NASA TECHNICAL MEMORANDUM

NASA TM X-68220

NASA TM X-68220

EFFECT OF PREMIXING ON NITRIC OXIDE FORMATION

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TECHNICAL PAPER proposed for presentation at the 75th National
Meeting of the American Institute of Chemical Engineers
Detroit, Michigan, June 3-6, 1973

ABSTRACT

Emissions from a simple 10-cm (4-in.) diameter tube combustor burning a premixed, gaseous propane/air mixture were measured. Inlet conditions included a temperature of 590 K (600 F), pressure of 5.5 atm., and reference velocity of 23 m/s (75 ft/s) for a range of equivalence ratios from the lean limit to slightly richer than stoichiometric. A nitric oxide emission index of 1 g NO_2/kg fuel was measured for an equivalence ratio of 0.57.

E-7418

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SUMMARY

The effect on nitric oxide emissions of using a premixed, prevaporized fuel/air system in turbojet combustors was investigated. Emissions from a simple 10-cm (4-in.) diameter tube combustor burning a premixed gaseous propane/air mixture were measured. Inlet conditions included a temperature of 590 K (600 F), pressure of 5.5 atm., and reference velocity of 23 m/s (75 ft/s). Concentrations of nitric oxide, carbon monoxide, and unburned hydrocarbons were measured at a point 46 cm (18 in.) downstream of the flameholder for a span of fuel-air ratios ranging from the lean blowout limit to slightly richer than stoichiometric.

With combustion efficiencies greater than 99 percent for the entire range of stoichiometries tested, nitric oxide concentration was 10 g NO_2/kg fuel for an equivalence ratio of 0.7 and 1 g NO_2/kg fuel for $\varphi = 0.57$.

Combustion instability occurred for equivalence ratios less than 0.54, and the lean blowout was at $\varphi = 0.5$.

INTRODUCTION

This study employed a simulation of a turbojet combustor primary zone to determine the effect of premixing fuel and air on nitric oxide emissions.

In the conventional turbojet combustor, liquid fuel is sprayed directly into the primary zone to give a mean fuel-air ratio near stoichiometric. Combustion is initiated and stabilized in this zone; some reactions can continue in the secondary zone where dilution air is admitted to bring the combustion temperature down to the level required at the turbine inlet.

The injection of fuel in a spray results in a wide variation of local fuel-air ratio with a spectrum of locally lean to locally rich values. Because nitric oxide formation is exponentially dependent on local flame temperature, this distribution of stoichiometries results in large quantities of NO being produced in some regions and virtually none in others even for fuel-air ratios far from stoichiometric. Thus, nitric oxide concentration cannot easily be predicted from the average reaction zone fuel-air ratio in a conventional combustor with a nonuniform mixture.

For a premixed, prevaporized fuel system, on the other hand, the fuel-air ratio may be made uniform throughout the primary zone; the result is a very strong dependence of nitric oxide concentration on stoichiometry.

Heywood and associates (refs. 1 to 3) have studied the effect of primary zone uniformity on nitric oxide production. Their work was based on a statistical evaluation of the equivalence ratio distribution in the primary zone. A crossplot of some of the typical analytical results from Fletcher and Heywood (ref. 1) is shown in figure 1 where the strong effect of uniformity on NO concentration can be seen. It is apparent from figure 1 that for a lean, uniformly mixed primary zone, significant reductions in nitric oxide concentration could be realized compared with a nonuniform conventional combustor operating near stoichiometric conditions.

The reactions responsible for the formation of nitric oxide are relatively slow compared with the other reactions which define the combustion process. Therefore, the concentration of nitric oxide is also strongly dependent on the residence time of the hot gases in the combustor. Since a premixed configuration will burn more intensely, and with a shorter flame zone, than will a conventional combustor, it should be possible to decrease the hot-gas residence time by decreasing the combustor length for a premixed system.

Although a lean premixed primary zone will result in lower concentrations of nitric oxide compared with those from a conventional combustor, combustion stability can be expected to suffer. The lean flammability limit for most hydrocarbon fuels is about 50 percent of stoichiometric. In a nonuniform system, however, the mean fuel-air ratio can be considerably less than the lean limit and locally rich zones will maintain combustion. For the uniform system which results from premixing this advantage is lost and blowout will occur near the lean flammability limit.

