NASA Technical Memorandum 105722

Nitric Oxide Formation in a Lean, Premixed-Prevaporized Jet A/Air Flame Tube: An Experimental and Analytical Study

Chi-Ming Lee
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

Jean Bianco
Ohio Aerospace Institute
Brook Park, Ohio

John M. Deur
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Bahman Ghorashi
Cleveland State University
Cleveland, Ohio

November 1992

NASA

Nitric Oxide Formation in Lean Premixed-Prevaporized Jet A/Air System: An Experimental and Analytical Study

by

Chi-Ming Lee
NASA Lewis Research Center
Cleveland, OH

Jean Bianco
Ohio Aerospace Institute
NASA Lewis Research Center
Cleveland, OH

John Deur
Sverdrup Technology Inc.
NASA Lewis Research Center Group
Cleveland, OH

and

Bahman Ghorashi
Cleveland State University
Cleveland, OH

ABSTRACT

A series of experiments were conducted in which the NOx emissions of a lean premixed prevaporized system of Jet A/air were measured in a flametube apparatus. Tests were conducted at inlet temperatures ranging from 750 to 870 ^{o}K, pressures from 10 atm to 16 atm, and equivalence ratios from 0.37 to 0.62. From the measured data two correlations were developed to predict NOx emissions. NOx emission index was found to be well represented by the expressions:

$$\ln (E_{NOx}) = -142 + 17.3 \ln (T) + 0.174 \ln (t)$$

where T is the adiabatic flame temperature (^{o}R), v is the combustor inlet velocity (ft/s) and t is the combustor residence time (m sec). The expressions are independent of pressure and inlet air temperature, over the range of 10 atm to 16 atm and inlet air temperatures of 750 ^{o}K to 870 ^{o}K.

These equations were then applied to experimental data obtained from the literature; good correlation of this data also was achieved.

E-7121

NITRIC OXIDE FORMATION IN A LEAN, PREMIXED-PREVAPORIZED JET A/AIR FLAME TUBE: AN EXPERIMENTAL AND ANALYTICAL STUDY

Chi-Ming Lee
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Jean Bianco
Ohio Aerospace Institute
Brook Park, Ohio 44142

John M. Deur
Sverdrup Technology Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

and

Bahman Ghorashi
Cleveland State University
Cleveland, Ohio 44115

SUMMARY

An experimental and analytical study was performed on a lean, premixed-prevaporized Jet A/air flame tube. The NO_x emissions were measured in a flame tube apparatus at inlet temperatures ranging from 755 to 866 K (900 to 1100 °F), pressures from 10 to 15 atm, and equivalence ratios from 0.37 to 0.62. The data were then used in regressing an equation to predict the NO_x production levels in combustors of similar design. Through an evaluation of parameters it was found that NO_x is dependent on adiabatic flame temperature and combustion residence time, yet independent of pressure and inlet air temperature for the range of conditions studied. This equation was then applied to experimental data that were obtained from the literature, and a good correlation was achieved.

INTRODUCTION

Studies are being conducted at NASA's Lewis Research Center in support of the High Speed Research (HSR) Program. These studies will provide combustion technology for engine development for a High Speed Civil Transport (HSCT). Controlling the production of oxides of nitrogen (NO_x), which act as a catalyst in ozone destruction in the stratosphere, where the HSCT will fly, is a top priority for these studies. Because of the growing concern over further ozone layer depletion, the focus has been placed on developing a low-NO_x HSCT combustor.

Two promising combustion concepts are being studied. The two concepts are a rich burn/quick quench/lean burn (RQL) staged combustor system and a lean, premixed-prevaporized (LPP) system. The LPP combustor was proven as a viable concept by Roffe and Ferri (ref. 1) in earlier studies. They showed that an order-of-magnitude reduction in the NO_x levels from current combustors could be achieved by separating the mixing and reaction zones. The LPP concept is based on burning at a lean fuel/air ratio and thus lower flame temperatures, thereby producing lower NO_x emissions. The NASA experiments are being performed in a square-cross-section flame tube rig. The rig consists of a multijet fuel injector, a mixing section, a flameholder, and a combustion section with gas sampling probes.

Nitric oxide formation in a combustion process was fairly well established in earlier investigations (refs. 2 to 4) by using the Zeldovich et al. (ref. 5) reaction mechanism:

$$O_2 = 2O$$

$$O + N_2 = NO + N$$

$$N + O_2 = NO + O$$

The NASA Lewis code of Bittker and Scullin (ref. 6), modeling a plug flow reactor, is based on this reaction mechanism. The NO_x levels ($NO_x = NO + NO_2$) that were measured in the LPP flame tube were compared with the code predictions. The NO_x emissions index (EI), with units of grams of NO_x per kilogram of fuel, was determined from the total of the measured NO and NO_2 in parts per million (ppm) and the mass flow rate of the fuel being used. This NO_x EI was then plotted against adiabatic flame temperature. The code prediction was superimposed as shown in figure 1. From the graph it can be seen that the code cannot adequately predict NO_x emissions for lean, premixed-prevaporized combustor flame tubes. Work is continuing on the development of an improved code.

EXPERIMENTAL APPARATUS AND PROCEDURE

Test Facility

The combustor is mounted in the CE5B test facility, which is located in the Engine Research Building (Bldg. 5) at NASA Lewis Research Center. Tests were conducted with combustion inlet air pressure ranging from 10 to 15 atm (147 to 221 psia). A natural gas preheater was used to supply nonvitiated air at 755 to 866 K (900 to 1100 °F) inlet temperature. The temperature of the air was controlled by mixing the heated air with cold bypass air. Downstream of the combustor rig, quench water was sprayed into the gas stream to cool the exhaust to below 333 K (140 °F). The total pressure of the combustor and the airflow through the heat exchanger and the bypass flow system were regulated by remotely controlled valves.

