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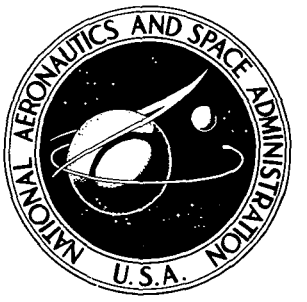

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EFFECT OF INCREASED FUEL TEMPERATURE ON EMISSIONS OF OXIDES OF NITROGEN FROM A GAS TURBINE COMBUSTOR BURNING NATURAL GAS

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16. Abstract

An annular gas turbine combustor was tested with heated natural-gas fuel to determine the effect of increasing fuel temperature on the formation of oxides of nitrogen (NO_x). Fuel temperatures ranged from ambient to 800 K (980° F). Combustor pressure was 6 atmospheres and the inlet-air temperature ranged from 589 to 894 K (600° to 1150° F). The NO_x emission index increased with fuel temperature at a rate of 4 to 9 percent per 100 K (180° F) increase in fuel temperature, depending on the inlet-air temperature. The rate of increase in NO_x was lowest at the highest inlet-air temperature tested.

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SUMMARY

An annular gas turbine combustor was tested with heated natural-gas fuel to determine the effect of increasing fuel temperature on the formation of oxides of nitrogen (NO_x). Fuel temperatures ranged from ambient to 800 K (930° F). Combustor pressure was 6 atmospheres and the inlet-air temperature ranged from 589 to 894 K (600° to 1150° F). The NO_x emission index increased with fuel temperature at a rate of 4 to 9 percent per 100 K (180° F) increase in fuel temperature, depending on the inlet-air temperature. The rate of increase in NO_x was lowest at the highest inlet-air temperature tested.

INTRODUCTION

This report presents the results of combustor tests which were conducted with heated natural-gas fuel to determine the magnitude of the effect of increased fuel temperature on the formation of oxides of nitrogen (NO_x).

Natural gas has been proposed as a possible fuel for supersonic flight applications (refs. 1 to 3). The fuel, which has a high heat-sink capacity and a low tendency to fuel decomposition, could be utilized as a heat sink in supersonic flight. Natural gas also has an advantage over kerosene fuels in that it produces lower NO_x emissions (ref. 4).

Using fuel as a heat sink will raise the fuel temperature. Fuel temperatures significantly higher than those currently used could produce higher flame temperatures and significantly higher exhaust-gas emissions of NO_x since the formation of nitric oxide (NO) is sensitive to flame temperature. However, higher fuel temperatures also increase the flammability limits of the fuel. Increased flammability may allow the primary zone of the combustor to be designed to burn at lean fuel-air ratios, where the formation of NO_x is lower than at stoichiometric fuel-air ratios.

Tests were conducted on a ram induction combustor over a range of fuel temperatures from ambient to 800 K (980° F) to determine the effect of fuel temperature on NO_x emissions. Combustor pressure was 6 atmospheres. Combustor inlet-air temperature ranged from 589 to 894 K (600° to 1150° F) and reference Mach number ranged from 0.065 to 0.080. Emissions of NO_x, carbon monoxide (CO), unburned hydrocarbons (H/C), and carbon dioxide (CO_2) were measured.

The units for physical quantities in this report are given in both the International System of Units (SI) and the U.S. customary system. However, measurements during the investigation were made in the U.S. customary system.

FACILITY

Testing was conducted in a closed-duct test facility of the Engine Components Research Laboratory of 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 5. 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 6. 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 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 outer diameter is about 1.06 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 annual 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.

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 liners

can be seen, as well as the openings in the headplate for the fuel nozzles and swirlers. 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 liquid fuel nozzles and swirlers in place. There are a total of 24 fuel nozzles in the combustor. The fuel nozzles were modified for use with natural gas.

Figure 4 shows a gas fuel nozzle and its installation. The nozzle has six holes of 0.476-centimeter (0.188-in.) diameter at a 13.5° angle from the nozzle centerline. Fuel flow was restricted by the small supply hole through the fuel strut, which was originally designed for liquid fuel.

FUEL SYSTEM

The fuel pumping system was capable of providing only 0.45 kg/sec (1 lb/sec) of natural gas at 800 K (980° F) to the combustor because of the previously described flow restriction in the fuel strut. The fuel heat exchanger was therefore sized accordingly.

The chemical and physical properties of the natural-gas fuel are presented in table I. The natural-gas composition reported is representative of the natural gas used during the test program. The gas composition varies and is dependent upon the season, the demand, and the gas field from which it is obtained.

TEST PROCEDURE

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 three circumferential locations (120° apart) and at five radial positions, through water-cooled stainless-steel probes. The exit instrumentation plane is shown in figure 2. The sample probe is pictured in figure 5.

Gas sampling system. - The samples collected by the three sampling probes were common manifolded to one sampling line. Approximately 18 meters (60 ft) of 0.95-centimeter (3/8-in.) stainless-steel line was used to transport the sample to the analytical instruments. To prevent condensation of water and to minimize adsorption-desorption effects of hydrocarbon compounds, the line was electrically heated to 420 K (310° F). Sampling line pressure was maintained at 1.7 atmospheres absolute to supply

sufficient pressure to operate the instruments. Sufficient sample was vented at the instruments to provide a line residence time of about 2 seconds.

