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MEASUREMENT OF GASEOUS EMISSIONS FROM A TURBOFAN ENGINE AT SIMULATED ALTITUDE CONDITIONS

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16. Abstract

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SUMMARY

Gaseous emissions from a TFE 731-2 turbofan engine were measured over a range of fuel-air ratios from idle to full power at simulated altitudes from near sea level to 13 200 meters and flight Mach numbers of 0.6 and 0.8. Gas samples were collected at the core engine exit and were analyzed for carbon monoxide, unburned hydrocarbons, oxides of nitrogen, and carbon dioxide.

Carbon monoxide and unburned hydrocarbon emissions were highest at idle and lowest at high power settings; oxides of nitrogen exhibited the reverse trend. As the altitude was increased, carbon monoxide and unburned hydrocarbons increased. Oxides of nitrogen emissions decreased with increasing altitude.

A correlating parameter consisting of combustor variables was successful in correlating the emissions of oxides of nitrogen to within an emission index value of ±0.5 for the range of test conditions investigated.

INTRODUCTION

The purpose of this report is to document the gaseous emissions from a turbofan engine at various simulated altitudes. Particular emphasis was placed on measurement of the oxides of nitrogen.

In preparation for formulating emissions standards for aircraft gas turbines the Environmental Protection Agency undertook an extensive program of engine emission testing. The results of these studies are presented in reference 1. As the primary purpose of these data was to assess the environmental impact of pollutant emissions in the vicinity of the airport, all data were gathered at ground level static conditions.

The effect of high-altitude vehicle flight on the environment and meteorology is also of concern. The Climatic Impact Assessment Program of the Department of

Transportation (ref. 2) addresses itself directly to this problem. For constant Mach number flight the anticipated effect of altitude on gaseous emissions is to increase carbon monoxide and unburned hydrocarbons and to decrease the oxides of nitrogen. Experimental data from recent studies (refs. 3 and 4) have exhibited this trend with turbojet engines. This report presents data from a turbofan engine.

Measurements of engine exhaust emissions were made on a TFE 731-2 turbofan engine tested in an altitude test cell. The test conditions included simulated altitudes from 640 to 13 200 meters and flight Mach numbers of 0.6 and 0.8. Additional data were taken at a constant engine inlet-air temperature of 294 K (70° F) with varying pressure altitudes. It was hoped that some correlation could be found between the two sets of data as all engine altitude test facilities do not have the required refrigerated air capacity to simulate wide ranges of altitude and flight Mach number. A successful correlation would obviate the requirements of conducting engine tests with refrigerated air. All tests were conducted with ASTM Jet-A fuel. Exhaust gas samples were continuously analyzed for oxides of nitrogen, unburned hydrocarbons, carbon monoxide, and carbon dioxide.

APPARATUS

Engine

The TFE 731-2, shown schematically in figure 1, is a twin-spool turbofan engine consisting of a geared fan and a four-stage axial compressor driven by a three-stage axial turbine and a single-stage centrifugal compressor driven by a single-stage axial turbine. The annular combustor is a reverse-flow design. The engine has a rated sea-level static thrust of 15 560 newtons (3500 lb) and a bypass ratio of 2.67. The fan and cycle pressure ratios are 1.54 and 15.09, respectively.

Facility

The engine was installed in the propulsion systems laboratory altitude chamber at the Lewis Research Center. This facility is capable of simulating altitudes from near sea level to 24 000 meters (80 000 ft) at airflow rates of 220 and 23 kilograms per second (480 and 50 lb/sec), respectively. Facility air handling equipment was available to supply sufficient flow rates at pressures and temperatures necessary to simulate the Mach number range from static to 1.5 at sea level. The thrust stand was not used for these tests.

The engine was instrumented to record and monitor the engine operating parameters. The measurements were recorded by the Lewis central automatic digital data acquisition system (ref. 5).

Gas Sample Probe

The uncooled stainless-steel probe used in these tests is shown in figure 2. It was located at the exit plane of the engine core. Four sampling holes of 0.15-centimeter (0.060-in.) diameter in each arm were spaced so that the sample was collected in four quadrants at the center of four equal annular areas of the core engine tailpipe. This design conforms to SAE recommendations (ref. 6). The four sampling arms were brought to a common manifold in the central mixing chamber.

Gas Sample System

Approximately 14 meters (45 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 heated with steam at 428 K (310° F). For the majority of test conditions a heated metal bellows pump was required to supply sufficient pressures, 69 kilonewtons per square meter (10 psig), to operate the analytical instruments. At the higher simulated altitude conditions the pump capacity was sufficient to provide a line residence time of about 5 seconds, while at lower simulated altitudes the line residence time was about 1 second.

The exhaust gas analysis system (fig. 3) 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 the IBM 360 computer for on-line analysis and evaluation of the data.

The hydrocarbon content of the exhaust gas is determined by a flame ionization detector hydrocarbon analyzer.

The concentration of the oxides of nitrogen is determined by a chemiluminescent analyzer. The instrument includes a thermal converter to reduce nitrogen dioxide (NO_2) to nitric oxide (NO) and was operated at 973 K (1290° F).

Both carbon monoxide (CO) and carbon dioxide (CO_2) analyzers are of the nondispersive infrared (NDIR) type. The CO analyzer has four ranges: 0 to 100 ppm, 0 to 1000 ppm, 0 to 1 percent, and 0 to 10 percent. These ranges of sensitivity are accomplished by using stacked cells of 0.64 - and 33-centimeter (0.25- and 13.5-in.) length. The CO_2 analyzer has two ranges, 0 to 5 percent and 0 to 15 percent, with a sample cell length of 0.32 centimeter (0.125 in.).

