailed description of the facility and instrumentation are contained in reference 3. All fluid flow rates and pressures are controlled remotely.

Water Addition

Water was sprayed into the air stream just downstream of the second heat exchanger. Two different spray nozzles were used to cover the range of flow conditions in order to provide good atomization. A photograph of the high range spray nozzle is shown in figure 2. Flow straighteners downstream of the water injection point ensured that the water vaporized and mixed into the air stream.

The air flow was measured with an orifice stationed between the two heat exchangers. The humidity of the air at this point was also measured and taken into consideration in the calculations.

Exhaust-Gas Temperatures

Combustor exhaust-gas temperatures were measured at 3° increments around the circumference with three five-point aspirated thermocouple probes which traverse circumferentially in the the exit plane. Five hundred eighty 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 determined by gas sampling measurements.

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 as shown in figure 3.

Gas Sample System

The samples collected by the two sample probes were common manifolded to 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. 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 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 (fig. 4) 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 360/67 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 non-dispersive infrared (NDIR) type (Beckman Instruments model 315B). The CO analyzer has four ranges: 0-100 ppm, 0-1000 ppm, 0-1 percent, and 0-10 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 0-15 percent, with a sample cell length of 0.32 centimeter (0.125 in.).

Analytical Procedure

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

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included both inlet-air humidity and water vapor from combustion. The equations used were obtained from reference 4.

The emission levels of all the constituents were converted to an emission index EI parameter. The EI may be computed from the measured quantities as proposed in reference 4, or an alternate procedure is to use the metered fuel-air ratio when this is accurately known. Using the latter scheme the EI for any constituent X is given by:

$$EI_X = \frac{m_X}{m_E} \cdot \frac{(1 + f)}{f} \cdot (X) \cdot 10^{-3}$$

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 dry air plus water content)
(X) = Measured concentration of X in ppm

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

TEST COMBUSTOR

The combustor tested was designed using the ram-induction approach and is described in reference 5. 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 5. The outer 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 on 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 6. Figure 6(a) is a view looking upstream into the combustor liner. The scoops in the inner and outer liner can be seen and the openings in the headplate for the fuel nozzles and swirlers. Figure 6(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 6(c) gives a closer view of the liner and headplate showing the fuel nozzles and swirlers in place. There are a total of 24 fuel nozzles in the combustor.

TEST CONDITIONS

Water content in the ambient air can vary over several orders of magnitude. Figure 7 is a semi-log plot of the air's water content at 100 percent relative humidity (saturation) as a function of temperature (ref. 6). To determine the effect of humidity on exhaust-gas emissions, water was added up to at least 4.3 percent of the air flow to cover the range up to 100 percent humidity on a 311 K (100° F) day.

The nominal combustor operating conditions are listed in table I. The inlet-air temperature was varied to determine whether the effect of humidity varied with inlet-air temperature. Tests were run at a constant pressure of 6 atmospheres and reference Mach number of 0.065. The reference Mach number was held constant for these tests since variations in Mach number produce variations in pressure drop, turbulence and mixing patterns.

The combustor inlet-air temperature was maintained constant while increasing the water flow by increasing the exit temperature of the No. 2 heat exchanger. Data were taken over a range of inlet-air temperatures from 506 K (450° F) to 838 K (1050° F). Because the exit temperature limit on the No. 2 heat exchanger is 922 K (1200° F) only limited data could be taken at 838 K (1050° F) due to the temperature drop from the water addition.

The combustor was operated at a constant fuel-air ratio to give a desired exit temperature of 1478 K (2200° F) with zero humidity. At the 506 K (450° F) inlet-air temperature condition however, the fuel flow required for an exit temperature of 1478 K (2200° F) could not be supplied and an exit temperature of 1366 K (2000° F) was run instead.

RESULTS AND DISCUSSION

Tests were conducted on three different days. Agreement in the data over the testing period was excellent and resulted in very little scatter of the data.

Combustion Efficiency

The combustor used in these tests operated at nearly 100 percent combustion efficiency over all conditions tested. Variations in combustion efficiency from 100 percent were not detectable by means of thermocouples.

Combustion efficiency as determined by gas sampling varied only slightly from 100 percent. The lowest efficiency measured by gas sampling was at the lowest inlet-air temperature tested (506 K (450° F)) and the highest humidity (0.042). The efficiency at this point was 99.73 percent.

Carbon monoxide. - Combustion inefficiency measured by gas sampling was primarily due to the amount of unburned carbon monoxide. Figure 8 shows the effect of humidity on the emission index of carbon monoxide from this combustor. At inlet-air temperatures equal to or greater than 589 K (600° F) variations in humidity had no effect on the level of carbon monoxide in the exhaust. The level of the emission index decreases with increasing inlet-air temperature as expected. At the 506 K (450° F) inlet-air temperature condition, an increase in carbon monoxide is observed at humidity values greater than 0.02.

The increase in carbon monoxide is not large for this combustor but may indicate a problem area at idle conditions for low pressure ratio engines which have low combustor inlet-air temperatures, especially if the combustors are also designed to be low nitric oxide emitters. The effect of inlet-air humidity on carbon monoxide emissions from these combustors at idle conditions may be substantial.

Unburned hydrocarbons. - Gas sampling measured negligible amounts of unburned hydrocarbons. The emission index of unburned hydrocarbons was less than 0.01 (0.001 percent inefficiency) at all conditions except the 506 K (450° F) inlet-air temperature condition. Figure 9 shows the effect of humidity on unburned hydrocarbons at this condition. The increase in unburned hydrocarbon is coincident with the increase in carbon monoxide at a humidity of 0.02 for this combustor. Although the level of unburned hydrocarbons is not high, the trend again indicates a potential hydrocarbon and carbon monoxide emissions problem for low pressure ratio engines at idle conditions on high humidity days.

The efficiency data indicates that the combustion process was not seriously impaired by the increase in humidity. The NO_X emissions results are therefore applicable to any combustor whose efficiency is close to 100 percent.

NO_X Emissions

Effect of inlet-air humidity. - The effect of inlet-air humidity on the formation of oxides of nitrogen is shown in figure 10. The effect is essentially the same over the range of inlet-air temperatures tested from 506 to 838 K (450° to 1050° F). At constant inlet-air temperature, the emission index decreases with increasing humidity at a constant exponential rate:

$$\frac{NOX}{NOX_0} = e^{-19.H}$$

where

NOX is the measured emission index
NOX_o is the emission index at zero humidity
H is the humidity in (g water/g dry air)

In order to determine the emission index at zero humidity, the measured value is multiplied by e^{+19H}:

$$NOX_o = (NOX)\ e^{+19.H}$$

The correction (e^{+19H}) is more definitive than any linear correction (i.e., the linear 25 percent or 20 percent per percent humidity previously used, refs. 1 and 2). The problem with any linear correction is the implicit statement that at some point a 100 percent reduction in the pollutant is accomplished or that there is no pollutant left. At a nitric oxide reduction rate of 25 percent per percent humidity one would expect zero NO_x with a humidity of 0.04 g water per g dry air. If an engine exhaust were measured for pollutants under these circumstances, the correction to determine its emission index at zero humidity would be infinite.