The present program was conceived to determine the effect of premixing on nitric oxide formation for conditions applicable to turbojet combustors. A 10-cm (4-in.) diameter combustor burning gaseous propane fuel was used. The flame was stabilized with a drilled-plate which provided a total pressure drop of 4 percent of the upstream total pressure, a value typical of that in a turbojet combustor. Inlet conditions were maintained at a temperature of 590 K (600° F) and 5.5 atm. pressure; the reference velocity was 23 m/s (75 ft/s). Concentrations of nitric oxide, carbon monoxide, carbon dioxide and unburned hydrocarbons were measured for a range of fuel-air ratios from lean blowout to slightly rich.

APPARATUS AND INSTRUMENTATION

Details of the apparatus are given in figure 2. Air entering the test section was indirectly preheated to 590 K (600 F) for all tests. Gaseous propane fuel was introduced through a fuel tube located about 2 m (7 ft) upstream of the test combustor to allow sufficient time for thorough mixing of fuel and air. A small swirler was located on the end of the fuel tube to give some initial mixing.

The flameholder was made by drilling 61 holes of 0.6 cm (0.25 in.) diameter in a 0.6 cm (0.25 in.) thick stainless steel plate. The hole pattern is shown in figure 3. This arrangement resulted in an open area of 25 percent of the inlet duct cross-sectional area. At 23 m/s (75 ft/s) reference velocity and 590 K (600° F) inlet temperature, the total pressure drop across the plate was 4 percent of the upstream total pressure.

The combustor was 10 cm (4 in.) in diameter, the same as the inlet duct, and 60 cm (24 in.) long (see fig. 2). Water cooling was used. At the downstream end quench water was sprayed into the gas stream to cool the exhaust to about 370 K (200° F). This mixture of combustion products and water passed through a remotely operated back-pressure valve for control of rig pressure.

Rakes for inlet instrumentation were avoided to eliminate any possible flameholders in the inlet duct. Instead, static pressure was measured at the wall and a single Chromel-Alumel thermocouple was inserted to a depth of about 2 cm (3/4 in.) from the duct wall. Downstream static pressure was measured at a tap in the spark igniter boss, about 5 cm (2 in.) downstream of the flameholder. ASME standard orifices were used to measure air and fuel flow.

Details of the water-cooled stainless-steel gas-sampling probe are also shown in figure 2. The probe was 1.3 cm (0.5 in.) outside diameter with a center sampling tube of 0.6 cm (0.25 in.) diameter. Samples were drawn only from a single position on the combustor centerline at a point 46 cm (18 in.) downstream from the flameholder.

It is well known that metal probes can cause a catalytic reduction of the nitric oxide by carbon monoxide. However, Halstead and Munro (ref. 4) found that for equivalence ratios less than unity, there was virtually no reduction in nitric oxide concentration by this mechanism. For fuel-rich conditions they found a reduction in concentration greater than an order of magnitude.

Stainless steel tubing of 0.6 cm (0.25 in.) diameter connected the gas sample probe with the exhaust gas analyzers. To prevent condensation of unburned hydrocarbons this sample line tubing was heated by electrical tracing to maintain the sample gas temperature between 410 K (280° F) and 450 K (350° F). The sample line was approximately 18 m (60 ft) long.

Gas analysis equipment included a Beckman Flame Ionization Detector for measuring unburned hydrocarbons, Beckman nondispersive infrared analyzers for measuring concentrations of carbon monoxide and carbon dioxide, and a Thermo-Electron Chemiluminescent instrument for nitric oxide concentration.

Commercial grade (92 percent pure) gaseous propane was used for all tests (see table I). Propane has a heating value near that of jet aircraft fuels so that combustion characteristics, especially NO production, are similar. By using a gaseous fuel, problems associated with atomization were avoided and it was possible to simulate a prevaporized as well as a premixed system.

The propane was supplied and stored as a liquid, then superheated to 370 K (200° F) at 10 atm. to insure complete vaporization before metering the flow.

After each change in conditions a delay of 3 to 5 minutes was allowed for stabilization before taking data. All the millivolt signals from pressure transducers, thermocouples, and gas analysis equipment for each test point could be recorded in less than 3 seconds by the automatic data system used.