ANALYTICAL PROCEDURE

All analyzers were checked for zero and span 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 the calibration accuracy without disrupting testing.

Where appropriate, the measured quantities were corrected for water vapor removed. The correction includes both inlet air humidity and water vapor from combustion. The equations used are given in reference 6.

The emission levels of all the constituents were converted to an emission index parameter EI_X. The emission index is defined as

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

where

EI_X emission index for X, g X/kg fuel burned

M_X molecular weight of X

M_e average molecular weight of exhaust gas

f fuel-air ratio

[X] measured concentration of X, ppm

The fuel-air ratio may be computed from the measured exhaust gas products as proposed in reference 6, or alternatively, the metered fuel-air ratio may be used, when it is accurately known. Both procedures yield identical results when the sample validity is good. For this report the value computed from the measured emissions was used.

TEST CONDITIONS

The engine test conditions are presented in table I. Facility limitations prohibit the operation of the engine with the altitude chamber at atmospheric pressure. Thus, true sea-level static operation was not obtained. The lowest simulated altitude was 640 meters. The engine was operated at simulated flight Mach numbers of 0.6 and 0.8, and the engine inlet-air temperature was controlled to match that of actual altitude ram conditions. At each of these conditions the fuel-air ratio was varied over a limited range.

Additional test data shown in table II were taken at varying pressure altitudes with a constant engine inlet-air temperature. At each of these pressure altitude conditions the fuel-air ratio was varied over a limited range.

RESULTS AND DISCUSSION

The emission data obtained during the test program are presented in tables I and II.

Carbon Monoxide Emissions

The carbon monoxide emission index is shown in figure 4 as a function of the combustor fuel-air ratio. Also shown for comparison are supplementary data taken at a constant engine inlet-air temperature of 294 K (70° F).

With increasing combustor fuel-air ratio carbon monoxide emissions decreased. The maximum emission levels occurred at engine idle, while the reduced emissions at higher fuel-air ratios corresponded to nominal cruise conditions. At a given altitude the small change in flight Mach number resulted in minor changes in combustor inlet temperature and pressure and hence negligible effect on combustor efficiency as manifest by CO emissions. Increasing altitude with a constant cruise power setting produced little effect until the 13 200-meter condition was reached. At this altitude CO emissions were increased, as evidenced by the separate curve in figure 4. As shown in table I, it was not until this condition was reached that increasing altitude resulted in reduced combustor inlet temperature and pressure.

Unburned Hydrocarbon Emissions

The flame ionization detector used to measure hydrocarbons is calibrated to count carbon atoms, and the results are expressed as parts per million carbon (ppm C). In order to calculate a value for the emission index, it is necessary to make some assumption as to the structure of the unburned hydrocarbon molecule. The assumed form was CH_2.

The unburned hydrocarbon data are presented in figure 5 as a function of the combustor fuel-air ratio. In general, the emission values were quite low. The maximum values occurred at idle and decreased with increasing throttle setting. At the cruise throttle setting all the emission index values were less than 0.2, which implies a combustion inefficiency due to unburned hydrocarbons of less than 0.02 percent. The variation shown in the data at these low levels was due to data scatter involved in making measurements of 6 ppm C or less.

At a constant cruise throttle setting the highest emission index value occurred at the 13 200-meter-altitude condition. However, care should be taken in placing too great a significance on this for the reasons just discussed.

Oxides of Nitrogen Emissions

Among other things, the production of oxides of nitrogen (NO_x) is dependent on the water content (humidity) of the air. As proposed in reference 7, NO_x data may be corrected to zero humidity by multiplying by the factor e^{19H}, where H is grams of water per gram of air. For these tests the conditioned air had a humidity of 0.0005 gram of water per gram of air. The humidity correction may then be safely neglected with a consequent error of less than 1 percent. The remainder of this section discusses the engine NO_x production in terms of the combustor operating conditions.

The oxides of nitrogen emission index is presented in figure 6. When plotted on semilogarithmic coordinates the data displayed the anticipated straight line relation, which indicates NO_x formation is an exponential function of combustor inlet-air temperature. This result was first implied by Lipfert (ref. 8) and recently by more extensive correlations (refs. 7 and 9). For altitudes greater than 4570 meters there was a distinct decrease in NO_x with increasing altitude. The NO_x emissions were more sensitive to changes in combustor operating conditions than either carbon monoxide or unburned hydrocarbons. At a constant inlet-air temperature increasing altitude resulted in decreasing combustor pressure and increasing combustor reference Mach number (see table I). Both effects resulted in less NO_x being formed.