The exhaust gas analysis system shown in figure 6 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 converter to reduce NO_2 to NO and was operated at 973 K (1290° F). Both NO and total NO_x data were taken. 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-centimeter (13.5-in.) length. The CO_2 analyzer has two ranges, 0 to 5 percent and 0 to 10 percent, with a sample cell length of 0.32 centimeter (0.125).

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

Where appropriate, the measured quantities were corrected for water vapor removed. The correction included inlet-air humidity, water injected, and water vapor from combustion. The equations used were obtained from reference 7.

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 7 or by an alternate procedure which uses the metered fuel-air ratio when this is accurately known. With the latter scheme the EI for any constituent X is given by

$$EI_X = \frac{M_X}{M_e} \frac{1+f}{f} [X] \times 10^{-3} \qquad (1)$$

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

[X] measured concentration of X in ppm

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

Test Conditions

Tests were conducted at a constant pressure of 6 atmospheres and a constant airflow of 50 kg/sec (110 lb/sec). Combustor inlet-air temperature was varied from 589 to 894 K (600° to 1150° F). Nominal reference Mach numbers ranged from 0.065 to 0.080 because of the changes in inlet-air temperature.

Fuel flow rates were limited by a flow restriction in the fuel nozzle strut. All tests were conducted at the maximum fuel flow rates attainable. The fuel flow varied with fuel temperature and resulted in a fuel-air ratio of 0.0125 ± 0.0035.

Data were taken at fuel temperatures near 300, 550, and 800 K (80°, 530°, and 980° F).

RESULTS AND DISCUSSION

Data taken during the test program are presented in table II. The NO_x emissions data were adjusted to zero inlet-air humidity by multiplying the measured values by e^{19H}, where H is the absolute humidity (g of water/g of dry air), reference 8. The NO_x emissions data were also adjusted to nominal reference Mach numbers by assuming that NO_x varies inversely with Mach number, reference 8.

Effect of Fuel Temperature on Oxides of Nitrogen

The NO_x emission index increased with increasing fuel temperature, as shown in figure 7. The increase in NO_x with fuel temperature is attributed to increased flame temperature in the primary combustion zone, which is caused by the increased enthalpy of the fuel. Increasing flame temperature increases the rate of formation of nitric oxide (NO) with time, reference 8:

$$[\dot{NO}] = 9.5\, k_2 \left\{ \exp\left(\frac{-75.5 \text{ kcal/g-mole}}{RT_f} \right) \right\} \times [O] \times [N_2] \qquad (2)$$

where

$[\dot{NO}]$	rate of formation of NO, $d[NO]/dt$
k_2	$(13\pm4)\times10^{12}$ $cm^3mole^{-1}sec^{-1}$
R	1.987 cal/(g-mole)(K)
[NO]	concentration of NO
[O]	concentration of O
$[N_2]$	concentration of N_2
T_f	flame temperature, K

If the concentrations of N_2 and O remain constant, the rate equation (2) implies an exponential increase in NO formation with increasing flame temperature. The data are therefore plotted on semilog coordinates and the best straight line is drawn through the data. Variations from the constant exponential increase in NO_x with fuel temperature are attributed primarily to repeatability of the data.

The rate of increase in NO_x which might be expected from an increase in fuel temperature can be calculated based on a simplified combustion model. The model specifies that all the NO_x is formed in a primary combustion zone where the fuel-air ratio is stoichiometric and that all the additional enthalpy of the fuel raises only the primary-zone flame temperature, affecting the rate of formation of NO (eq. (2)). The change in flame temperature may be calculated from the change in enthalpy of the heated fuel:

$$\Delta T_{flame} = \frac{\Delta H_{fuel}}{C_p} \left(\frac{f/a}{1 + f/a} \right) \tag{3}$$

with

ΔT_{flame}	change in flame temperature
ΔH	change in enthalpy of the fuel due to heating
C_p	specific heat at constant pressure of the combustion gases at a stoichiometric fuel-air ratio (ref. 9)
f/a	stoichiometric fuel-air ratio

The specific heat C_p of the combustion gases increases with increasing flame temperature and increasing fuel-air ratio. The stoichiometric flame temperature increases with increasing inlet-air temperature.

By using equations (2) and (3), the increase in formation rate of NO concentration may be calculated:

$$\frac{[\dot{N}O]}{[\dot{N}O]_o} = \frac{\exp\left[\frac{-75.5}{R(T_o + \Delta T)}\right]}{\exp\left(\frac{-75.5}{RT_o}\right)} \tag{4}$$

where $[\dot{N}O]_o$ corresponds to the rate of formation of $[\dot{N}O]$ at ambient fuel temperature for a stoichiometric flame temperature T_o.

This calculation was carried out for the minimum and maximum inlet-air temperatures tested. Figure 8 shows the theoretical results and the actual data results normalized to the value with ambient fuel temperature, 300 K (80° F). At the high inlet-air temperatures the data agree very well with the model. The NO_x emission index increased approximately 4 percent per 100 K (180° F) increase in fuel temperature. At the lowest inlet-air temperature, the increase in NO_x was higher than predicted by the model and was approximately equal to a 9 percent increase in NO_x per 100 kelvin (180° F) increase in fuel temperature. The model does predict a greater increase in NO_x due to fuel heating at lower inlet-air temperatures, partially because of the difference in specific heat and partially because of the steeper gradient of the exponential function at the lower flame temperature.