The fuel used for this work is specified by the ASTM Jet-A turbine fuel designation. This multicomponent kerosene type of fuel is commonly used in gas turbine engines. Ambient-temperature Jet A, with a hydrogen/carbon ratio of 1.96, was supplied to the fuel injector. Flow rates were measured with a calibrated turbine flowmeter and were varied from 0.1 to 4.0 gal/min with a supply pressure of 650 psig.

Test Rig

The high-pressure and -temperature test rig used in this experiment consisted of an inlet section, a fuel injection and vaporization section, a flameholder, and a combustion section. The combustor test rig is illustrated schematically in figure 2. The test section was square having an area of 58 cm^2 (9 $in.^2$). A square-cross-sectional flame tube was chosen because of the need to incorporate windows for nonintrusive diagnostic measurements. The fuel injection and prevaporization section and the combustion section were 27 cm (10.5 in.) and 74 cm (29 in.) long, respectively. A ceramic refractory material was used as a liner in the combustion section. This insulating material enabled the reactor to be characterized as a one-dimensional, adiabatic plug flow reactor.

Fuel Injector

Jet A fuel was introduced into the airstream by means of a multiple-tube fuel injector shown in figure 3. The fuel injector was designed to provide good fuel dispersion in the airstream by injecting equal quantities of fuel into each of the individual air passages. The injector used in these tests had 16 square passages. Each passage was machined to form a converging/diverging flow path. The 64-percent blockage helped to ensure a uniform velocity profile over the entire flow field. The pressure drop across the injector ranged between 3 and 6 percent of the inlet pressure.

Fuel was discharged from the sixteen 0.7-mm (0.027-in.) inside diameter (ID) tubes into the converging upstream end of each air passage. The fuel tubes were 16.5 cm (6.5 in.) long and were routed through 0.32-cm (0.125-in.) diameter holes. These holes were routed through a plenum that supplied cooling air to prevent the fuel from coking and plugging the tubes. The cooling air was discharged into the main airstream and amounted to about 5 percent of the total airflow.

Flameholder

A 1.27-cm (0.50-in.) thick perforated-plate flameholder was made from Inconel 718 and is shown in figure 4. The plate, which was used to stabilize the flame, contained a staggered array of 36 holes, 0.64 cm (0.25 in.) in diameter, which resulted in a flow blockage of 80 percent. The holes had a smooth inlet radius on the upstream side of the plate and a thermal barrier coating (ZrO) on the downstream side of the plate for extended thermal wear. The total pressure drop across the flameholder ranged from 5 to 12 percent of inlet air pressure.

Combustion Section

The water-cooled combustion section had a square cross-sectional area of 58 cm^2 (9 $in.^2$) and was 74 cm (29 in.) long. A sketch of the cross section is shown in figure 5. For the inlet conditions listed previously, adiabatic flame temperatures ranging from 1700 to 2089 K (2600 to 3300 °F) were measured in the combustion section. The flow path was lined with a high-temperature castable refractory material to minimize the heat loss. A high-temperature, insulating, ceramic fiber paper was placed between the refractory material and the stainless steel water-cooled housing. The paper served two purposes: (1) to reduce the heat loss and minimize cold-wall effects; and (2) to compensate for the difference in thermal expansion between the ceramic and the housing. The stainless steel housing was water cooled through copper tubing coils that were wrapped and welded to its outer diameter.

Instrumentation

The combustion gases were sampled with six water-cooled sampling probes that were located 10.2, 30.5, and 50.8 cm (4, 12, and 20 in.) downstream of the flameholder (fig. 2). There were two probes at each axial location, with the top probes positioned 1.57 cm (0.62 in.) to the left of center (when looking downstream) and the bottom probes positioned the same distance to the right of center. The probes were 1.57 cm (0.62 in.) in diameter with five 1.02-mm (0.040-in.) ID sampling tubes manifolded together and terminating 1.51 cm (0.594 in.) apart along the probe length. Steam-traced stainless steel tubing, 6.4 mm (0.25 in.) in outside diameter (OD) and approximately 15.2 m (50 ft) in length, connected the gas sample probes to the gas analysis equipment. The steam tracing prevented the condensation of unburned hydrocarbons in the line. The probes were mounted on pneumatically operated cylinders that were interconnected with remotely operated solenoid valves, which allowed two probe positions: in and out. The sample gas was analyzed by inserting only one probe into the combustion section at a time, thus minimizing flow disturbances that could affect rig operation.

In addition to gas analysis, pressure and temperatures were measured along the test rig. At the exit of the inlet plenum a rake containing five total pressure probes and a wall static tap were used to determine the air velocity profile. The inlet temperature was measured with two Chromel/Alumel thermocouples. Pressure and temperature were also measured upstream of the flameholder to determine the presence of upstream burning and the fuel injector pressure drop. The adiabatic flame temperature in the combustion section was measured with two platinum/rhodium thermocouples that were located 40.6 cm (16 in.) and 58.4 cm (23 in.) downstream of the flameholder. A pressure tap at the combustor exit was used to calculate the pressure drop across the flameholder and the combustion section.

