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EFFECT OF PREMIXING QUALITY ON OXIDES OF NITROGEN IN GAS TURBINE COMBUSTORS

Gerald Roffe and Antonio Ferri

Prepared by

GENERAL APPLIED SCIENCE LABORATORIES, INC.

Westbury, N. Y. 11590

for Lewis Research Center



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| 16. Abstract Experiments were conducted to determine the effectiveness of several premixing prevaporizing gas turbine combustor designs in reducing formation of oxides of nitrogen at the supersonic cruise condition (entrance temperature, 833 K; entrance pressure, 4×10^5 N/m ² ; and reference velocity, 46 m/sec). An atomized spray from a single injector mounted on the axis of the mixer tube produced a high initial concentration of fuel near the axis and only moderate premixed conditions entering the combustor. A fuel spray produced by 12 flush-mounted normal injection orifices in the mixer tube wall produced a good initial despersion of fuel and resulted in nearly complete premixing. Oxides of nitrogen emission levels of the order of 0.2 g NO ₂ /kg fuel were obtained at 99 percent combustion efficiency at an equivalence ratio of 0.4. Overall total pressure drop was less than 3 percent through the 1-meter combustor module. | | | |
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SUMMARY

The objective of this program was to evaluate the effectiveness of a number of design parameters in producing premixed prevaporized combustion of JP-5 fuel in a simulated gas turbine combustor in order to reduce undesirable emissions, with particular emphasis on low NO_x operation. Tests were conducted at the supersonic cruise condition, defined by an entrance temperature of 833K (1500°R), pressure of $4 \times 10^5 \text{ N/m}^2$ (4 atm), Mach number of 0.25, reference velocity of 46 m/sec (150 ft/sec) and equivalence ratios from lean blowout to 0.6. Overall length of the combustor module was one meter. Overall total pressure drop was less than 3 percent.

Several means of fuel injection were tested in a flame tube apparatus. Injecting fuel through a set of twelve wall orifices normal to the airstream produced the highest degree of premixing and lowered NO_x levels to the order of 0.2 g- NO_2 /kg-fuel at 99% efficiency at an equivalence ratio of 0.4. Single fuel injectors mounted on the axis of the mixer tube produced the lowest degree of premixing due to their inability to penetrate far into the high velocity mixer airstream. A number of injectors were tested ranging from pressure atomizing nozzles to an air assisted atomizer. Injectors which produced smaller droplet sizes produced better combustion efficiency, but all produced NO_x levels far higher than those obtained using normal injection.

Preheating the liquid fuel prior to injection had little effect on emission levels but extended the lean blow off limit well below that encountered for unheated fuel. Increasing combustor turbulence level by installing screens in the mixer tube also had little effect on emission levels. Shortening the mixer from 53 cm to 33 cm produced somewhat higher combustion efficiency but increased NO_x levels by a factor of 2.

INTRODUCTION

Combustion in a gas turbine engine represents a unique problem with regard to controlling the production of oxides of nitrogen.* Since gas turbine fuels are generally free of nitrogen bearing compounds, the NO_x which they produce is the result of reactions which involve molecular nitrogen or molecular oxygen. The extreme stability of these molecules results in high activation energies for reactions in which they participate and, as a result, NO_x formation reactions become important only at high temperatures. Since the air in a gas turbine combustor is preheated by the action of a compressor, temperature levels in the combustion zone are considerably higher than those which would prevail in a similar flame at atmospheric pressure. As a result, gas turbine combustion is particularly prone to the production of NO_x .

In References (1) and (2), a suggestion was put forward for the control of thermal NO_x , that is, NO_x generated solely as the result of high temperature reactions. The idea was basically simple: since NO_x production rates are extremely sensitive to temperature, eliminate regions of locally high fuel concentration and correspondingly high temperature by thoroughly premixing fuel and air prior to combustion to an equivalence ratio which will yield an acceptably low temperature. Burning lean without premixing does not result in a significant reduction in NO_x levels. Since chemical reactions take place on a molecular scale, uniformity must be on a molecular scale as well. A "uniform" fog of liquid droplets in air would not satisfy the uniformity condition set forth here, since local regions of high fuel concentration could be found around each droplet. Therefore, premixing fuel with air for thermal NO_x control produces the corollary requirement that the fuel must be pre vaporized as well.

The technique has been demonstrated experimentally using liquid JP-5 fuel (Reference 3), as well as with gaseous propane, Reference (4). In the liquid fuel experiments, JP-5 was sprayed into a premixing duct upstream of a simulated gas turbine combustor and allowed to evaporate and diffuse through the

*The specific oxides referred to here are nitric oxide, NO and nitrogen dioxide, NO_2 , the sum of which is designated as NO_x .

air prior to combustion. NO_x levels as low as 0.6 gm NO_2 /kg-fuel were obtained with 99% combustion efficiency at a combustor inlet temperature of 833K (1500^oR) and pressure of 4×10^5 N/m² (4-atm). The test combustor, which utilized a convergent-divergent fuel injection section was subject to occasional flashback from the combustion zone into the premixer and subsequent stabilization of a flame in the premixing duct. The device tested utilized a two stage combustion system in which approximately 10% of the inlet air could be preheated by conventional combustion and mixed with the remaining air at the premixer entrance. The ability to preheat the incoming air was found to be of no significant advantage at the supersonic cruise condition and tended to exacerbate flashback problems.

The purpose of the work described here is to extend the work of Reference (3) to investigate the effects of fuel injection technique, fuel preheating, combustor turbulence level and premixer length on operation of a premixing pre-vaporizing gas turbine combustor. In addition, the design employed in these tests utilizes a straight cylindrical fuel injection section and mixer to reduce the possibility of flame stabilization upstream of the combustor section.

Tests were conducted in a flame tube apparatus at the supersonic cruise condition, that is, at a combustor entrance total temperature of 833K (1500^oR), total pressure of 4×10^5 N/m² (4 atm) and entrance Mach number of 0.25. The combustor reference velocity* was 43 m/sec (150 ft/sec). The combustor was 15.2 centimeters in diameter and 46 centimeters in length.

*Reference velocity is defined as the mass flow rate divided by the combustor entrance density and maximum combustor cross sectional area.

TEST APPARATUS AND PROCEDURES

Combustor Test Rig

The combustor test apparatus is illustrated in Figure (1). Air from a pebble bed heater enters the apparatus through a bell mouth transition and reaches a Mach number of 0.25 in the 8.9 cm diameter premixing duct. Fuel is injected at stations from 15 to 19 cm from the entrance face, the exact location depending on the particular geometry of the fuel injector being tested. The fuel and air flow through the premixing duct at a velocity of approximately 135 m/sec and over a 10° half angle hollow based conical flameholder located at the combustor entrance station. The mixer duct diameter expands by 64% at the combustor entrance station to provide some diffusion of the high velocity air in order to reduce stagnation pressure losses associated with the sudden expansion and combustion which occurs downstream.

The combustor flame is anchored by the recirculation region in the 5 cm diameter flameholder base and the separated flow at the 19 mm annular step at the combustor entrance. The combustor is cylindrical with a diameter of 15.2 cm and a length of 46 cm. The combustor exit station is equipped with a water cooled cruciform rake containing sixteen sampling ports located at the centers of equal flow areas. A hydrogen-air gas igniter initiates combustion at a point just downstream of the annular step and is shut off once ignition is achieved.

The apparatus is constructed using a heavy outer shell for pressure containment and a thin (1.6 mm) stainless steel liner to produce rapid equilibration of interior wall temperature. The gap between the pressure shell and the liner is sealed in the mixer section to insulate and minimize losses. Cold air is injected into the gap between the liner and the pressure wall in the combustor section as a means of limiting liner temperature and preventing mechanical failure. During operation, the mixer wall temperature was approximately 800K and the combustor liner temperature approximately 1000K, varying somewhat with equivalence ratio.

The exit of the combustion apparatus is a choked orifice, sized to produce a stagnation pressure of approximately 75% of the desired level at the design mass

flow. The combustor liner cooling air is added to the combustor exhaust gas along with a separately controlled quantity of air which is injected just upstream of the exit orifice. The amount of additional air added upstream of the exit orifice is controlled to produce the desired $4 \times 10^5 \text{ N/m}^2$ (4 atm) combustor stagnation pressure. This aerodynamic valve provides a means of maintaining constant combustor pressure as equivalence ratio, and thus exit temperature, is varied.

Test Apparatus

Two basic methods of fuel injection were tested during this program. The first was normal injection, utilizing a set of twelve flush wall-mounted orifices to spray fine (0.38 mm diameter) jets of fuel across the mixer airstream as illustrated in Figure (2). Using the method of Reference (6), penetration of liquid jets is calculated to be three quarters of the mixer duct radius, placing the liquid in close proximity to over 90% of the airstream. Each transverse jet of fuel creates a sheet of fine droplets which need only diffuse through the small lateral distance between adjacent sheets to mix with the airstream.

The second method of injection, illustrated in Figure (3), utilizes single axially mounted nozzles. Four separate atomizing nozzles were tested. Three employed pressure atomization and produced 60° semisolid spray patterns. The fourth was an air atomizing nozzle (Sonicore Model 250J-1) and produced a slightly narrower spray. The nozzles differed in orifice size and each produced a different pressure drop and mean droplet size for a given fuel flow rate. The nozzles were mounted for streamwise injection as shown in Figure (3a). The pressure atomizing nozzle with the smallest orifice was also mounted for contrastream injection as shown in Figure (3b).

Two flameholders were used during the course of the program. Both utilized a 10° half angle conical centerbody with a hollow base, supported by a set of hollow base struts. Flameholder I, shown in Figure (4a) employed unswept struts to support the centerbody such that its base was located in the plane of the annular step at the combustor entrance. Flameholder II, shown in Figure (4b),

employed swept struts to move the base of the centerbody 4.4 cm downstream. As a result of this movement, the combustor entrance area of Flameholder II is 12.5% larger than that of Flameholder I.

The combustor turbulence level was increased in a number of tests by installing a screen in the mixer immediately upstream of the flameholder. The screen, which was held in place by a thin metal ring, consisted of a square mesh 8.5 mm on a side constructed of 1 mm stainless steel wire. The effect of preheating the liquid JP-5 prior to injection was investigated using a 1.6 meter coil of 64 mm stainless steel tubing mounted in the entrance to the mixer tube as illustrated in Figure (5). Fuel could be supplied to any of the injectors tested either directly or by way of the preheat coil. Fuel routed through the preheat coil was delivered to the injector at a temperature of approximately 500K, varying slightly with fuel flow rate.

Fuel System and Properties

Liquid JP-5 fuel is stored in a tank which is pressurized with nitrogen and connected to the apparatus through a cavitating venturi and turbine flowmeter. The flow rate through the cavitating venturi is a function of the upstream pressure which is controlled by regulating the pressure of the nitrogen supply. A physical analysis of the JP-5 used is presented in TABLE I.

TABLE I
JP-5 PHYSICAL ANALYSIS

| | |
|---------------------------------|--|
| Specific gravity at 288K (60°F) | 0.815 (42.1 deg A.P.I.) |
| Flash point, PM | 329K (134°F) |
| Pour point | 227K (-50°F) |
| Viscosity at 310K (100°F) | $1.5 \times 10^{-6} \text{ m}^2/\text{sec}$ (31 sec. S.S.U.) |
| Initial boiling point | 452K (355°F) |
| 10% Distillate | 469K (385°F) |
| 20% Distillate | 477K (400°F) |
| 50% Distillate | 499K (440°F) |
| 90% Distillate | 544K (520°F) |
| Final boiling point | 555K (540°F) |
| Residue, % by volume | 3 |

Instrumentation

A rake located in the combustor entrance duct defines mixer stagnation pressure and temperature and static pressure taps are provided along the walls of the apparatus along with thermocouples to measure liner surface temperature. Figure (6) summarizes the instrumentation locations and dimensions of the basic configuration.

A sixteen point cruciform sampling rake is located at the combustor exit station. The rake is constructed of stainless steel and is cooled by an internal flow of water which is discharged downstream to cool the combustor exhaust gas. The sixteen individual ports are located at the centroids of equal flow areas and are manifolded externally to provide an average gas sample for chemical analysis.

The gas sampling system is shown schematically in Figure (7). The sampling manifold is connected by a 6.4 mm (1/4-inch) stainless steel line to a high flow pressure regulator and dump valve. The sample, collected at a pressure of $4 \times 10^5 \text{ N/m}^2$ (4 atm) is regulated down to a pressure of $2 \times 10^5 \text{ N/m}^2$ (2 atm) before being divided by a set of metering valves into four individual streams. The sample line is heated to a temperature of 450K (350°F) up to a Beckman Model 402 hydrocarbon analyzer which accepts one of these streams: the remaining three sample streams are allowed to cool to 365K (195°F). The sample line is heated by wrapping it with an asbestos cloth resistance heater and enclosing the assembly with a fiberglass/plastic foam insulating sheath. One of the sample streams is passed through a Beckman Model 951 NO/NO_x analyzer (chemiluminescence). Another leads to a Beckman Model 864 infrared analyzer (CO₂), a Beckman Model 742 oxygen analyzer (Polarographic) and a Beckman Model 315B infrared analyzer (CO), connected in series. The last line is used as a dump. Flow rates through the system are kept high by maximizing the amount of sample dumped both up and downstream of the pressure reduction regulator. Calibration gas is introduced through a three way valve located just downstream of the sample manifold. Zero gas for the oxygen, CO₂ and CO analyzers (dry nitrogen) enters through a three way valve located upstream of the set of metering valves. The NO/NO_x and hydrocarbon analyzers provide internal sources of zero gas. Gas analysis procedures and data reduction equations were in accordance with ARP 1256, Reference (5). The

data reduction procedures and instrument calibration curves are presented in the appendix.

Facility

The experiments were carried out using the pebble bed blow-down facility of General Applied Science Laboratories, Inc. whose pertinent components are illustrated in Figure (8). Mechanical compressors fill a bank of storage bottles with air at a pressure on the order of 10^7 n/m². The air is dried prior to storage and contains less than 2×10^{-4} kg of water per kg of air. Prior to a test, a bed of aluminum oxide pebbles is heated by electric glow-bars to a preset temperature. Air from the storage bank is passed through the bed of heated pebbles and into the combustion apparatus. The experiments were conducted at a nominal flow rate of 1.36 kg/sec (31b/sec) under which condition the pebble bed pressure was approximately 14×10^5 N/m² (200 psia).

As with any blow-down facility, useful test time was limited by the ability to store an adequate amount of high pressure air and to provide sufficient heat. For these tests, heat storage capacity was the limiting quantity. Figure (9) shows typical temperature histories in the pebble bed exhaust plenum. At the time that tunnel flow is initiated, the pebble bed is at its maximum temperature but the air delivery lines and combustion apparatus are at low temperature and produce the maximum cooling of the air entering the combustor. As a test progresses, although the bed temperature drops, prior heating of the delivery line reduces subsequent losses and the temperature of the air at the combustor entrance rises slightly. The considerable thermal inertia of the system results in a fairly flat peak and slow decline in the temperature curve. By allowing the apparatus to warm up for approximately 45 seconds, a test time of over 3 minutes is obtained with a temperature variation of ± 6 K (10° R). Longer running time is possible when a greater variation in combustor entrance temperature can be tolerated.

Test Procedure

In the normal sequence of testing, steady air flow is first established. The air flow continues for approximately 45 seconds to allow the tunnel temperature

to come up, during which time the hydrogen air igniter is turned on. Once steady conditions are verified, fuel flow is initiated at the desired initial equivalence ratio. The apparatus is allowed to operate for approximately one minute during which time the gas analysis instruments are checked to verify that each is reading on the proper scale. At that point, all instrument readings are recorded using a bank of Honeywell visicorders. Once the data record is acquired, the fuel flow rate is changed and the procedure repeated. The process continues for anywhere from one to six minutes depending on flow rates or temperature requirements.

RESULTS AND DISCUSSION

The baseline test combustor utilized the ring nozzle normal fuel injector and a mixer length of 53 cm. This configuration was tested over a range of inlet air temperatures from 800K to 980K to establish a means to assess the effect of inlet temperature variations which might be encountered during the course of further testing. Emission levels were then established for this configuration which characterized all further testing. The flameholder geometry was changed from configuration I to configuration II with no measureable effect. Tests were then repeated using an abbreviated (33 cm) mixer tube. Axially mounted pressure and air atomizing nozzles were tested using the original mixer section for both streamwise and contrastream injection. The fuel preheat temperature was changed to assess its effect on combustor performance. Finally, the combustor turbulence level was increased by adding screens to the mixer section to assess the sensitivity of the results to turbulence level.

Before proceeding to a detailed discussion of the emission characteristics of the individual design variations tested, some remarks are in order regarding operation of the overall apparatus. The total pressure drop from the mixer entrance to the combustor exit was measured during a number of tests and was found to vary between $1\frac{1}{2}\%$ and 3%. The exact value was a function of the particular geometry being tested and of the equivalence ratio. However, except for tests where a turbulence-generating screen was installed in the mixer, in no case measured did the total pressure drop exceed 3%.

An important aspect of the operation of the present design is the complete absence of flashback for the conditions covered in the present program. (The mixer employed here consists of a straight section of cylindrical tubing with a gas velocity of 134 m/sec.) As will be noted later, although most testing was carried out at the supersonic cruise condition (833K) some tests were performed at inlet temperatures as high as 980K (1764^oR) and even at these conditions burning was confined to the combustor section. This is a considerable improvement over the results reported in Reference (3) where a convergent-divergent fuel injection section was employed with an even higher mixer velocity. The straight cylindrical mixer tube appears to avoid flashback problems

by eliminating regions of locally separated flow which are capable of providing adequate residence time to anchor a flame. It is certainly possible that a mixer velocity lower than 134 m/sec could be tolerated although further tests would have to be made to determine the lower limit. Decreasing the mixer tube velocity would lower the 1½% to 3% pressure drop somewhat by decreasing the sudden expansion loss at the combustor section entrance and reducing the combustor entrance Mach number. Nevertheless, the present values for total pressure drop appear to be quite acceptable. It must be kept in mind, however, that since the tests described here involve only primary combustion with no dilution a complete burner employing dilution air would be expected to operate with a somewhat higher pressure drop.

In all tests reported here, the fuel/air ratio obtained from chemical analysis of the gas sample agreed with the metered fuel/air ratio to within 5%. As a result, the manifolding of the sixteen sampling ports appears to provide a representative sample of the combustor effluent gas.