As mentioned previously, the effect of combustor inlet-air temperature on NO_x formation is exponential. Data taken from references 7 and 9 indicate that NO_x emission index varies with combustor reference Mach number to the -1 power, and data taken from references 7, 9, 10, and 11 indicate that the NO_x emission index varies with pressure to approximately the 0.5 power. In addition, the NO_x correlation of references 7 and 9 indicates a dependence on combustor exit temperature. In view of these factors, an attempt was made to correlate the NO_x emission data on the basis of the measured combustor operating parameters. In this case the parameters were grouped as follows:

$$\frac{e^{\theta}\delta^{0.5}f^{1.5}\times 10^4}{M_3}$$

where

θ combustor inlet total temperature normalized to standard sea-level temperature of 288 K (518.68° R)

δ combustor inlet total pressure normalized to standard sea-level pressure of 10.13 N/cm^2 (14.696 psia)

f fuel-air ratio (which is a measure of the exit temperature)

M_3 combustor inlet Mach number

The results of correlating NO_x emissions with these parameters are shown in figure 7. Also shown for comparison are the data of table II, where the engine was run with nonrefrigerated air. The latter data appear to define a curve which lies above the rest of the data. However, the parameter does correlate the two sets of data within an emission index span of 1. The correlation of all the data was improved by increasing the dependence on the combustor inlet-air temperature. Increasing the exponential temperature dependence to a factor of 2 (ref. 7 has determined 1.14) improved the correlation of NO_x emissions, as shown in figure 8. This indicates that characterization of the engine NO_x emissions could be obtained without running refrigerated inlet air providing the correct correlating parameters are known. It is not clear whether this correlating parameter may apply to other engines. Additional test data for a variety of engines are required.

An attempt was made to correlate the carbon monoxide and unburned hydrocarbon emissions by using this parameter. The results are not significantly different from those presented in figures 4 and 5 as a function of combustor inlet-air temperature alone.

Figure 9 shows the nitric oxide fraction of the total oxides of nitrogen. Considerable scatter exists in the data at the low power conditions. An indicated average ratio NO/NO_x of 0.5 to 0.6 at idle and 0.9 to 0.95 at high power puts the data of this report in agreement with the data of references 4 and 12.

Comparison With Data From Reference 1

The data are compared in table III with data from an identical model engine presented in reference 1. Since the data presented in this report were taken at various altitudes and the data of reference 1 were taken in a sea-level test bed, only the 640-meter-altitude data were compared. The two sets of data compare very well with the largest discrepancy occurring in the CO measurement at takeoff. At this condition the CO emission index was sensitive to instrument accuracy and to combustor inlet conditions (fig. 4).

Sample Validity

The measured values of CO, CO_2, and unburned hydrocarbons were used to compute an emission based fuel-air ratio, and this value was compared with the metered fuel-air ratio. The emission based fuel-air ratio was computed by the method suggested in reference 6. Results of this computation are shown in figure 10. At the high power settings the agreement was within ±10 percent. Sample validity at the low power settings was poor with the greatest discrepancy occurring at idle. In general, there is a high potential for sampling errors at idle with fixed position rakes because of the large concentration gradients in the plume at this condition.

SUMMARY OF RESULTS

Gaseous emissions from a TFE 731-2 turbofan engine were measured over a range of fuel-air ratios from idle to full power, at simulated altitudes from near sea level to 13 200 meters, and at flight Mach numbers of 0.6 and 0.8. Pollutant emissions obtained for carbon monoxide, unburned hydrocarbons, and oxides of nitrogen gave the following results:

1. Carbon monoxide and unburned hydrocarbon emissions were highest at idle and decreased with increasing throttle. At the highest altitude tested reduced combustor inlet temperature and pressure resulted in increased carbon monoxide and hydrocarbon emissions.

2. Oxides of nitrogen emissions were lowest at idle and increased with increasing throttle. Increasing altitude resulted in decreased oxides of nitrogen emissions. At idle the oxides of nitrogen consisted of 50 to 60 percent nitric oxide, which increased to 90 to 95 percent at high power levels.

3. Oxides of nitrogen were correlated to within an emission index value of ±0.5 by the parametric group $e^{2\theta}\delta^{0.5}f^{1.5}/M_3$, where θ is combustor inlet total temperature normalized to standard sea-level temperature of 288 K (518.68° R), δ is combustor inlet total pressure normalized to standard sea-level pressure of 10.13 newtons per square centimeter (14.696 psia), f is fuel-air ratio, and M_3 is combustor inlet Mach number. The correlation was successful for the range of altitude test conditions investigated and

also successfully correlated additional altitude data taken at a constant engine inlet-air temperature. It is not known if the correlation applies to other engine-combustor configurations.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 18, 1974,
501-24.

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TABLE I. - MEASURED GASEOUS EMISSIONS FOR TFE 731-2

[Inlet air humidity, 0.0005 g water/g air; all emissions corrected for water removed.]