RESULTS AND DISCUSSION

Sample Validity

It was important to determine if the emissions measured from the gas sample were representative of the average concentrations in the exhaust. For this purpose an equivalence ratio based on the measured carbon concentrations was compared with that from fuel and air flow measurements. The agreement should be within ±15 percent to insure good sample validity (ref. 5). The comparison is shown in figure 4 for the test data reported here. Agreement between the two equivalence ratios was generally within 10 percent showing that the single centerline probe was able to provide a good sample for analysis.

Data will be reported as a function of the equivalence ratio computed from the emissions measurements.

Combustor Heat Losses

Because the combustor was water cooled, quenching of the combustion could have occurred at the walls. Heat loss through cooling was measured to be consistently about 10 percent. However by sampling gases only at the combustor centerline it should be possible to assume that the sample is the same as would result from an adiabatic combustor.

Combustion Stability

Combustion was stable for the present test conditions at an equivalence ratio as low as 0.54. For leaner mixtures the combustion became unstable until blowout occurred at $\varphi = 0.5$. The fuel-rich combustion limit was not investigated.

Nitric Oxide Concentration

In this study, the only nitrogen oxide concentration measured was that of nitric oxide. The only other one of importance to turbojet combustors is nitrogen dioxide. Other studies (ref. 6) have shown that total NO_x (i.e., $NO + NO_2$) concentration can be on the order of 10 percent more than the NO concentration for the range of conditions studied here.

The measured concentrations of nitric oxide are given in figure 5. By convention, these are reported in terms of the emission index of NO_2 (g NO_2/kg fuel); this value is obtained by multiplying the nitric oxide emission index (g NO/kg fuel) by the ratio of molecular weights of NO_2 to NO. The equilibrium concentration of NO is shown for reference in figure 5.

Also given are the concentrations predicted at $\varphi = 1$ by a well-stirred-reactor and well-stirred-reactor-plus-plug-flow analytical solutions. The former used the model of Edelman and Economos (ref. 7) with a reactor volume of 344 cm^3 (21 $in.^3$); this is equivalent to assuming that the recirculation zone extends about 4.2 cm (1.7 in.) downstream from the flameholder. The results of this analysis were used as input to a plug-flow program to determine the effect of continued reaction for a distance of 40 cm (16 in.); that is, the distance to the gas sampling probe in the test combustor.

The experimental data show the strong dependence on equivalence ratio that can be expected from premixed, prevaporized operation. For the inlet temperature used for the present tests (590 K (600° F)), it was possible to obtain emission indexes of less than 1 g NO_2/kg fuel for equivalence ratios less than 0.57. This compares with a minimum emission index of about 2 g NO_2/kg fuel from an experimental combustor designed for low NO_x (ref. 6), operating at about the same inlet conditions, but with the advantage of a quick quench after a very short primary zone. Values for more conventional combustors are in the range of 3 to 5 g NO_2/kg fuel for these inlet conditions.

For fuel-rich equivalence ratios (values greater than 1) the data approach the equilibrium concentrations. This result suggests that probe catalytic effects are absent from the present experiments.

The strong effect of residence time on nitric oxide concentration can be seen by comparing the well-stirred-reactor and well-stirred-reactor-plus-plug-flow analytical solutions. At $\varphi = 1$, these results predict that an order of magnitude increase in nitric oxide concentration results during the time the hot combustion products flow from the end of the reaction zone to the probe (about 4 msec). It is likely that the nitric oxide concentrations near the flameholder are significantly less than those reported here, even for regions where the combustion is essentially complete. In a practical combustor rapid quenching of combustion reactions by dilution air introduced at the end of the recirculation region could prevent concentrations from growing to the levels reported here. For this reason the emissions from a practical premixed combustor could be lower than the values reported here and might approach the concentrations predicted by the well-stirred-reactor solution.

Carbon Monoxide, Unburned Hydrocarbons, and Combustion Efficiency

These reported concentrations of nitric oxide are only meaningful if the combustion reactions have gone to completion so that essentially 100 percent combustion efficiency is realized. For this reason, concentrations of carbon monoxide and unburned hydrocarbons were measured.

From figure 6 it can be seen that the measured carbon monoxide concentrations were essentially at the equilibrium level for the entire range of equivalence ratio covered.