One factor which the model does not take into account is the increased flammability limits of the fuel when it is heated. Increased flammability allows the fuel to burn over a wider range of fuel-air ratios, where the rate of formation of NO_x is lower than at the stoichiometric fuel-air ratio. The combustor would have to be redesigned to take advantage of this possibility.

Effect of Fuel-Air Ratio on Oxides of Nitrogen

The data shown in figure 7 were taken at varying fuel-air ratios. There was no significant difference in NO_x emission index with varying fuel-air ratio between these data and data from the same combustor burning ASTM Jet-A fuel (ref. 10). However, data at constant fuel-air ratio with natural gas have not been taken. If the NO_x emission index increases with increasing fuel-air ratio, the increase in NO_x with fuel temperature would probably be larger than that shown in figures 7 and 8.

Combustion Efficiency

Combustion efficiency was over 99.6 percent at all the test conditions. The effi-

ciency data determined from gas sample measurements are shown in table II. Combustion efficiency was lowest at the lowest inlet-air temperature and increased with increasing inlet-air temperature.

Effect of Inlet-Air Temperature on Emissions of Oxides of Nitrogen

Figure 9 shows the effect of inlet-air temperature on NO_x emissions when natural gas was used at ambient temperatures. The data have been adjusted to a constant reference Mach number of 0.065 for comparison with liquid ASTM Jet-A fuel from reference 8 for the same combustor. The use of natural gas gave less NO_x emissions than the use of liquid fuel, as has been experienced by others (ref. 4). Also the effect of inlet-air temperature on NO_x emission index appears to be slightly larger when using natural gas, tending to bring the curves together at high inlet-air temperatures. This implies that the NO_x emissions may be the same with both fuels if the reactant temperatures are very high.

Sample Validity

A calculation of the gas sample fuel-air ratio was made for each data point. The ratio of the gas sample fuel-air ratio to the metered fuel-air ratio (fuel-air-ratio ratio) is presented in table II. The maximum data scatter is ± 4.5 percent about a mean of 1.105. The fact that the mean value is 10.5 percent high is probably symptomatic of the location of the sampling probes and is not expected to influence the trends in the data.

SUMMARY OF RESULTS

Tests were conducted to determine the effect of increasing fuel temperature on the formation of oxides of nitrogen (NO_x). An annular gas turbine combustor was tested with natural-gas fuel at fuel temperatures from ambient to 800 K (980° F). Combustor pressure was 6 atmospheres and the inlet-air temperature ranged from 589 to 894 K (600° to 1150° F). The following results were obtained:

1. The NO_x increased with increasing fuel temperature. The rates of increase in NO_x were between 4 and 9 percent per 100 K (180° F) increase in fuel temperature depending on the inlet-air temperature. The rate of increase in NO_x was lowest at the highest inlet-air temperatures tested.

2. With fuels at ambient temperature using natural gas gave less NO_x emissions than using liquid ASTM Jet-A in the same combustor. With higher inlet-air temperatures the difference between the NO_x emissions with Jet A fuel and natural gas was lessened.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 1, 1973,
501-24.

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TABLE I. - PHYSICAL PROPERTIES OF NATURAL GAS

Density[a], kg/m^3 (lb/ft^3)	0.7320 (0.0457)
Net heat of combustion (calculated), J/kg(Btu/lb)	4.977×10^7 (2.140×10^4)
Normalized chromatographic analysis (calculated), vol.	
Methane	93.50
Ethane	3.53
Propane	0.53
Hydrocarbons (C_4, C_5, C_6)	0.32
Nitrogen	1.05
Carbon dioxide	1.07
Oxygen	Trace

[a]Density in kg/m^3 is at 289 K (1.02×10^5 N/m^2 at 273 K). Density in lb/ft^3 is at 60° F (30 in. Hg at 32° F).

