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USING RICH-LEAN TWO-STAGE COMBUSTION (NASA)
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SUMMARY

A flame tube was used in experimental parametric studies of two-stage, rich-lean combustion to evaluate techniques for minimizing the conversion of fuel-bound nitrogen to nitric oxides in a premixed, homogeneous combustion system. Air at 670 K and 0.48 MPa was premixed with fuel blends of propane, toluene, and pyridine, then burned at primary equivalence ratios of 0.5 to 2.0 and secondary equivalence ratios of 0.5 to 0.7. These fuel mixtures were proportioned to yield hydrogen compositions of 9.0 to 18.3 weight percent and fuel nitrogen compositions of zero to 1.5 weight percent. Two distillates of a coal syncrude produced by the SRC-II process also were tested for NO_x emissions and the results compared with the propane-toluene-pyridine data. In addition to oxides of nitrogen, the exhaust gas was sampled for carbon monoxide, carbon dioxide, unburned hydrocarbons, and smoke.

Rich-lean two-stage combustion was successful in reducing the conversion rate of fuel-bound nitrogen. Rates of less than 10 percent were observed for the optimum primary equivalence ratios, which ranged between 1.4 and 1.73 with a secondary equivalence ratio of 0.5.

Fuel hydrogen and nitrogen content both influenced the values at which the optimum primary equivalence ratio occurred. The amount of fuel-bound nitrogen also affected conversion rate, since the conversion rate dropped as fuel nitrogen content increased. Exhaust NO_x levels, however, still increased with additional fuel nitrogen.

INTRODUCTION

This report summarizes the results of flame tube experiments which investigated the effects of two-stage combustion operating conditions and fuel properties on nitric oxide emissions from fuels containing high levels of nitrogen.

Projected diminishing supplies of petroleum fuels has spurred growing interest in utilizing coal-derived fuels for utility and industrial gas turbine operation. Unfortunately, coal-derived fuels contain significantly larger amounts of chemically bonded fuel nitrogen than is found in petroleum fuels. Fuel nitrogen can be substantially reduced by hydro-treating the fuel, but this involves a large consumption of energy. Under normal combustion conditions as much as sixty to eighty percent of this nitrogen combines with oxygen to form nitrogen oxides (refs. 1 and 2), thereby increasing NO_x emissions. If stationary gas turbines are to be operated with minimally processed coal-derived fuels, while still meeting EPA emission limits, it appears necessary to evolve fundamental combustion concepts for minimizing fuel nitrogen to NO_x conversion.

One of the most promising approaches for reducing fuel nitrogen conversion has been to employ rich-lean two-stage combustion (refs. 3 to 5). Reduced oxygen availability in a rich primary zone limits the production of NO while the fuel nitrogen reacts to form N_2 and other nitrogen compounds. When followed by a rapid introduction of additional air in a lean zone where combustion is completed, NO_x formation is substantially reduced since the nitrogen compounds formed in the primary zone are less reactive than fuel nitrogen and its intermediates, and thermal NO_x is held down in the secondary zone by lowered combustion temperatures. The subject study was conceived to extend current knowledge of rich-lean combustion by studying the relationship between fuel properties, combustion conditions, and exhaust emissions, with emphasis on high-nitrogen content fuels.

To achieve two-stage combustion a flame tube with secondary air injection capability was fabricated. Fuel blends of propane, toluene, and pyridine were blended to provide a range of fuel carbon, hydrogen, and nitrogen values encompassing typical coal syncrude properties. Two distillates of a coal syncrude produced by the SRC-II process (ref. 5) were also tested and the results compared to those yielded by the fuel blends. Primary and secondary equivalence ratios were varied, as were primary zone volume (primary residence time) and secondary residence time. Combustion air inlet temperature and pressure were maintained at 672 K (750° F) and 0.48 MPa (70 psia), respectively. The exhaust gas was sampled for emissions of nitrogen oxides, carbon monoxide, carbon dioxide, unburned hydrocarbons, and at a few points, exhaust smoke number. Combustion efficiencies were calculated from the carbon monoxide and unburned hydrocarbon measurements, and the percentage of fuel nitrogen to NO_x conversion was computed from NO_x measurements and known fuel nitrogen content.

APPARATUS AND PROCEDURE

Test Rig

The flame tube is shown schematically in figure 1 and pictured in figure 2. In operation, air indirectly heated to 672 K (750° F) first passed through a 10.2-cm (4-in.) diameter inlet instrumentation section, where inlet pressure and temperature were measured. Immediately downstream of this section was the propane injector, which is shown in figure 3. Propane was fed into 19 chambers by a network of supply tubes, with each chamber being supplied by a 0.254 by 0.064 cm tube and a 0.318 by 0.046 cm tube. Only the smaller tubes were fueled at the lower propane flow rates, while all of the supply tubes were used at the higher propane flow rates.

The toluene, pyridine, and coal syncrudes were sprayed into the flow through a special assembly just downstream of the propane injector. Four pressure atomizing spray nozzles, spaced at 90° intervals and retracted out of the path of flow except during use, were used to cover the desired liquid-fuel flow range.