Effect of Inlet Temperature

It should be noted that although the mixer entrance temperature is defined for this test series as 833K (1500^OR), the use of a pebble bed heater always produces some deviation from this temperature, especially when test periods on the order of 5 minutes are employed. Since NO_x production rates are clearly sensitive to final flame temperature, for a fixed equivalence ratio they will be sensitive to combustor inlet temperature as well. In order to account for the effect of entrance temperature variation, a series of data points were obtained using the ring nozzle injector to produce a constant equivalence ratio of 0.4 while the entrance temperature was varied. The results of these tests are shown in Figure (10).

NO_x level is seen to increase exponentially with initial temperature at a rate which indicates an order of magnitude increase for each 311K temperature rise. As a result, assuming that the slope of the temperature sensitivity curve is not a strong function of equivalence ratio, NO_x data taken at initial temperatures different than 833K can be corrected by the factor

$$C_1 = 10^{\left(\frac{833-T}{311}\right)}$$

Since increasing the temperature increases chemical reaction rates, unburned hydrocarbons disappear more rapidly as the temperature rises. The results presented in Figure (10) indicate that this phenomenon requires that hydrocarbon emission indices be corrected by the factor

$$C_2 = 10^{\left(\frac{T-833}{136}\right)}$$

Increasing reaction rates also drives CO levels toward their equilibrium values more rapidly. However, unlike the hydrocarbon species, the equilibrium CO level is an exponentially increasing function of temperature. As a result, CO emission index is not a monotonic function of temperature and does not lend itself to the use of a temperature correction coefficient. However, the difference between the CO emission index at a given temperature and the equilibrium CO emission index at that temperature is a direct function of reaction rates alone and can be corrected accordingly. From Figure (10), the data shows that the correction factor

$$C_3 = 10^{\left(\frac{T-833}{76}\right)}$$

can be applied to the difference between the CO emission index and the CO emission index for chemical equilibrium. Since the equilibrium emission index is a known function of equivalence ratio and final temperature, the factor C_3 can be used to derive a temperature corrected CO level.

Finally, combustion inefficiency, a function of both hydrocarbon emission index and the CO emission index in excess of equilibrium lends itself to the same type of correction. From Figure (10), the data is seen to indicate the factor

$$C_4 = 10^{\left(\frac{T-833}{170}\right)}$$

In order to assess the validity of the derived temperature correction factors at equivalence ratios other than 0.4, the ring nozzle combustor configuration was operated over a range of equivalence ratio at mixer inlet temperatures ranging from 798K to 980K. Figure (11) presents the measured combustion emission levels, corrected to an entrance temperature of 833K using the factors C_1 to C_4 as functions of equivalence ratio. Depending upon the mixer inlet temperature, the factors range from one to forty seven. Despite this extremely large range of correction, the data is seen to collapse quite nicely, confirming the applicability of the derived factors.

The NO_x levels obtained using normal injection (ring nozzle), Figure (11a), are extremely low, ranging from 0.1 g- NO_2 /kg-fuel at an equivalence ratio of 0.3 to approximately 1 g- NO_2 /kg-fuel at an equivalence ratio of 0.6. Figure (11b) shows that combustion is highly efficient as well, with an efficiency of 99% at equivalence ratio 0.4 where the NO_x level is 0.2 g- NO_2 /kg-fuel. The CO emission index decreases exponentially with increasing equivalence ratio and reaches the equilibrium level at an equivalence ratio of 0.5. The hydrocarbon emission index is also an exponentially decreasing function of equivalence ratio.

Mixer Length

The effect of changing mixer duct length was investigated by decreasing that section from its original length of 53 cm (21 in.) to one of 33 cm (13 in.). Figure (12) shows the results of this change. The NO_x level increases by a factor of 2 over the entire range of equivalence ratio while CO and unburned hydrocarbon levels drop somewhat below the values obtained with the longer mixer. This behavior is characteristic of increasing local equivalence ratio and indicates that decreasing the mixer length adversely affects the degree of uniformity achieved by the combustor entrance station.

Pressure Atomization - Streamwise Injection

The emission characteristics obtained using a single pressure atomizing nozzle mounted axially in the mixer tube are shown in Figure (13). NO_x levels are far higher than those obtained using normal injection. The minimum NO_x level of 2.5 g- NO_2 /kg-fuel was obtained at an equivalence ratio of 0.32 with over 5% combustion inefficiency. Attempts to burn at lower equivalence ratio produced

unstable combustion and occasional flameout.

The hydrocarbon emission index parallels the behavior of the combustion inefficiency, dropping slowly with increasing equivalence ratio. However, the unburned hydrocarbon level is quite high for this method of fuel injection implying that a small but significant fraction of the fuel may be entering the combustor still in the liquid phase. Carbon monoxide levels are high at low equivalence ratio and drop slowly with increasing fuel flow, approaching equilibrium as the overall equivalence ratio approaches 0.7.

The data presented in Figure (13) were obtained using the smallest of the three pressure atomizing nozzles tested. The nozzle pressure drop, which is proportional to the square root of fuel flow rate, is $6.8 \times 10^5 \text{ N/m}^2$ (100 psia) at equivalence ratio 0.25. Two other nozzles were tested which had greater flow ratings (lower pressure drop at a given flow rate) and produced larger droplet sizes. The NO_x levels and combustion inefficiencies obtained using these nozzles were both higher than those for the smallest nozzle although the magnitude of the difference was not large.

The NO_x levels obtained using the single axially mounted nozzle are higher than those produced by the normal injection configuration indicating a lower degree of premixing by the combustor entrance station. The droplet size produced by the pressure atomizer varies between 50 and 150 microns and trajectory calculations indicate that streamwise acceleration of the droplets in the high velocity mixer airflow is so large that lateral penetration of the liquid is no greater than 3 cm by the end of the mixer section. As a result, the initial fuel jet acts as a 6 cm diameter cylinder within the 8.9 cm diameter mixer duct. Within this cylinder, the initial dispersion of fuel droplets would be expected to produce a reasonably uniform mixture. However, because the air within this streamtube comprises less than 50% of the total flow, the local equivalence ratio would be expected to be on the order of twice the overall value. Coaxial jet mixing cannot produce a uniform mixture within the length of the mixer tube ($l/d \approx 8$). As a result, the flame would be expected to display premixed combustion characteristics for overall equivalence ratios below 0.5 but these characteristics would correspond to the local equivalence ratio, approximately

twice the overall value. For equivalence ratios greater than 0.5, the central jet behaves as a conventional diffusion flame, burning as the fuel-rich core mixes with the outer sheath of air.

The high CO levels appear to be the result of rapid quenching of the outer edge of the central flame and, again, are characteristic of non-premixed combustion. The level of unburned hydrocarbons cannot be adequately accounted for by incomplete mixing. It would appear that the rapid acceleration of the fuel droplets to a condition of nearly zero velocity relative to the rapidly flowing (170 m/sec) mixer air and their mixer residence time of only 3 msec is inadequate for complete evaporation of droplets as large as those of 150 micron diameter produced by the pressure atomizer.

Contrastream Injection

The effect of contrastream injection using the same axially mounted pressure atomizing nozzle is shown in Figure (14). Contrastream injection produced noisy combustion with considerable low frequency (< 100 cps) oscillations and the data shows considerable scatter. NO_x levels are lower than those for costream injection although the decrease is quite small. Combustion inefficiency is highly sensitive to the less stable combustion mode and shows points both above and below the streamwise data, although a least squares fit to the data is virtually coincident with the results of the costream injection tests. As before, the hydrocarbon emission index behaves as the combustion inefficiency since there is relatively little change in the CO level with equivalence ratio.

Air-Assisted Atomization

Replacing the pressure atomizing nozzle with an air assist atomizer produced an interesting result. As with the earlier costream injection tests, combustion was smooth and quiet with little scatter in the results. NO_x levels, shown in Figure (15a), are virtually unaffected by the finer atomization produced by the air assist nozzle, confirming the earlier supposition that the high NO_x levels were the result of improper mixing rather than inadequate evaporation. Combustion inefficiency, Figure (15b), displays a pronounced improvement with the finer atomization device, a direct reflection of the large

decrease in hydrocarbon emission level, shown in Figure (15c). Carbon monoxide emission, Figure (15d), is only slightly improved. As noted earlier, high CO levels are typical of diffusion flames surrounded by high velocity air where rapid quenching at the edges of the flame precludes final oxidation of the CO.

Fuel Preheat and Combustor Turbulence Level

The effects of preheating the fuel to approximately 500K (900°R) and of increasing turbulence level by placing screens in the mixer are illustrated in Figure (16). The effect of screens is seen to be of no more than second order importance. Their effect on NO_x and CO emission levels is particularly small. A slight increase in hydrocarbon emission level is evident and is reflected by a correspondingly small increase in combustion inefficiency.

Preheating the fuel prior to injection produced no substantive effect on emission levels or combustion inefficiency. However, where it was not possible to maintain combustion at equivalence ratios below 0.43 with unheated fuel, preheating produced stable combustion down to the lowest equivalence ratio tested. Combustion inefficiency was unacceptably high at the lowest equivalence ratio, but there was no tendency for the flame to blow out.

CONCLUDING REMARKS

The problem of reducing oxides of nitrogen produced by gas turbine combustors is an important one, regardless of the application in which the engine may be used. However, the problem becomes especially important when one considers propulsion systems for commercial supersonic aircraft. This particular application is especially critical in that conditions in the stratosphere, where SST's will operate, are such that large quantities of NO_x can potentially reduce the earth's protective ozone layer.

In Reference (8), there is a discussion of the concept of the "zero impact" aircraft. The concept is based on the observation that while the NO_x contained in engine exhaust gases can reduce stratospheric ozone through long term chemical reaction, the water content of these same gases produces just the opposite effect by reducing the level of stratospheric NO . Therefore, a small, but finite, amount of NO_x in the exhaust gas of a stratospheric aircraft is necessary to balance the effect of the water being discharged. It is calculated that a NO_x emission index of $0.3 \text{ g-NO}_2/\text{kg-fuel}$ will produce zero impact on the stratospheric ozone layer. This result is of great importance, for if this emission level can be achieved the possibility of environmental damage to the stratosphere by engine NO_x will be eliminated, regardless of the number of aircraft which may eventually come into service.

The NO_x levels produced by conventional gas turbine engines operating at the supersonic cruise condition is anywhere from 18 to $20 \text{ g-NO}_2/\text{kg-fuel}$. In the experimental clean combustor program NO_x levels of 4 to $10 \text{ gm NO}_2/\text{kg-fuel}$ have been demonstrated at the supersonic cruise condition, Reference (9), still an order of magnitude above the zero impact level of $0.3 \text{ gm NO}_2/\text{kg-fuel}$.

As the degree of fuel premixing improves, the NO_x level decreases and combustion efficiency improves. The single axially mounted nozzle design tested here produced $10 \text{ gm NO}_2/\text{kg-fuel}$ at 99% combustion efficiency and $2.5 \text{ gm NO}_2/\text{kg-fuel}$ when combustion efficiency dropped to 95%. As premixing was improved by employing a set of four pressure atomizing nozzles spraying at 75° to the flow axis, the combustor produced NO_x levels of $2 \text{ gm NO}_2/\text{kg-fuel}$ at 99% combustion ef-

efficiency and 0.45 gm NO₂/kg-fuel with 98% combustion efficiency, Reference (3). Finally, the 12 orifice normal injection technique employed here produced 0.4 gm NO₂/kg-fuel at 99.7% efficiency and below 0.2 gm NO₂/kg-fuel at 99% combustion efficiency, the latter number being below the zero impact goal. As the degree of premixing and prevaporization is improved, it appears that the zero impact goal can be met.

It is clear that the details of the individual design are of great importance for it is difficult to produce a completely uniform gaseous mixture of fuel and air within a space of a fraction of a meter and with a residence time on the order of a few milliseconds. The results summarized in Figure (17) indicate the importance of the initial distribution of liquid fuel. A single axially mounted nozzle cannot produce adequate penetration of a high velocity mixer flow and results in only partial premixing and fairly high NO_x levels. Four injectors produce a better initial fuel distribution and an intermediate NO_x level. Twelve injectors produce an even better initial distribution and the lowest NO_x level of all designs tested. Calculations indicate even lower NO_x levels should be achievable, pointing out that mixing could still be improved. Although there appears to be no justification for attempting to lower NO_x levels below the zero impact point, mechanical designs which produce even better initial dispersion of the fuel will allow shortening the combustor below the one meter length used in this program.

Flashback avoidance is an important design feature for premixing combustors. Since a combustible mixture flows through the premixing duct, care must be taken to assure that ignition does not occur until mixing has been completed. Premature ignition will result in higher NO_x levels and can potentially damage the mixer duct. In the experiments performed here, flashback was avoided by designing the mixer duct with a high velocity (134 m/sec) and avoiding wakes or separated flow regions which could anchor a flame. The exact limits for precluding flashback have yet to be determined as functions of combustor entrance temperature and pressure and this data is clearly necessary for working designs to be generated.

The problem of throttling a premixing combustor still remains to be attacked. Since premixing designs operate at very low equivalence ratio, even at cruise

power conditions, attempting to throttle by reducing equivalence ratio will produce poor combustion efficiency. Both staged combustion and variable geometry have been proposed as potential means of implementing premixing combustion in a practical engine design, but feasibility experiments have yet to be carried out.

Implementation of premixing designs into practical engines will require considerable development for successful operation at all conditions including idle, takeoff and altitude relight. Work needs to be done to satisfy performance goals and EPA regulations at all operating conditions.

CONCLUSIONS

Premixing has been demonstrated to be an extremely powerful technique for reducing undesirable gas turbine emissions. As the degree of premixing and prevaporization is improved the pollutant emissions are reduced. For the 12 orifice normal injection technique, NO_x levels reached the zero impact level ($0.3 \text{ g-NO}_2/\text{kg-fuel}$) at a combustion efficiency of 99.5% at the supersonic cruise condition. Work needs to be performed to incorporate these results into an operational gas turbine combustor.