TABLE II. - EXPERIMENTAL DATA

Airflow, kg/sec	Inlet total pressure, atm	Inlet total temperature, K	Fuel temperature, K	Emission indices				Humidity	NO_x at zero humidity	Fuel-air ratio	Fuel-air-ratio ratio[a]	Combustion efficiency	Reference Mach number, M_4	Nominal M_4	NO_x corrected to nominal M_4	NO_x corrected to $M_4 = 0.065$	Percent NO in NO_x
				H/C	CO	CO_2	NO_x										
50.79	6.16	598	532	1.33	7.85	3053	5.61	0.00432	6.09	0.0109	1.123	99.71	0.0642	0.065	6.00	6.00	67
51.46	6.19	597	533	1.45	8.24	3056	5.60		6.08	.0109	1.125	99.66	.0647		6.04	6.04	
51.15	6.22	593	533	1.65	9.29	3050	5.30		5.75	.0109	1.123	99.65	.0639		5.65	5.65	
50.66	6.10	596	804	.932	6.48	3034	6.76		7.33	.0092	1.114	99.76	.0646		7.25	7.25	75
50.63	6.10	595	805	.946	6.55	3129	6.97		7.56	.0089	1.149	99.77	.0645		7.50	7.50	
50.62	6.10	595	806	.946	6.81	3041	6.83		7.41	.0093	1.116	99.76	.0646		7.37	7.37	
50.17	6.11	753	535	.02	3.50	3038	9.03		9.80	.0111	1.114	99.92	.0723	.072	9.84	10.90	84
49.90	6.10	754	535	.02	3.29	3034	9.07		9.85	.0112	1.113	99.92	.0722		9.88	10.94	84
49.96	6.11	755	536	.02	3.00	3098	9.39		10.19	.0108	1.136	99.93	.0722		10.22	11.32	84
50.14	6.16	760	802	.08	4.13	2985	10.57		11.47	.0093	1.093	99.90	.0721		11.48	12.72	85
50.11	6.21	761	801	.04	4.22	3022	10.82		11.75	.0094	1.107	99.90	.0716		11.69	12.95	85
50.10	6.21	760	799	.04	3.85	3051	10.93		11.86	.0094	1.118	99.91	.0714		11.79	13.06	85
49.66	6.14	841	804	.03	2.69	3044	14.83		16.10	.0093	1.114	99.94	.0756		15.60	18.72	86
49.15	6.17	842	803		3.14	2985	14.53		15.77	.0095	1.092	99.93	.0727		14.70	17.64	86
49.45	6.19	844	802		3.07	3108	15.11		16.40	.0090	1.138	99.93	.0748		15.73	18.88	86
52.11	6.11	839	535		2.54	3013	12.20		13.24	.0106	1.104	99.94	.0796		13.50	16.20	89
51.70	6.10	839	532	.04	2.32	3021	12.36		13.41	.0107	1.107	99.94	.0791		13.60	16.32	89
52.15	6.12	840	527	.03	2.17	3063	12.52		13.59	.0104	1.122	99.95	.0797		13.90	16.68	89
50.20	6.17	897	529	.01	.97	2949	15.4		16.7	.0111	1.080	99.98	.0787	.080	16.45	20.24	91
49.49	6.18	899	530	.01	.74	2949	15.67		17.00	.0114	1.080	99.98	.0776		16.50	20.31	
49.55	6.19	900	530	.01	.59	2991	15.87		17.22	.0112	1.095	99.99	.0776		16.72	20.58	
50.19	6.08	902	794	0	2.32	3028	18.35		19.22	.0093	1.108	99.95	.0802		19.95	24.55	
50.22	6.05	902	808	0	2.07	2997	18.37		19.94	.0093	1.096	99.95	.0806		20.10	24.73	
50.06	6.11	902	813	0	2.16	3020	18.68		20.28	.0092	1.105	99.95	.0796		20.20	24.86	
50.79	6.10	591	290	.41	5.34	2911	4.84	.00423	5.22	.0159	1.108	99.84	.0645	.065	5.18	5.18	--
49.71	6.16	761	309	0	1.12	2934	8.76	.00538	9.70	.0156	1.085	99.97	.0715	.072	9.63	10.58	88
49.23	6.14	846	320	0	.51	2896	11.67	.00640	13.18	.0149	1.070	99.99	.0752	.078	12.70	15.23	89
49.84	6.12	897	318	0	.61	2876	14.9	.00737	17.13	.0150	1.062	99.99	.0788	.080	16.88	21.1	88

[a]Ratio of sample fuel-air ratio to metered fuel-air ratio.

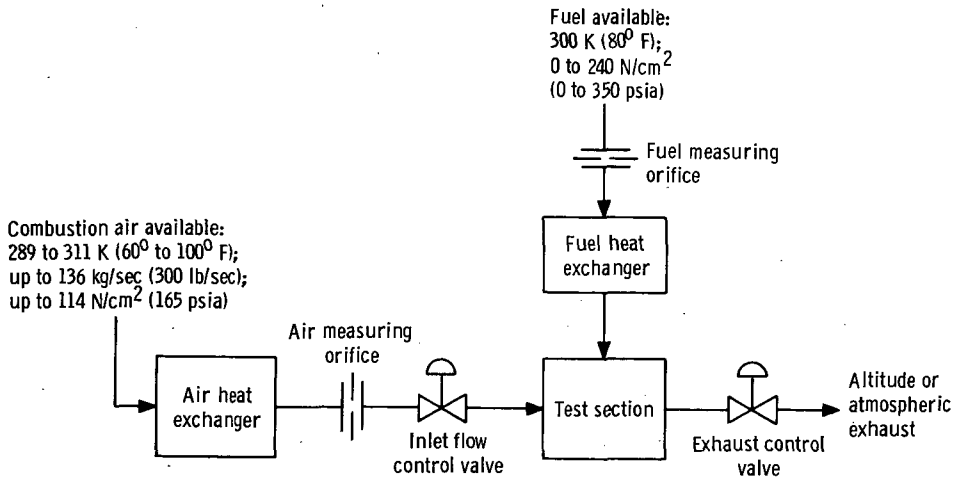


Figure 1. - Test facility.