Downstream of the liquid-fuel injection section was a 1.8-m (6-ft) length of 10.2-cm (4-in.) pipe where the fuel mixed and vaporized with the air. The mixture then entered the water-cooled perforated plate flameholder (fig. 4), which provided about 10 percent open flow area. Primary combustion occurred downstream of the flameholder in a 10.2-cm (4-in.) diameter water- and air-cooled pipe section; three sections of 15.24, 24.76, and 35.56 cm (6, 9-3/4, 14 in.) lengths were evaluated in this program to investigate the effects of primary residence time.

A 10.2- by 20.4-cm (4- by 8-in.) transition section and a 20.4-cm (8-in.) secondary section, both water and air-cooled, were located downstream of the primary section. Secondary air was injected at a temperature and pressure essentially equal to the inlet conditions through 4, 8, 12, or 16 ports symmetrically spaced around the circumference of the front portion of the secondary section. The number of ports used varied according to secondary air flow rate to promote good mixing and jet penetration. Figure 5 is a picture showing the primary, transition, and secondary sections before the installation of air-cooling shrouds and insulating material.

A tertiary or dilution section was not simulated. Downstream of the secondary section, the exhaust gases were cooled by a water spray quench section, passed through a back-pressure valve used to control rig pressure, and finally exhausted into the atmosphere through an afterburner designed to burn any remaining fuel. A view of the back-pressure valve and afterburner can be found in figure 6.

Fuel System

Because of the toxicity of the liquid fuels used, particular care was taken in the design and operation of the research fuel system. The pyridine and toluene were pumped and metered separately from 55 gallon drums, which were enclosed in special containment drums. These are pictured in figure 7. Fluidyne flowmeters with wide flow range and low flow rate capability were used to monitor the liquid-fuel flow rates. The toluene side of the fuel system was also used for the SRC-II fuel.

Downstream of the Fluidyne meters, the toluene and pyridine flows were merged into a single line for mixing and piped to the fuel-injection section of the rig. Just upstream of the injection point was a fuel sampling system (fig. 8). This system was capable of obtaining up to five samples, which could be analyzed to verify that the fuel blends entering the test rig matched the required mixtures. Additional samples were taken directly from the fuel barrels and analyzed to determine the composition of the toluene, pyridine, and SRC-II syncrude.

INSTRUMENTATION AND DATA ACQUISITION

Total and secondary airflow rates were measured with standard ASME orifices. Inlet-temperature and staticand total-pressure probes were positioned upstream of the fuel-injection sections. Additional thermocouples were placed in the flow just upstream of the flameholder to record fuel-air mixture temperature and occurrences of flashback. Thermocouples were also located on the inner and outer surfaces of the primary and secondary combustion, and quench sections. A static-pressure tap was situated in the secondary combustion section to record rig pressure losses.

Propane flow rates were measured with standard ASME orifices; propane temperature and pressure were recorded at the orifice and at the propane injector. The liquid-fuel temperatures and pressures were measured at the flowmeters and at the liquid-fuel injector.

The exhaust emissions were collected by the water-cooled probe pictured in figure 9. Samples were drawn through four sets of four holes spaced 90° apart and located on centers of equal area. The probe was mounted on a positioning mechanism (fig. 10) capable of axial and rotational movement. This device allowed the probe to be moved to different axial points in the secondary combustion section, thereby varying secondary residence time. Circumferential traverses examining exhaust emission profiles were also obtained by rotating the probe.

The emissions were analyzed for nitric oxide concentrations by a thermo-electron chemiluminescent instrument, and for unburned hydrocarbons by a Beckman flame ionization detector. Beckman nondispersive infrared analyzers used to measure carbon monoxide and carbon dioxide concentrations. A smoke sampling console meeting SAE requirements was used to collect soot particles for determination of smoke numbers.

On-line data analysis was performed by a PDP-11 minicomputer, allowing instrument readings and calculated combustion information to be monitored in the control room. Final data reduction was done by a more sophisticated computer program on an IBM 360 system.

TEST CONDITIONS

A large number of combustion conditions and fuel properties was investigated. Inlet air was maintained at 0.258 kg/sec (0.57 lb/sec) at a temperature and pressure of 672 K (750° F) and 0.48 MPa (70 psia). Primary equivalence ratio was varied from 0.5 to 2.0; secondary equivalence ratios ranged from 0.5 to 0.7. Primary zone volumes (primary and transition section) of 4359, 5145, and 6030 cm^3 (266, 314, and 368 in^3) were tested, resulting in primary residence times of 10 to 14 msecs. Secondary-zone residence times of 1 to 5 msecs., measured from the secondary air holes' centerline, were examined; secondary-air injection hole patterns of 4, 8, 12, and 16 holes were used for different secondary airflow rates.

Fuel blends of propane, toluene, and pyridine resulted in fuel hydrogen compositions of 9.0 to 18.3 weight percent, and fuel nitrogen was varied from zero to 1.5 weight percent. SRC-II naptha and SRC-II middle-heavy distillate blend syncrudes were also used. Fuel properties are listed in table I.

RESULTS AND DISCUSSION

Initial Investigations

Initial experiments were designed to checkout rig operation and narrow the range of testing through selection of an optimum secondary equivalence ratio and secondary residence time. These values, which would be used for the remainder of the fuel blend tests, were chosen by noting the secondary-zone conditions at which minimum NO_x was obtained with acceptable combustion efficiencies.