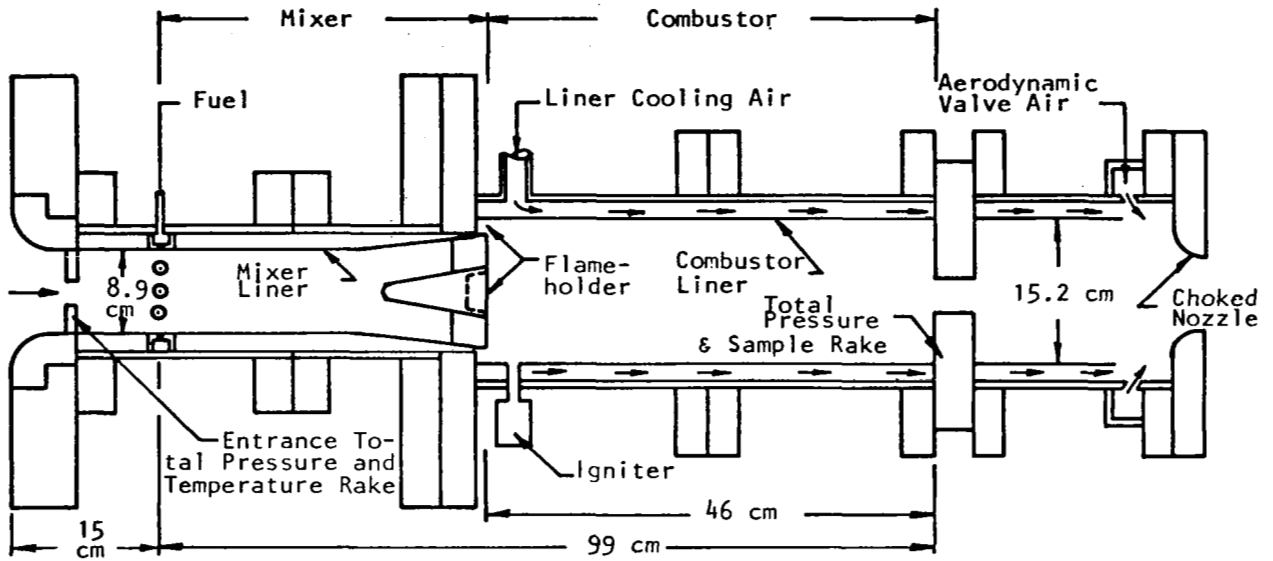


FIGURE 1. COMBUSTION TEST APPARATUS

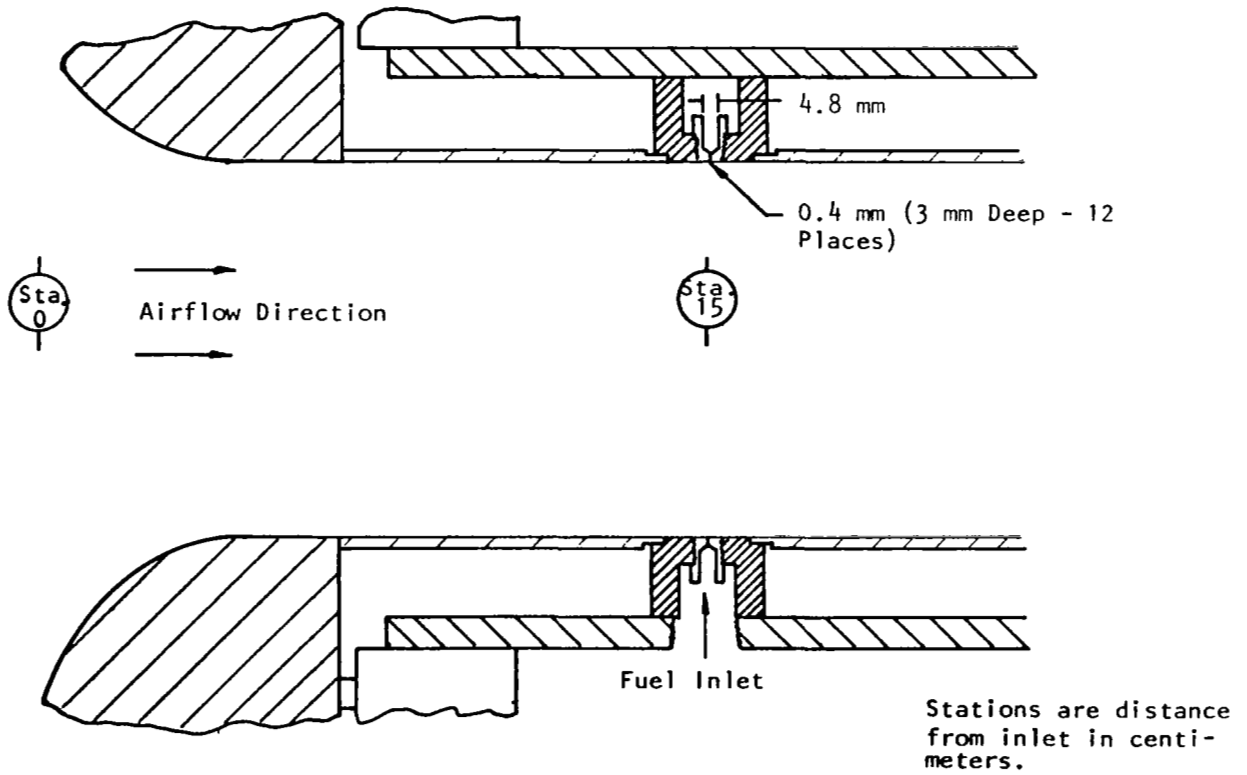
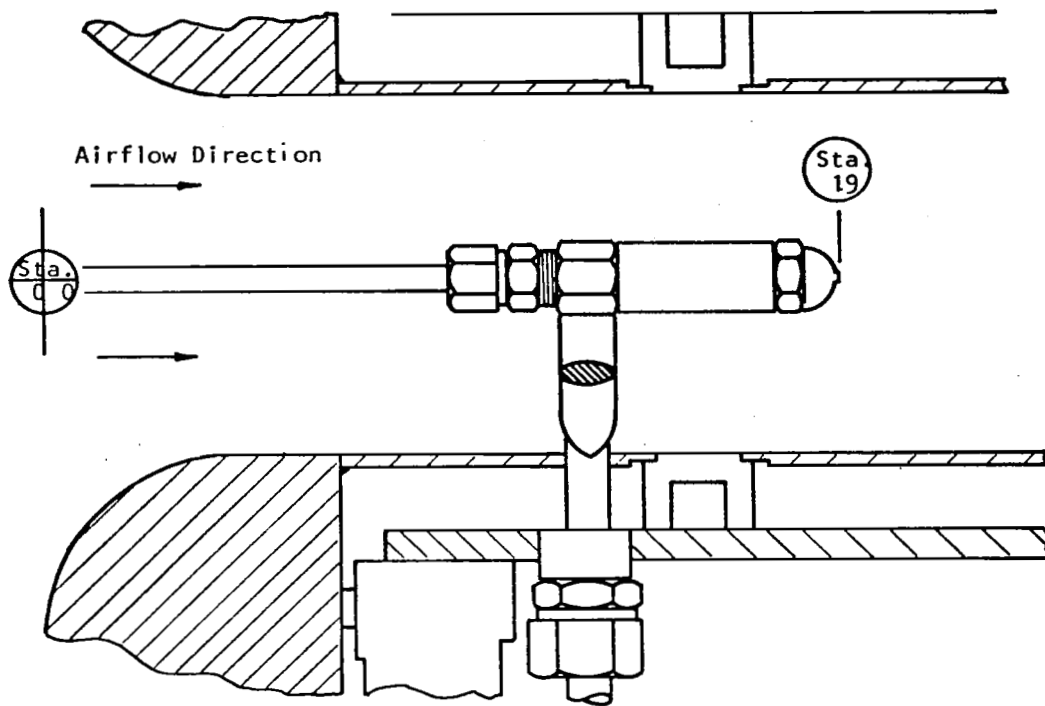
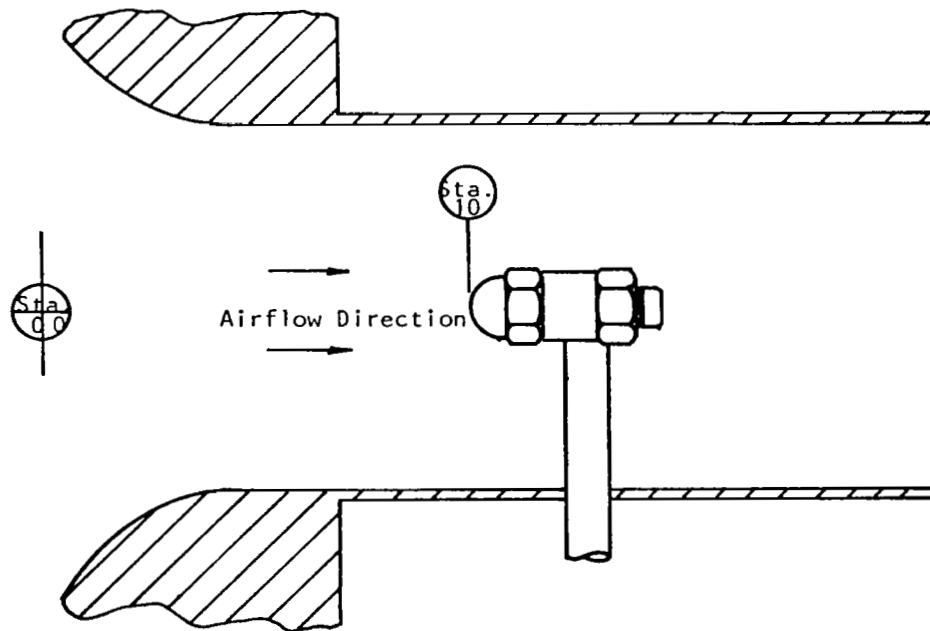


FIGURE 2. NORMAL INJECTION RING NOZZLE

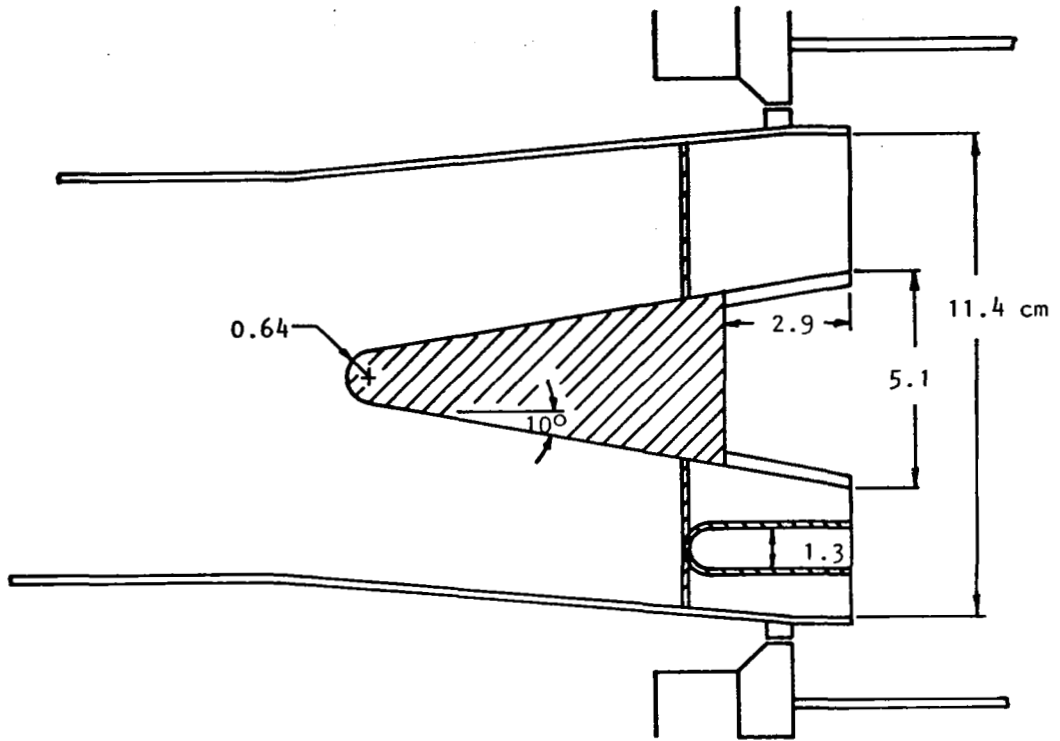


(a) Streamwise Injection

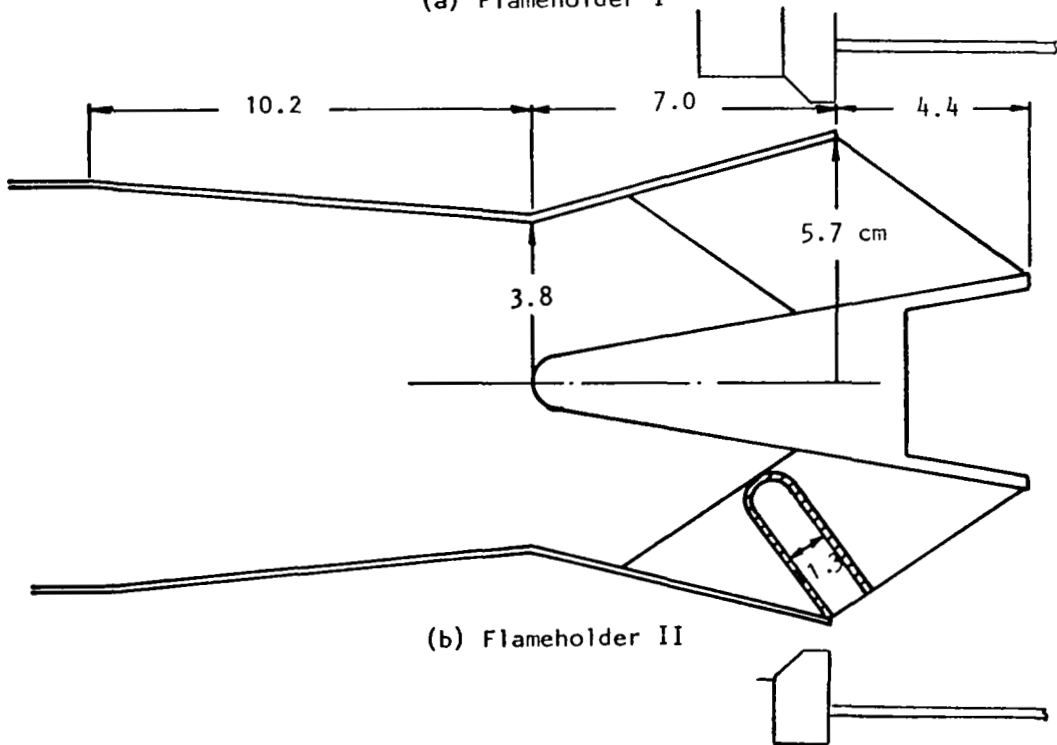


(b) Contrastream Injection

FIGURE 3. COAXIALLY MOUNTED FUEL INJECTORS



(a) Flameholder I



(b) Flameholder II

FIGURE 4. FLAMEHOLDER DETAILS

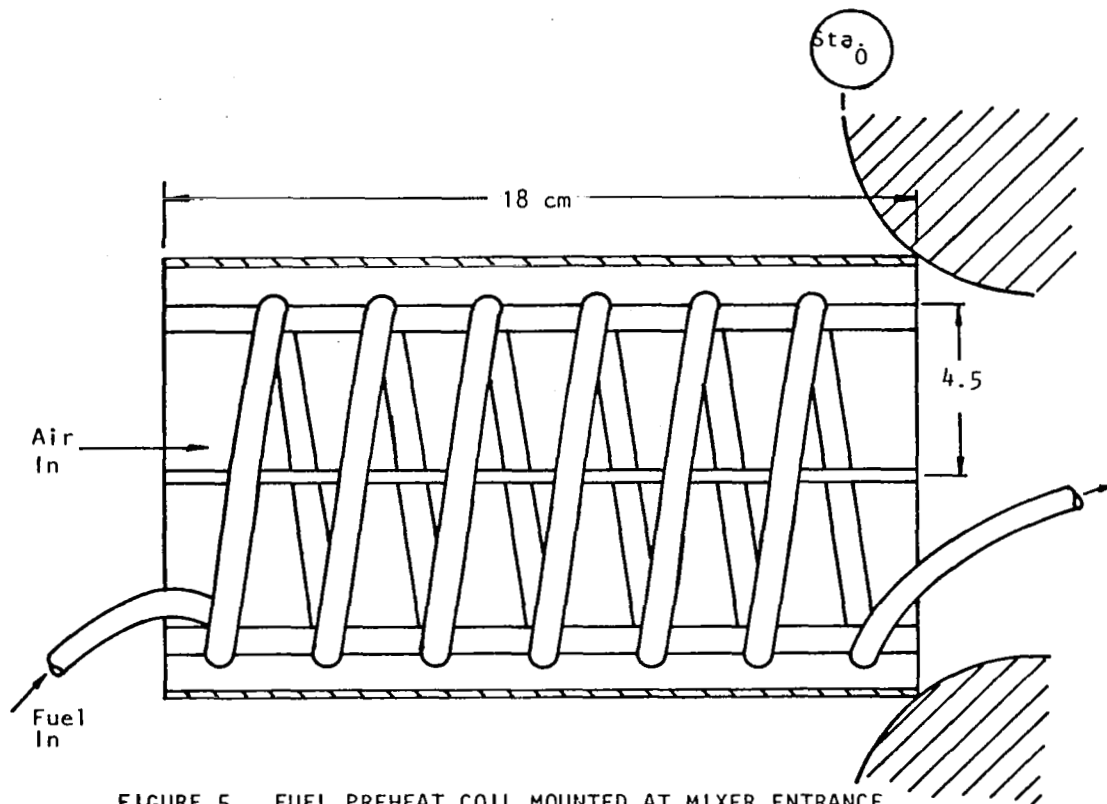


FIGURE 5. FUEL PREHEAT COIL MOUNTED AT MIXER ENTRANCE STATION

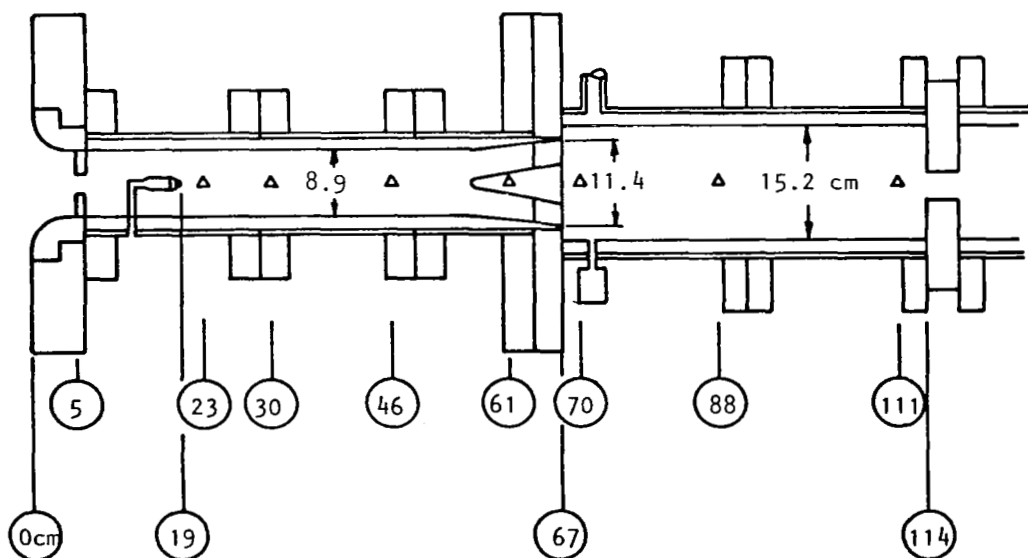


FIGURE 6. COMBUSTION APPARATUS - INSTRUMENTATION STATIONS DENOTED BY TRIANGLES - CIRCLED DIMENSIONS ARE AXIAL DISTANCE FROM ENTRANCE IN CENTIMETERS