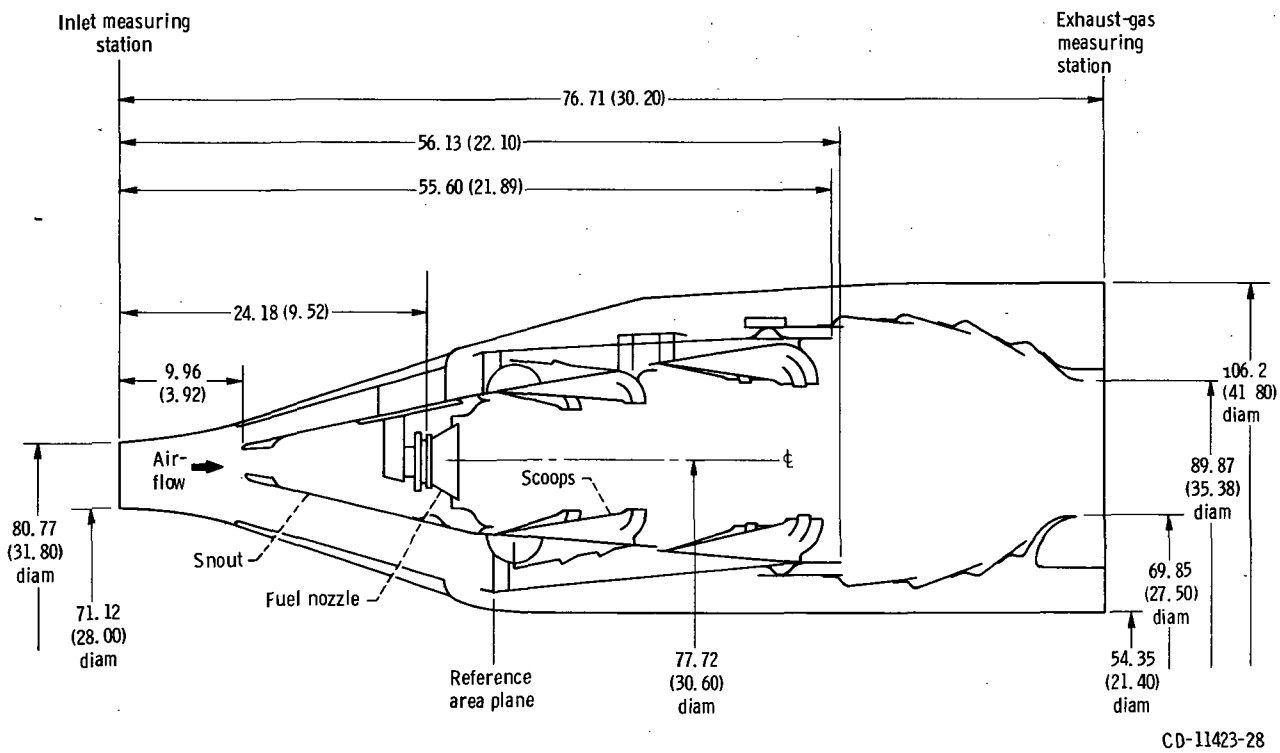
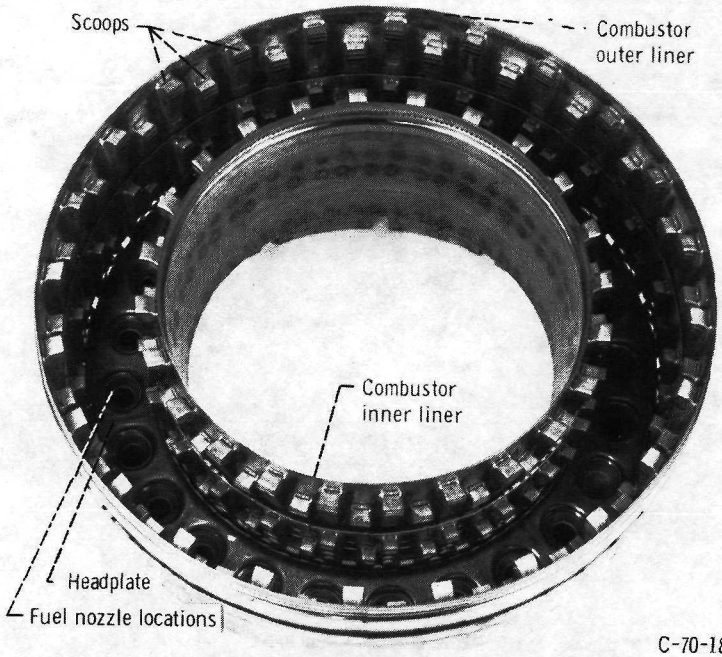
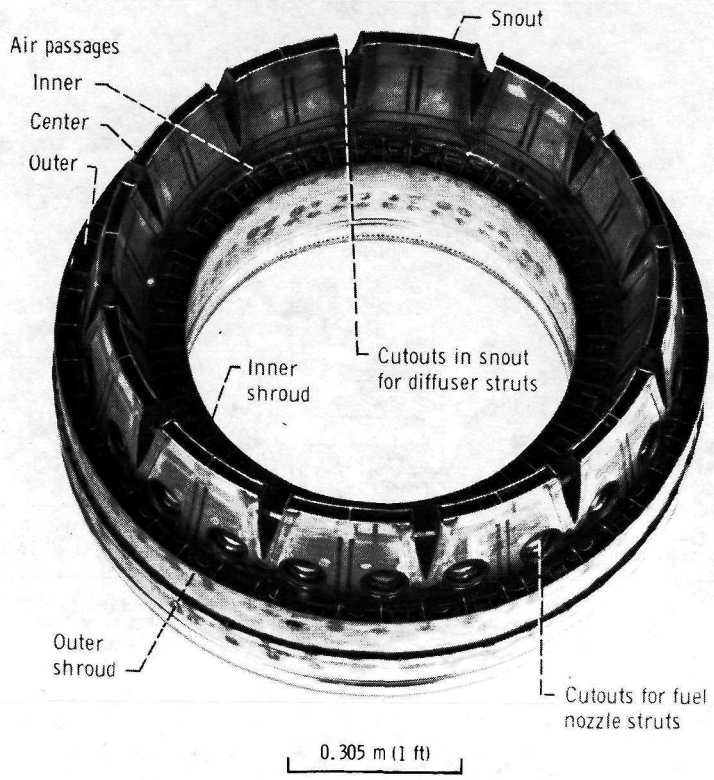