The measurements of unburned hydrocarbons showed concentrations less than 0.4 gHC/kg fuel over the entire span of stoichiometries investigated. Such values are negligible.

Combustion efficiency can be determined from the difference between the measured and equilibrium concentrations of carbon monoxide and unburned hydrocarbons. Since both emissions were virtually at the equilibrium level, the computed combustion efficiency for these tests was greater than 99 percent for all test points.

SUMMARY OF RESULTS

Emission levels from a simple 10-cm (4-in.) diameter tube combustor burning a premixed gaseous propane/air mixture were measured. Inlet conditions included a temperature of 590 K (600° F), pressure of 5.5 atm., and reference velocity of 23 m/s (75 ft/s). Concentrations of nitric oxide, carbon monoxide and unburned hydrocarbons were measured at a point 46 cm (18 in.) downstream of the flameholder for a span of fuel-air ratios ranging from the lean blowout limit to slightly richer than stoichiometric. These were the results:

1. Nitric oxide was strongly dependent on equivalence ratio with an emission index of 10 for an equivalence ratio of 0.7 and 1 for $\varphi = 0.57$.

2. Measured levels of carbon monoxide corresponded with equilibrium concentrations, unburned hydrocarbons were negligible, and combustion efficiencies were greater than 99 percent for the entire range of fuel-air ratios.

3. Combustion instability occurred for equivalence ratios less than 0.54; the lean blowout limit was $\varphi = 0.5$.

REFERENCES

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3. Pompei, F., and Heywood, J. B., "The Role of Mixing in Burner Generated Carbon Monoxide and Nitric Oxide," Comb. and Flame, 19, 407 (1972).
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5. Anon., "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," SAE ARP 1256 (Oct. 1971).
6. Niedzwiecki, R. W., and Jones, R. E., "Pollution Measurements of a Swirl-Can Combustor," NASA TM X-68160 (1972).
7. Edelman, R., and Economos, C., "A Mathematical Model for Jet Engine Combustor Pollutant Emissions," AIAA Paper 71-714 (1971).

TABLE I. - PROPERTIES OF COMMERCIAL GRADE PROPANE USED IN THIS STUDY

Analysis:	C_3H_8	82 percent
	C_2H_4	1-2
	C_3H_6	4-6
	C_4H_{10}	1-2
	Volatile S	4-6 grains/100 ft^3

Dew point: 244 K (-20° F)

Heat content: 11 900 cal/g (21 400 Btu/lbm)

Vapor pressure: 11.9 atm. at 310 K (175 psi at 100° F)

Specific gravity: 0.508

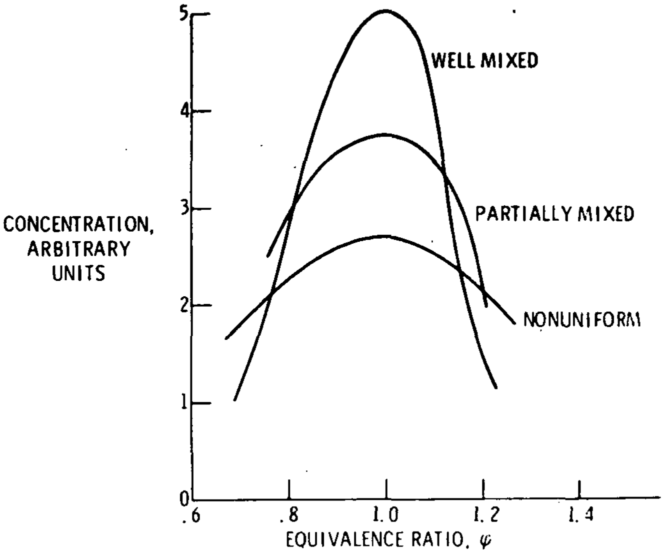


Figure 1. - Effect of equivalence ratio distribution on nitric oxide concentration (crossplot of analytical results presented in figure 4 of Fletcher and Heywood (ref. 1).)