Test condition	Altitude, m	Mach number	Fuel-air ratio	Combustor inlet temperature, T_3, K	Normalized combustor inlet total pressure, δ	Oxides of nitrogen			Carbon monoxide		Hydrocarbons	
						ppm	g/kg fuel	NO/NO_x	ppm	g/kg fuel	ppm	g/kg fuel
Idle	640	---	0.008	371	1.87	12.8	1.89	0.690	565	50.7	290	13.0
		---	.008	371	1.87	13.1	1.94	.690	568	51.2	292	13.2
30 Percent power	640	---	0.010	486	4.26	36.0	4.59	0.700	254	19.8	64.7	2.52
		---	.010	486	4.25	36.2	4.63	.700	257	20.0	64.5	2.51
Takeoff	640	---	0.016	656	11.2	133	13.3	0.934	59	3.6	1.7	0.05
		---	.016	656	11.1	133	13.3	.934	53	3.2	1.4	.04
		---	.016	658	11.1	135	13.4	.935	57	3.4	1.4	.04
Altitude	4 570	0.6	0.005	407	2.15	11.2	2.04	0.828	393	43.5	205	11.4
			.016	665	10.01	152	14.6	.956	67	3.9	1.6	.05
			.016	664	10.01	151	14.5	.956	63	3.7	1.5	.04
			.015	646	9.26	124	12.6	.952	71	4.4	1.6	.05
			.015	648	9.24	124	12.7	.952	71	4.4	1.5	.05
	9 140	0.8	0.0105	538	3.62	45	5.88	0.845	236	8.7	44.7	1.8
			.0105	539	3.61	46	5.96	.845	240	19.0	44.6	1.8
			.016	641	6.47	116	11.3	.934	49	2.9	.2	.005
			.016	641	6.50	116	11.3	.734	49	2.9	.1	.002
			.017	648	6.86	129	12.2	.948	43	2.5	.1	.002
			.017	648	6.88	130	12.3	.948	41	2.4	.1	.003
			.016	632	6.39	109	10.9	.929	52	3.2	.4	.013
			.016	632	6.39	109	10.9	.929	50	3.0	.5	.015
		0.6	0.016	619	5.84	103	10.2	0.925	65	3.9	0.1	0.004
			.017	638	6.31	124	11.5	.930	48	2.7	.1	.004
			.017	638	6.32	124	11.5	.930	48	2.7	.1	.004
			.0155	612	5.66	94	9.5	.897	69	4.3	.2	.007
			.016	612	5.68	95	9.6	.897	65	4.0	.2	.006
	13 200	0.8	0.016	607	3.13	83	8.32	0.931	136	8.29	1.6	0.05
			.016	607	3.12	84	8.40	.932	135	8.21	1.6	.05
			.015	591	2.87	73	7.72	.933	175	11.2	4.5	.14
			.015	591	2.88	73	7.98	.932	173	11.0	4.5	.14
			.015	586	2.79	70	7.45	.928	192	12.5	5.2	.17
			.015	586	2.79	70	7.50	.928	188	12.3	5.3	.17
			.0175	632	3.51	103	9.53	.944	90	5.1	.2	.004
			.018	632	3.51	103	9.62	.944	91	5.1	.1	.004
		0.6	0.016	584	2.59	72	7.36	0.902	191	11.8	6.0	0.18
			.016	584	2.59	72	7.35	.902	194	12.0	6.2	.19
			.017	598	2.85	81	7.88	.940	146	8.6	4.6	.14
			.017	598	2.86	81	7.94	.940	142	8.5	4.9	.14
			.018	622	3.15	98	9.04	.951	104	5.8	3.9	.11
			.018	621	3.14	98	9.04	.951	105	5.8	4.0	.11

TABLE II. - MEASURED GASEOUS EMISSIONS FOR TFE 731-2 AT ALTITUDE TAKEN AT CONSTANT ENGINE INLET TEMPERATURE OF 294 K (70° F)

[All emissions corrected for water removed.]

Altitude, m	Fuel-air ratio	Combustor inlet temperature, T_3, K	Normalized combustor inlet total pressure, δ	Oxides of nitrogen			Carbon monoxide		Hydrocarbons	
				ppm	g/kg fuel	NO/NO_x	ppm	g/kg fuel	ppm	g/kg fuel
4 570	0.0045	416	2.33	10.5	2.43	0.420	270	37.8	206	14.4
	.005	416	2.33	10.6	2.43	.430	270	37.9	208	14.6
	.016	673	9.36	142	14.7	.947	54	3.2	.1	.004
	.016	673	9.36	143	14.6	.947	56	3.3	~0	------
	.016	677	11.36	158	15.4	.938	51	3.1	.4	.01
	.016	677	11.36	159	15.45	.938	48	2.9	.4	.01
9 140	0.0115	571	3.24	51.4	6.52	0.938	181	14.0	20	0.77
	.012	571	3.25	51.8	6.60	.938	183	14.2	20	.79
	.017	672	4.78	121	11.6	.949	52	3.0	.5	.014
	.0175	672	4.78	122	11.6	.744	53	3.1	.5	.014
	.017	676	5.70	128	12.2	.925	84	4.9	~0	------
	.017	676	5.69	128	12.3	.925	84	4.9	~0	------
13 200	0.0185	654	2.07	90.4	9.0	0.914	135	8.2	~0	------
	.018	655	2.04	87.2	8.85	.913	137	8.4	~0	------
	.0175	662	2.60	97.1	9.42	.960	112	6.6	.1	0.002
	.0175	662	2.60	97.8	9.50	.960	113	6.6	.1	.003
	.017	645	2.38	83.6	8.6	.978	135	8.4	~0	.001
	.017	639	2.34	80.9	8.45	.963	141	9.0	~0	------
	.017	640	2.34	81.4	8.54	.963	136	8.6	~0	------

TABLE III. - COMPARISON OF EXPERIMENTAL EMISSION INDEX DATA FOR ALTITUDE OF 640 METERS WITH THOSE OF REFERENCE 1

Test condition	Oxides of nitrogen		Carbon monoxide		Unburned hydrocarbons	
	This report	Ref. 1	This report	Ref. 1	This report	Ref. 1
	Emission index					
Idle	1.92	1.89	51.0	48.2	13.1	15.3
Approach (30 percent power)	4.61	4.65	19.9	14.5	2.52	1.99
Takeoff	13.3	14.1	3.4	1.16	.04	.043