Figure 2. - Cross section of combustor. Dimensions are in cm (in.).

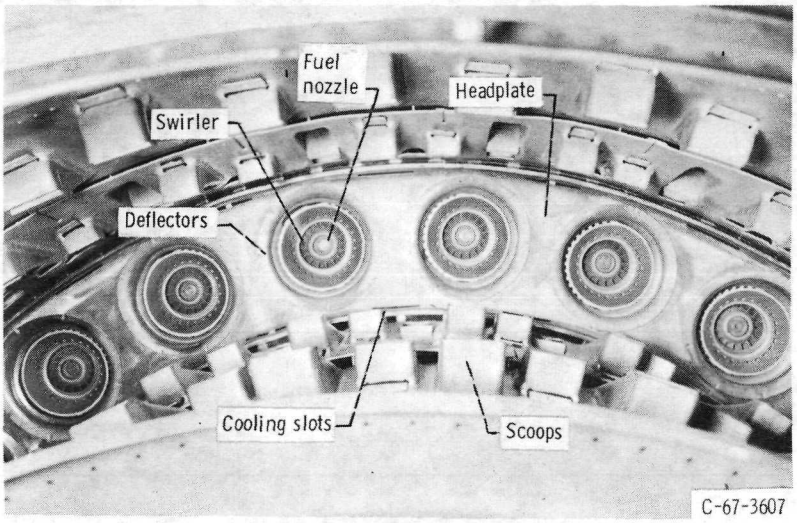


(a) View from downstream end.



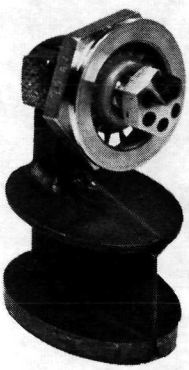
(b) View from upstream end.

Figure 3. - Annular ram-induction combustor.



(c) Closeup view from downstream end.

Figure 3 - Concluded.



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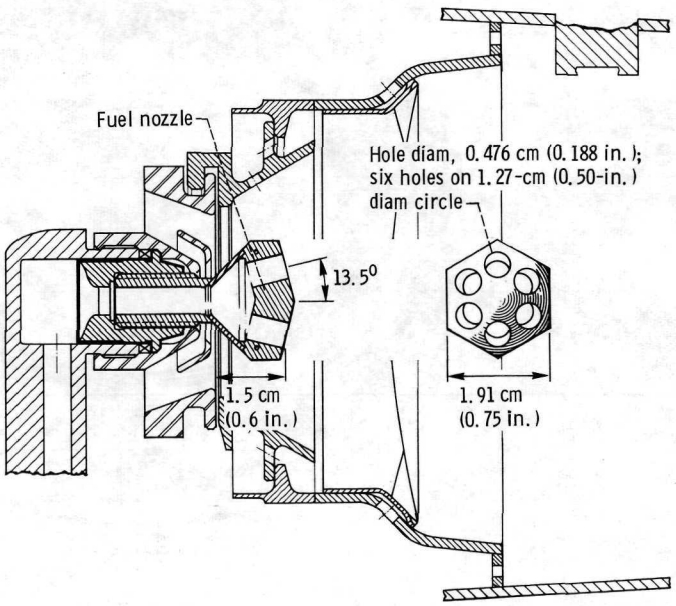


Figure 4. - Natural gas fuel nozzle.