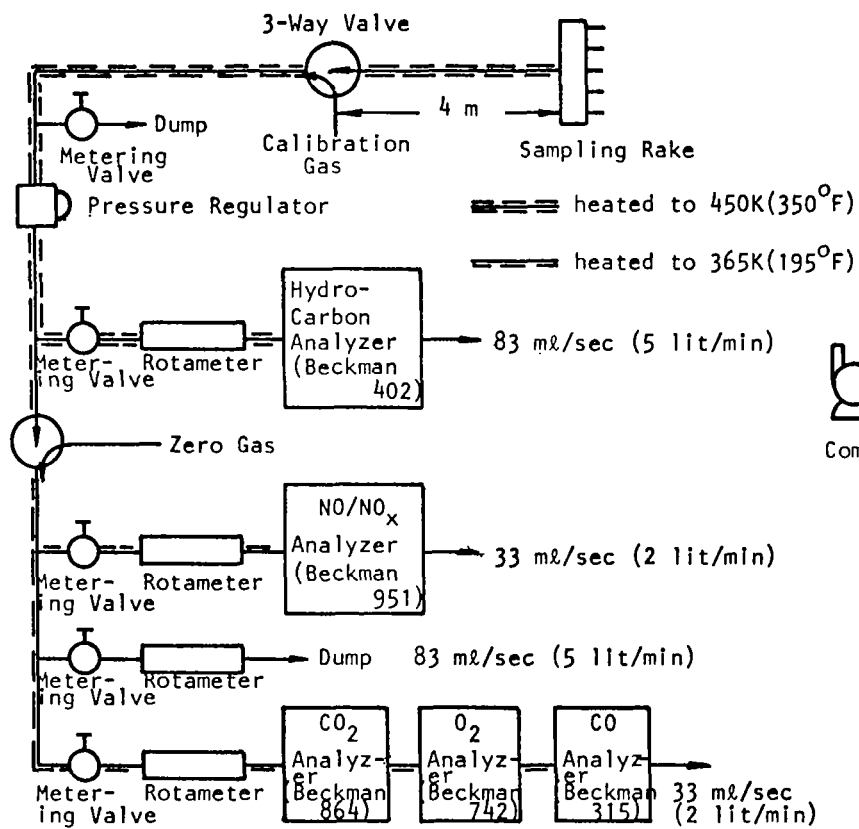


FIGURE 7. SAMPLING SYSTEM SCHEMATIC

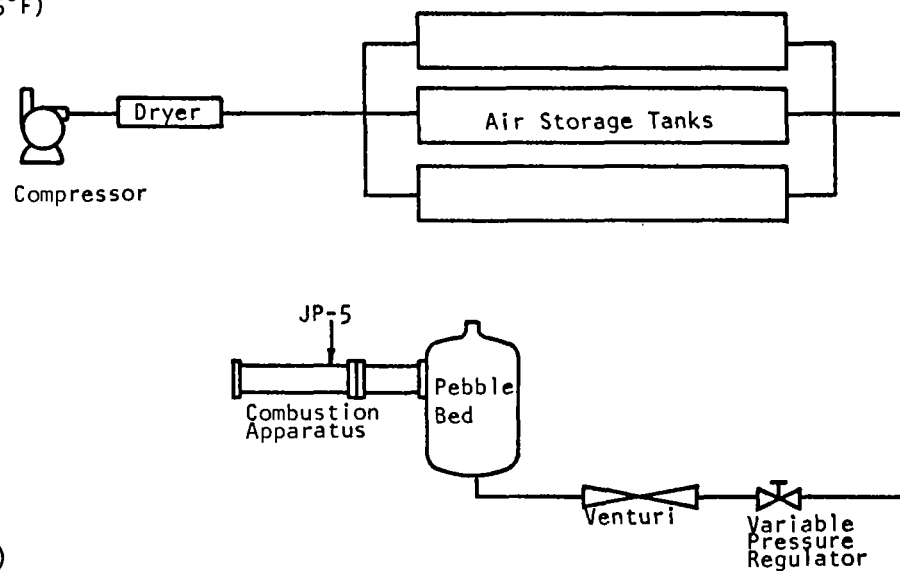


FIGURE 8. SCHEMATIC OF GAS PEBBLE BED COMBUSTION TEST FACILITY

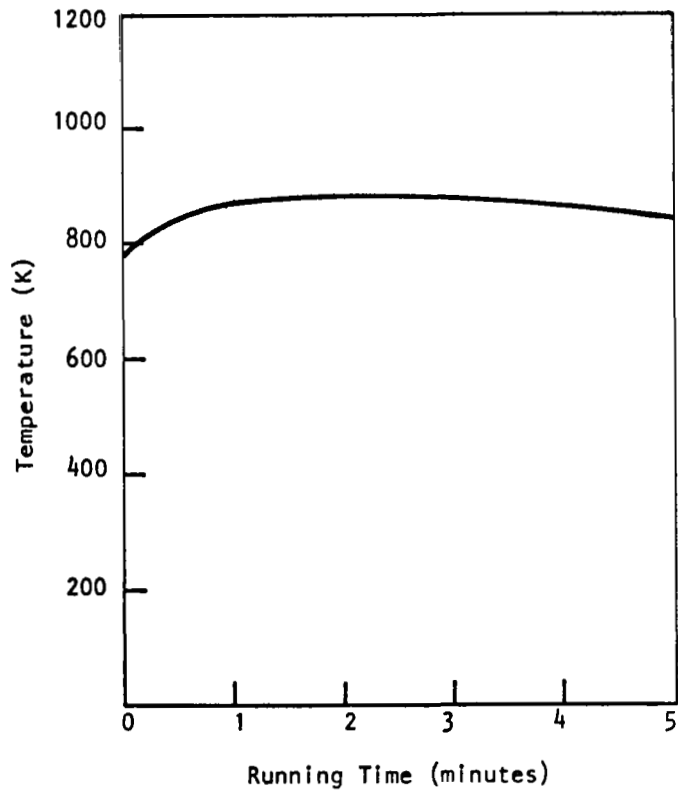


FIGURE 9. TEMPERATURE CHARACTERISTIC OF GASL PEBBLE BED HEATER (MASS FLOW 1.36 kg/sec)