The semi-log plot of figure 11 shows the correction factor that would be applied by using the exponential e^{+19H} and the linear rates to correct measured data to the emission index value at zero humidity. The correction factor that would be applied by using the linear rates is always higher than the one using the exponential rate. The curve illustrates how the linear rates diverge rapidly from the exponential and tend to infinity.

By examining the physical process, one should conclude that the NO_x must be reduced exponentially with an increase in inlet-air humidity.

Correcting to standard humidity. - No standard humidity H_{std} has yet been established. If such a standard were established, NO_x emission index data could be corrected to the standard humidity level by multiplying the emission index at zero humidity by $e^{-19.H_{std}}$:

$$NOX_{std} = NOX_o\ e^{-19.H_{std}} = (NOX)\ e^{+19.(H-H_{std})}$$

Nitric oxide (NO). - The instrument used to measure the oxides of nitrogen also allows measurement of the quantity of nitric oxide (NO). Figure 12 shows the percent of the NOX emission index which was found to be NO for this combustor. At zero humidity, NO made up approximately 91 percent of NOX emission index at all inlet-air temperatures. At the 755 K (900° F) inlet-air temperature, variation in inlet humidity had no effect on the percent of NO in the NOX emission index. At lower inlet-air temperatures a decrease in the percent of NO is observed with increasing humidity. Although slight, this variation in NO percent of NOX with humidity may be of interest to those who study analytical combustor models.

Sample Validity

A comparison of gas sample to metered fuel-air ratios for all the data is shown in figure 13. Most of the data exhibit a scatter of ±3 percent about the mean value. The fact that the mean value is 10 percent high is probably symptomatic of the location of the two fixed sampling probes.

Results and Recommendations

Tests were conducted to determine the effect of inlet-air humidity on the formation of oxides of nitrogen from gas-turbine type combustors. Combustor inlet-air temperature ranged from 506 K (450° F) to 838 K (1050° F). Tests were primarily run at a constant pressure of 6 atmospheres and reference Mach number of 0.065. The following results were obtained:

1. The NO_x emission index decreased with increasing inlet humidity at a constant exponential rate of 19 percent per mass percent water vapor in the air. This effect of humidity on NO_x emission index was found to be independent of combustor inlet-air temperature over the range of conditions tested.

2. A standard humidity level (either zero or an arbitrary value) should be established. The measured NO_x emission index could be corrected to the standard humidity level by multiplying the measured value by $e^{+19(H-H_{std})}$.

3. Nitric oxide made up 91 percent of the oxides of nitrogen emission index at zero humidity. At 755 K (900° F) inlet-air temperature, variation in inlet humidity had no effect on the percent of NO in NO_x emission index. At lower inlet-air temperatures a slight decrease in the percent of NO was observed with increasing humidity.

4. Combustion efficiency as measured by gas sampling was close to 100 percent at all test conditions. A slight deviation from 100 percent was noted at the lowest inlet-air temperature tested (506 K (450° F)) which indicates a potential carbon monoxide and unburned hydrocarbon emissions problem for low pressure ratio engines at idle conditions on high humidity days.

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4. Anon.: Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines. Aerospace Recommended Practice 1256, SAE, Oct. 1, 1971.

5. Rusnak, J. P.; and Shadowen, J. H.: Development of an Advanced Annular Combustor. Rep. PWA-FR-2832, Pratt & Whitney Aircraft (NASA CR-72453), May 30, 1969.

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TABLE I. - NOMINAL OPERATING CONDITIONS

Pressure, atm	Reference Mach no.	Inlet-air temperature		Exit temperature	
		K	°F	K	°F
6	0.065	506	450	1366	2000
↓	↓	589	600	1478	2200
		672	750	↓	↓
		755	900		
		838	1050		