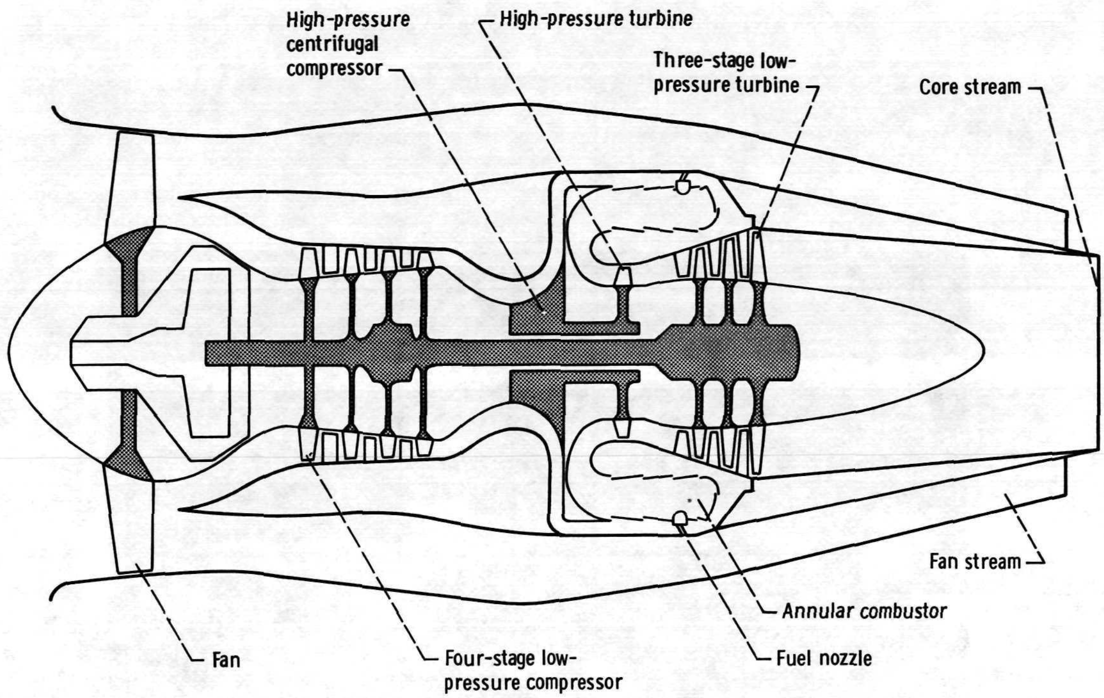

Figure 1. - TFE 731-2 turbofan engine.

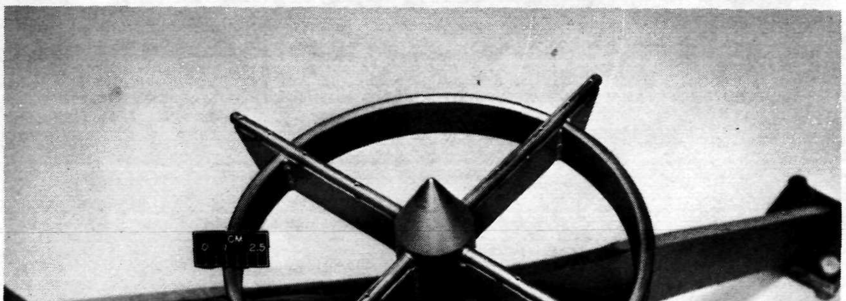

Figure 2. - Uncooled gas sample probe.

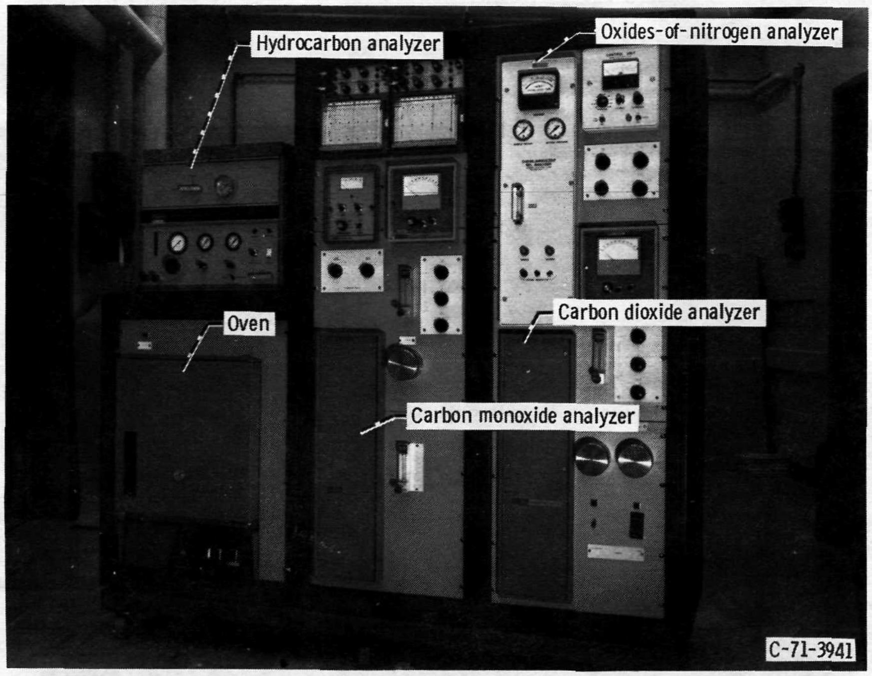

Figure 3. - Gas sampling instrument console.