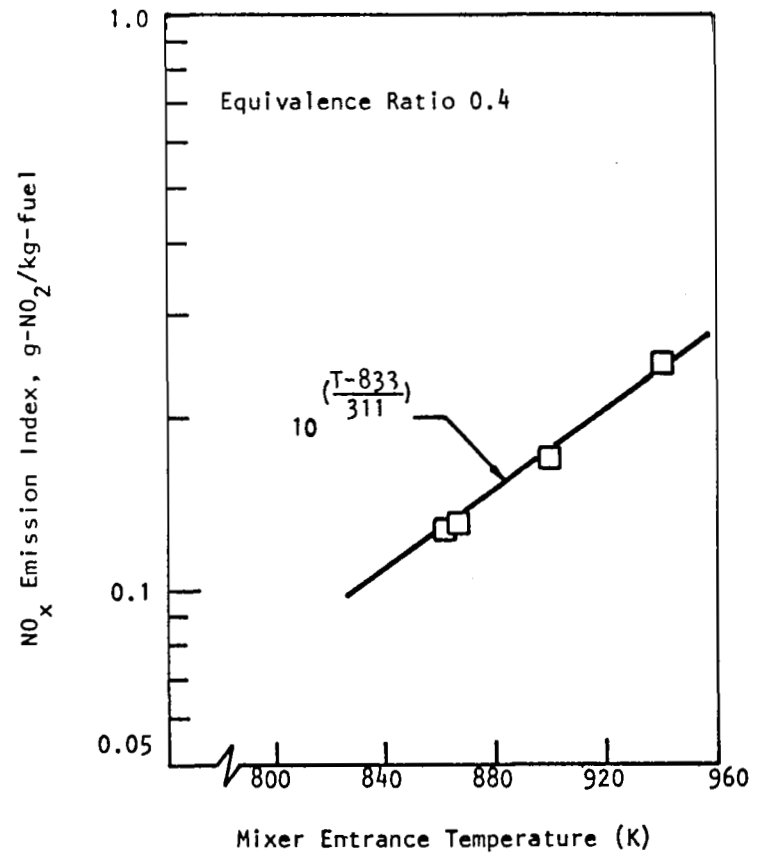


FIGURE 10a. OBSERVED VARIATION OF NO_x EMISSION WITH MIXER ENTRANCE TEMPERATURE

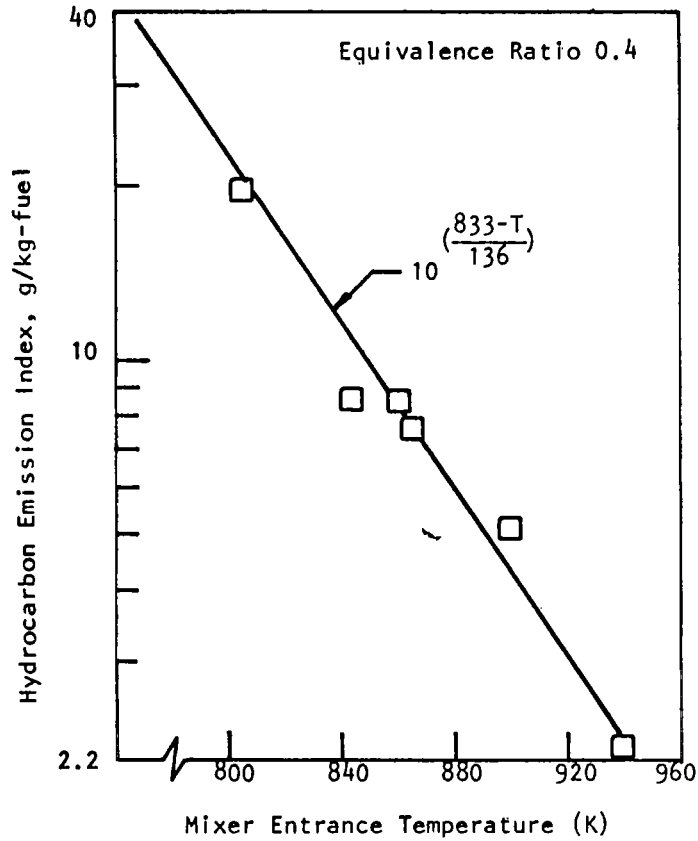


FIGURE 10b. OBSERVED VARIATION OF HYDRO-CARBON EMISSION WITH MIXER ENTRANCE TEMPERATURE

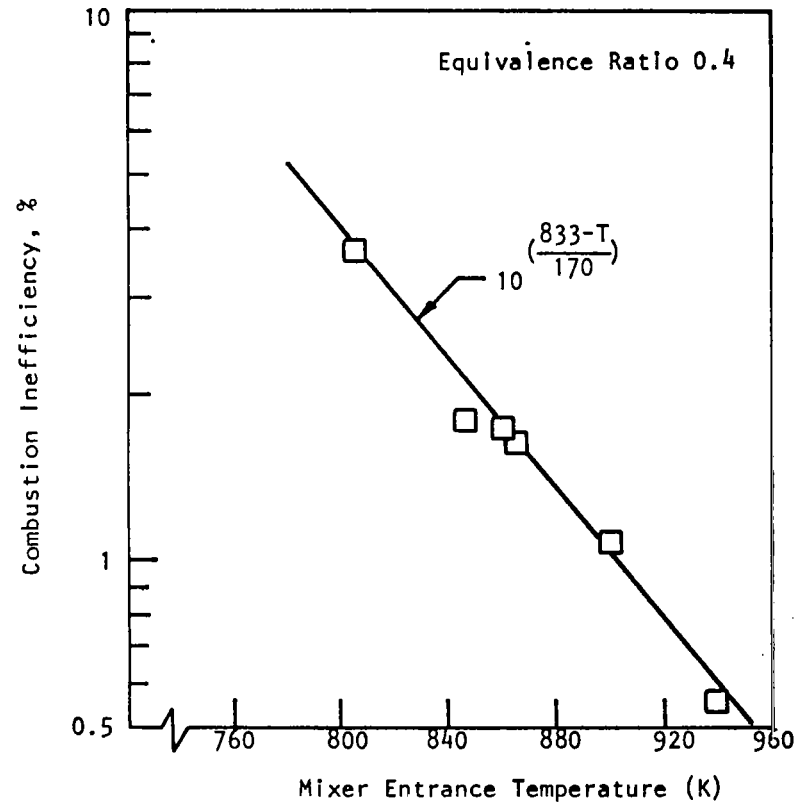


FIGURE 10c. OBSERVED VARIATION OF COMBUSTION INEFFICIENCY WITH MIXER ENTRANCE TEMPERATURE

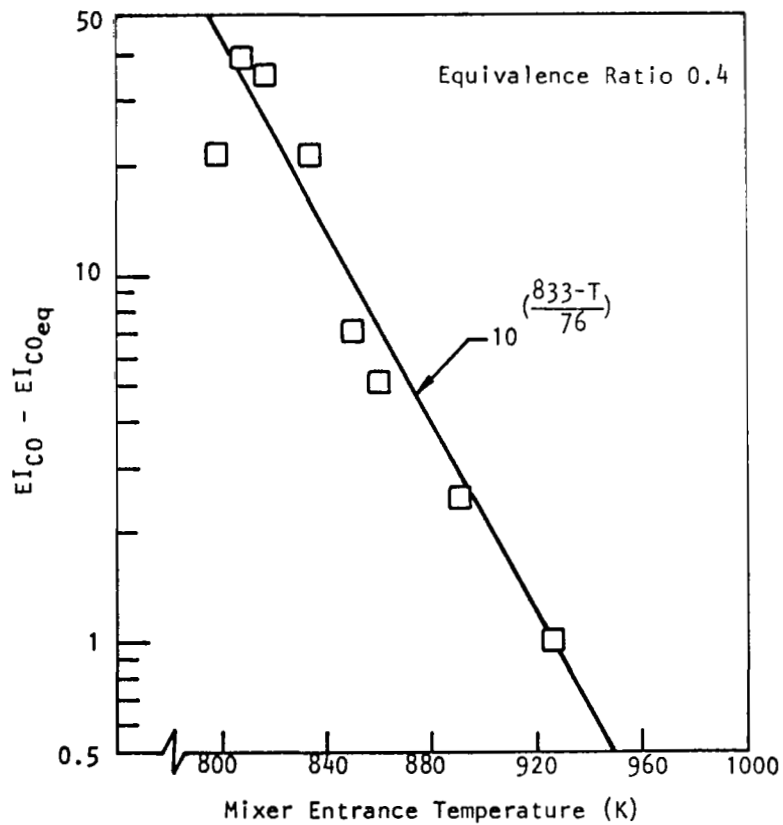


FIGURE 10d. OBSERVED VARIATION OF COMBUSTION INEFFICIENCY WITH MIXER ENTRANCE TEMPERATURE

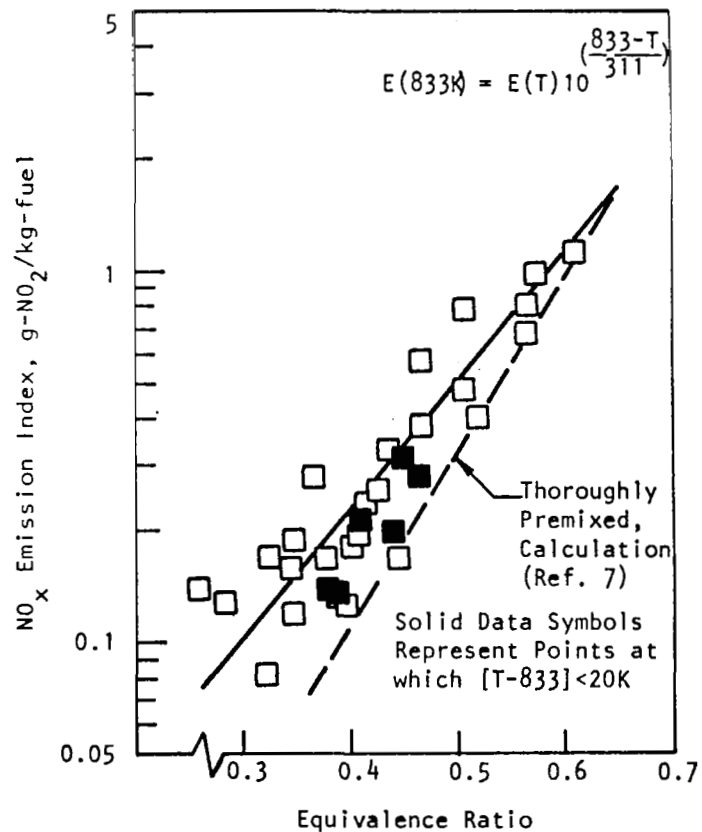


FIGURE 11a. CORRECTED NO_x EMISSION INDEX FOR VARIABLE INLET TEMPERATURE TESTS

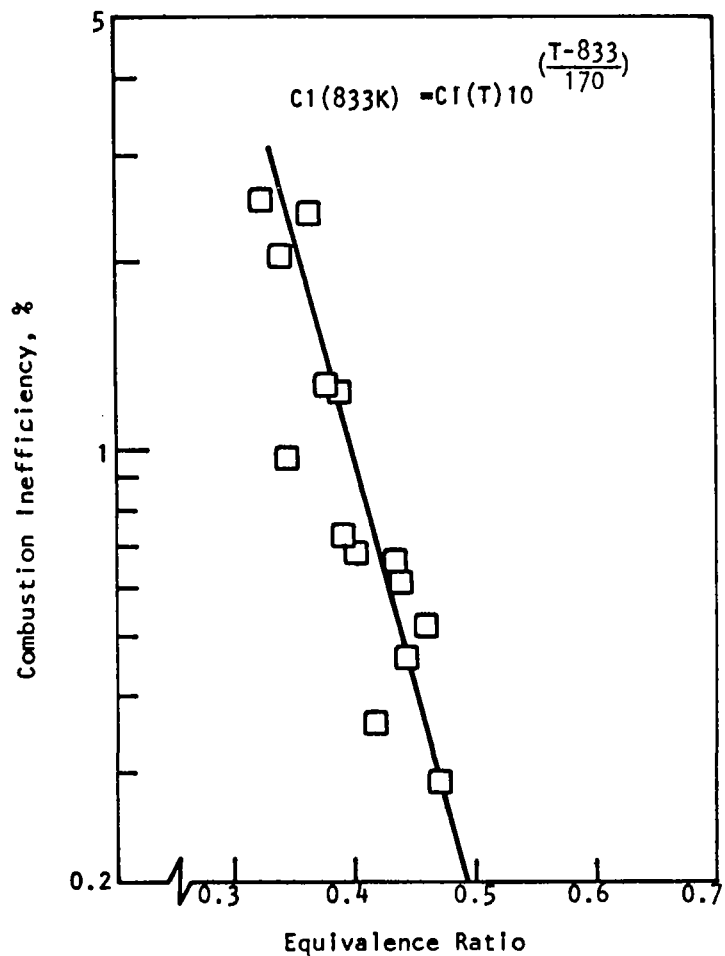


FIGURE 11b. CORRECTED COMBUSTION INEFFICIENCY FOR VARIABLE INLET TEMPERATURE TESTS

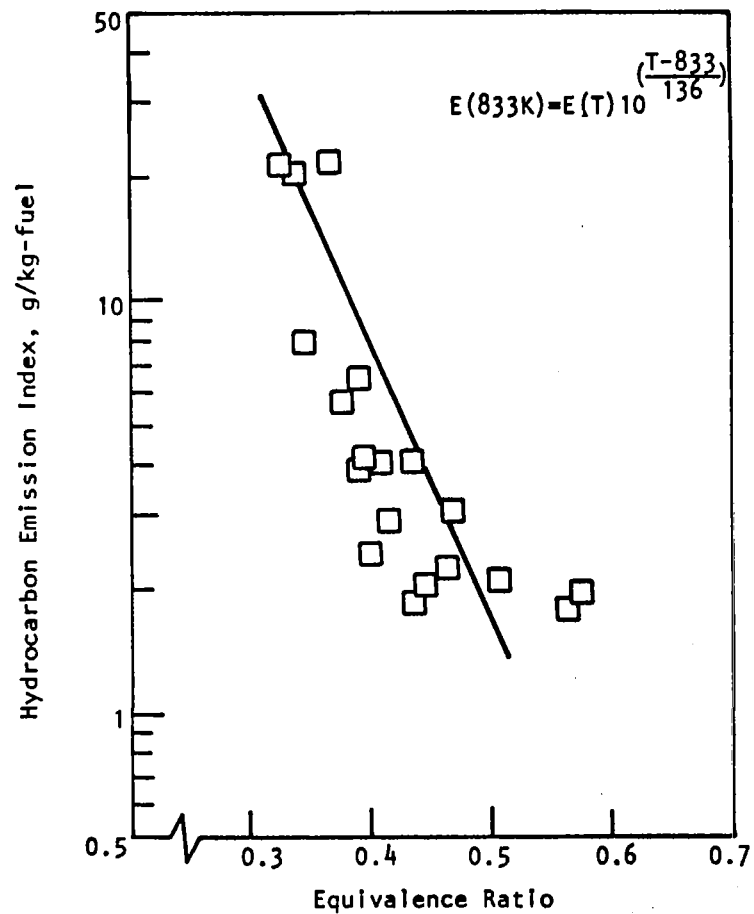


FIGURE 11c. CORRECTED HYDROCARBON EMISSION INDEX FOR VARIABLE INLET TEMPERATURE TESTS

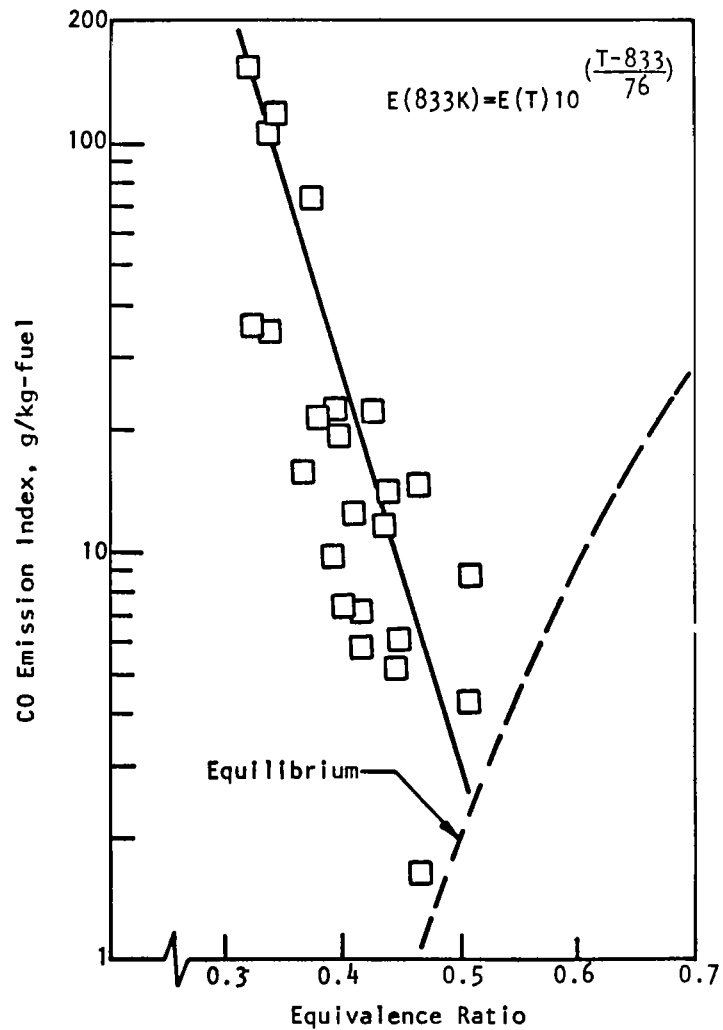


FIGURE 11d. CORRECTED CO EMISSION INDEX FOR VARIABLE INLET TEMPERATURE TESTS

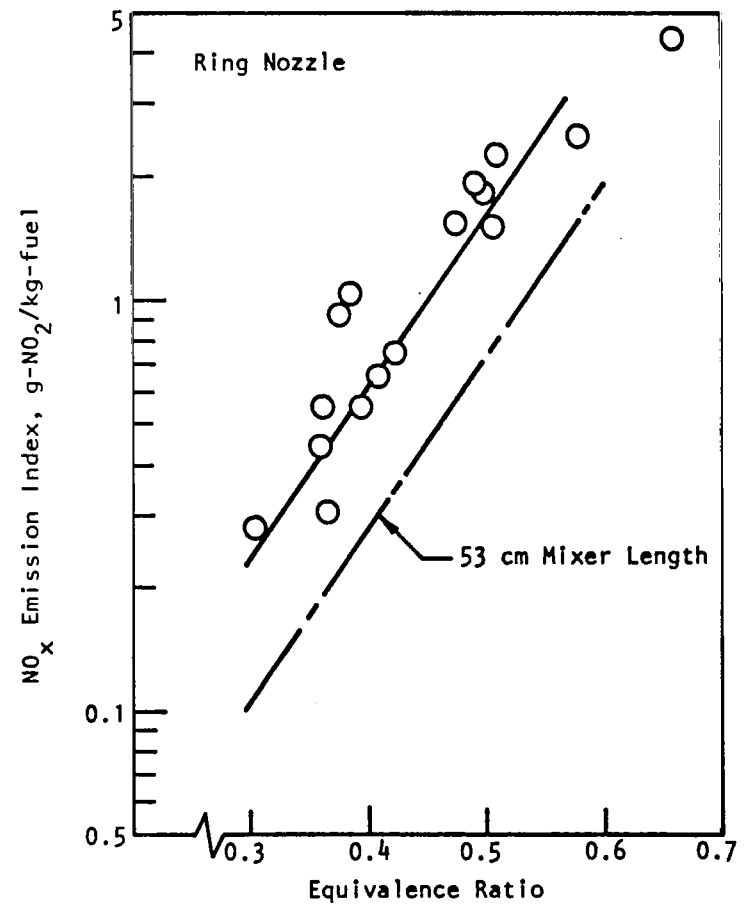


FIGURE 12a. NO_x EMISSION INDEX USING SHORT (33 cm) MIXER

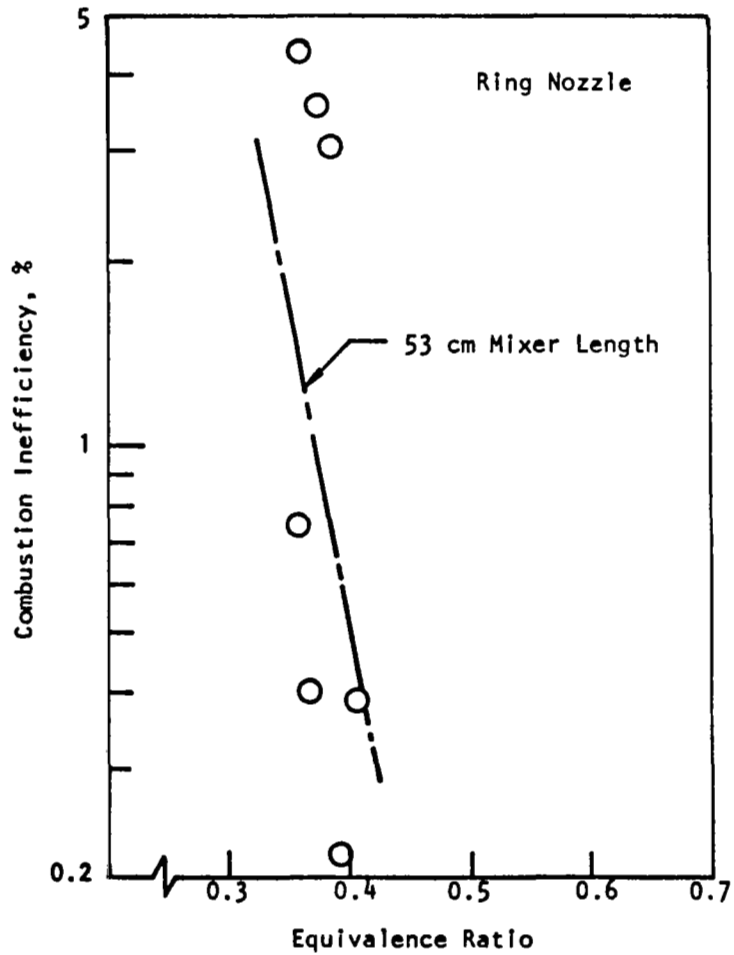


FIGURE 12b. COMBUSTION INEFFICIENCY USING SHORT (33 cm) MIXER

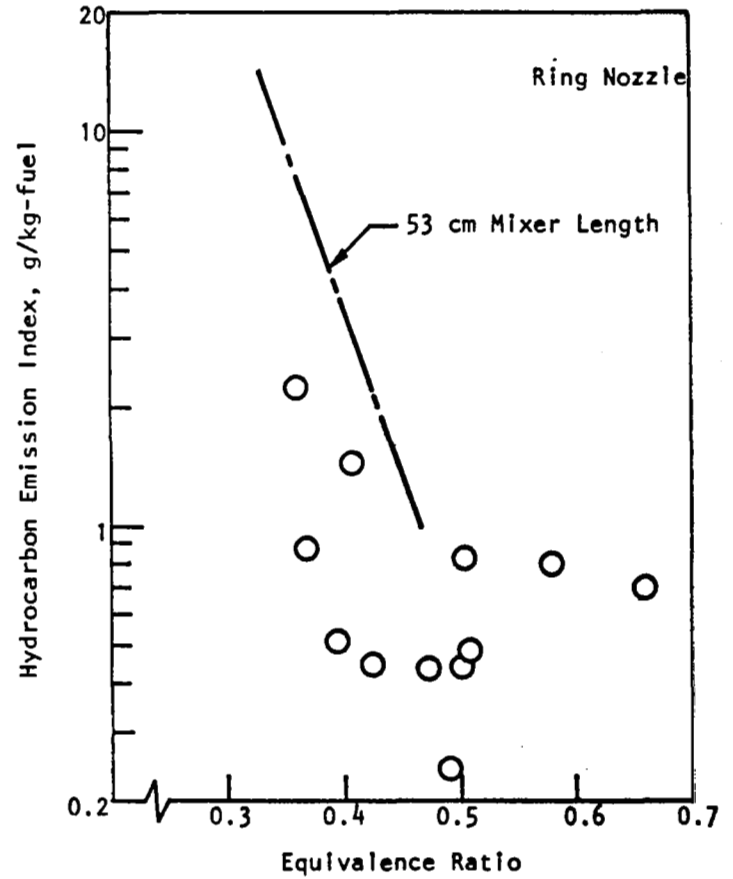


FIGURE 12c. HYDROCARBON EMISSION INDEX USING SHORT (33 cm) MIXER

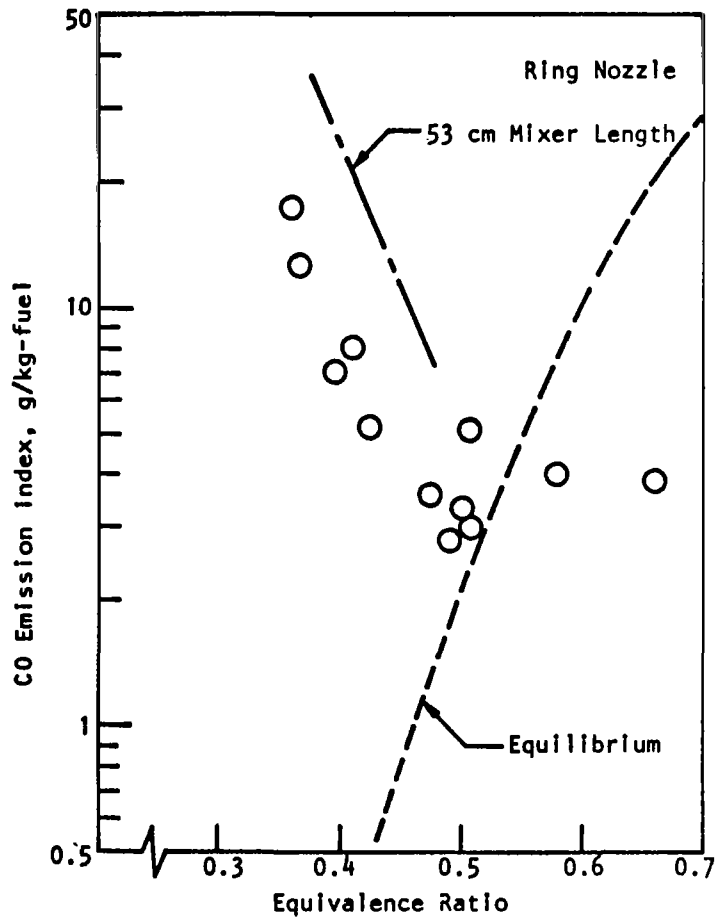


FIGURE 12d. CO EMISSION INDEX USING SHORT (33 cm) MIXER

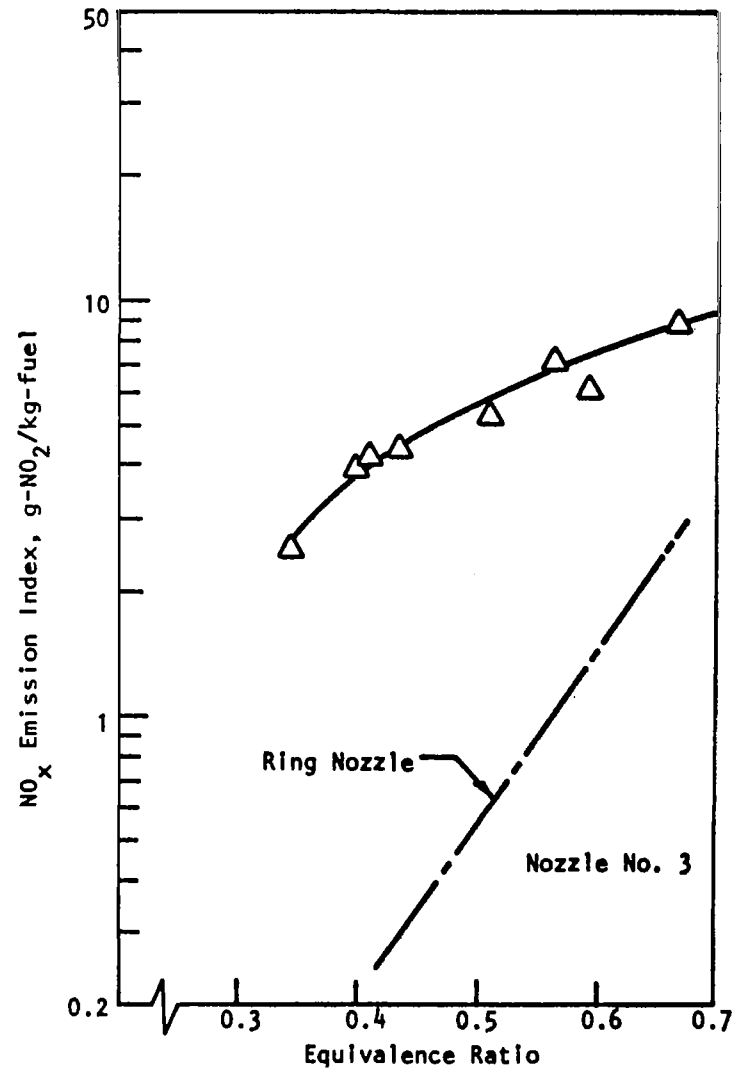


FIGURE 13a. NO_x EMISSION INDEX FOR A SINGLE AXIALLY MOUNTED PRESSURE ATOMIZING NOZZLE (STREAMWISE INJECTION)

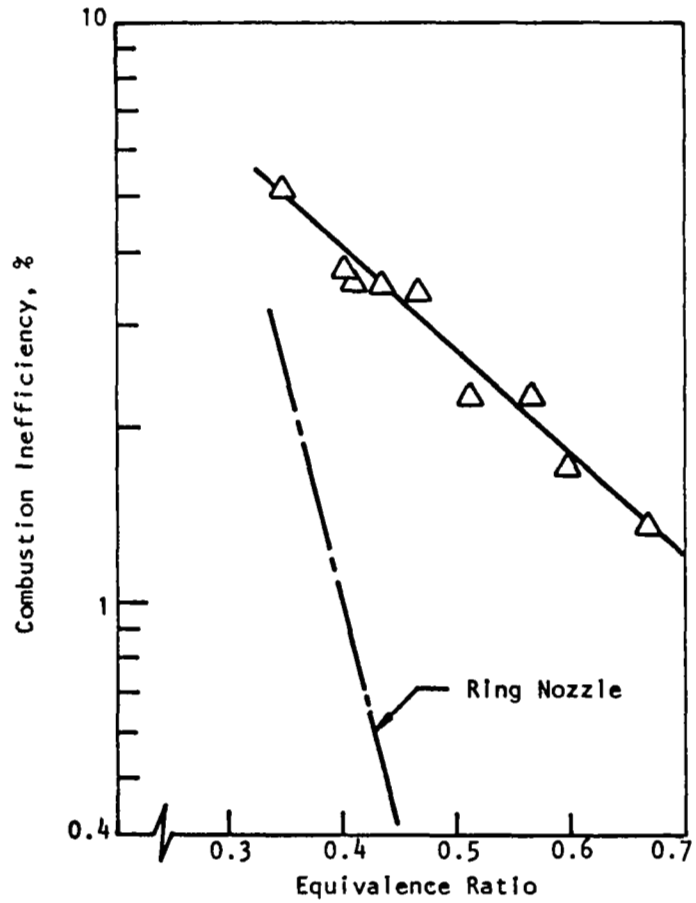


FIGURE 13b. COMBUSTION INEFFICIENCY FOR A SINGLE AXIALLY MOUNTED PRESSURE ATOMIZING NOZZLE (STREAMWISE INJECTION)

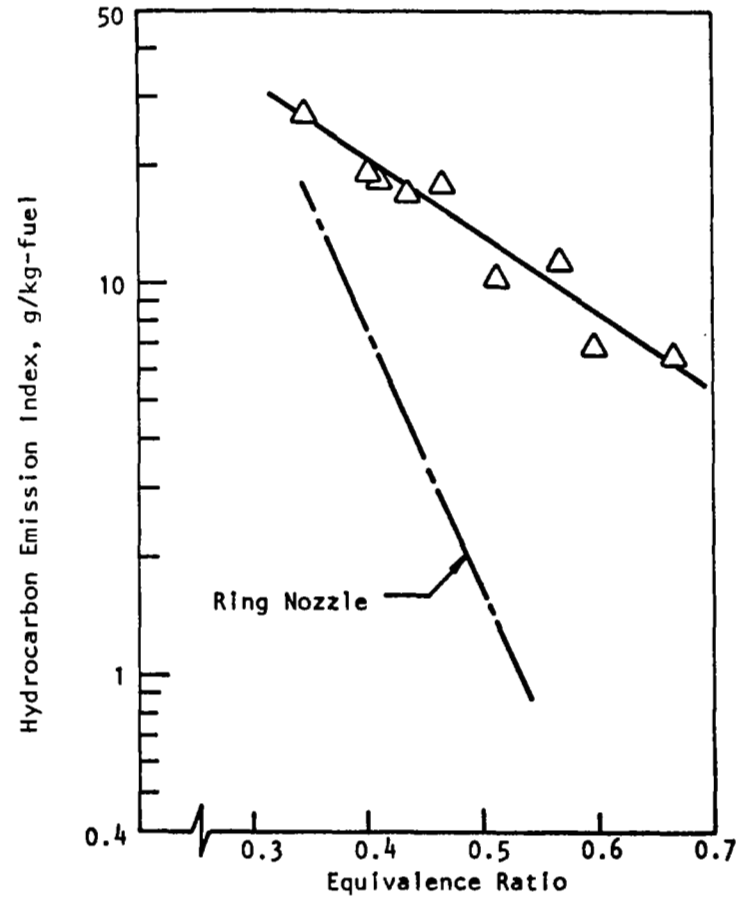


FIGURE 13c. HYDROCARBON EMISSION INDEX FOR A SINGLE AXIALLY MOUNTED PRESSURE ATOMIZING NOZZLE (STREAMWISE INJECTION)