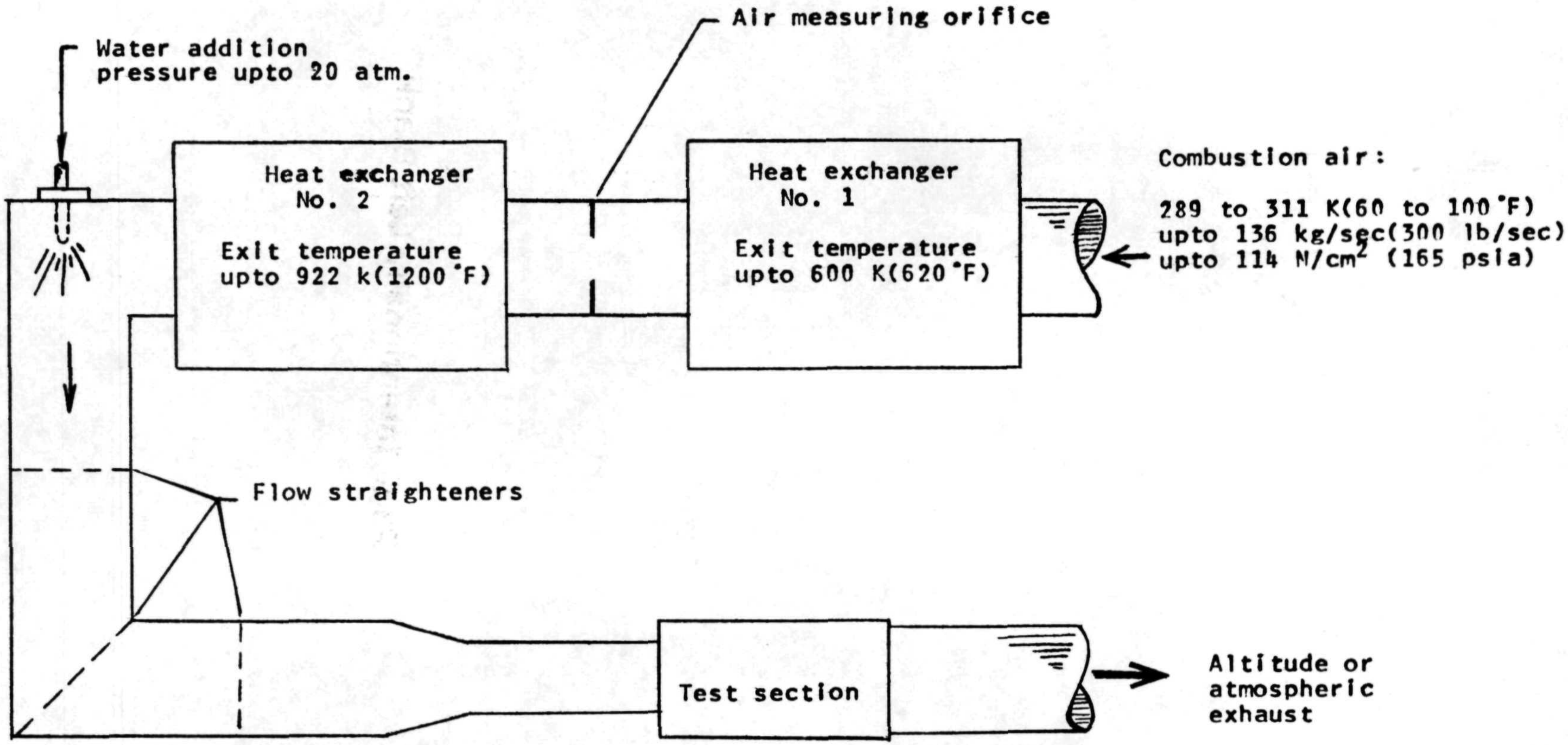

Figure 1. Test facility

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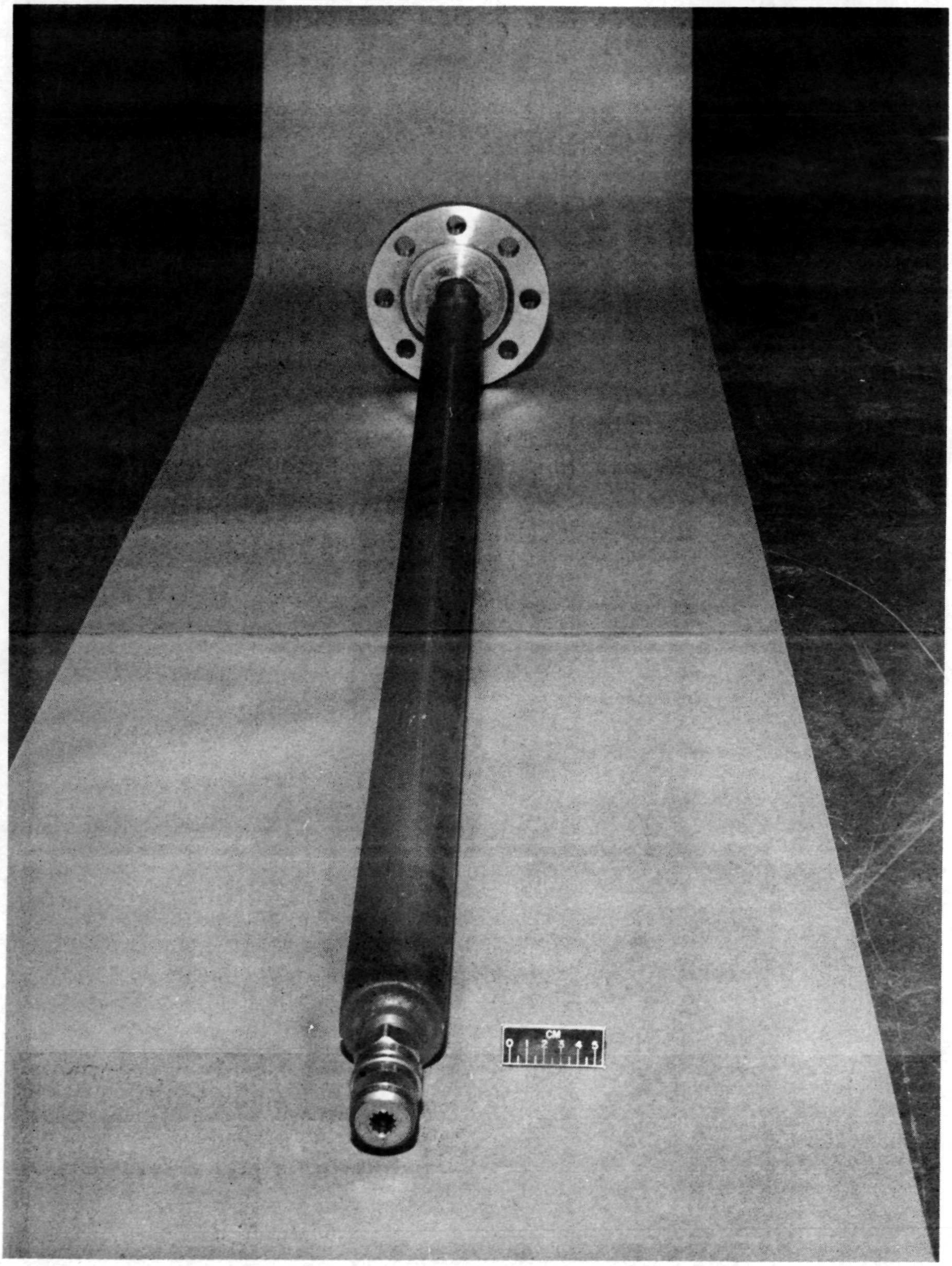

Figure 2. Nozzle for water addition; high range

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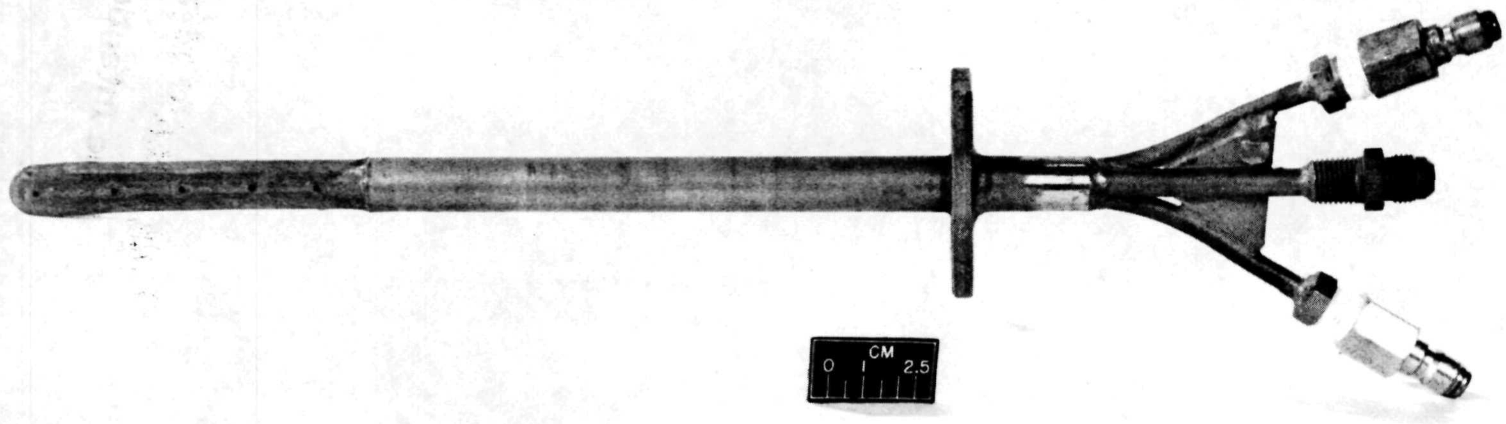

Figure 3. Exhaust gas sampling probe.