Propane tests. - Initially, investigations were carried out using propane as the fuel. Some typical NO_x emissions for lean and rich primary conditions, corrected to 15 percent oxygen in the exhaust, are shown in figure 11. The primary zone volume was 6030 cm^3 (368 in^3) for these results, while the secondary equivalence ratio and residence time were 0.5 and 2 msec, respectively. Figure 11(a) shows that for lean primary equivalence ratios NO_x steadily increased with equivalence ratio as more thermal NO_x was generated by the increase in combustion temperature. This is typical of lean combustion results reported by others (refs. 7 to 9). On the rich side of stoichiometric, a minimum in the NO_x curve occurs at approximately a primary equivalence ratio of 1.4, then the NO_x increases again with equivalence ratio as shown in Figure 11(b). The NO_x minimum is apparently due to decreased NO_x formation as greater percentages of fuel nitrogen are converted to HCN and NH_3 as the primary-zone mixture becomes richer. The turnaround and upward swing of the curve above 1.4 can be explained by greatly increased formation of NO_x intermediates such as hydrogen cyanide and ammonia in the primary zone, which are subsequently converted to NO_x in the secondary zone (ref. 9).

Secondary zone tests. - Once the rig was checked out with propane, experimentation was undertaken to define optimum secondary-zone operating conditions. In these tests a blended fuel mixture of propane and toluene was burned at a primary equivalence ratio of 1.5 and secondary equivalence ratios between 0.4 and 0.7. Secondary residence times were varied between 2 and 5 msec. The tests were conducted at a fuel hydrogen content representing the median value of the liquid-fuel blends, which was 11.3 percent hydrogen. The medium-sized primary section was used, giving a primary zone volume of 5145 cm^3 (314 in^3). Combustion efficiencies and NO_x emissions were measured and are shown in figure 12.

Combustion efficiency and NO_x emissions both increased with increasing secondary residence times, as one would expect. Nitrogen oxides emissions also increased with secondary equivalence ratio (as shown in fig. 12(a)), but corresponding combustion efficiency (fig. 12(b)) decreased. The increased NO_x emissions at higher equivalence ratios were expected, because the increase is probably largely due to thermal NO_x produced by the well-known extended Zeldovich reactions. The drop in efficiency as the secondary becomes richer is a function of increased carbon monoxide formation. The effect of carbon dioxide dissociation, which results in increased carbon monoxide due to increased combustion temperature and not combustion inefficiency, has been accounted for in these efficiency calculations. Thus the decrease in efficiency was apparently a consequence of dilution effects, reaction kinetics, and mixing effectiveness. Much of this efficiency loss could be recovered if a tertiary zone were present as is the case in actual combustor hardware. On the basis of these data, it was decided to operate the secondary zone at an equivalence ratio of 0.5 and measure the exhaust gas emissions at 2 msec residence time. At these conditions efficiency is well above 99 percent while NO_x emissions are still relatively low.

Secondary air injection. - A parametric survey was undertaken to determine the best secondary-air injection-hole patterns for different secondary airflow rates. Secondary-zone conditions were the optimum values described previously. The primary determinants for best hole-pattern selection were, as before, minimum NO_x at acceptable combustion efficiency. The results indicated that 16 holes were optimum for primary equivalence ratios of 2.0 and above, while 12 holes proved best for rich primary equivalence ratios below 2.0. Four holes were used for all lean primary equivalence ratios.

Primary volume. - Additional investigations were carried out using all three primary sections to determine the effect of primary-zone volume, and thus primary residence time, on NO_x emissions. Fuel blends containing 9.0 and 11.3 percent hydrogen were used in the tests, while the secondary conditions were maintained at the previously described optimum values. The measured NO_x emissions for the three primary zones operating at rich equivalence ratios are presented in figure 13. It can be seen that the smallest primary produced significantly higher levels of NO_x than the other two. Because the smallest primary was relatively short, its observed high NO_x emissions may have been caused by secondary air penetrating into the primary zone and leaning out this section. The short primary may not have been long enough to allow the development of a uniform pressure profile across the exit plane upstream of the transition section. The resulting pressure gradients could permit secondary-air penetration into the primary zone, thus lowering the primary equivalence ratio to higher NO_x-producing values. Considerable combustion instability was also encountered with this primary, which probably was an indication of a non-uniform pressure profile at the exit. In light of the high NO_x emissions and stability problems, it was decided to exclude the smallest primary section from any further evaluation.

Blended Fuel Nitrogen Tests

Fuel blends of propane, toluene, and pyridine were used to simulate syncrudes of various hydrogen, carbon, and nitrogen contents. Secondary-zone equivalence ratio and residence time were held at 0.5 and 2 msec, respectively, and the two larger primary zone volumes, 6030 cm^3 and 5145 cm^3, were evaluated. The NO_x emissions were all corrected to the 15 percent oxygen in exhaust standard.

Emissions of NO_x for different fuel nitrogen levels are shown in figure 14 for lean primary equivalence ratios, and in figure 15 for rich primary conditions. These data were obtained for the largest primary section (6030 cm^3), and at the fuel hydrogen contents listed in the figures. A comparison of the two figures verifies the effectiveness of rich-lean staged combustion in reducing NO_x emissions; lean combustion (figs. 14(a) and (b)) resulted in much higher NO_x levels than did the rich-lean combustion shown in figure 15. Also apparent are points of minimum NO_x on the rich primary curves; similar results have been reported by other investigators (refs. 3 to 5 and 10).