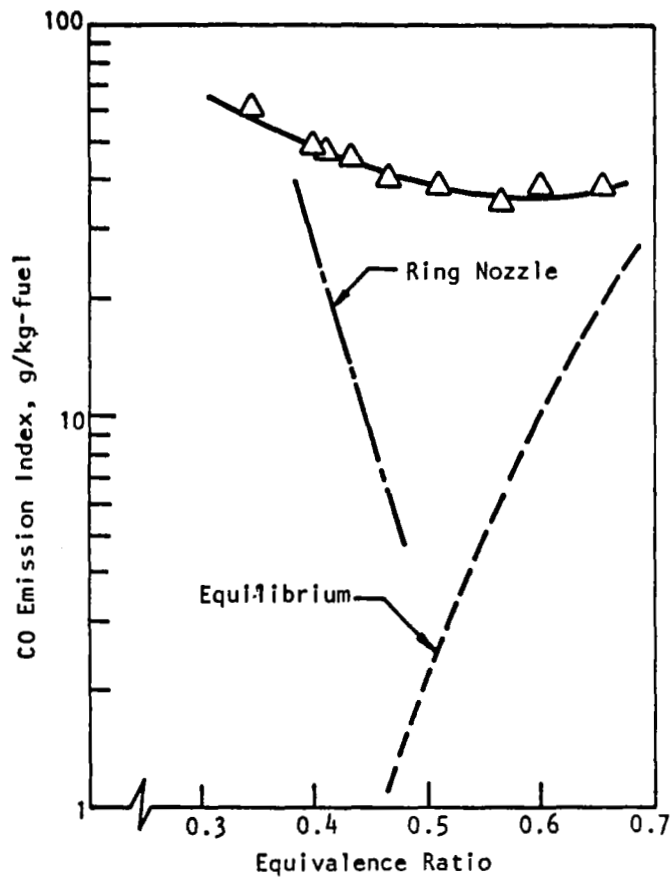


FIGURE 13d. CO EMISSION INDEX FOR A SINGLE AXIALLY MOUNTED PRESSURE ATOMIZING NOZZLE (STREAMWISE INJECTION)