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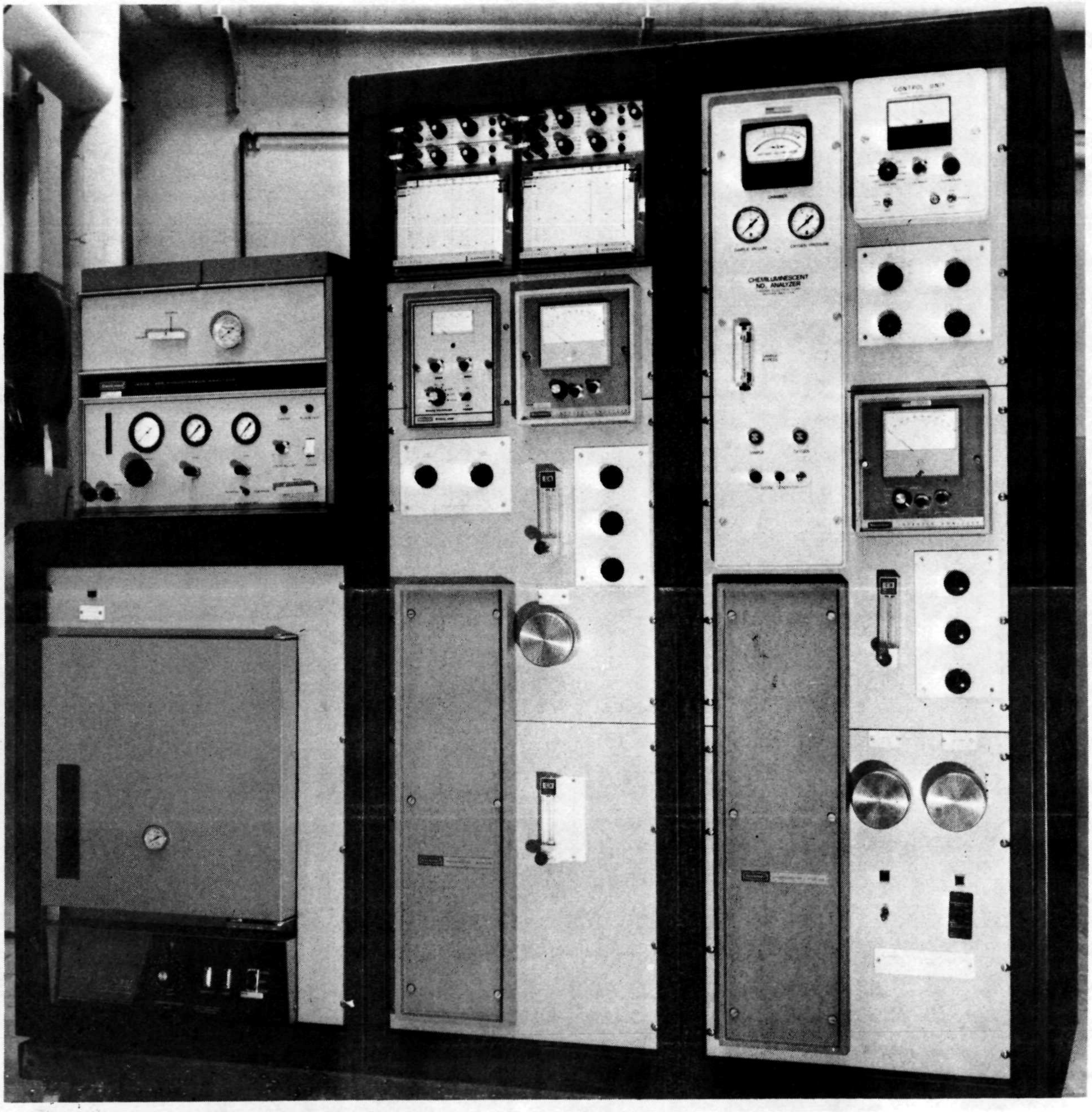

Figure 4. Exhaust gas analysis system.

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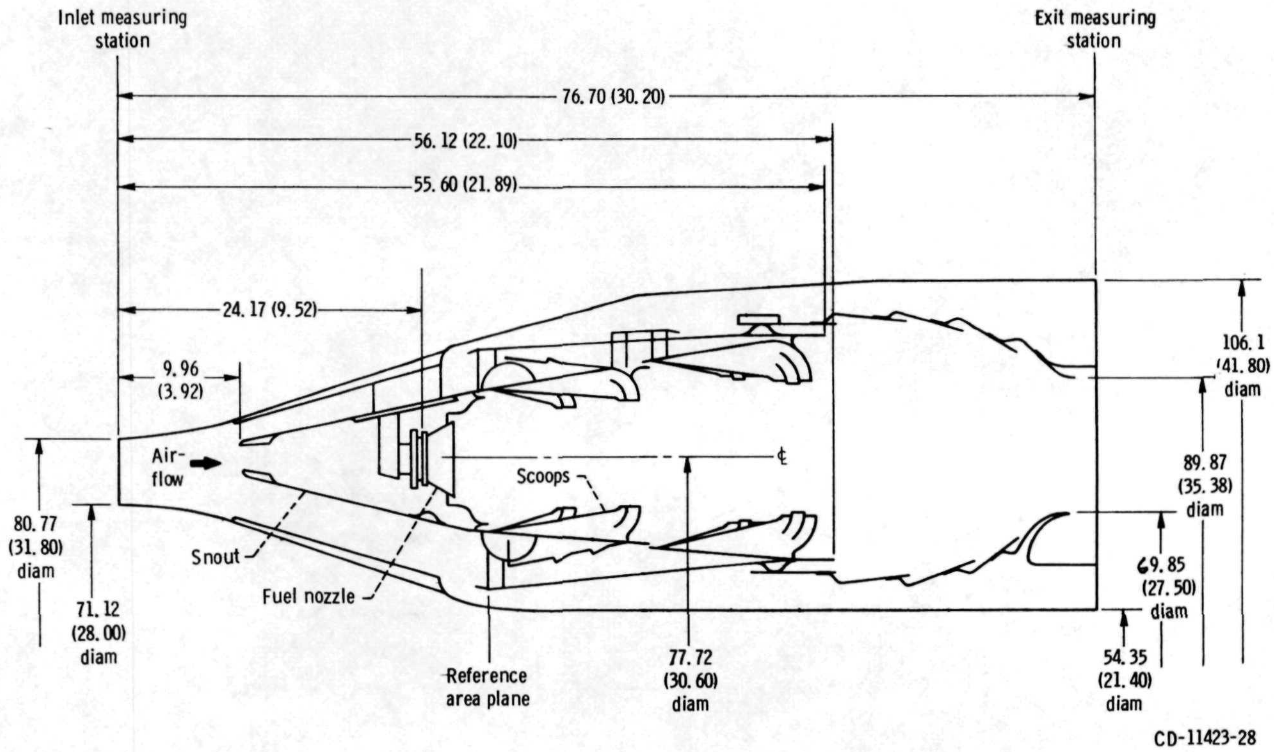

Figure 5. Cross section of combustor. Dimensions are in cm(in.).