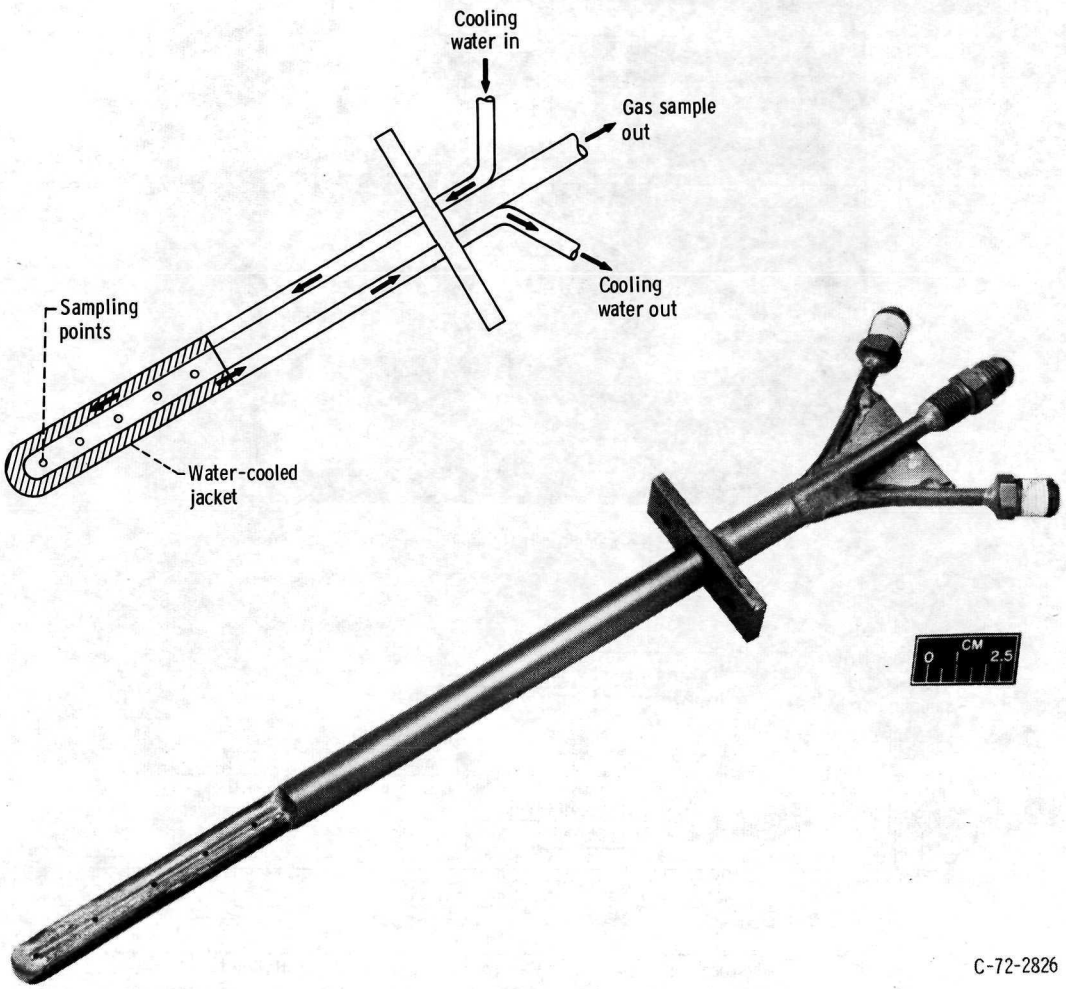
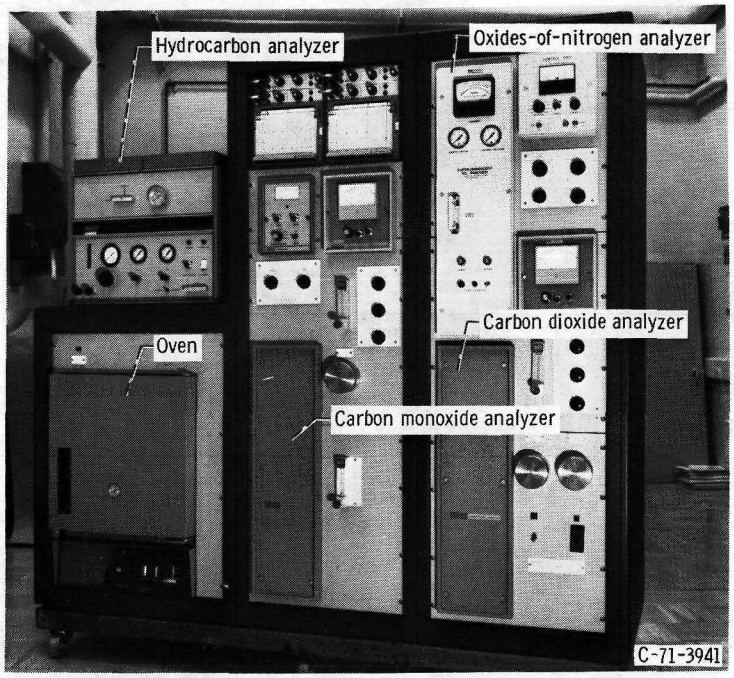
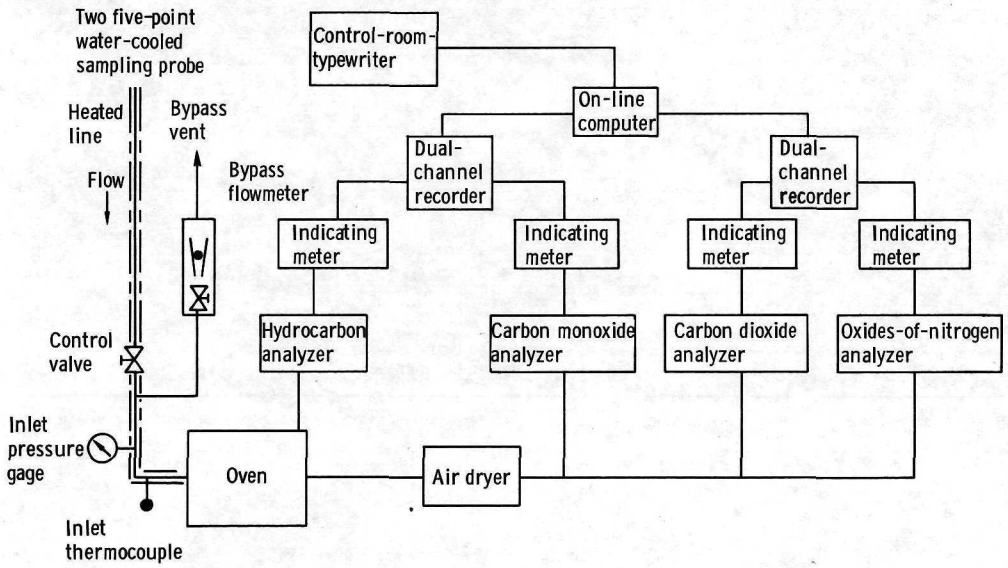