Figure 15 indicates that the optimum primary equivalence ratio of minimum total NO_x shifted to lower values as the amount of nitrogen in the fuel increased. It can also be noted that the curves tend to become closer-spaced as fuel nitrogen increases, indicating that a smaller percentage of the fuel nitrogen was converted to NO_x as its concentration increased. This phenomena has been observed in other investigations (refs. 11 and 12), and has been explained as the inhibition of the thermal NO_x production by the fuel NO_x (ref. 13). The fuel nitrogen conversion rates for the data in figures 14 and 15 are given in figures 16 and 17. These conversion rates have been calculated by subtracting the thermal NO_x (bottom curve) from the other NO_x curves (in ppmm), multiplying this difference by the percentage of nitrogen in the NO_x, and then dividing by the amount of fuel nitrogen each curve represents (in ppmm of the total air and fuel flows). Values of fuel bound nitrogen conversion under 10 percent are achievable for the optimum rich primary conditions.

Further examination of the results also reveals that the optimum primary equivalence ratio shifts slightly as the hydrogen content of the fuel changes. Figure 18, for example, shows this relationship for the case of the largest primary. The optimum primary equivalence ratio drops from about 1.72 at 9 percent hydrogen to 1.4 at 18.3 percent hydrogen for no fuel nitrogen, and shows similar trends for the cases with fuel nitrogen.

The effect of using two different primary zone volumes is illustrated in figure 19, where the fuel hydrogen content was 9.0 percent. The lower end of the volume range represents primary residence times of roughly 12 msec, and the upper volume corresponds to residence times of about 14 msec, exact values depending on the the primary equivalence ratio. As can be seen in the figure, NO_x increased with volume for all fuel nitrogen levels. This figure is consistant with data at primary equivalence ratios of 1.5 and 1.7 as well. Since this is not easily explained by chemical considerations, it probably was the result of hardware dissimilarities. It was likely, for example, that the cooling heat removal was not exactly the same for all primary sections, which could effect the temperatures and reaction chemistry in the primary zones.

SRC-II Tests

Two different coal syncrude fuels were tested in this program, a naphtha and a 2.9:1 blend of middle and heavy distillates. Both fuel oils came from the SRC-II process (ref. 6) using Powhatan no. 5 mine coal. Some of the more important properties of these two fuels are listed in table I.

Preliminary tests indicated that a secondary equivalence ratio of 0.5 was again very close to optimum in terms of minimum NO_x production, so data were obtained for this condition. This also allowed direct comparison with results from the propane-toluene-pyridine tests.

The medium primary zone volume (5145 cm^3) was used in the naphtha test, while the secondary residence time was 1 msec. The shorter secondary residence time was the result of problems in maintaining constant pressure in the secondary zone, which were brought about by continual plugging of the flameholder by the naphtha. It appears possible to eliminate this problem by modifications to the fuel injectors, mixing section, and flameholder.

The naphtha data shown in figure 20 indicate that minimum NO_x is generated between primary equivalence ratios of 1.6 and 1.8. Since the combustion efficiency dropped as the equivalence ratio increased in this region, from about 99.5 percent to 98.5 percent, the optimum primary equivalence ratio is approximately 1.6. Using the hydrogen and nitrogen content of the naphtha to select a predicted optimum primary equivalence ratio from the simulated syncrude data in figure 19 would give the same result, about 1.6.

The middle-heavy distillate was burned in the largest primary using a secondary residence time of 2 msec, and can be compared directly with the blended fuels data. One such comparison is made in figure 21, where NO_x emissions for the middle-heavy distillate blend are plotted along with the corresponding curve of simulated syncrude data. Agreement between the two sets of data is quite good.

The agreement between the fuel blends data and the SRC-II results seems to indicate that toluene and pyridine effectively simulated the combustion properties of the SRC-II fuels. Because of molecular dissimilarities in fuel nitrogen bonding, however, the propane-toluene-pyridine results may not be applicable to all synfuels.

Smoke Samples

A limited number of smoke samples was taken for rich primary conditions while burning propane-toluene pyridine blends and the SRC-II synfuel. The resulting smoke numbers were relatively high, indicating a possible smoke problem at those primary equivalence ratios that were most effective in reducing fuel nitrogen conversion. A compromise between operating conditions that minimize NO_x and those that alleviate smoke may be required for controlling emissions when burning coal syncrudes. Sufficient data were not obtained in these tests to identify these tradeoffs.

Results Versus EPA Standards

The EPA (Environmental Protection Agency) regulations for stationary gas turbines, larger than 10.7 GJ/hr power input (1100 hp out), limit NO_x emissions to 75 ppm in metropolitan areas for fuels devoid of fuel-bound nitrogen and a cyclic efficiency under 25 percent. This limit is increased for various levels of fuel nitrogen up to a maximum of 125 ppm for fuels containing more than 0.25 percent nitrogen. In nonmetropolitan areas these limits are 150 ppm and 200 ppm, respectively. Small engines and many special-class intermittent-duty engines have no NO_x standard. Table II shows the effect of cyclic efficiency on NO_x values. A comparison of the fuel blends NO_x data obtained in this investigation with the regulations, using the lowest emissions from both the medium and large primary sections, results in a set of fuel hydrogen and nitrogen values for which the NO_x emissions were under both the EPA metropolitan and nonmetropolitan limits. These are shown in figure 22. For the range of fuel properties tested, only the blends with very low hydrogen content and more than 1 percent fuel nitrogen failed to meet the metropolitan area standards. Since these results have been acquired in a flame tube, they are only indicative of what can be attained in an actual gas turbine. Actual application of this technology in engine combustor hardware may involve additional tradeoffs to satisfy durability, size, and performance requirements.