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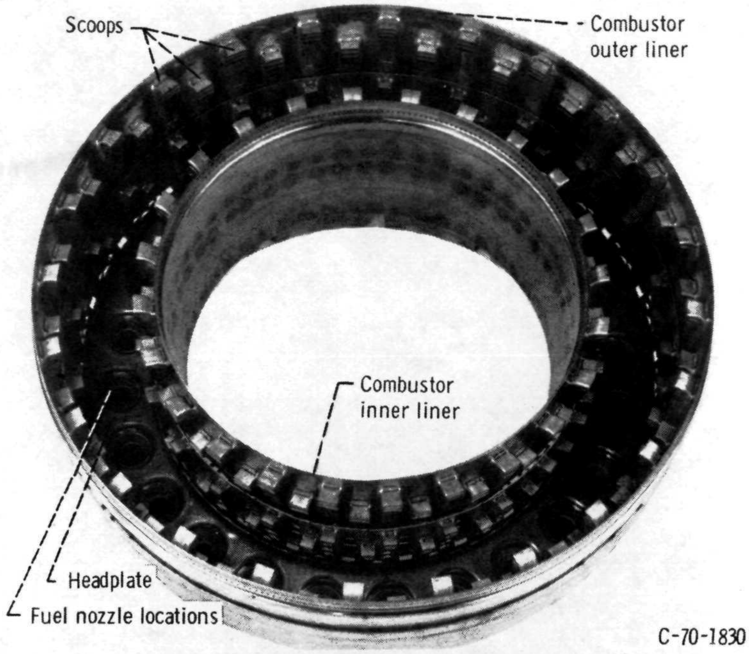
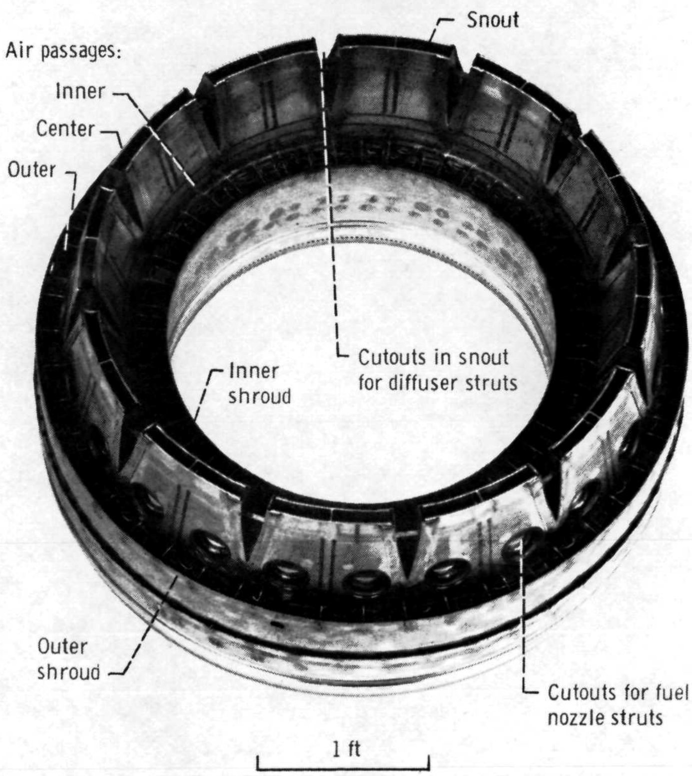


(a) View from downstream end.



(b) View from upstream end.

Figure 6. - Annular ram-induction combustor.

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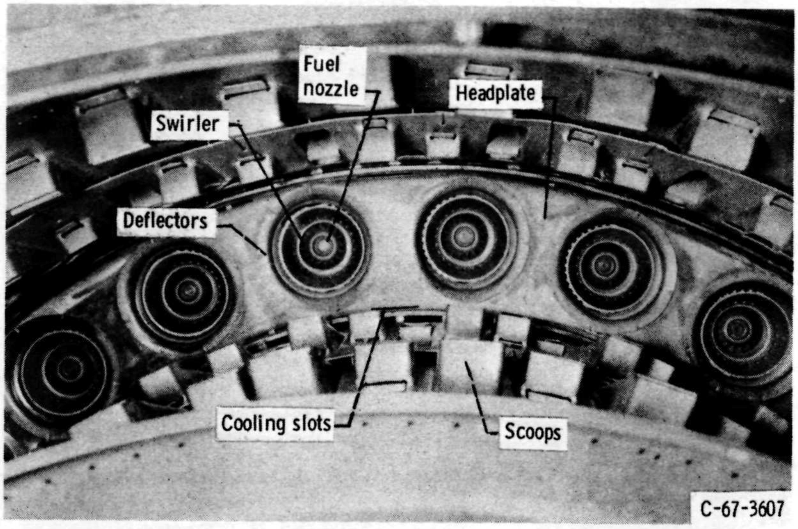

(c) Closeup view from downstream end.

Figure 6. - Concluded.

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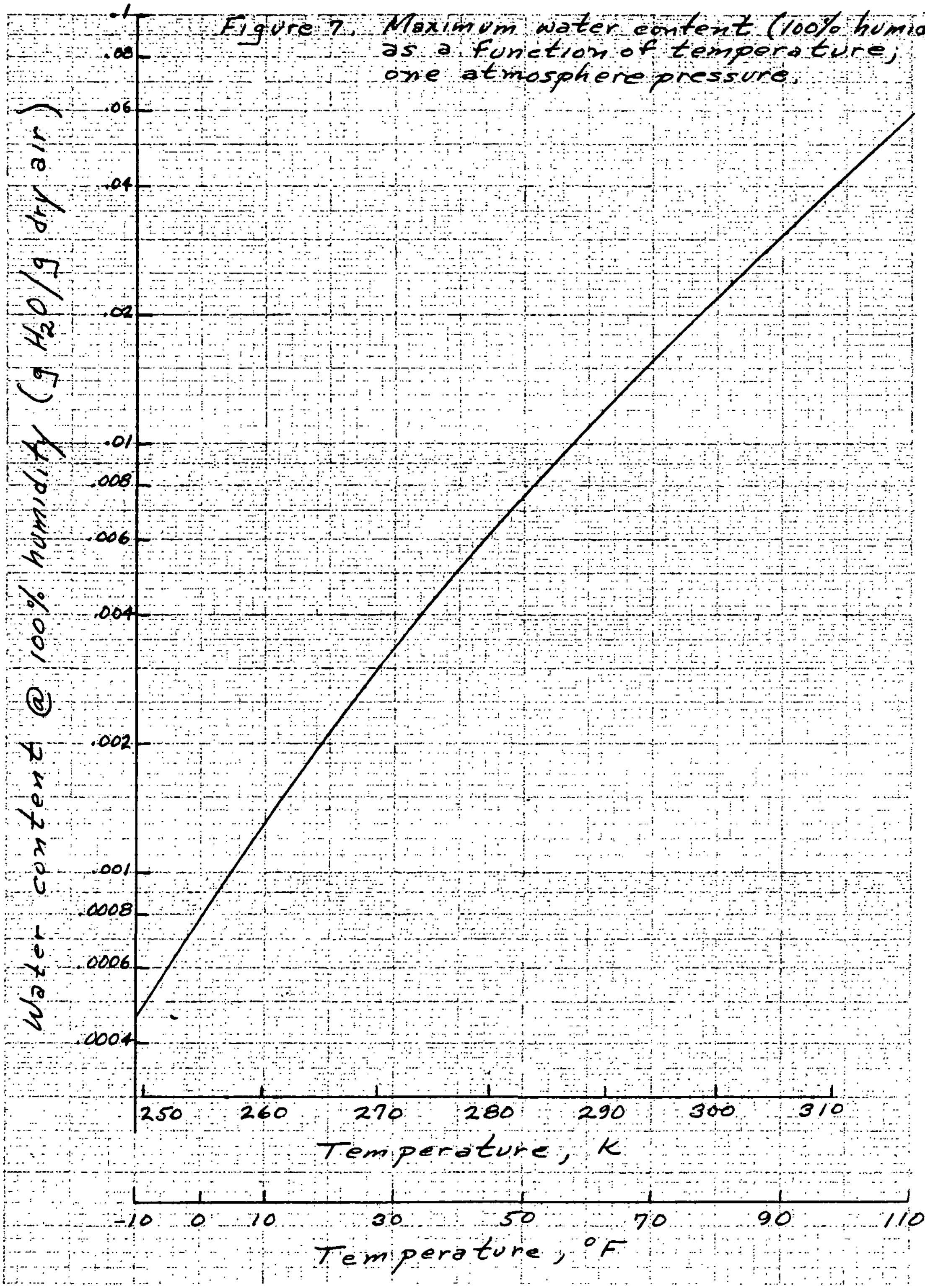
Figure 7. Maximum water content (100% humidity) as a function of temperature; one atmosphere pressure.