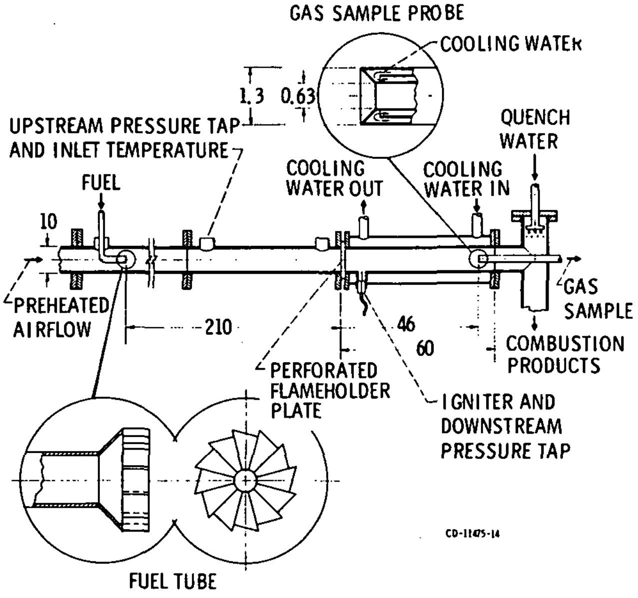


Figure 2. - Rig schematic. (Dimensions are in cm.)

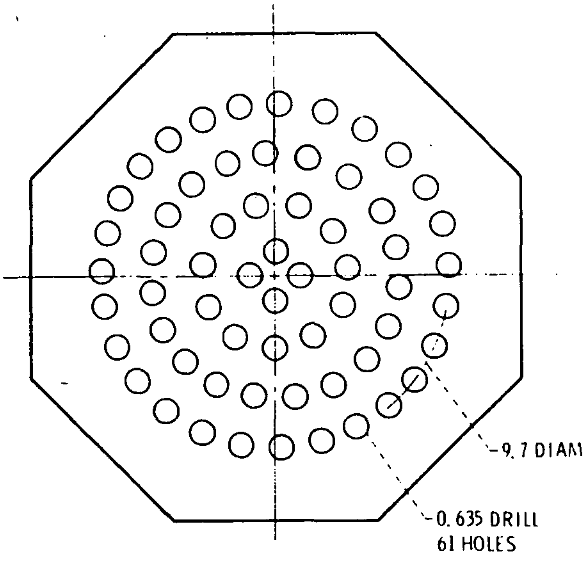


Figure 3. - Flameholder. (0.64 cm plate and 25 percent open area.)

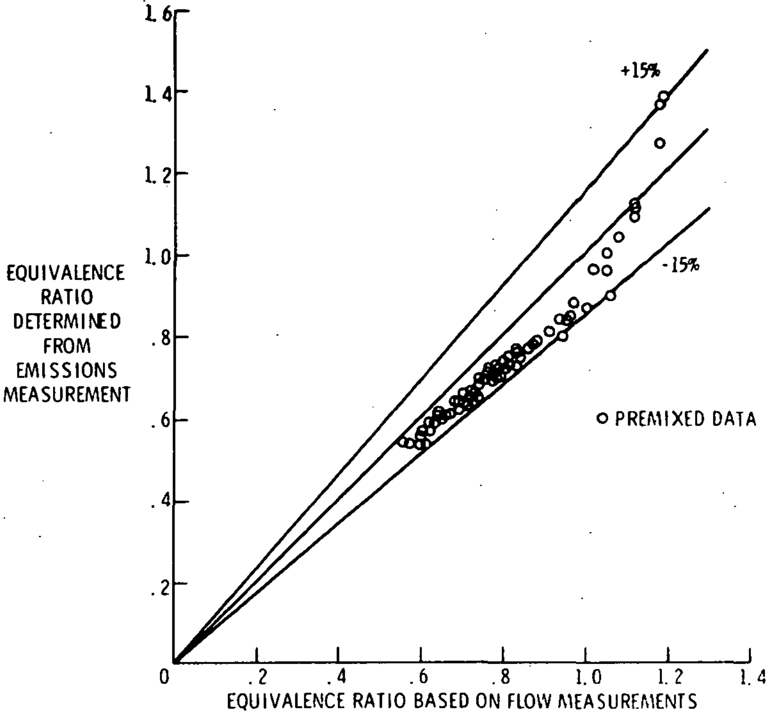


Figure 4. - Gas sample validity.