The SRC-II data follow the same pattern. The middle-heavy distillate, which contained close to 1 percent fuel nitrogen and only 8.6 percent hydrogen, yielded NO_x emissions from combustion that exceeded the EPA metropolitan area standards by approximately 20 ppm if one uses 25 percent cyclic efficiency. The naphtha data meet the standards, though the secondary residence time was only 1 millisecond; its nitrogen and hydrogen contents fall within the boundaries of fuel properties that met the EPA regulations. Some additional hardware modifications may be necessary to bring the emissions from fuels such as the SRC-II middle-heavy distillate down to acceptable levels.

SUMMARY OF RESULTS

A flametube was used in experimental two-stage, rich-lean parametric combustion studies to evaluate techniques for minimizing the conversion of fuel-bound nitrogen to nitric oxides in a premixed, homogeneous combustion system. Air at 670 K and 0.48 MPa was premixed with fuel blends of propane, toluene, and pyridine and burned at primary equivalence ratios of 0.5 and 2.0 and secondary equivalence ratios ranging from 0.5 to 0.7. These blended fuels were proportioned to vary hydrogen composition from 9.0 to 18.3 percent and fuel nitrogen composition from 0 to 1.5 weight percent. Distillates of a coal syncrude produced by the SRC-II process were also tested for NO_x emissions, and the results were compared to the data obtained with the propane-toluene-pyridine fuel blends. In addition to oxides of nitrogen, the exhaust gas was sampled for carbon monoxide, carbon dioxide, unburned hydrocarbons, and smoke. The major results of the investigation are the following:

1. Rich-lean two stage combustion successfully reduces fuel-bound nitrogen to NO_x conversion. Conversion rates of less than 10 percent (with a minimum of six percent) are easily achieved at the optimum primary conditions for 0.5 to 1.5 percent fuel nitrogen content.

2. The optimum primary equivalence ratios ranged between 1.4 and 1.7, and the optimum secondary equivalence ratio for these tests was about 0.5. These values resulted in minimum NO_x production at acceptable combustion efficiencies of 99 percent or more.

3. Fuel hydrogen content had some effect on the optimum primary equivalence ratio. Decreased hydrogen content shifted the optimum primary operating conditions to richer values.

4. Increased fuel nitrogen levels reduced the percentage of fuel nitrogen to NO_x conversion. Exhaust NO_x levels, however, always increased with additional fuel nitrogen. Increased fuel nitrogen content also tended to shift the optimum primary equivalence ratio downward.

5. Emissions of NO_x from SRC-II naphtha and middle-heavy distillate liquid-synfuels combustion matched those from the fuel blends used to simulate syncrudes very well. Thus the fuel blend data should be useful in choosing operating conditions for two-stage syncrude combustion when these SRC-II fuels are to be burned. The fuel blend data, however, may not simulate other synfuels.

6. A few smoke samples were obtained that resulted in relatively high smoke numbers, even at the relatively low pressures tested. Additional tests at the higher pressures normally found in ground-based gas-turbine combustors will be needed to develop techniques for reducing smoke while maintaining low NO_x emissions using rich-lean combustion.

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TABLE I. - FUEL PROPERTIES

	Propane	Toluene	Pyridine	SRC II Naphtha	SRC II Middle-heavy distillates
Specific gravity, 15.5 °/15.5° C (60°/60°F)	[a]1.56	0.8719	0.986	0.8324	0.9997
Boiling range, °C (°F)	-42 (-43)	111 (231)	114 - 117 (237 - 243)	60 - 216 (140 - 420)	170 - 400 (340 - 750)
Flash point, °C (°F)	-104 (-156)	4 (40)	20 (68)	32 (90)	71 (160)
Pour point, °C (°F)	-	-	-	-70 (-94)	-55 (-67)
Lower heating value, kJ/kg (Btu/lb) Viscosity[b] at 37.8° C (100° F)	46 125 (19 868) 0.3x10^{-3}Pa sec	40 451 (17 424) 0.55x10^{-6} m^2/sec	33 447 (144 407) 0.89x10^{-6} m^2/sec	39 692 (17 087) 0.8 - 14.0x$10^{-6}$$m^2$/sec	37 782 (16 274) 4.53x$10^{-6}$$m^2$/sec
Aromatics, vol. %	0	100	100	37.11	84.31
Smoke point	-	6	29	13.93	4.98
Carbon, wt %	81.46	91.25	75.41	83.36	86.21
Hydrogen, wt %	18.24	8.75	6.40	11.64	8.64
Nitrogen, wt %	-	-	17.59	0.4	0.95
Sulfur, wt %	-	-	-	0.6	0.21
Oxygen, wt %	0.04	-	0.6	4.0	3.99
Argon, wt %	0.26	-	-	-	-

[a] Referenced to air at 20° C.
[b] To convert m^2/sec to cs multiply by 10^6; to convert Pa sec to cp multiply by 10^3.