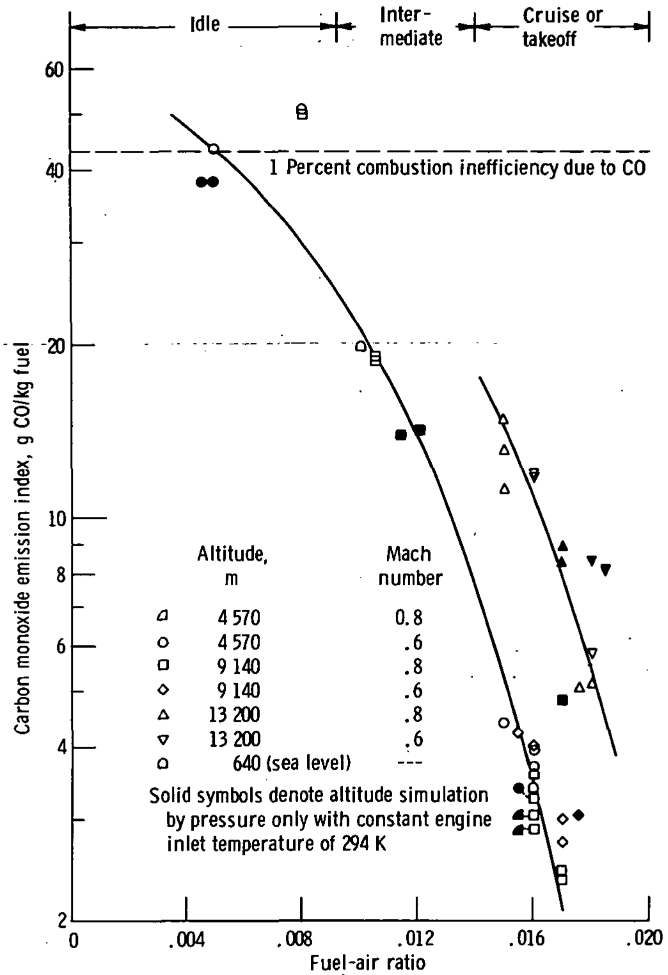

Figure 4. - Carbon monoxide emission index as function of combustor fuel-air ratio at various altitudes.

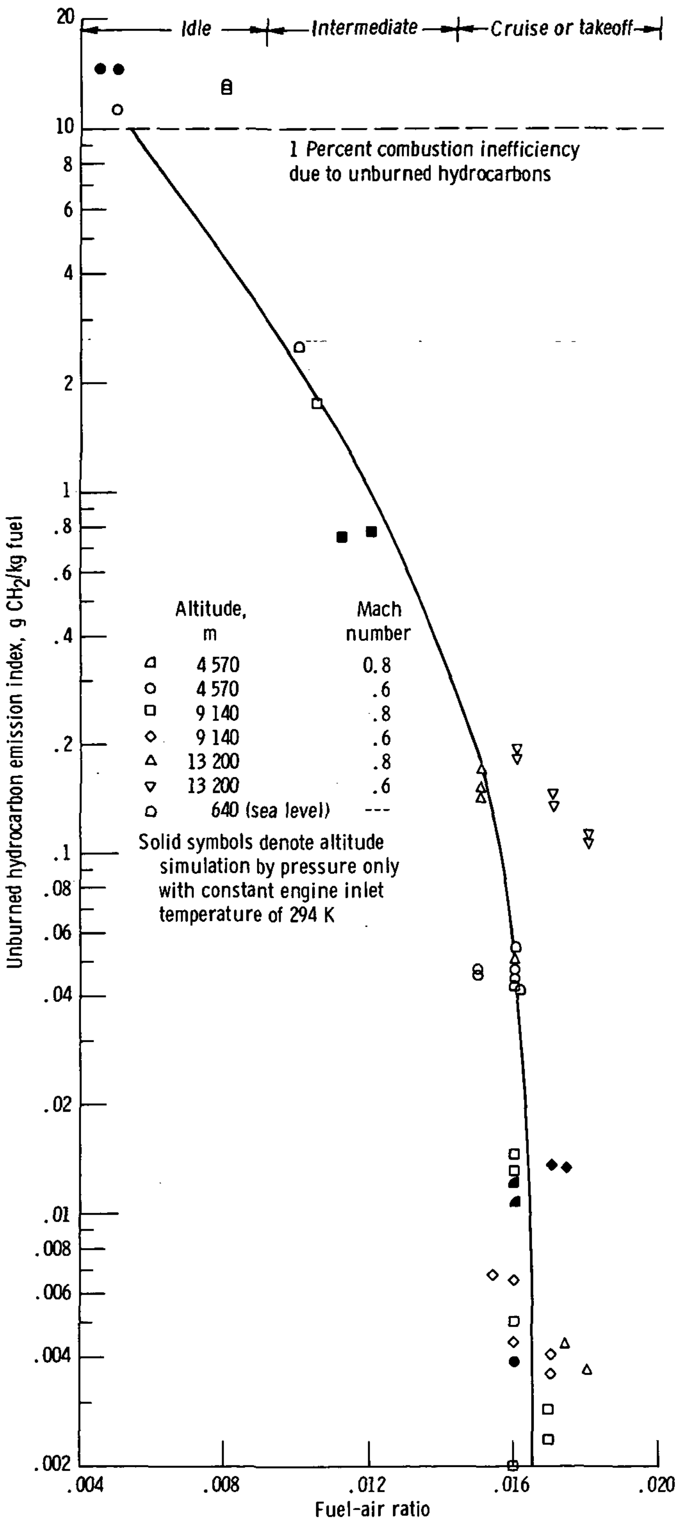

Figure 5. - Unburned hydrocarbon emission index as function of combustor fuel-air ratio at various altitudes.