Operating Procedure

The rig required a warmup with preheated air for at least 2 hr to reach the desired test conditions, 755 to 866 K (900 to 1100 °F). This procedure ensured steady-state temperature in the reactor. After the reactor reached a steady-state temperature, startup was initiated by adding fuel to the hot air and igniting the mixture. In most cases the fuel/air mixture autoignited and the flame stabilized downstream of the flameholder. A flush-mounted spark ignitor, which was located just downstream of the flameholder, was used, however, when conditions did not permit autoignition. A gas sample was drawn from one of the six probes and was then passed through the following analyzers: nondispersive infrared carbon monoxide, carbon dioxide, and hydrocarbon units; a chemiluminescent nitrogen oxides unit; and an electrochemical oxygen unit. Each analyzer was zeroed and calibrated with calibration gases prior to each test run. The fuel/air ratio that was based on the gas analysis carbon balance varied at most by ±7 percent from the fuel/air ratio that was determined by metered fuel flow and airflow rates. For further verification, during cold airflow operation a wide range of NO_x concentration gases were injected into the sample line 1.5 m (5 ft) upstream of the analyzers. The analyzers read within ±0.5 percent of the calibration gas, with NO_x concentrations ranging from 100 ppm down to 4 ppm.

PARAMETRIC STUDIES AND REGRESSED EQUATION

Prior to the regression analysis, several test parameters were evaluated to determine their effect on the NO_x EI. The NO_x emissions were plotted against each parameter. The parameters investigated were adiabatic flame temperature, combustor residence time, inlet air temperature, and inlet pressure.

Figure 1 contains the experimental NO_x EI's plotted against the adiabatic flame temperature. This plot shows that NO_x has a strong dependence on flame temperature. It was expected that the NO_x EI would be a strong function of the flame temperature because the chemical reaction involved has been found to proceed at a much faster rate at higher temperatures.

The next parameter evaluated was the combustion residence time. Residence time was calculated by using the hot-zone velocity in the combustor section and the distance from the flameholder to the gas probe being used. This procedure was based on the assumption that instantaneous ignition occurred at the downstream face of the flameholder. As mentioned previously, the gas probes were located at 10.2, 30.5, and 50.8 cm (4, 12, and 20 in.) downstream of the flameholder. The hot-zone velocity was calculated from the known flow area, the cold-stream velocity (which was determined from the measured inlet airflow, temperature, and pressure), and the measured temperature and pressure in the combustion section. For example, a hot-zone velocity of 300 ft/sec and the probe 2 location (12 in.) resulted in a residence time of 3.3 msec. Figure 6 shows a strong dependence of NO_x EI on the combustor residence time.

Figures 7 and 8 show the effect of inlet pressure and inlet air temperature, respectively, on NO_x EI. The data were taken by using gas sample probe 3, the probe that was located 50.8 cm (20 in.) downstream of the flameholder. From these graphs it can be concluded that NO_x EI is independent of both parameters for the range of conditions studied, except for their effect on the flame temperature.

Once the dependent variables were identified, a multivariable least-squares regression technique was applied to obtain the following expression for NO_x emission index as a function of adiabatic flame temperature T (in degrees Rankine) and combustor residence time t (in milliseconds) (table I):

$$NO_x \text{ EI} = (2.139\times 10^{-62})T^{17.3}t^{0.174}$$

Statistical analysis indicated that this expression has a reasonable coefficient of determination, or correlation, of 84.8 percent. However, because it is often difficult to judge the quality of the fit from statistics alone, a plot of the experimental values of the NO_x emission index versus the values obtained from the preceding equation has been included as figure 9. If the fit were perfect, the points would fall on the diagonal line (i.e., the experimental and fitted values would be identical). With real data there will always be some deviations. Even though this was the case here, the scatter was minimal, thus indicating that the expression was capturing the key aspects of the data.

To examine the generality of the expression just derived, comparisons will next be made with data for similar experiments available in the literature.

REGRESSED EQUATION VALIDATION

Marek and Papathakos (ref. 7) studied combustion emissions in an LPP flame tube at inlet air temperatures of 640, 800, and 833 K (692, 980, and 1040 °F), equivalence ratios from 0.3 to 0.7, a pressure of 5.5 atm (81 psi), and a reference velocity of 25 m/sec (82 ft/sec). They used liquid Jet A injected into a 10-cm (3.94-in.) diameter combustion section through a single pressure-atomizing fuel injector. NO_x measurements were made in this study for a hot-gas residence time of 2 msec. The NO_x EI's were calculated for this experiment by using the preceding equation. The predicted curve was then plotted along with the measured data, as shown in figure 10. Although the curve appears to be slightly displaced, the trend is similar. The discrepancy here can probably be attributed to differences in fuel injector geometries. These Marek/Papathakos data were obtained by using a single fuel injector rather than the 16-point injection used in the current study. With a single injector and a slightly larger flow area, it would be more difficult to achieve a homogeneous mixture of fuel and air, which would produce lower NO_x emissions.

Roffe and Venkataramani (ref. 8) performed tests with an LPP test rig. For these tests, gaseous propane fuel was injected into an airstream having temperatures of 600 and 800 K (620 and 900 °F) and pressures of 10 and 30 atm (147 and 441 psi). The fuel injector consisted of 52 injection tubes measuring 1.6 mm (0.063 in.) in diameter. Gas samples were taken at a location that corresponded to a combustor residence time of 2 msec. From the data a correlation was derived to predict the NO_x EI in an LPP system. As for the preceding equation, this equation also showed NO_x EI to be dependent on adiabatic flame temperature and combustor residence time. Once again, the preceding equation was compared with the data from this experiment. As shown in figure 11 the correlation was quite good.