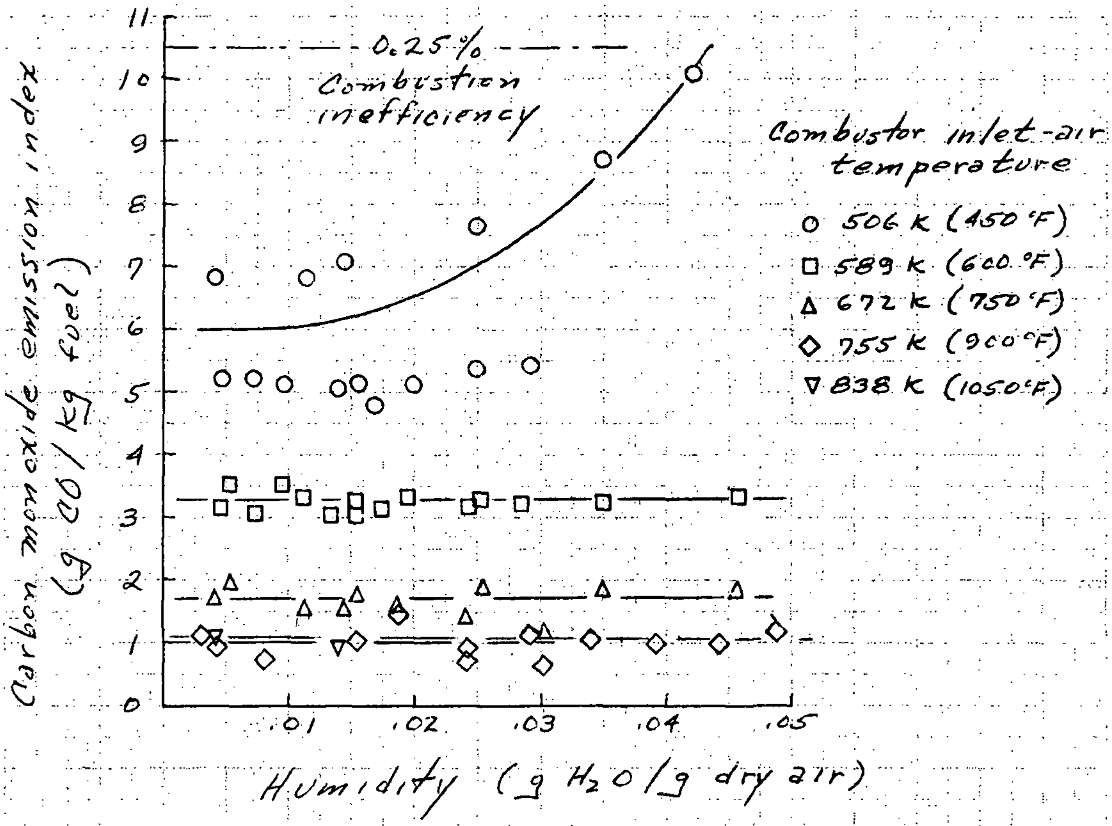


Figure 8. Effect of inlet-air humidity on carbon monoxide emission index. Combustor pressure, 6 atmospheres; reference Mach number .065; nominal exit temperature 1478 K (2200 °F)