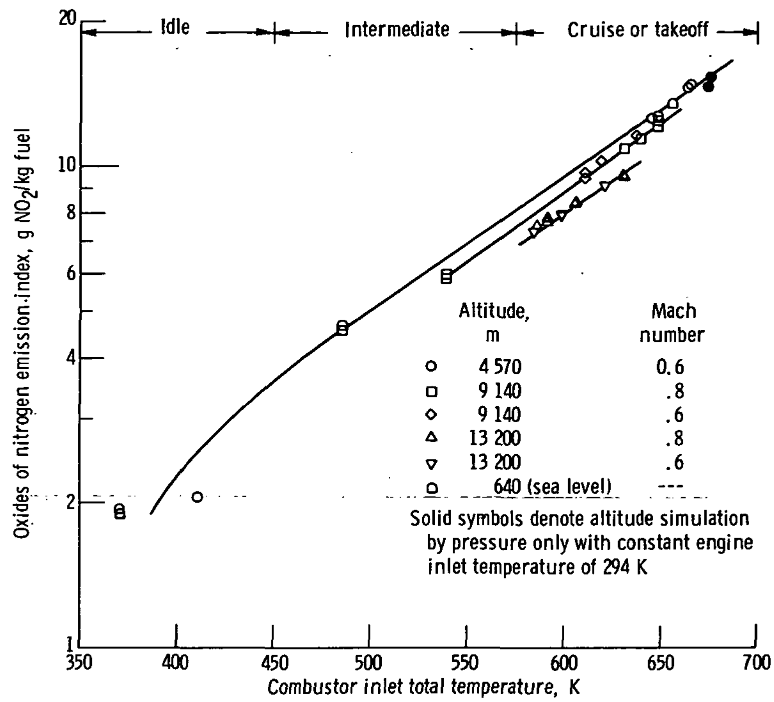

Figure 6. - Oxides of nitrogen emission index as function of combustor inlet total temperature at various altitudes.

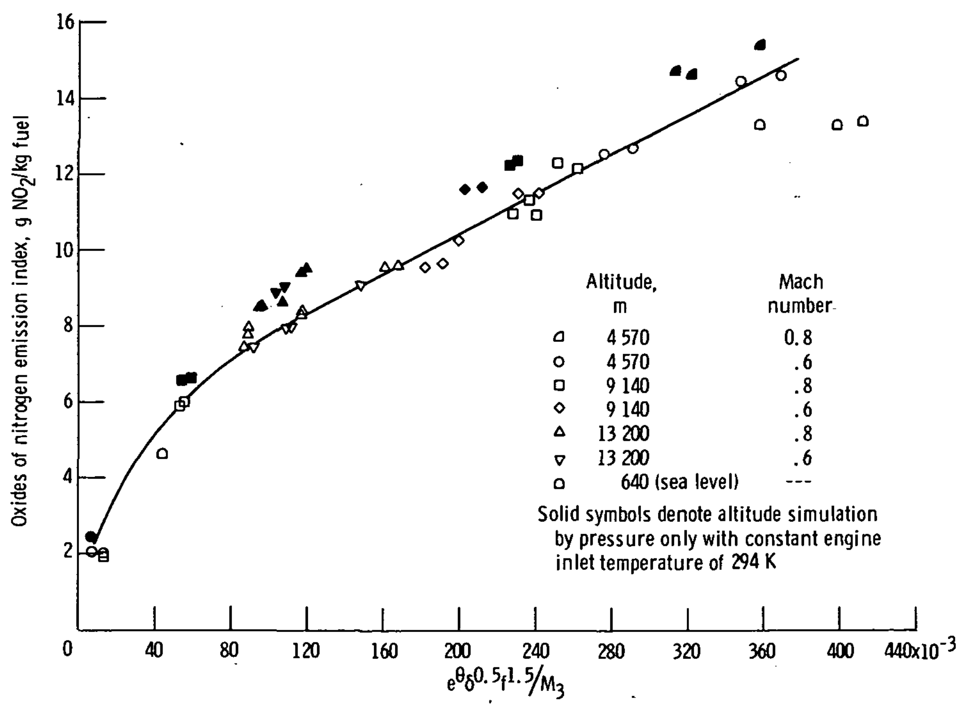

Figure 7. - Oxides of nitrogen correlation showing separation of data for refrigerated and non-refrigerated air cases.