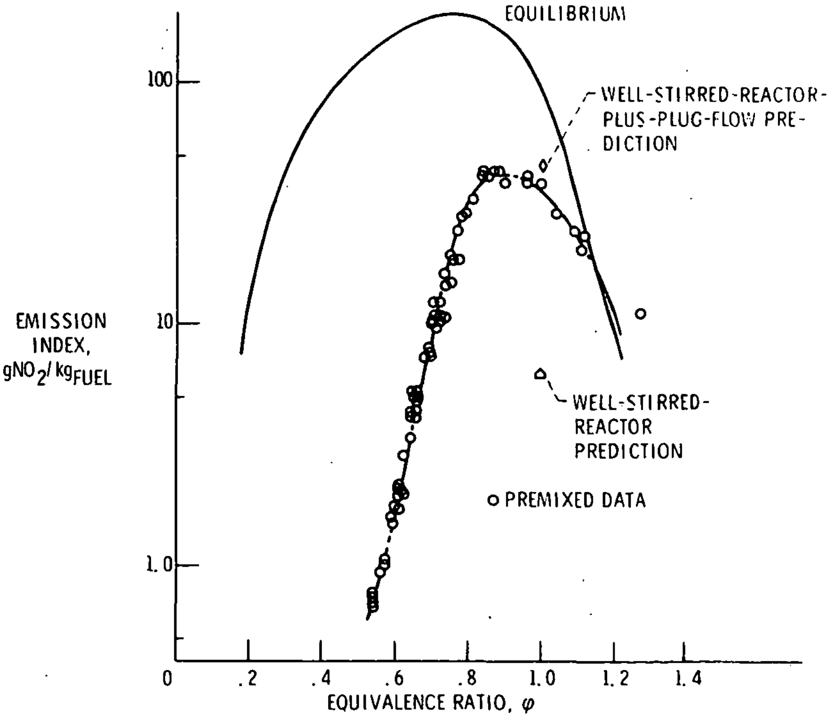
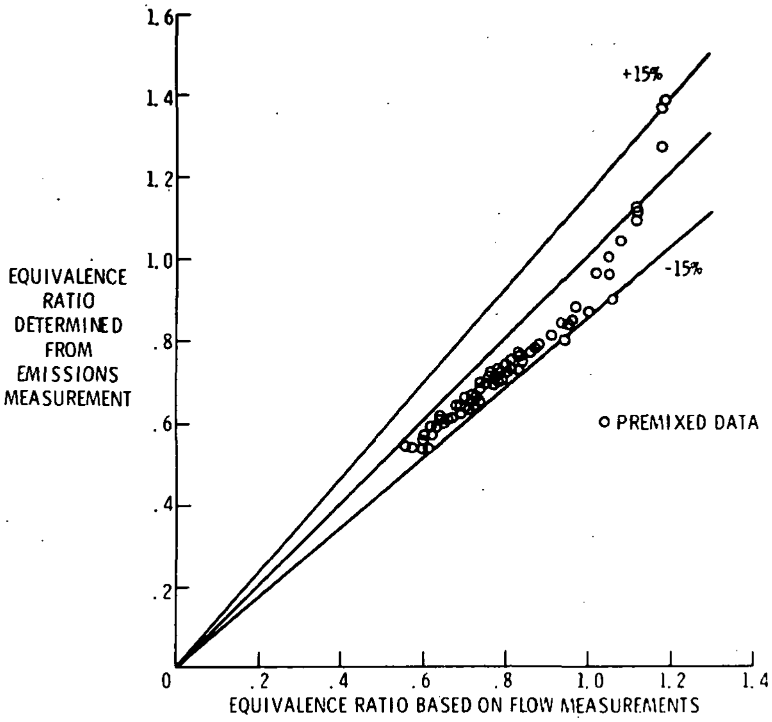


Figure 5. - Nitric oxide concentration. (T_3 = 590 K; p_3 = 5.5 atm; V_{ref} = 23 m/s.)