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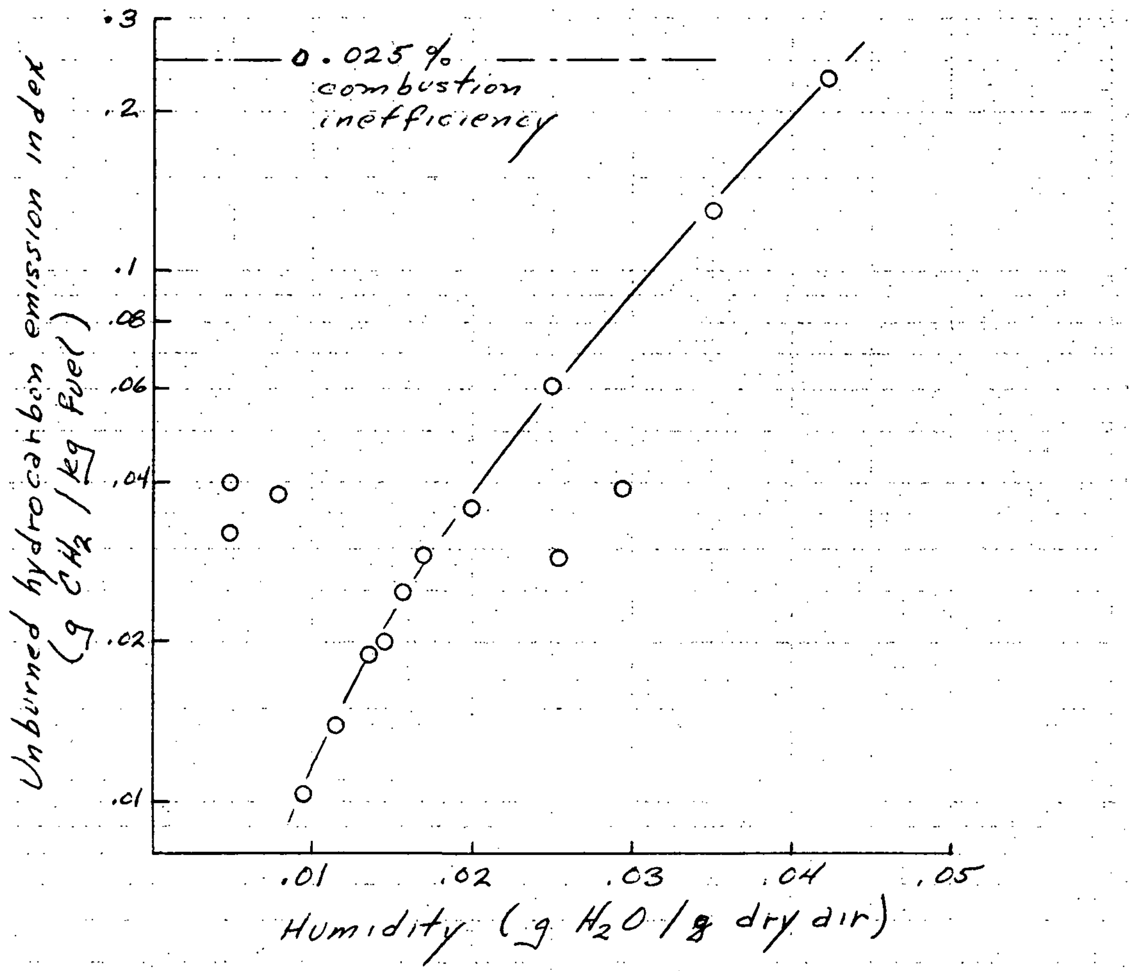
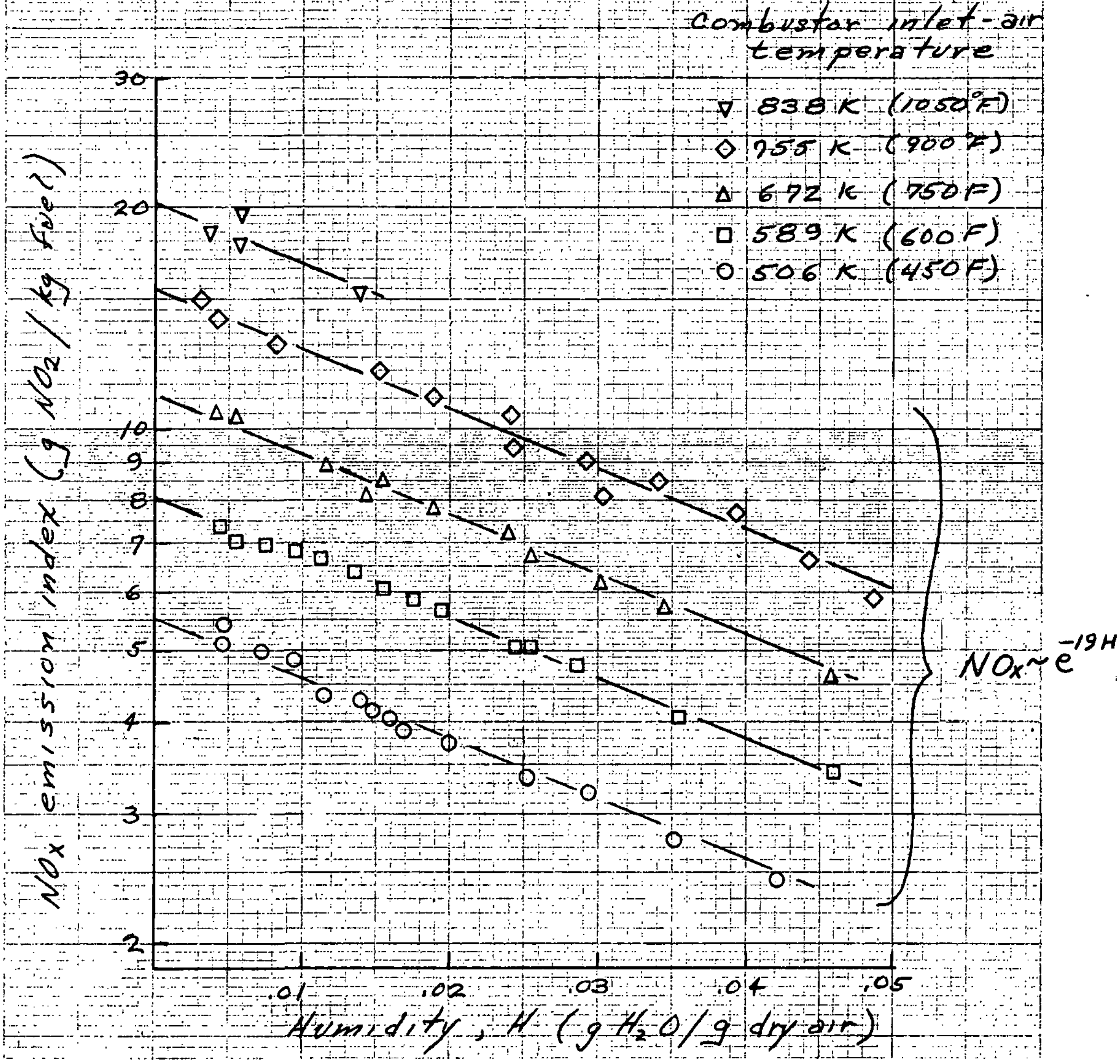


Figure 9. Effect of inlet-air humidity on unburned hydrocarbon emission index. Combustor pressure, 6 atmospheres; reference Mach number .065; inlet-air temperature 506 K (450°F); nominal exit temperature 1478 K (2200°F)

Figure 10. Effect of inlet air humidity on the formation of oxides of nitrogen. Combustor pressure, 6 atmospheres; reference Mach number .065 nominal exit temperature 1478 K (2200 F)



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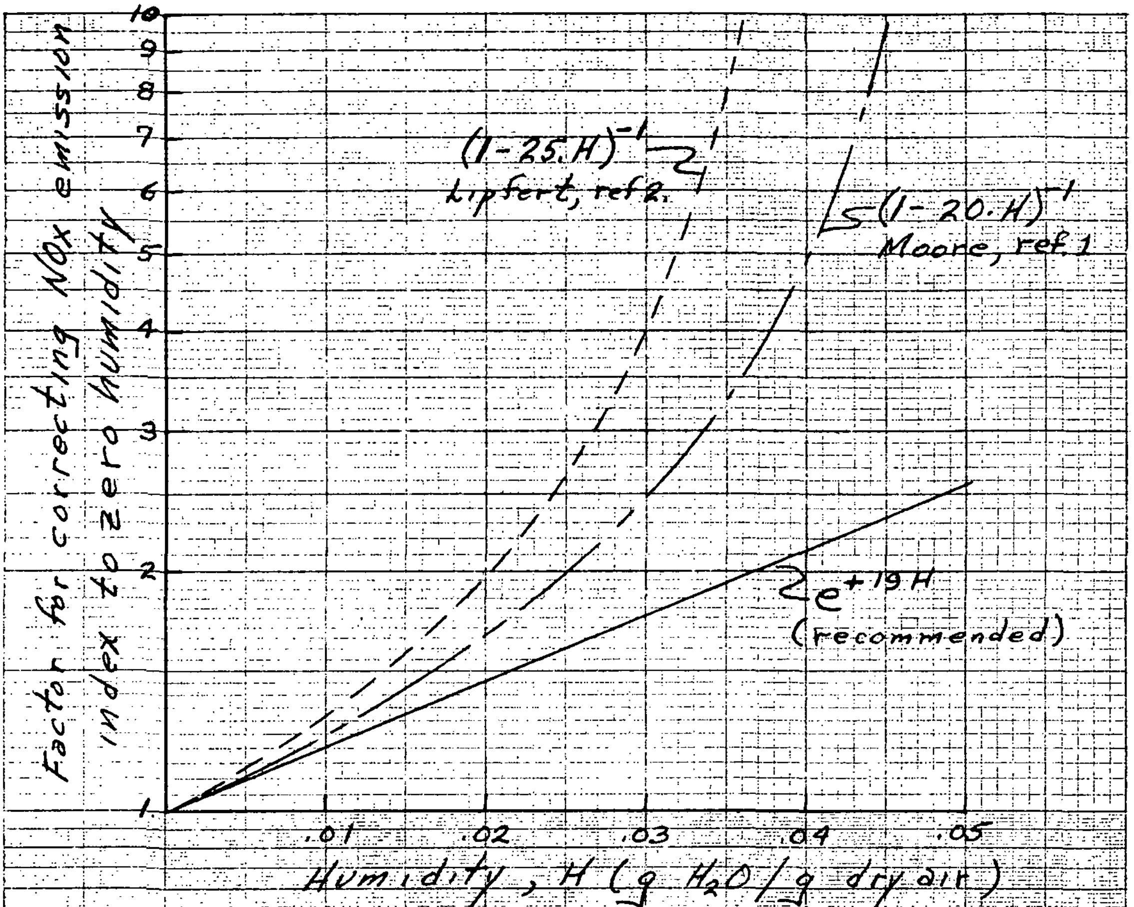

Figure 11. Correction factors for NOx emission index as a function of inlet-air humidity; correcting to zero humidity.