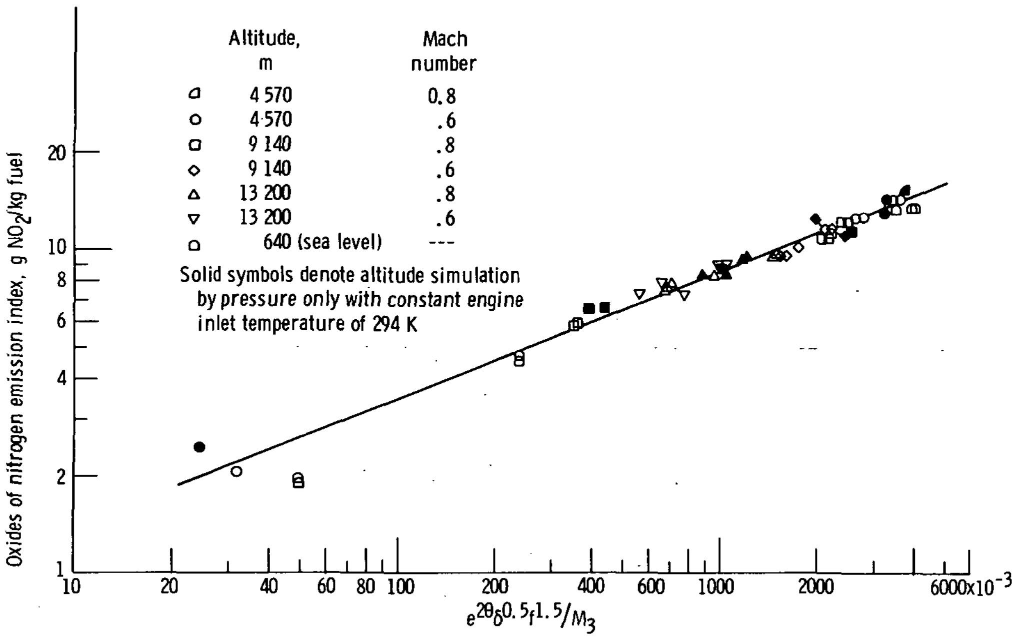

Figure 8. - Refined oxides of nitrogen correlation showing improved fit of data.

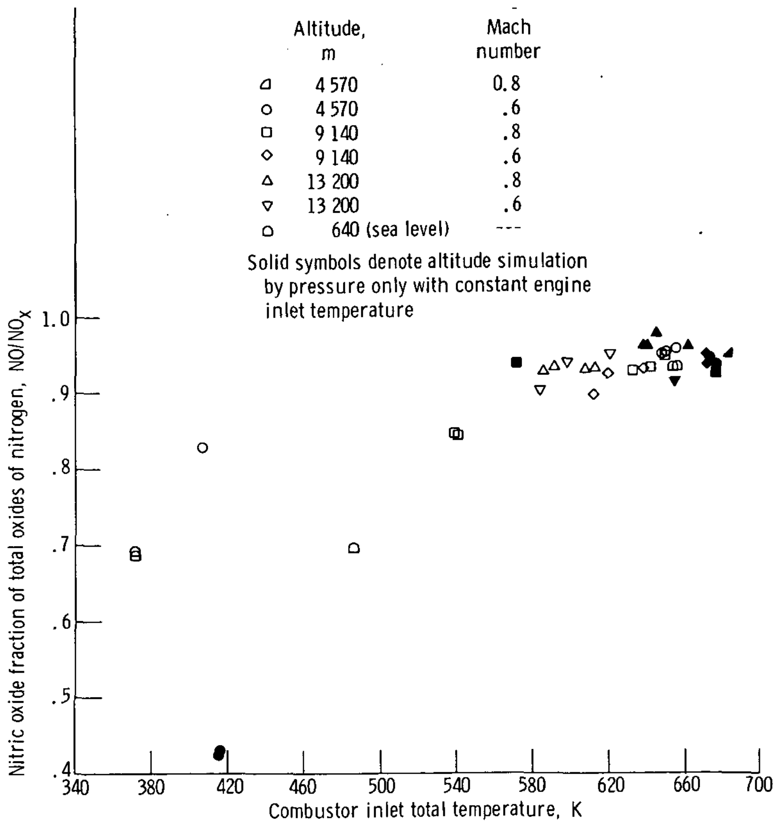

Figure 9. - Nitric oxide fraction of total oxides of nitrogen as function of combustor inlet total temperature at various altitudes.

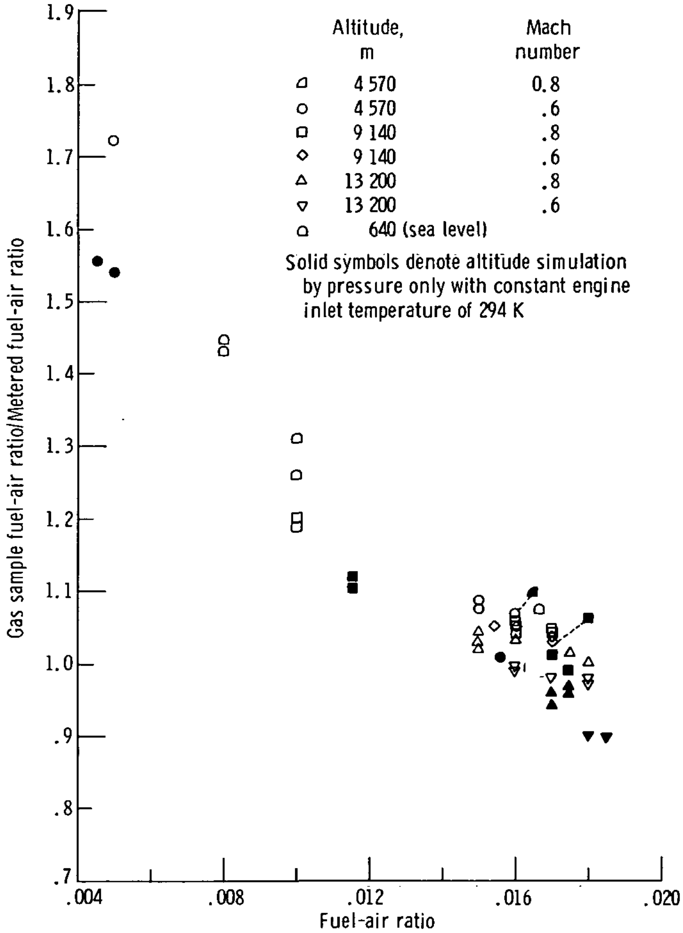

Figure 10. - Comparison of fuel-air ratios to check sample validity.

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