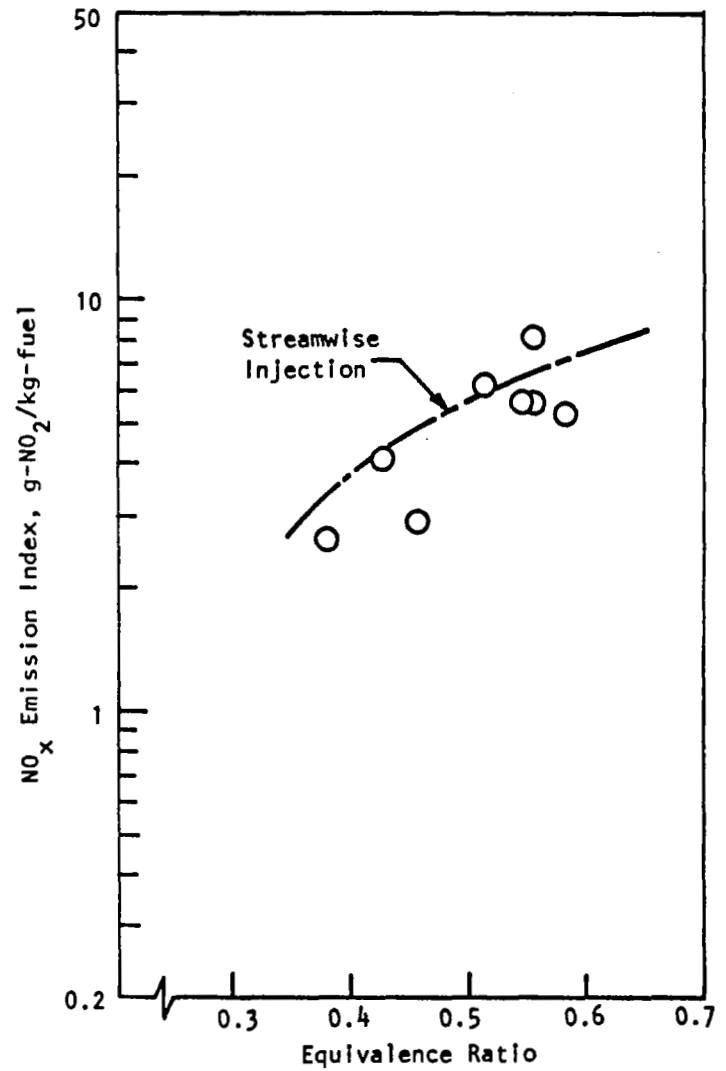


FIGURE 14a. EFFECT OF CONTRASTREAM INJECTION ON NO_x LEVEL

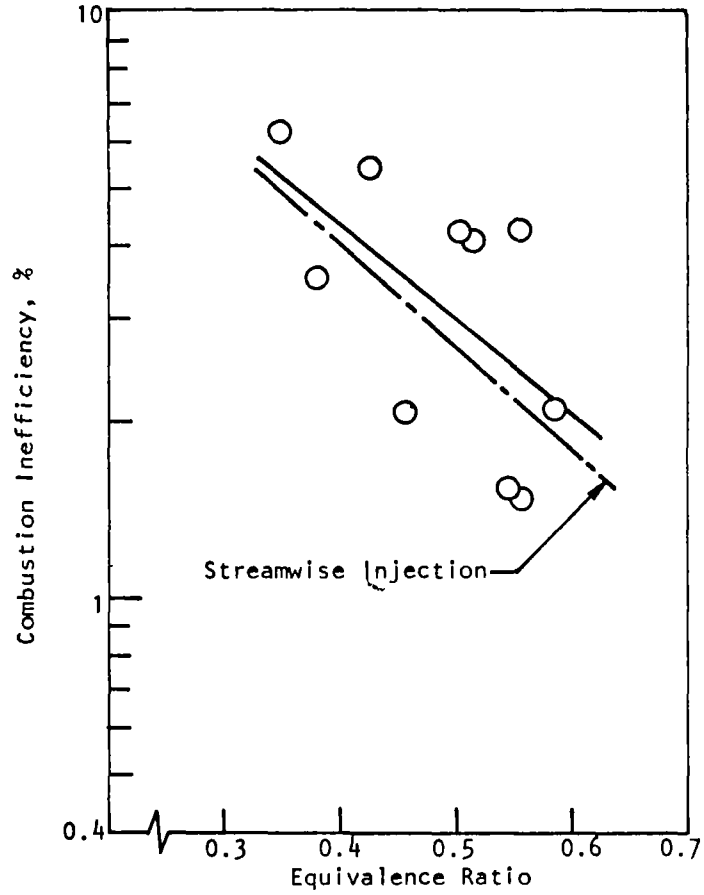


FIGURE 14b. EFFECT OF CONTRASTREAM INJECTION ON COMBUSTION INEFFICIENCY

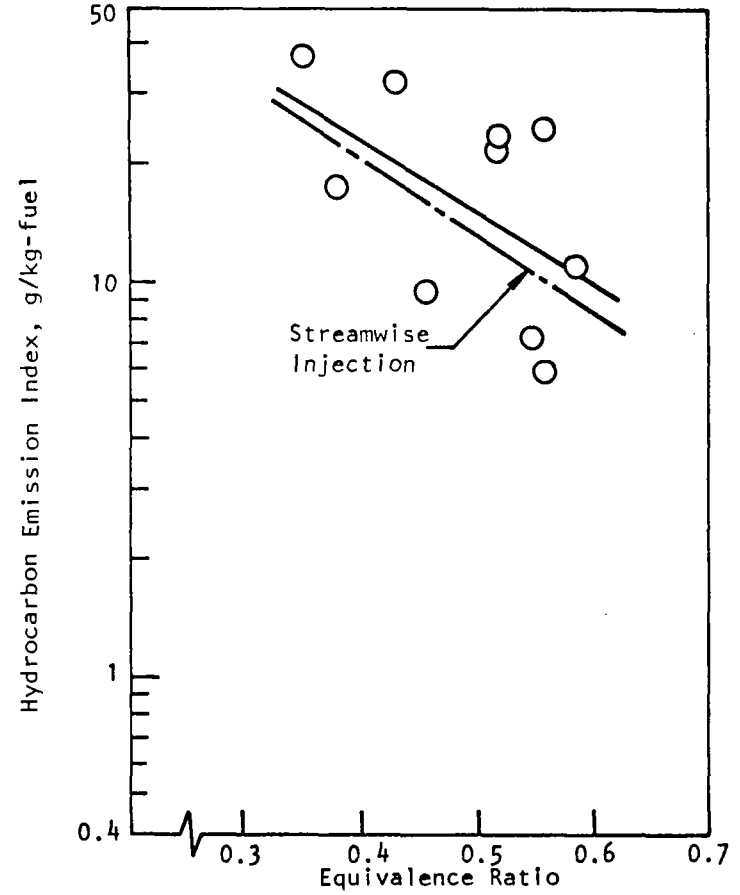


FIGURE 14c. EFFECT OF CONTRASTREAM INJECTION ON HYDROCARBON EMISSION

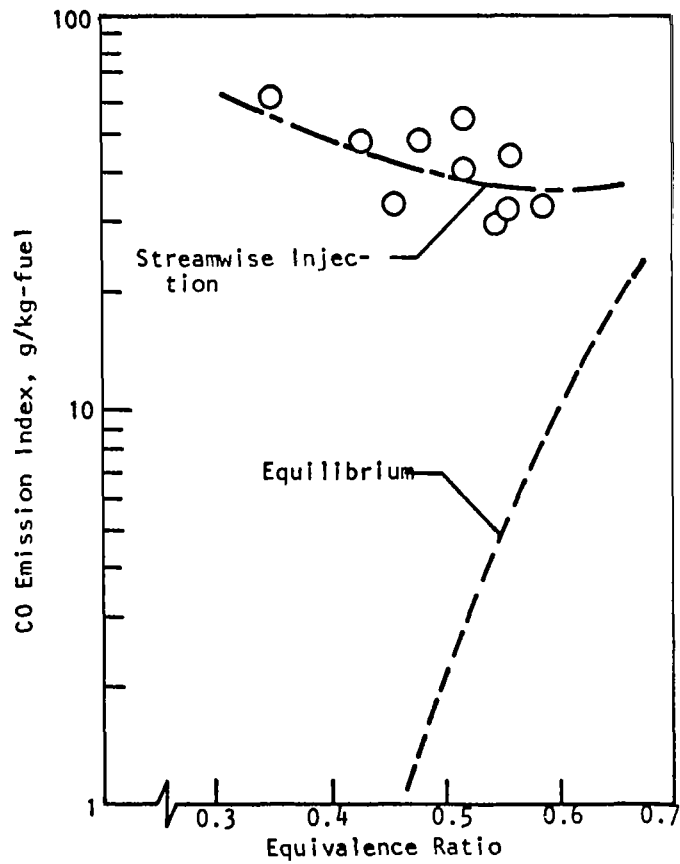


FIGURE 14d. EFFECT OF CONTRASTREAM INJECTION ON CO EMISSION

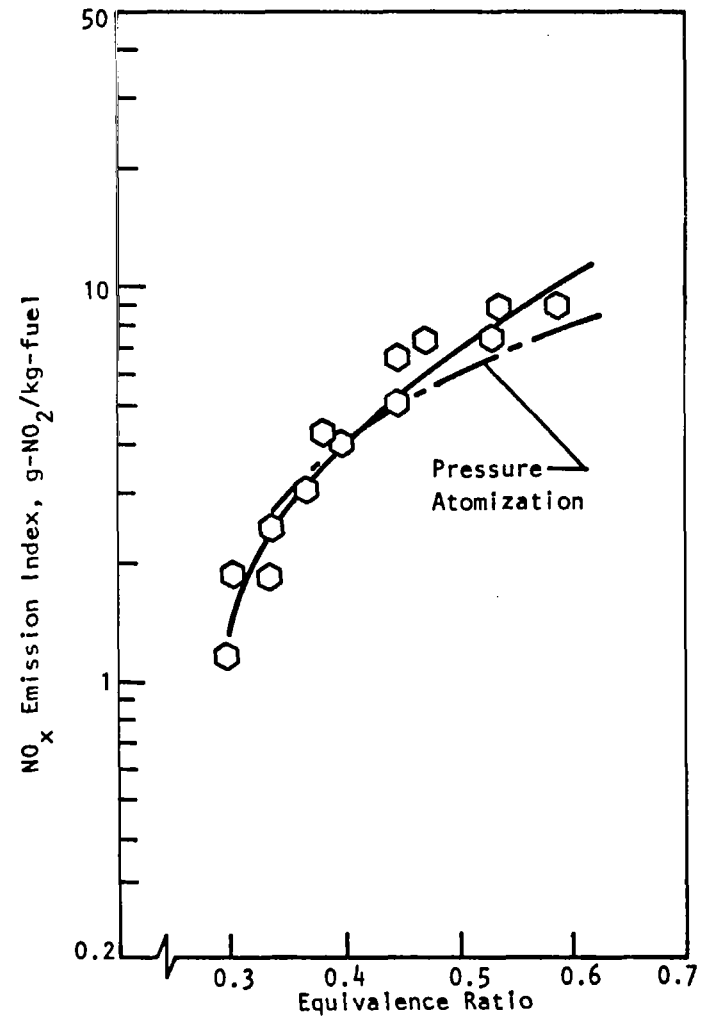


FIGURE 15a. NO_x EMISSION INDEX USING AN AIR ASSIST ATOMIZER

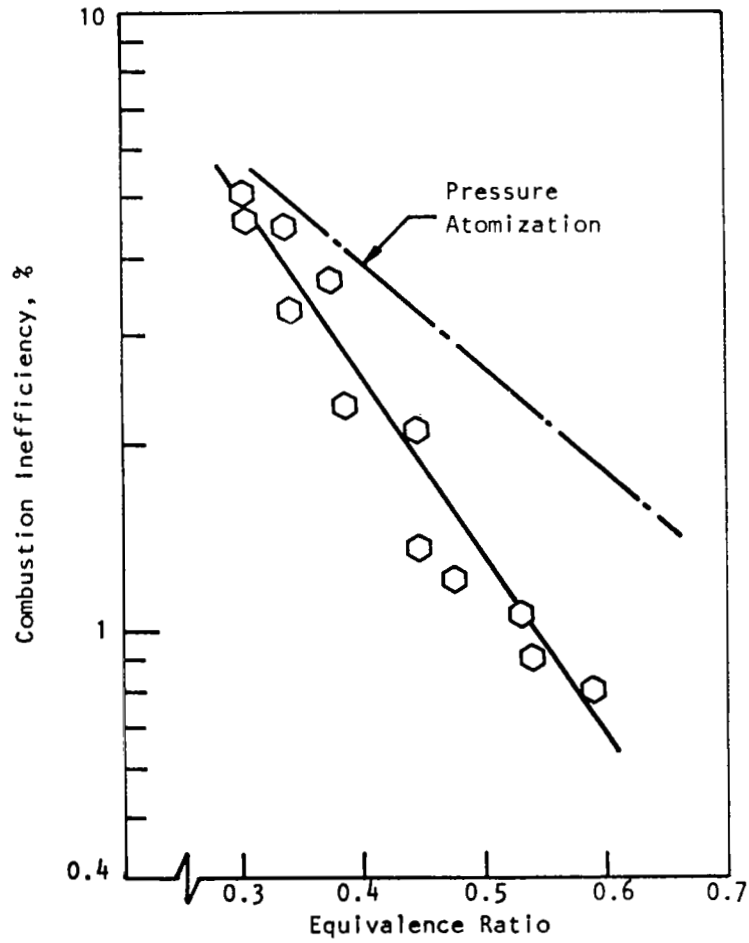


FIGURE 15b. COMBUSTION INEFFICIENCY USING AN AIR ASSIST ATOMIZER

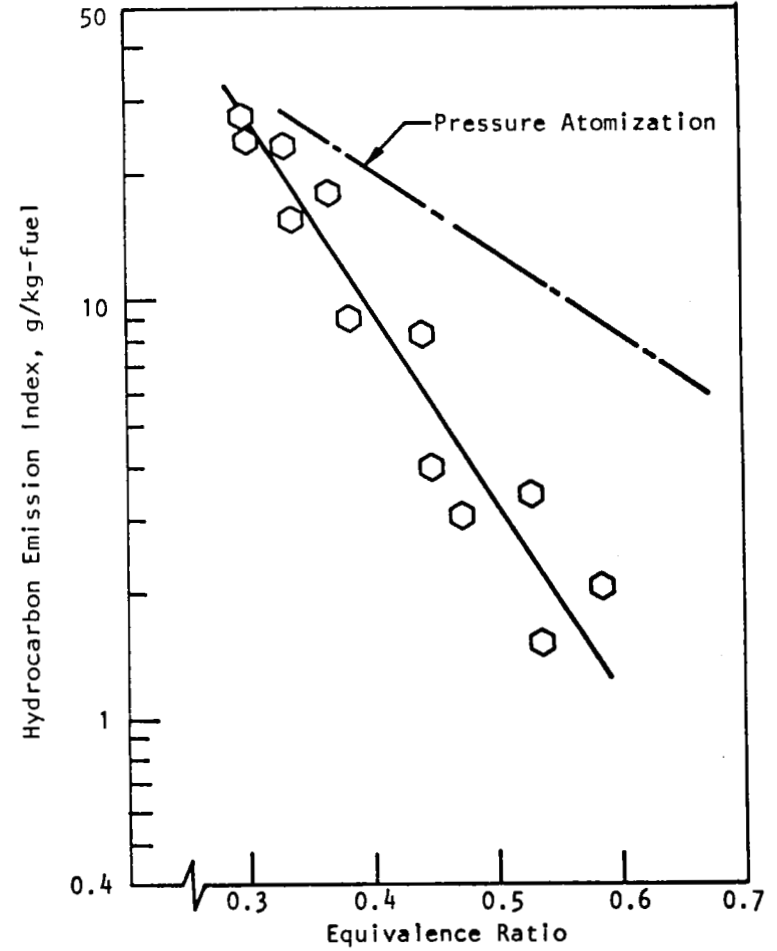


FIGURE 15c. HYDROCARBON EMISSION INDEX USING AN AIR ASSIST ATOMIZER

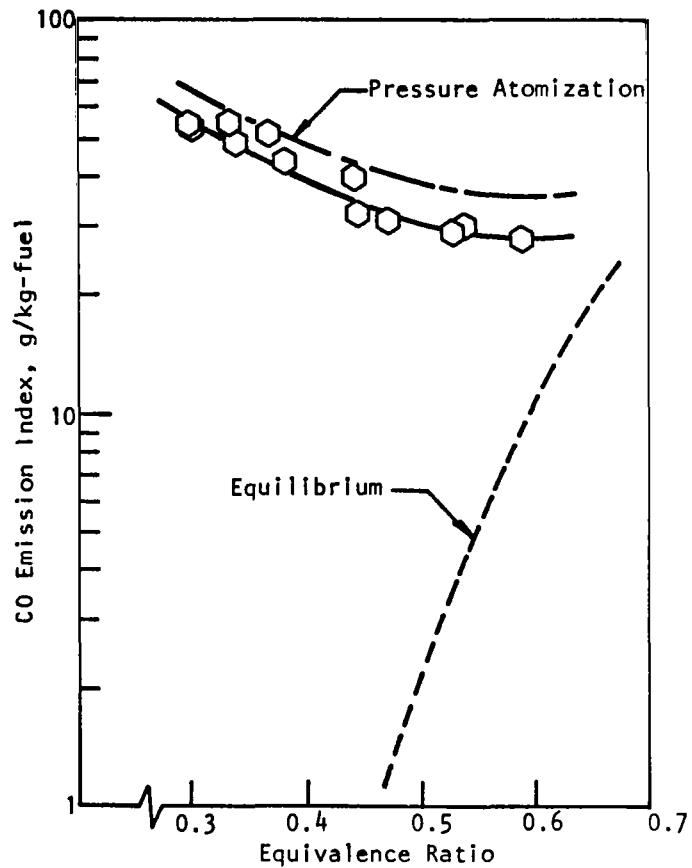


FIGURE 15d. CO EMISSION INDEX USING AN AIR ASSIST ATOMIZER

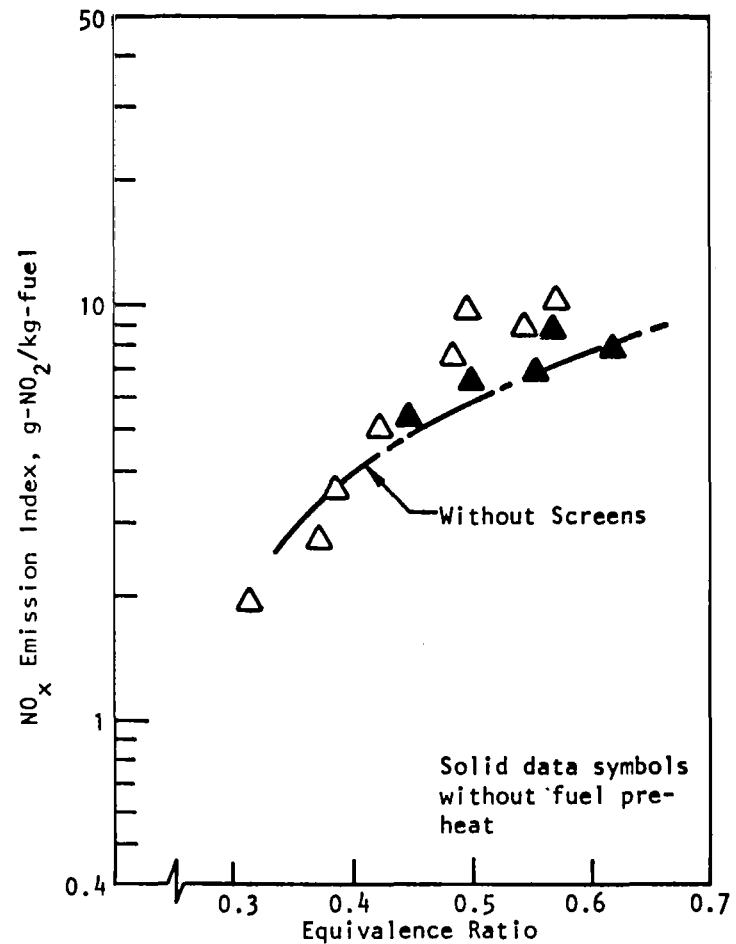


FIGURE 16a. EFFECT OF MIXER SCREENS ON NO_x EMISSION

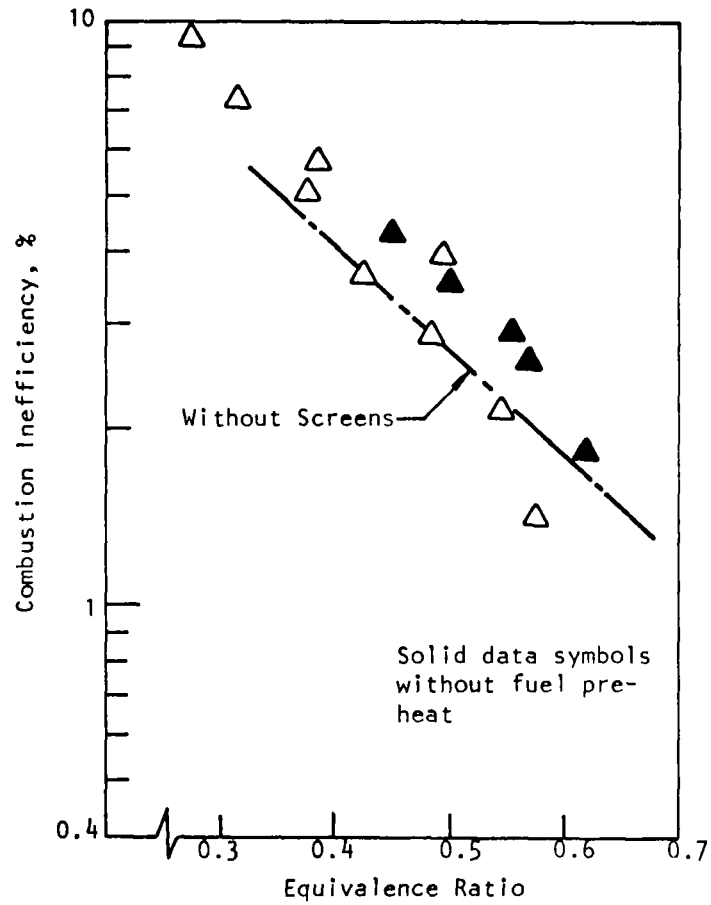


FIGURE 16b. EFFECT OF MIXER SCREENS ON COMBUSTION INEFFICIENCY

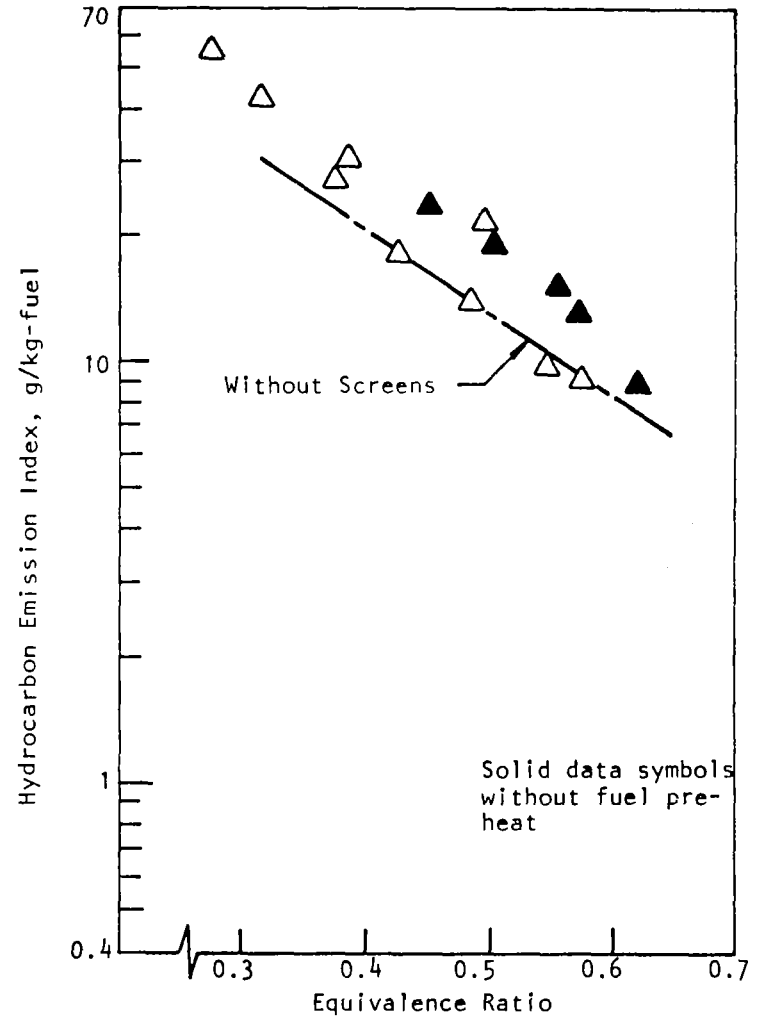


FIGURE 16c. EFFECT OF MIXER SCREENS ON HYDROCARBON EMISSION

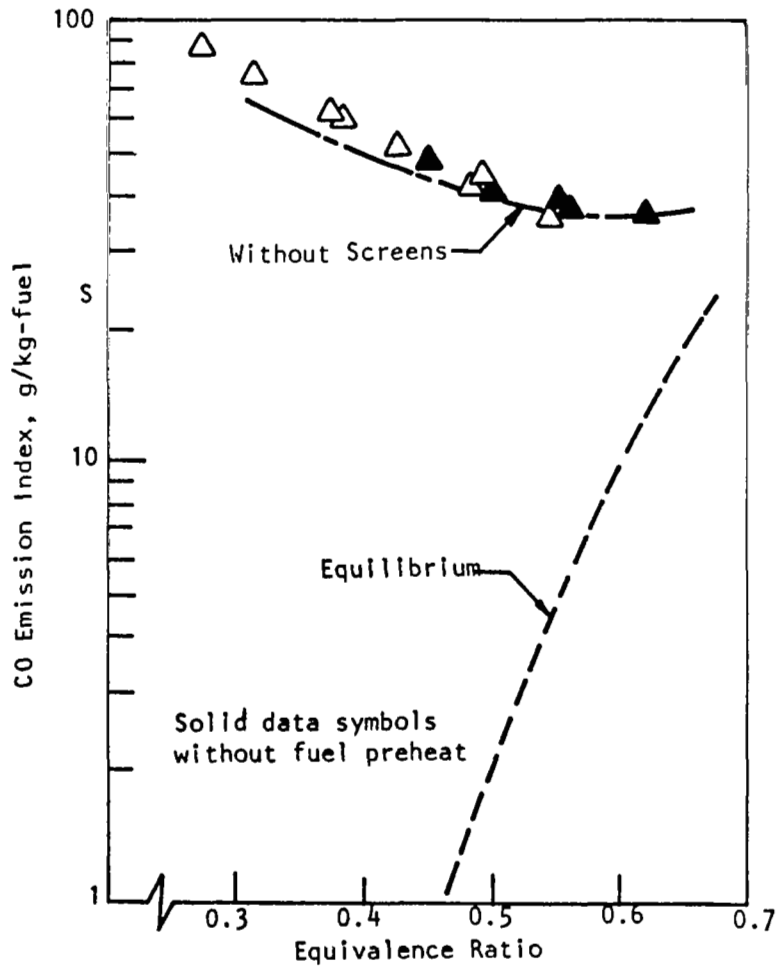


FIGURE 16d. EFFECT OF SCREENS ON CO EMISSION

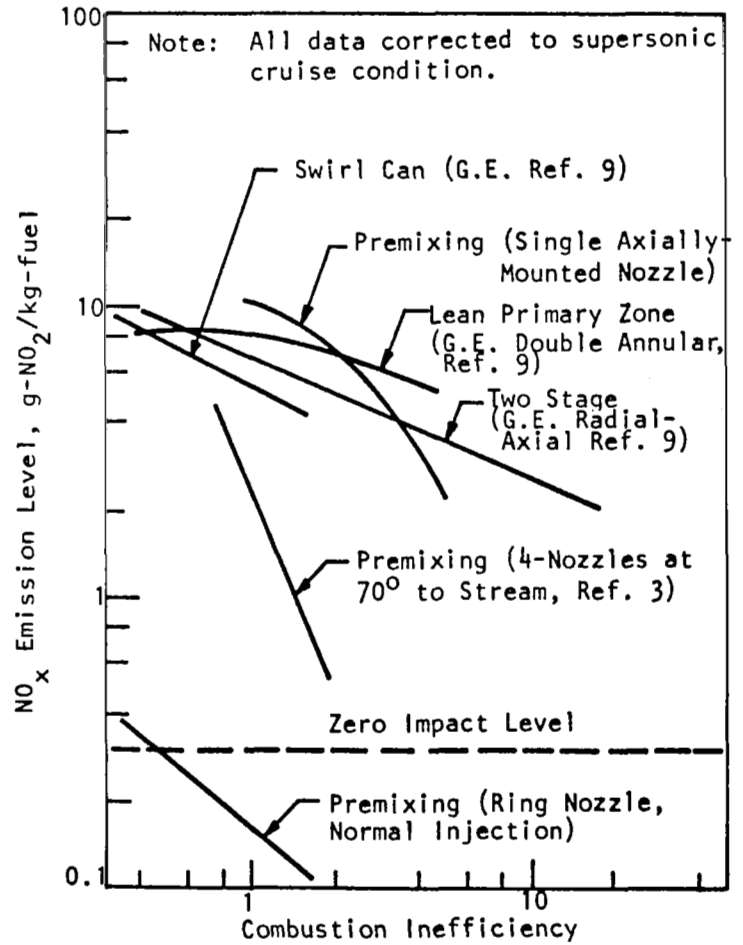


FIGURE 17. COMPARISON OF RESULTS FOR LOW NO_x COMBUSTORS

APPENDIX

DATA REDUCTION PROCEDURES

The gas analysis instrumentation provide raw data in the form of volume fractions of the particular gases being sampled. This raw data is converted into the more convenient form of emission index and equivalence ratio following the procedures detailed below.

Each of the gas analysis instruments must be calibrated in order to convert the instrument reading to the volume fraction of the particular gas being analyzed. In the case of the Beckman Model 402 hydrocarbon analyzer and the Beckman Model 315B CO analyzer, this calibration is accomplished by passing prepared mixtures of calibration gas through the instruments and establishing calibration curves. The hydrocarbon analyzer was calibrated using gas standards containing 50 ppm, 77 ppm and 275 ppm propane in nitrogen. The instrument output is proportional to the number of carbon atoms with hydrogen bonds. Thus pure hydrogen or pure carbon will produce no response and a given concentration of propane (C_3H_8) will produce three times the response of an equal concentration of methane (CH_4). The instrument responds to all C-H bonds. As a result, it measures the sum of both unoxidized hydrocarbon and partially oxidized hydrocarbon molecules. The instrument calibration curve is shown in Figure (18). The response is linear with hydrocarbon concentration, presented in units of ppmC, that is, the number of hydrogenated carbon atoms in parts per million.

Calibration of the Beckman Model 315B CO analyzer was accomplished using standard gases with 1010 ppm, 605 ppm, 305 ppm, 65 ppm and 35 ppm CO in nitrogen. As shown in Figure (19), the instrument has a linear response for low CO concentrations but becomes increasingly nonlinear as concentration increases. The instrument was used with a calibration curve throughout the program.

The Beckman Model 951 NO/NO_x analyzer and Model 864 CO₂ analyzer were both calibrated by actively diluting a standard gas with nitrogen using precision rotometers and a mixing tube in addition to using undiluted standards of varying concentrations. In the case of the CO₂ analyzer, this was done in order to obtain good coverage of the entire CO₂ scale. This coverage was required in order to properly adjust an internal linearizing circuit within the instrument. In the case of the NO_x analyzer, active dilution of a given standard gas provided a means of double checking the calibration gases against one another. This procedure was used to guard against inadvertent use of NO_x calibration gases which had decayed during storage, an occasional problem with NO_x standards.

The gases used for CO₂ calibration contained 10.2%, 5.0% and 2.0% CO₂ in nitrogen. The analyzer calibration curve is shown in Figure (20) and includes data points obtained by diluting the 10.2% CO₂ sample with nitrogen. The NO_x analyzer was calibrated using standards containing 252 ppm, 104 ppm and 97 ppm NO_x in nitrogen as well as by active dilution of the 252 ppm standard. The NO_x analyzer produces a slightly non-linear response as illustrated in Figure (21) and was used with a calibration curve throughout the program.

The gas analysis instruments were calibrated once each week using the entire set of standard gases. Zero gas and span gas were passed through all instruments immediately prior to each test and the instrument output recorded on the same data roll which was used for the subsequent test run.

Conversion of the molar concentrations (volume fractions) provided by the gas analysis instrumentation into the more convenient terms of emission index and equivalence ratio requires a prior knowledge of the ratio of carbon to hydrogen in the system. This is ascertained from a chemical analysis of the fuel used in the experiments. For the JP-5 fuel used here, the hydrogen to carbon ratio is 1.92 and the fuel/air ratio is given by Reference 5 to be

$$f/a = \frac{CO \times 10^{-4} + CO_2 + HC \times 10^{-4}}{183 - 1.79 \times 10^{-4} CO - 0.878 CO_2} \quad (1)$$

where CO and HC are the molar concentrations of carbon monoxide and unburned hydrocarbon in units of parts per million (ppm) and ppmC respectively and CO_2 is the volume fraction of carbon dioxide expressed as a percentage of total gas volume.