A final comparison was made with the NO_x data obtained by Semerjian and Vranos (ref. 9) in a lean, premixed-prevaporized Jet A/air system. The tests were performed at atmospheric pressure and an inlet air temperature of 750 K (890 °F). The test apparatus was a rectangular-duct flame tube with a combustion-zone cross section of 7.6 by 3.8 cm (2.99 by 1.50 in.). A toroidal-shaped fuel injector with eight equally spaced holes was used in this system. Gas sampling was obtained in this study at various axial distances within the combustion zone. For the purposes of comparison, only combustor residence times of 2 and 4 msec were evaluated. The residence times again were based on the inlet velocity and mass flow rate conditions tested. Two plots were made comparing the predicted NO_x EI with the measured data. Figure 12(a) compares the data at a residence time of 2 msec and figure 12(b) at a residence time of 4 msec. Although only limited data were available, the correlation once again was quite good. As can be seen, the extreme data point on both plots does not fall along the predicted curve. An explanation for this is that no data had been taken above the adiabatic flame temperatures of 2100 K. This required extrapolating the equation beyond the data, which may lead to inaccuracies.

CONCLUSIONS

From the recent experimental and analytical studies performed on a lean, premixed-prevaporized Jet A/air system, the following conclusions can be drawn:

1. The current NASA in-house Bittker/Scullin code for a plug flow reactor is not adequate for predicting the oxides of nitrogen (NO_x) production levels in a lean, premixed-prevaporized (LPP) combustor flame tube.

2. Through parametric studies on the data obtained from the NASA LPP combustor flame tube, it was determined that the NO_x emission index is strongly dependent on the adiabatic flame temperature and the combustion residence time. Also, the data appeared to be independent of inlet air temperature and inlet pressure for the range of conditions studied.

3. The following equation, with T being the adiabatic flame temperature and t the combustor residence time,

$$NO_x \; EI = (2.139\times10^{-62})T^{17.3}t^{0.174}$$

was found to predict with relative accuracy the NO_x production in an LPP combustor flame tube. The equation was validated by predicting additional NASA LPP data, as well as data from three other studies that are documented in the literature.

REFERENCES

1. Roffe, G.; and Ferri, A.: Prevaporization and Premixing to Obtain Low Oxides of Nitrogen in Gas Turbine Combustors. NASA CR-2495, 1975.

2. Fenimore, C.P.: Formation of Nitric Oxide in Premixed Hydrocarbon Flames. Symposium (International) on Combustion, 13th; Proceedings, The Combustion Institute, Pittsburgh, PA, 1971, pp. 373-380.

3. Newhall, H.K.; and Shahed, S.M.: Kinetics of Nitric Oxide Formation in High Pressure Flames. Symposium (International) on Combustion, 13th; Proceedings, The Combustion Institute, Pittsburgh, PA, 1971, pp. 381–389.

4. Shahed, S.M.; and Newhall, H.K.: Kinetics of Nitric Oxide Formation in Propane-Air and Hydrogen-Air-Diluent Flames. Combust. Flame, vol. 17, Oct. 1971, pp. 131–137.

5. Zeldovich, Y.B.; Sadovnikov, P.Y.; and Frank-Kamenetskii, D.A. (M. Shelef, transl.): Oxidation of Nitrogen in Combustion. Academy of Sciences of USSR, Institute of Chemical Physics, Moscow-Leningrad, 1947.

6. Bittker, D.A.; and Scullin, V.J.: GCKP84—General Chemical Kinetics Code for Gas-Phase Flow and Batch Processes Including Heat Transfer Effects. NASA TP–2320, 1984.

7. Marek, C.J.; and Papathakos, L.C.: Exhaust Emissions From a Premixing, Prevaporizing Flame Tube Using Liquid Jet A Fuel. NASA TM X–3383, 1976.

8. Roffe, G.; and Venkataramani, K.S.: Emission Measurements for a Lean Premixed Propane/Air System at Pressures up to 30 Atmospheres. NASA CR–159421, 1978.

9. Semerjian, H.; and Vranos, A.: NO_x Formation in Premixed Turbulent Flames. Symposium on Combustion (International), 16th; Proceedings. The Combustion Institute, Pittsburgh, PA, 1977, pp. 169–178.

TABLE I.—CURVE-FIT INPUT DATA AND RESULTS

[Regression equation

NO_x EI = −142 + 17.3 T + 0.174 t;

Predictor	Coefficient	Standard deviation
Constant	−142.032	9.024
T, °R	17.307	1.105
t, ms	0.17398	0.05595

standard deviation = 0.2701; R^2 = 84.8%; R^2(adj) = 84.2%.]