Figure 5. - Gas sampling probe.



(a) Gas sampling instrument console.



(b) Schematic diagram of gas analysis system.

Figure 6. - Exhaust-gas analysis system.

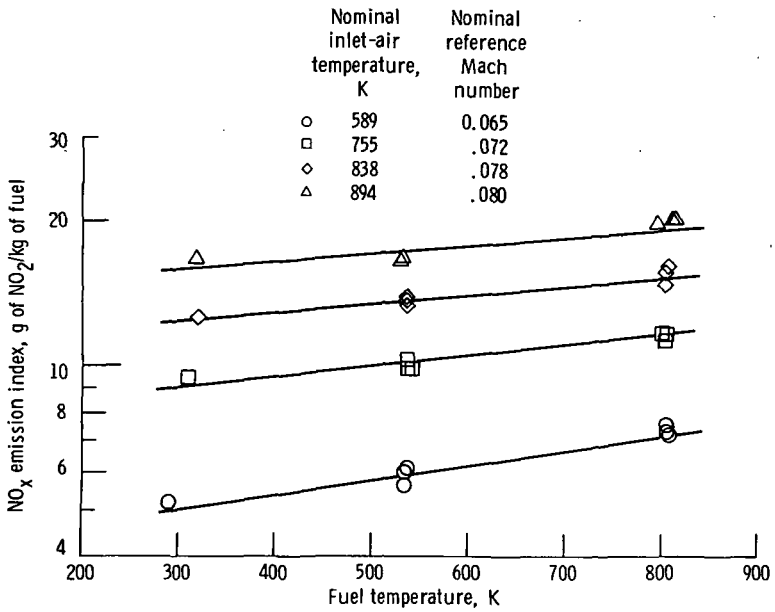


Figure 7. - Effect of fuel temperature on NO_x emission index. Pressure, 6 atmospheres (corrected to zero humidity).

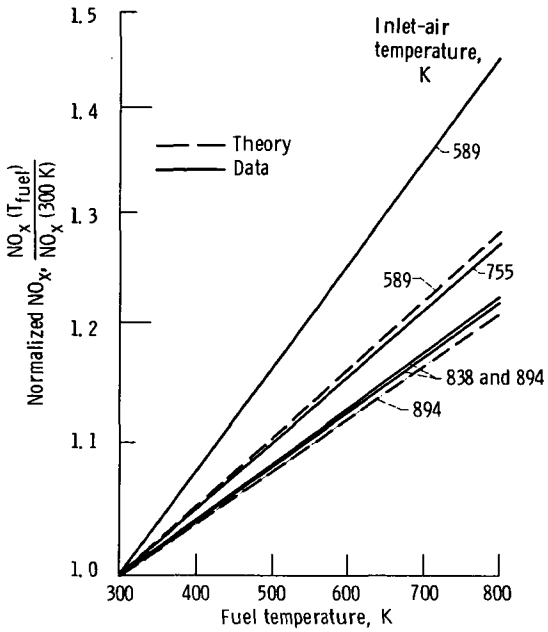


Figure 8. - Effect of fuel temperature on normalized NO_x emissions - compared to results of theoretical model. (Data points omitted for clarity of presentation.)

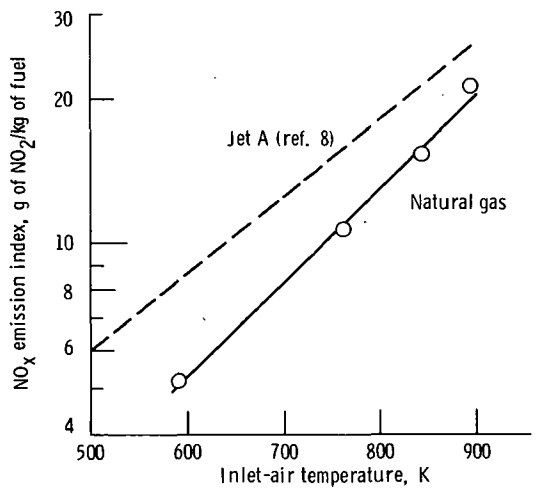


Figure 9. - Effect of inlet-air temperature on NO_x emission index for natural gas and Jet A fuel. Pressure, 6 atmospheres; reference Mach number, 0.065; zero inlet-air humidity; ambient fuel temperature; nominal fuel-air ratio, 0.0155.

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