The equivalence ratio is defined as the ratio of the actual fuel/air ratio to the stoichiometric fuel/air ratio. For JP-5,

$$\phi = 14.9 (f/a) \quad (2)$$

The combustion efficiency for a system producing significant quantities of NO_x is

$$\eta_b = 1 - \frac{0.464 CO + 1.11 HC + 0.148 NO_x}{10^4 CO_2 + CO + HC}$$

where NO_x is the molar concentration of NO plus NO_2 in units of ppm. The numerator of the second term represents the potential heat release which could be obtained by further oxidation of CO to form CO_2 , hydrocarbons to form H_2O and CO_2 , and NO to form NO_2 . However, a certain level of CO is required by chemical equilibrium considerations, this level being well represented by the following curve fit (for an initial temperature of 833K and pressure of $4 \times 10^5 \text{ N/m}^2$):

$$CO_{eq} = 10^{[4.37 (\phi - 0.46) 0.75]} \quad (3)$$

Since the production of the equilibrium CO level does not imply combustor inefficiency, the definition of combustion efficiency is altered slightly so that a penalty accrues only from that portion of the total CO produced which exceeds the equilibrium value. Thus,

$$\eta_b = 1 - \frac{0.464 (CO - CO_{eq}) + 1.11 HC + 0.148 NO_x}{10^{-4} CO_2 + CO + HC} \quad (4)$$

Finally, the measured volume fractions CO, hydrocarbons and NO_x are converted into emission indices (grams of component per kilogram of fuel) using the following expressions:

$$E_{CO} = \frac{CO (1 + f/a)}{1035 f/a} \quad (5)$$

$$E_{HC} = \frac{HC (1 + f/a)}{2081 f/a} \quad (6)$$

$$E_{NO_x} = \frac{NO_x (1 + f/a)}{630 f/a} \quad (7)$$

In Equation (7), the molecular weight of NO_x is taken to be 46. This reflects the assumption that all NO produced eventually becomes NO₂. The emission index is thus based on the molecular weight of the NO₂ molecule.

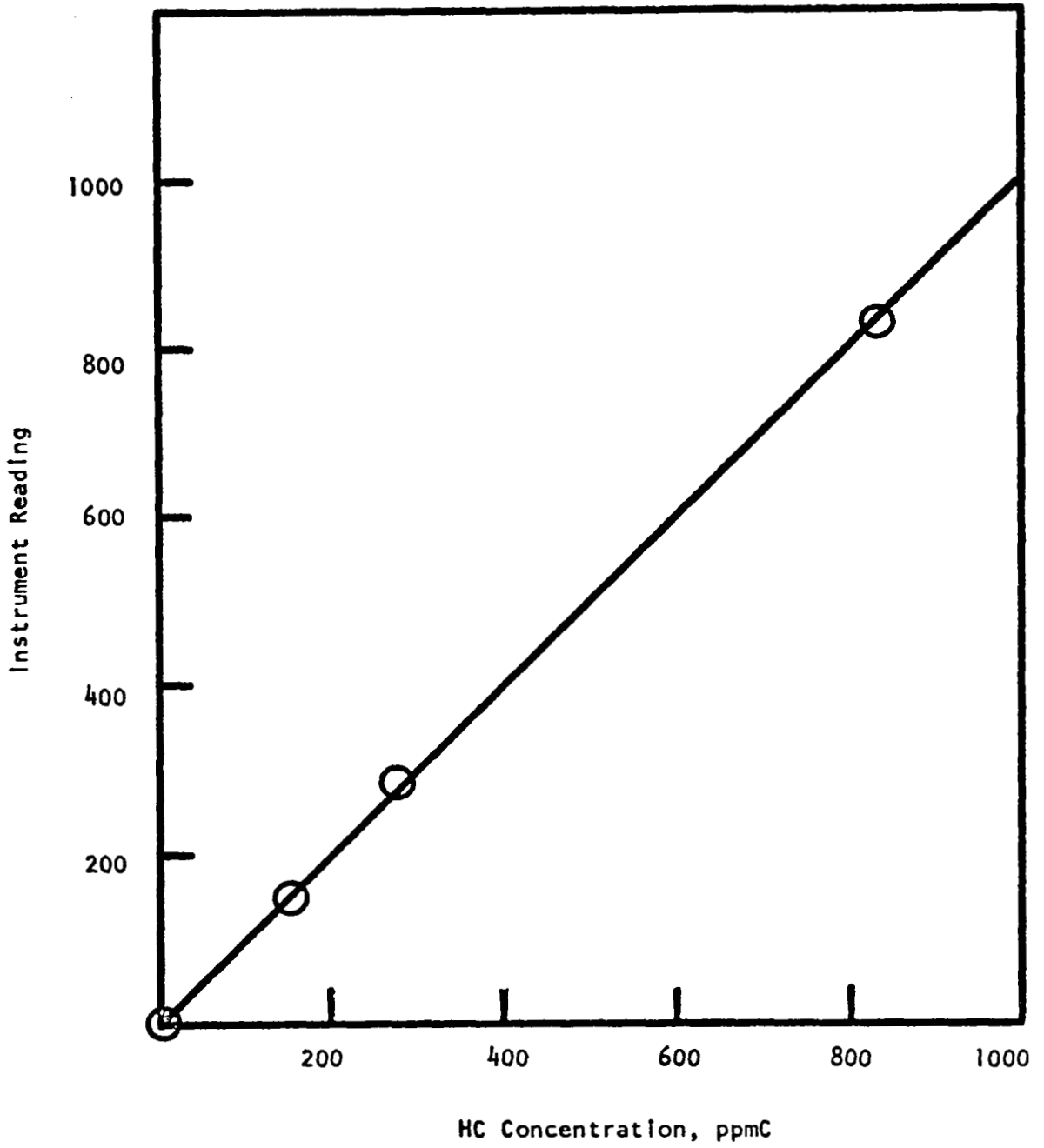


FIGURE 18. CALIBRATION OF BECKMAN MODEL 402 HYDROCARBON ANALYZER

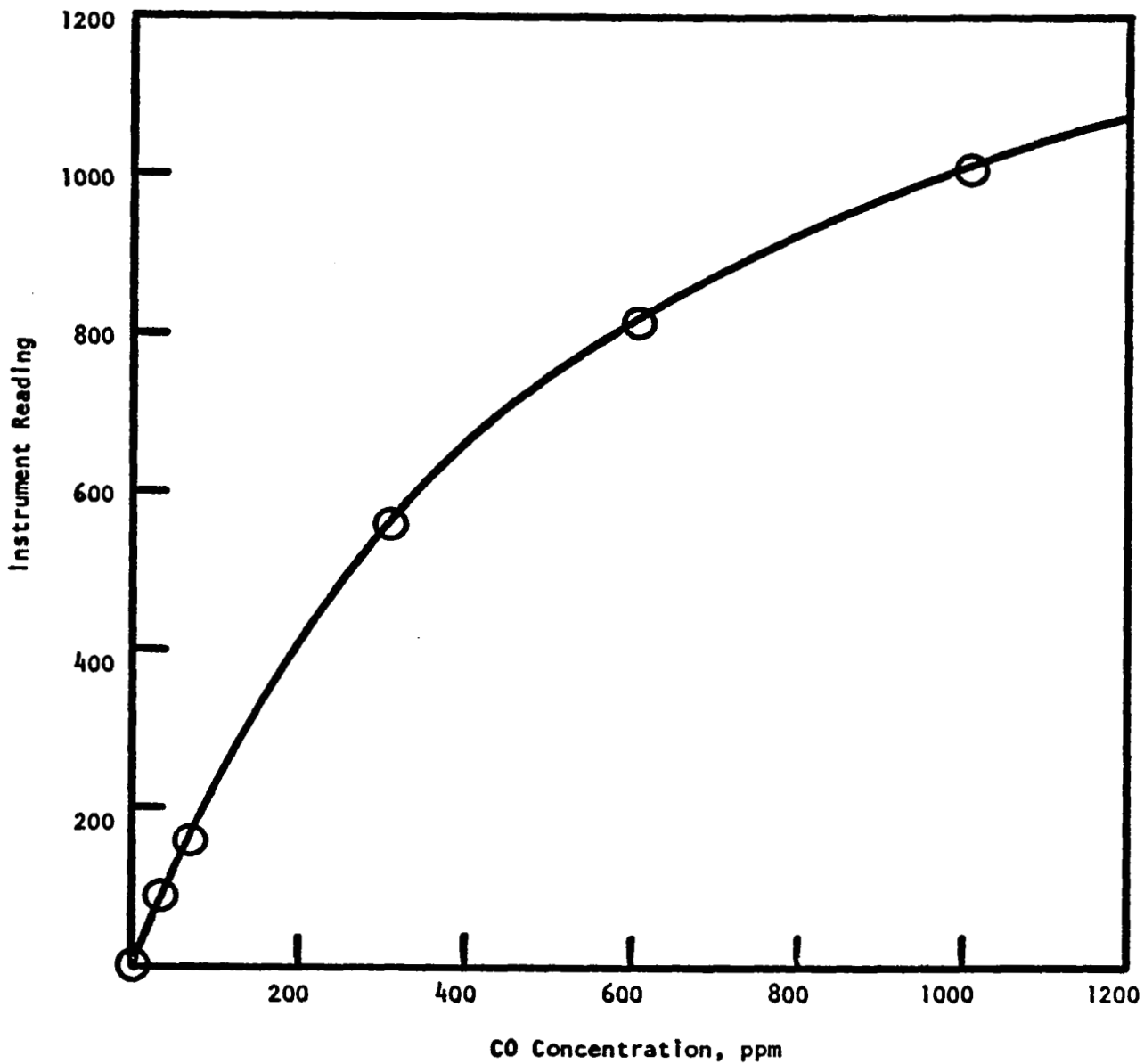


FIGURE 19. CALIBRATION OF BECKMAN 315B CO ANALYZER

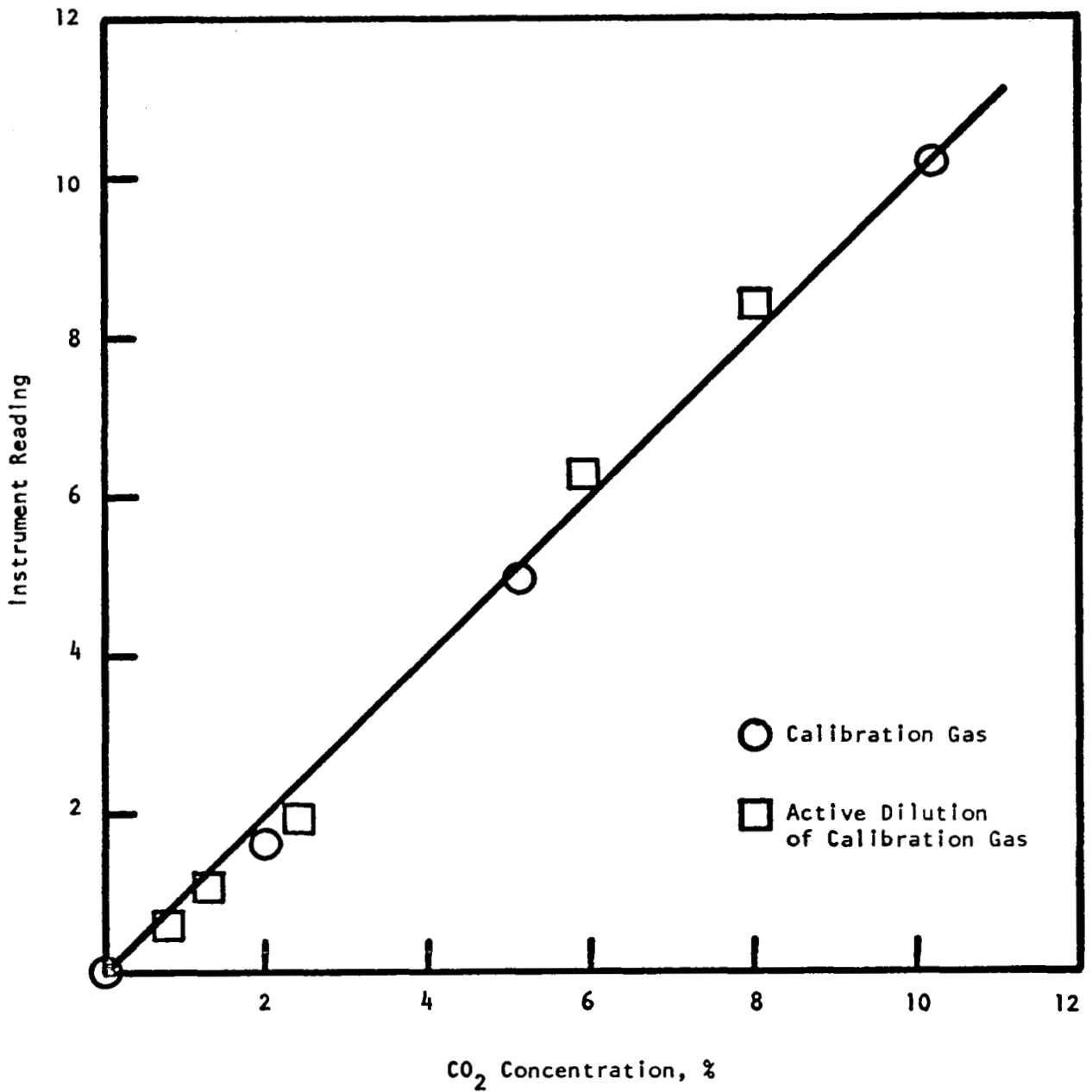


FIGURE 20. CALIBRATION OF BECKMAN MODEL 864 CO₂ ANALYZER

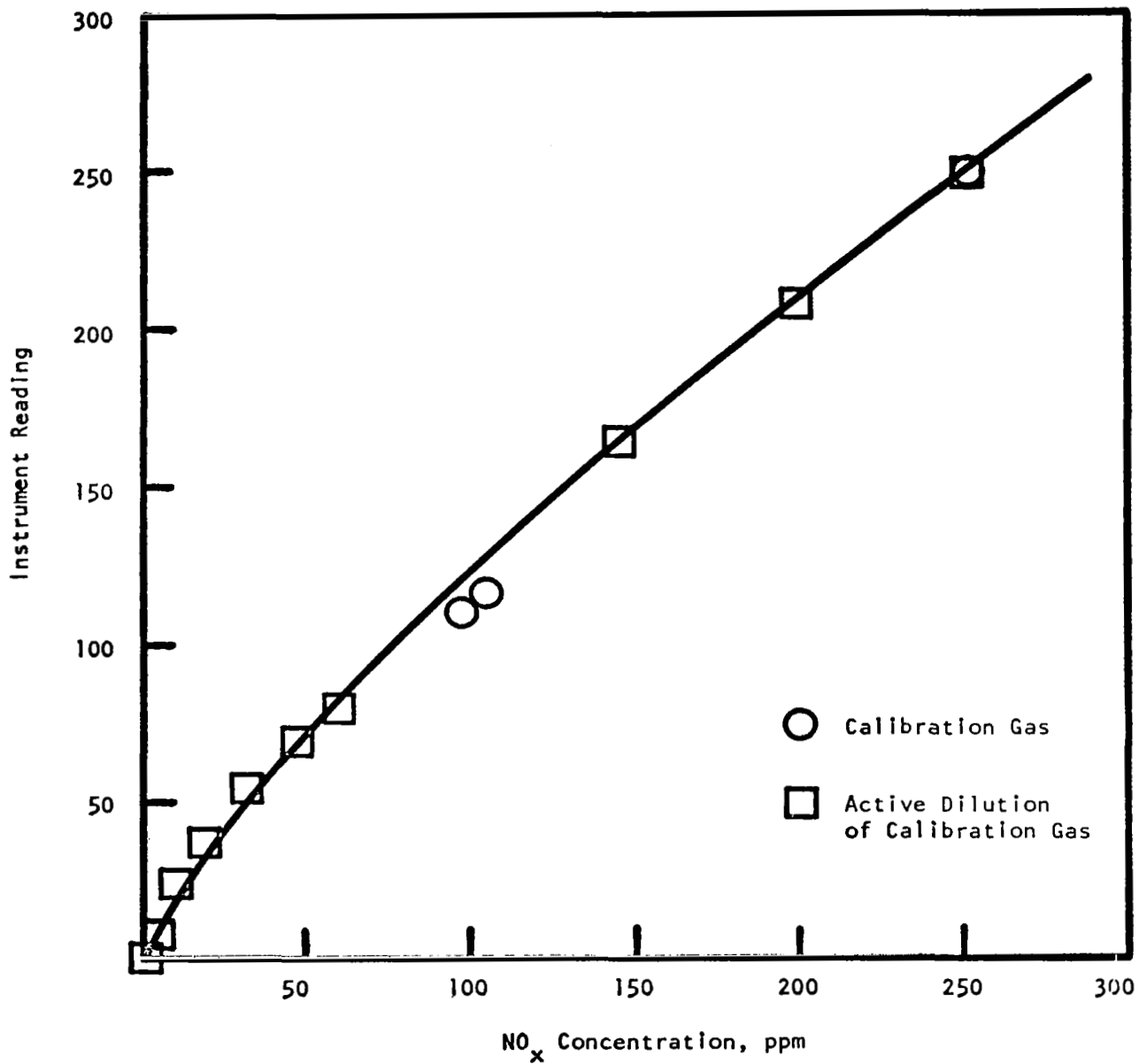


FIGURE 21. CALIBRATION OF BECKMAN MODEL 951 NO/NO_x ANALYZER

REFERENCES

1. Ferri, Antonio, "Better Marks on Pollution for the S.S.T.," *Aeronautics and Astronautics*, July 1972.
2. Ferri, Antonio and Roffe, Gerald, "Low NO_x Combustion Processes," 75th National Meeting, A.I.Che.E., June 1973.
3. Roffe, Gerald and Ferri, Antonio, "Prevaporization and Premixing to Obtain Low Oxides of Nitrogen in Gas Turbine Combustors," NASA CR-2495, March 1975.
4. Anderson, David, "Effect of Premixing on Nitric Oxide Formation," NASA TM X-68220, June 1973.
5. "Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines," Society of Automotive Engineers, ARP-1256, October 1971.
6. Chelko, Louis, "Penetration of Liquid Jets into a High Velocity Air-stream," NACA RM E50F21.
7. Ferri, A., "Reduction of NO Formation by Premixing," New York University School of Engineering and Science Report, NYU-AA-73-02, February 1973.
8. Ferri, A., "Possibilities and Goals for Future S.S.T.," (Dryden Lecture) AIAA Paper 75-254, AIAA 13th Aerospace Sciences Meeting, January 1975.
9. Bahr, D. W. and Gleason, C. C., "Experimental Clean Combustor Program - Phase I," NASA CR-134737, June 1975.
10. Niedzwiecki, Richard and Jones, Robert, "Parametric Test Results of a Swirl-Can Combustor," NASA TM X-68247, June 1973.