Observation	ln (T)	ln (NO_x EI)	Fit	Standard deviation fit	Residual	Standard residual
1	8.00	−1.1394	−1.6232	0.0881	0.4838	1.90
2	8.14	−.7985	−1.1356	.0716	.3371	1.29
3	8.17	−.4780	−.3333	.0504	−.1447	−.55
4	8.17	−.8210	−.3688	.0506	−.4521	−1.70
5	8.16	−.6162	−.5195	.0387	−.0967	−.36
6	8.19	.0296	.0499	.0502	−.0203	−.08
7	8.19	−.1625	−.0512	.0421	−.1113	−.42
8	8.19	−.5108	−.2744	.0742	−.2365	−.91
9	8.22	.3221	.3975	.0620	−.0754	−.29
10	8.22	−.1393	.2538	.0942	−.3930	−1.55
11	8.11	−1.3471	−1.6648	.0899	.3178	1.25
12	8.14	−.7765	−.8988	.0691	.1223	.47
13	8.15	−1.1087	−1.0184	.0687	−.0903	−.35
14	8.16	−.4155	−.4331	.0505	.0176	.07
15	8.20	.0583	.1383	.0514	−.0800	−.30
16	8.20	−.1054	.0052	.0443	−.1106	−.41
17	8.12	−1.4697	−1.5483	.0853	.0786	.31
18	8.17	−.2744	−.2719	.0482	−.0025	−.01
19	8.17	−.6162	−.3430	.0373	−.2732	−1.02
20	8.11	−1.2040	−1.3529	.0804	.1489	.58
21	8.14	−.9416	−1.1010	.0662	.1594	.61
22	8.16	−.7340	−.7069	.0610	−.0271	−.10
23	8.17	−.4155	−.3720	.0395	−.0435	−.16
24	8.19	−.1863	−.0097	.0572	−.1766	−.67
25	8.20	.2231	.1438	.0484	.0793	.30
26	8.20	.3646	.2010	.0604	.1636	.62
27	8.22	.8416	.4354	.0618	.4062	1.55
28	8.22	.9746	.6474	.0742	.3271	1.26
29	8.14	−.7985	−1.0974	.0647	.2989	1.14
30	8.16	−.5108	−.5373	.0410	.0264	.10
31	8.16	−.2231	−.4308	.0557	.2077	.79
32	8.20	−.3567	−.0995	.0729	−.2572	−.99
33	8.19	.0000	−.0531	.0419	.0531	.20
34	8.18	.1044	−.0736	.0533	.1780	.67
35	8.19	.1740	.0165	.0520	.1575	.59
36	8.21	.2070	.0885	.0866	.1185	.46
37	8.21	.4511	.3545	.0579	.0966	.37
38	8.21	1.3712	.4458	.0644	.9254	[a]3.53
39	8.21	.9002	.4358	.0650	.4644	1.77
40	8.24	.4824	.6057	.1053	−.1233	−.50
41	8.13	−1.4271	−1.1758	.0650	−.2513	−.96
42	8.14	−1.0498	−.8259	.0641	−.2239	−.85
43	8.16	−.4155	−.4377	.0506	.0222	.08
44	8.16	−.6539	−.5436	.0392	−.1103	−.41
45	8.19	.0392	−.0257	.0468	.0649	.24
46	8.11	−1.4697	−1.6440	.0929	.1743	.69
47	8.20	−.1278	.1263	.0483	−.2541	−.96
48	8.19	−.5108	−.2560	.0878	−.2549	−1.00
49	8.22	.1222	.3253	.0628	−.2030	−.77
50	8.11	−1.6094	−1.3830	.0774	−.2265	−.88
51	8.14	−1.2730	−.8855	.0511	−.3875	−1.46
52	8.15	−1.1087	−.7140	.0704	−.3946	−1.51
53	8.17	−.7765	−.3675	.0607	−.4090	−1.55

[a]Large standard residual.

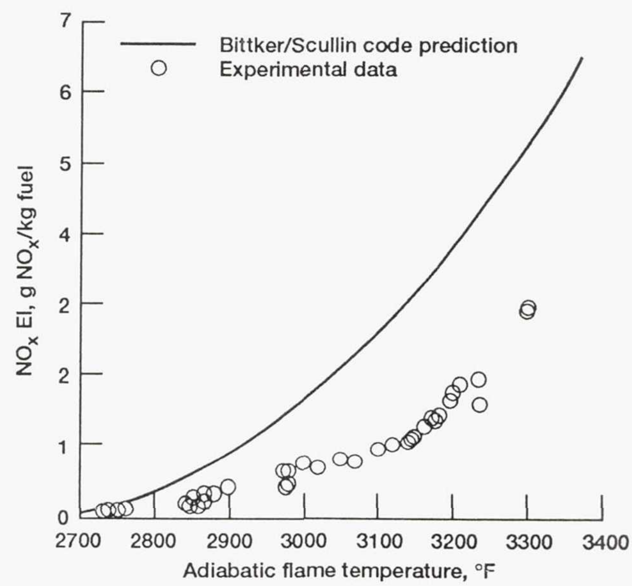

Figure 1.—NO_x emissions index as function of adiabatic flame temperature.

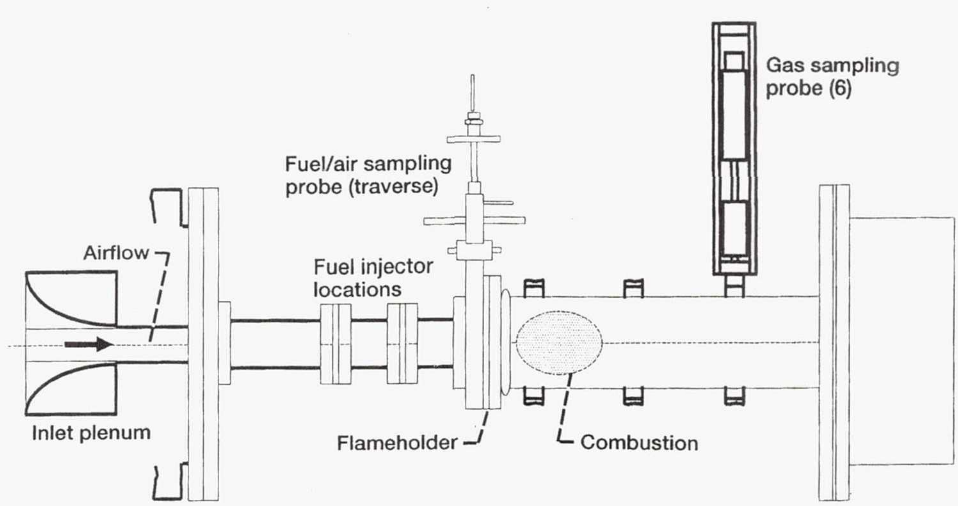

Figure 2.—NO_x experimental research rig—high-pressure and-temperature square flame tube.