TABLE II. - EPA NO_x EMISSION STANDARDS WITH 15 PERCENT OXYGEN IN EXHAUST AS A FUNCTION OF CYCLIC EFFICIENCY

Cyclic efficiency, %	Metropolitan area		Non-metropolitan area	
	Maximum without FBN	Maximum with FBN[a]	Maximum without FBN	Maximum with FBN[a]
25	75 ppm	125 ppm	150 ppm	200 ppm
30	90	140	180	230
35	105	155	210	260
40	120	170	240	290
45	135	185	270	320

[a] Assumes Fuel Bound Nitrogen (FBN) content equals or exceeds 0.25 percent.

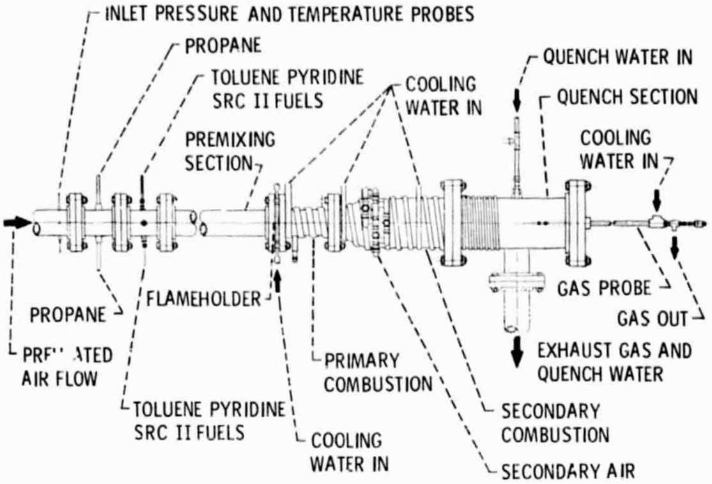

Figure 1. - Flame tube rig.

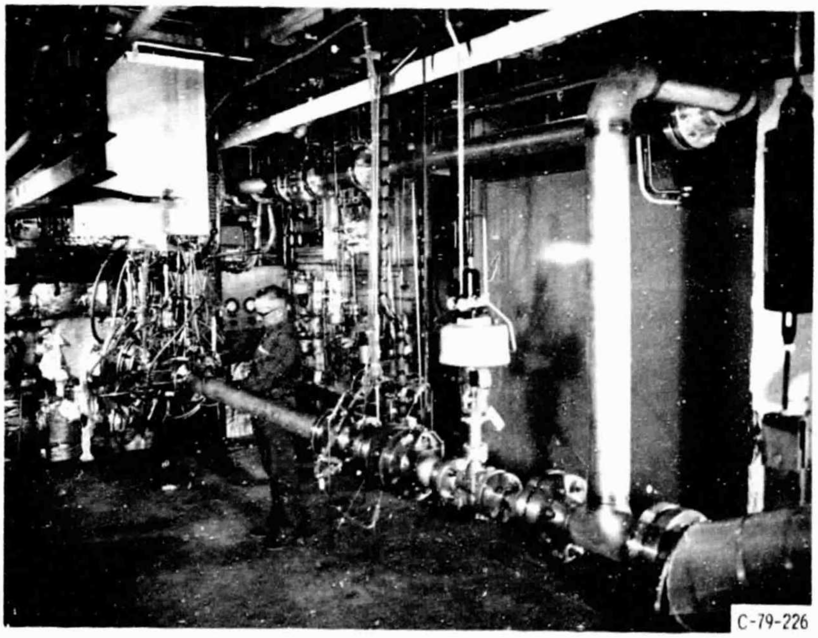

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Figure 2. - Flame tube rig installation.

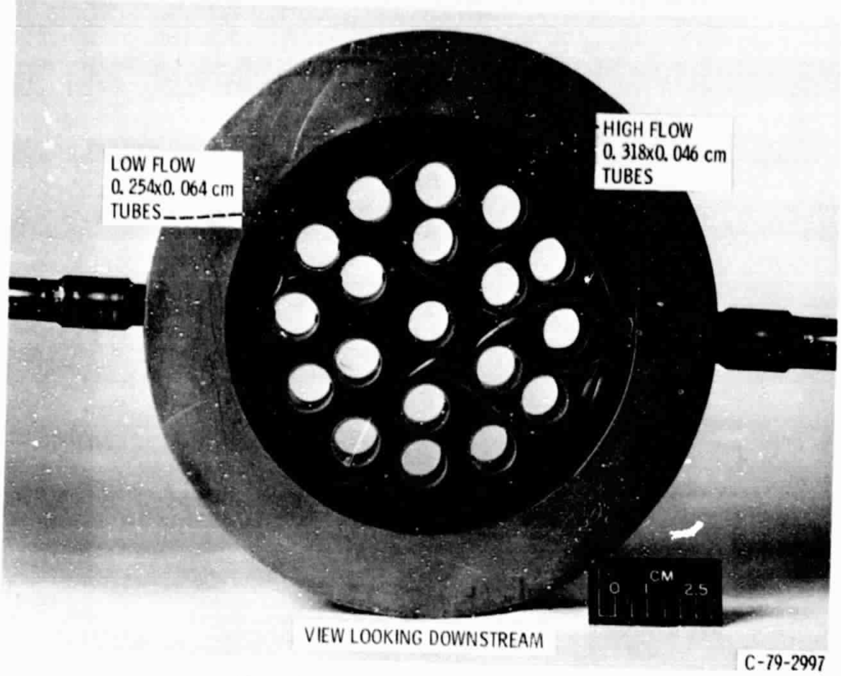

Figure 3. - Gaseous propane fuel injector.