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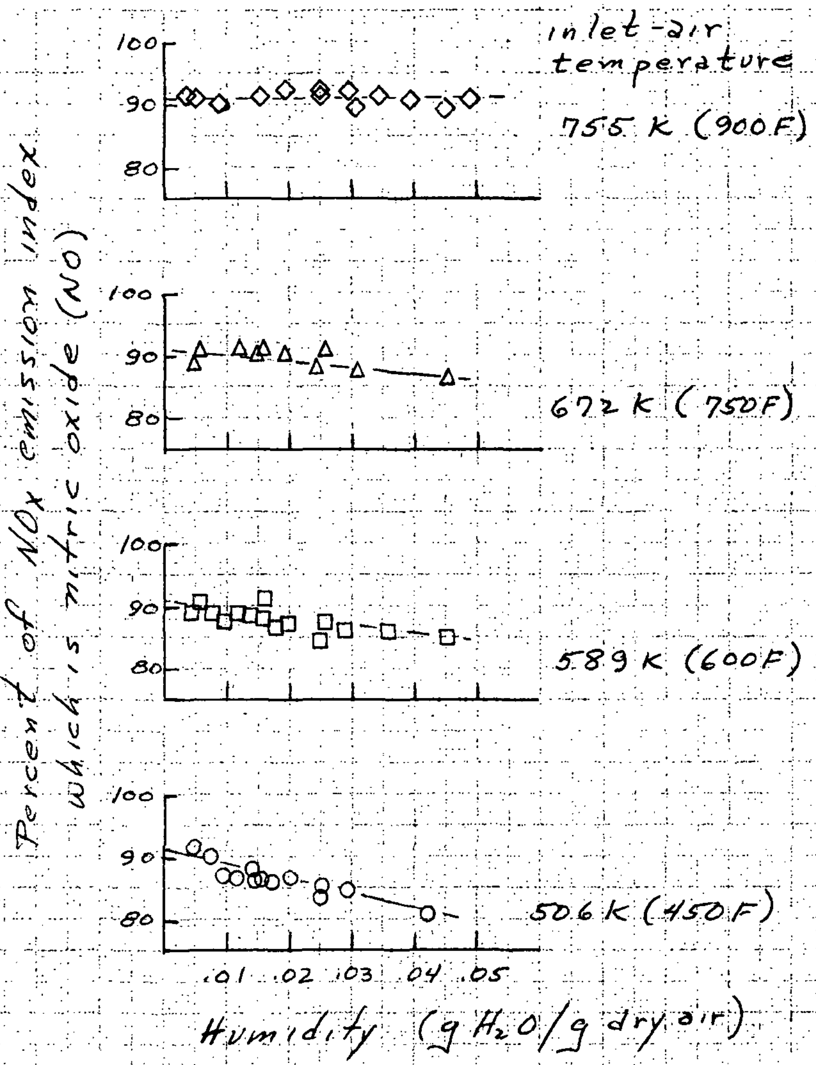

Figure 12. Effect of inlet air humidity on the percent of NO_x emission index which is nitric oxide.
Combustor pressure, 6 atmospheres; reference Mach number .065; nominal exit temperature 1478 K (2200°F)

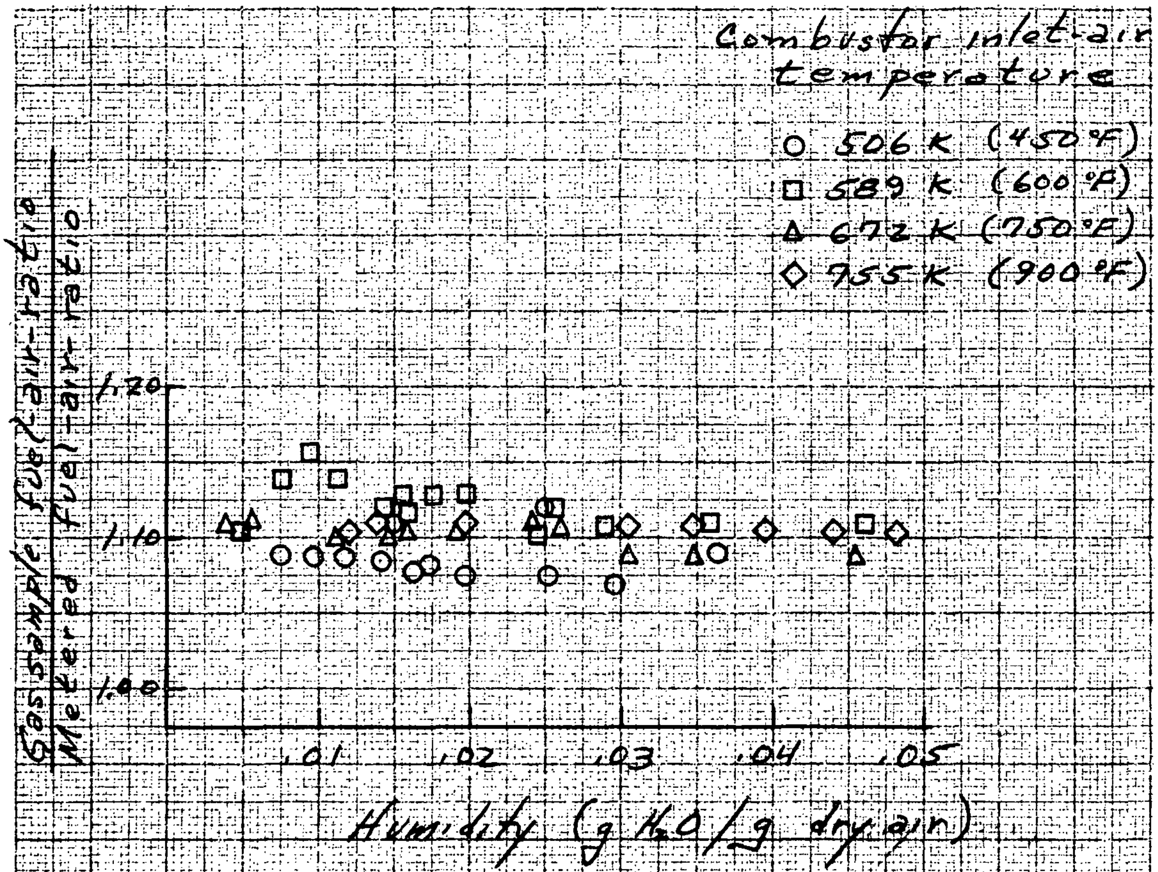

Figure 13. Fuel-air-ratio ratio comparison to check sample validity.

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