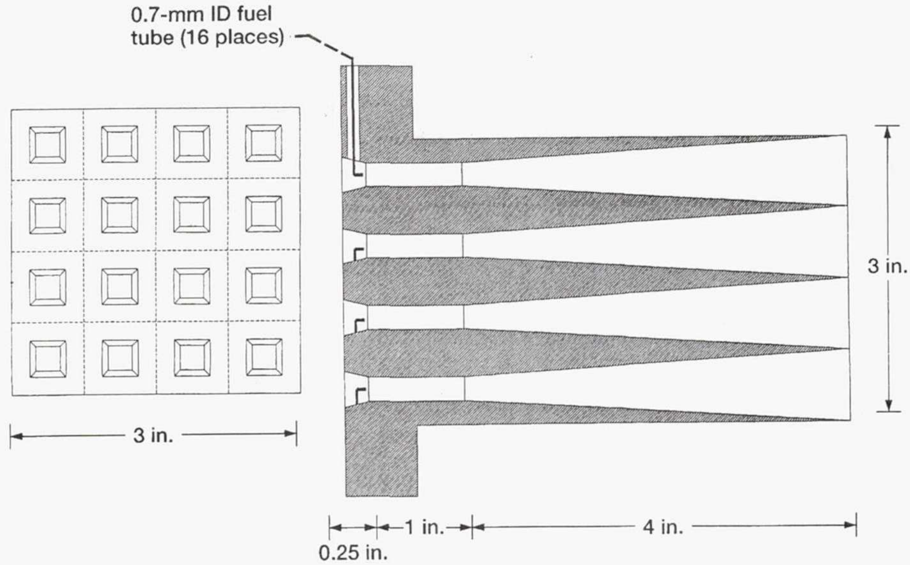

Figure 3.—Multiple-tube fuel injector.

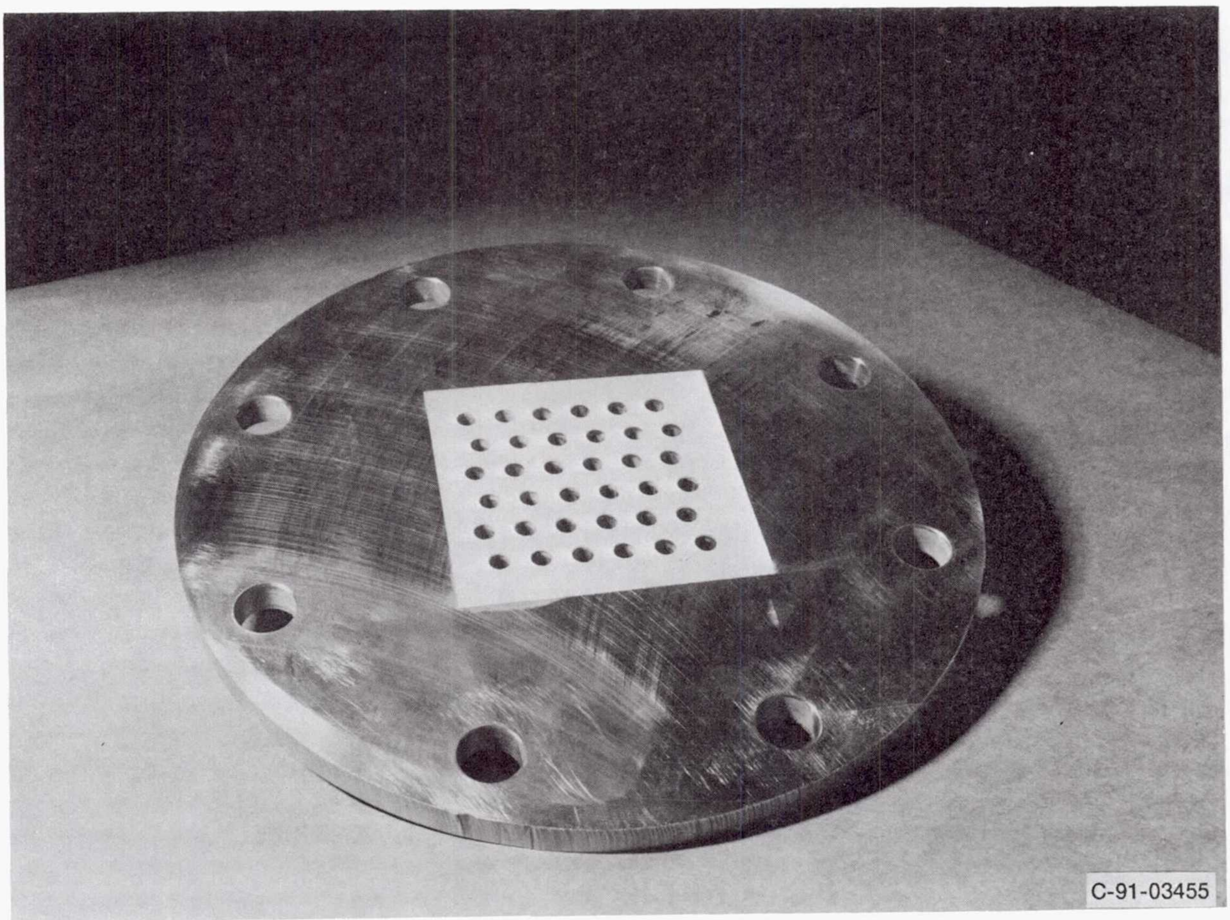

Figure 4.—Uncooled flameholder showing ZrO coating on downstream side.