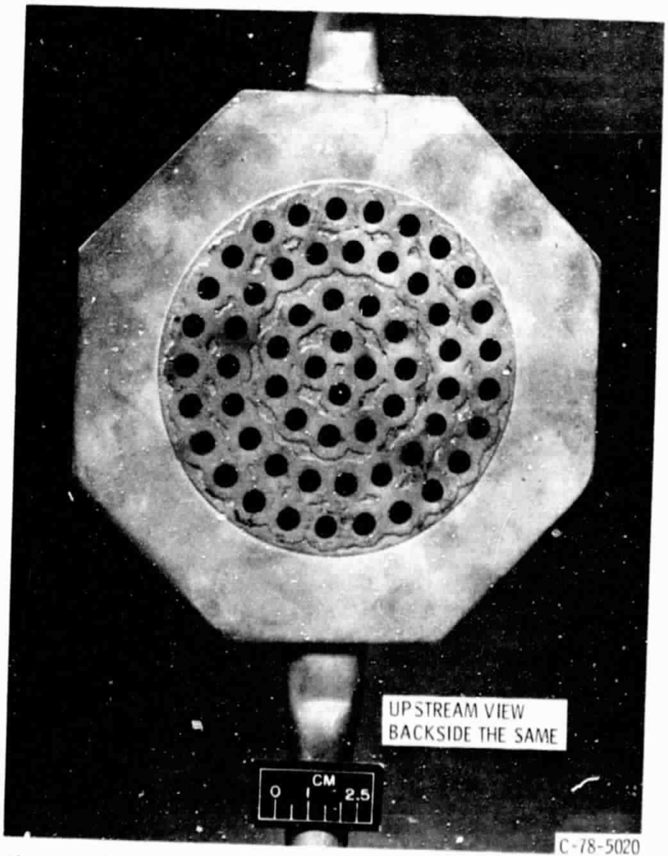

Figure 4. - Water cooled flameholder used for propane-toluene-pyridine combustion.

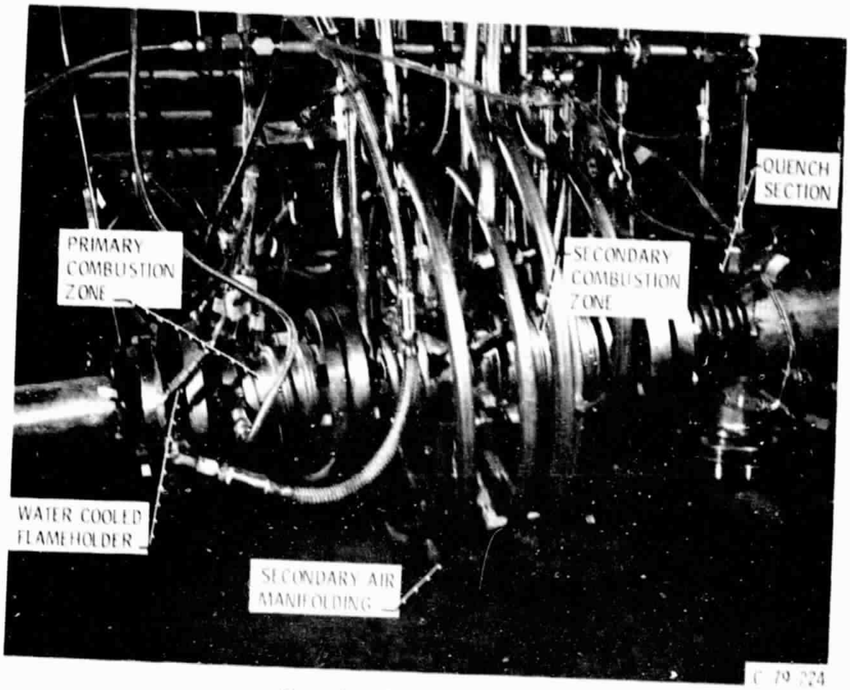

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Figure 5. - Flame tube rig hot section.