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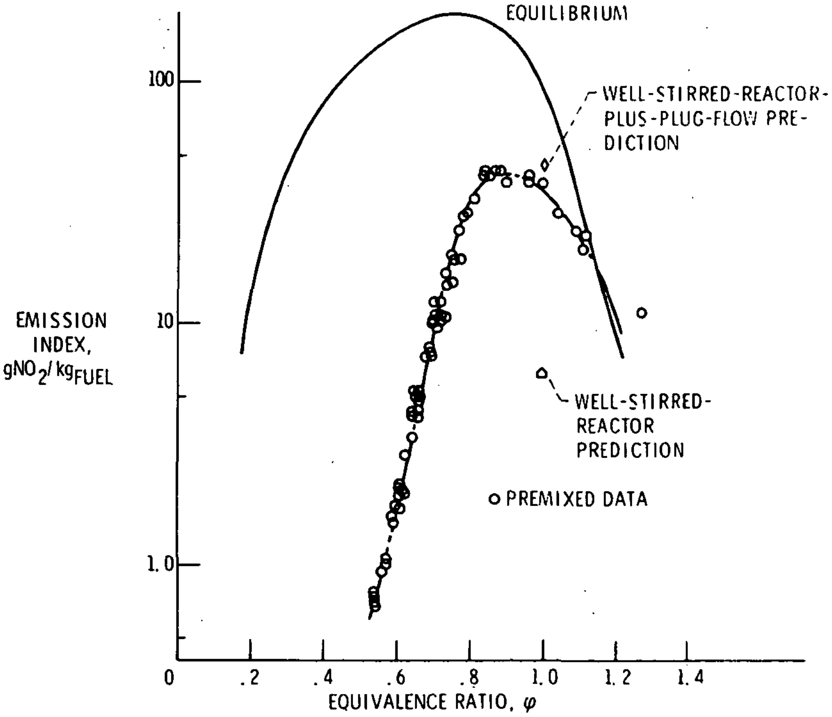

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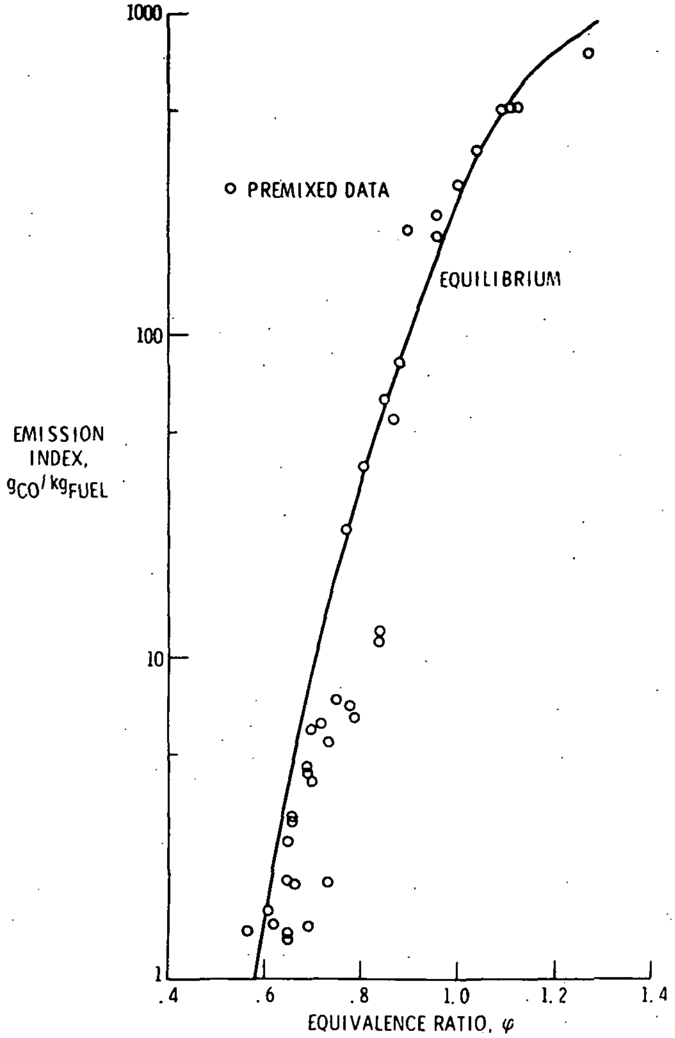

Figure 6. - Carbon monoxide concentration. (T_3 = 590 K (600° F); p_3 = 5.5 atm; V_{ref} = 23 m/s.)