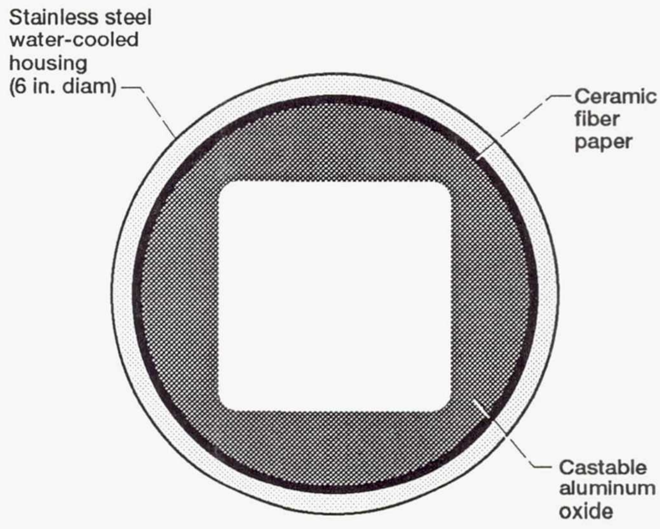

Figure 5.—Combustor cross section.

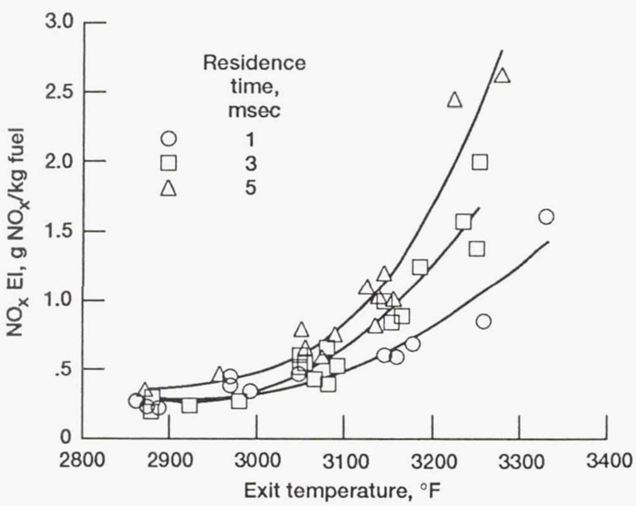

Figure 6.—NO_x emissions index as function of residence time.

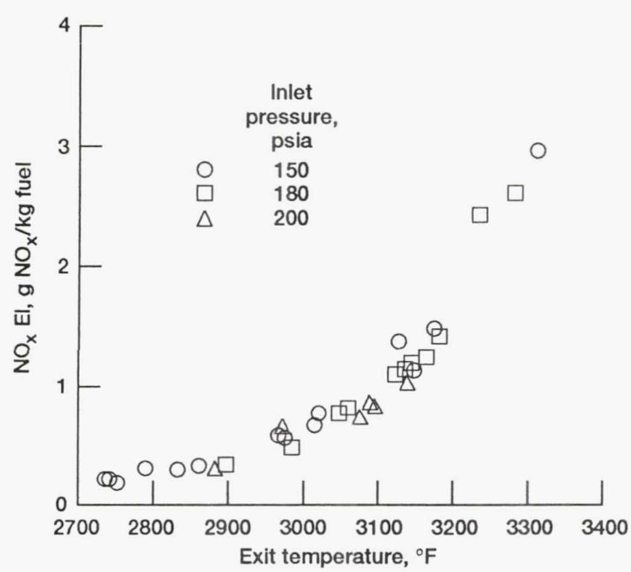

Figure 7.—NO_x emissions index as function of inlet pressure.

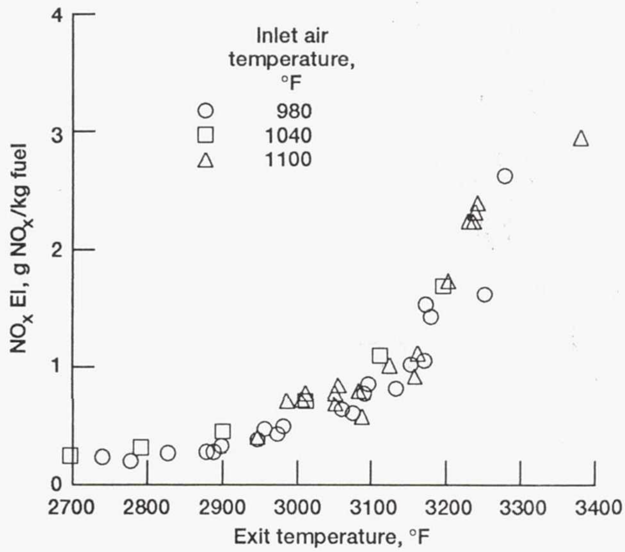

Figure 8.—NO_x emissions index as function of inlet air temperature.

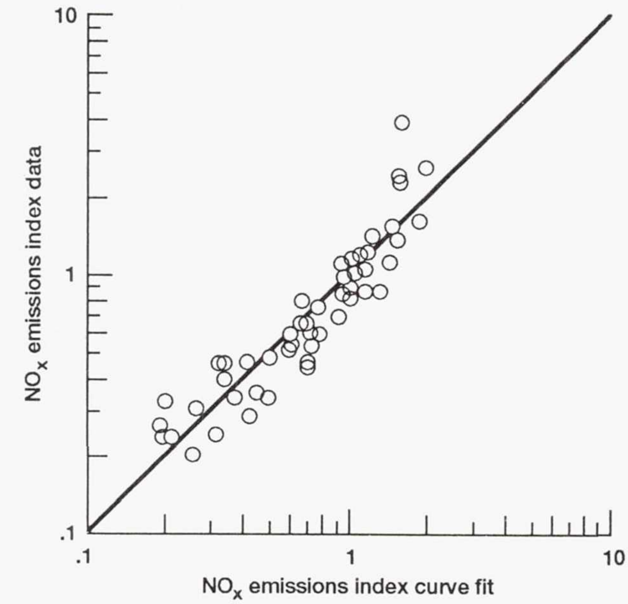

Figure 9.—Comparison of curve-fit equation and experimental data.

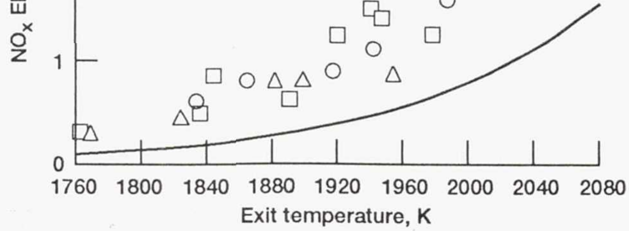

Figure 10.—Comparison of predicted NO_x emissions index and Marek and Papathakos's data for liquid Jet A residence time of at 2 msec.

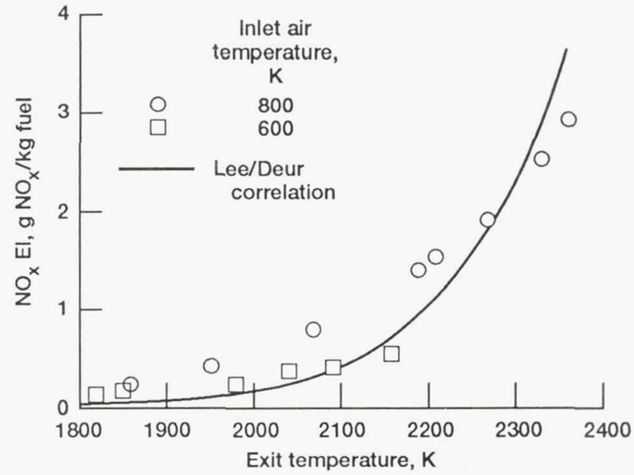

Figure 11.—Comparison of predicted NO_x emissions index and Roffe and Venkataramani's data for propane at residence time of 2 msec.

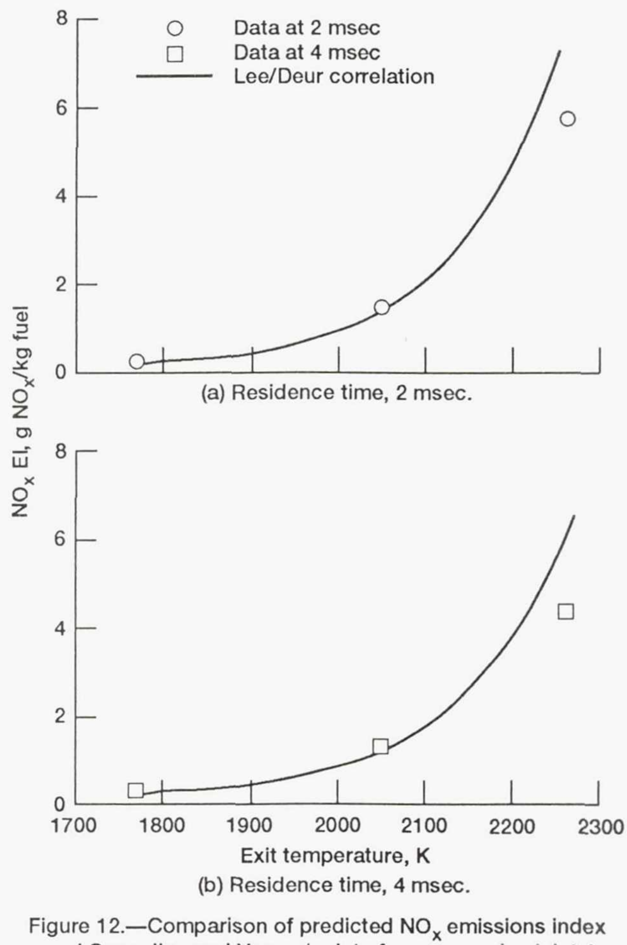

Figure 12.—Comparison of predicted NO_x emissions index and Semerjian and Vranos's data for prevaporized Jet A at inlet air temperature of 672 K.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1992	Technical Memorandum

4. TITLE AND SUBTITLE

Nitric Oxide Formation in a Lean, Premixed-Prevaporized Jet A/Air Flame Tube: An Experimental and Analytical Study

5. FUNDING NUMBERS

WU–537–01–11

6. AUTHOR(S)

Chi-Ming Lee, Jean Bianco, John M. Deur, and Bahman Ghorashi

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–7121

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–105722

11. SUPPLEMENTARY NOTES

Chi-Ming Lee, NASA Lewis Research Center, Cleveland, Ohio 44135; Jean Bianco, Ohio Aerospace Institute, 2001 Aerospace Parkway, Brook Park, Ohio 44142; John M. Deur, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142; and Bahman Ghorashi, Cleveland State University, Cleveland, Ohio 44115. Responsible person, Chi-Ming Lee, (216) 433–3413.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Limited
Subject Category 45

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

An experimental and analytical study was performed on a lean, premixed-prevaporized Jet A/air flame tube. The NO_x emissions were measured in a flame tube apparatus at inlet temperatures ranging from 755 to 866 K (900 to 1100 °F), pressures from 10 to 15 atm, and equivalence ratios from 0.37 to 0.62. The data were then used in regressing an equation to predict the NO_x production levels in combustors of similar design. Through an evaluation of parameters it was found that NO_x is dependent on adiabatic flame temperature and combustion residence time, yet independent of pressure and inlet air temperature for the range of conditions studied. This equation was then applied to experimental data that were obtained from the literature, and a good correlation was achieved.

14. SUBJECT TERMS

Nitric oxide; JP-5; Combustion; Premixed flames; Prevaporization

15. NUMBER OF PAGES

14

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102