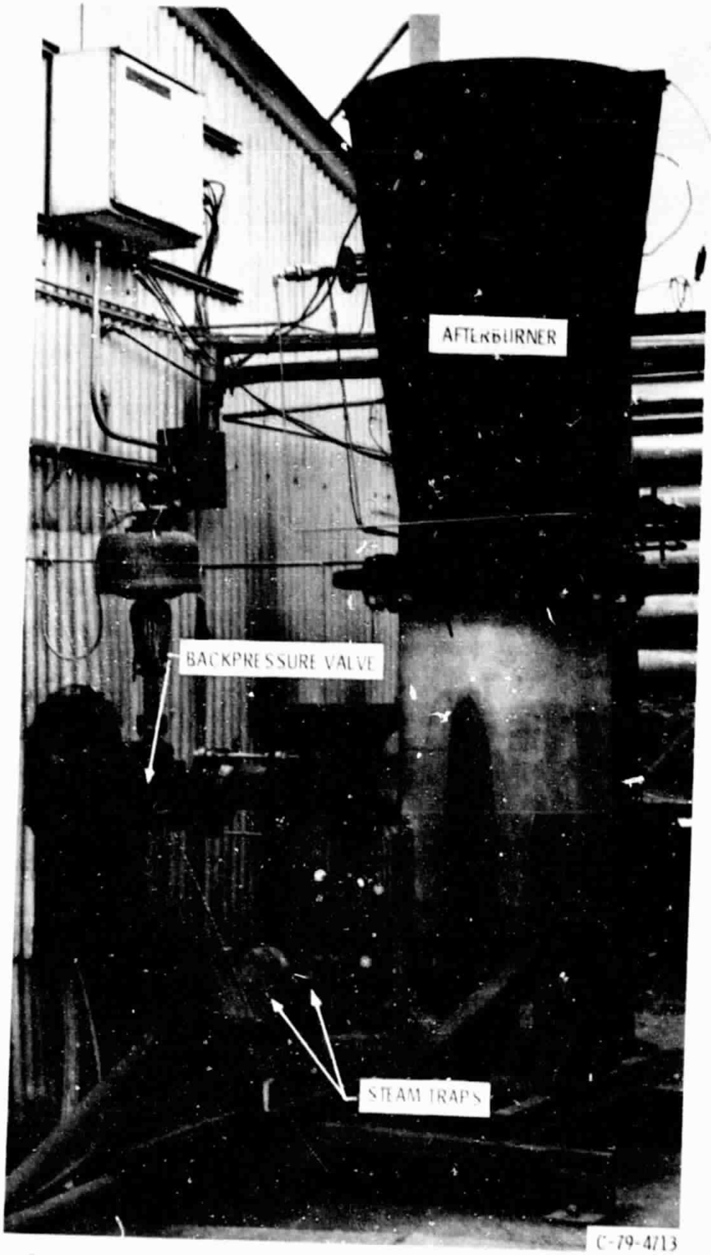


Figure 6. - Exhaust gas backpressure valve, water separator, and afterburner.

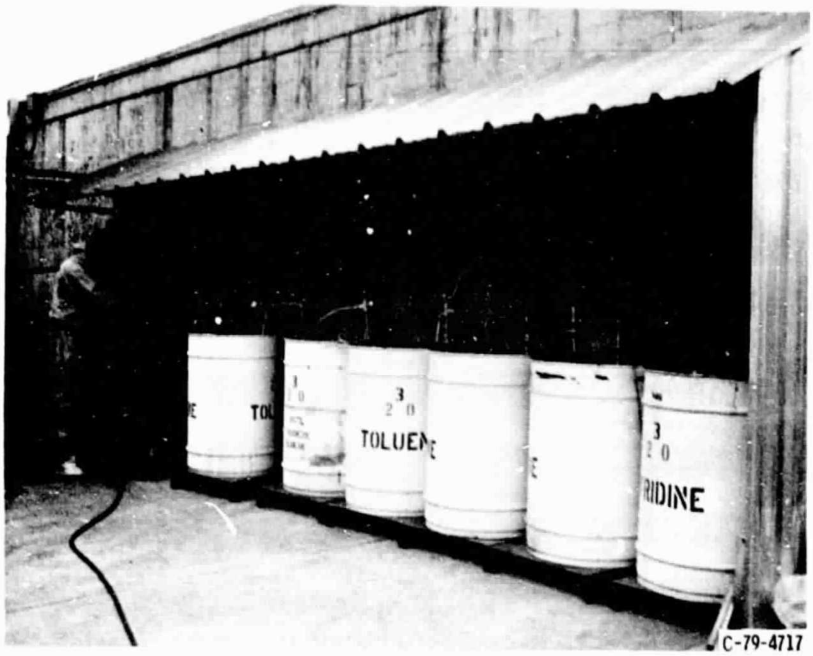


Figure 7. - Toluene-pyridine fuel system.

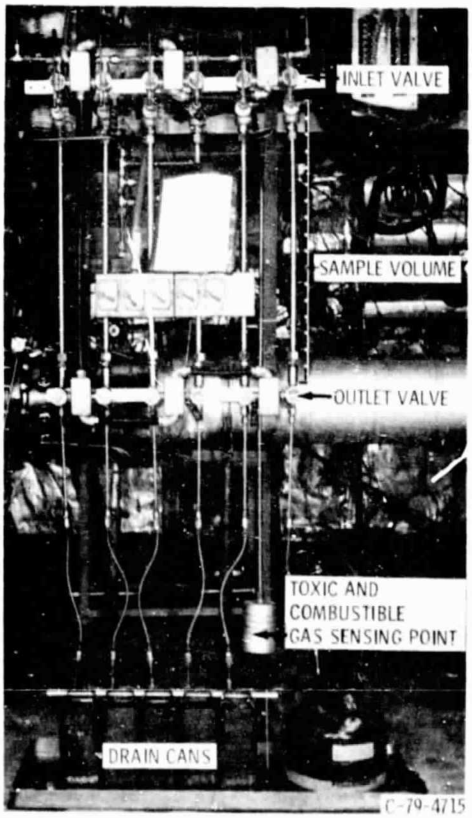


Figure 8. - Liquid fuel sampling system.

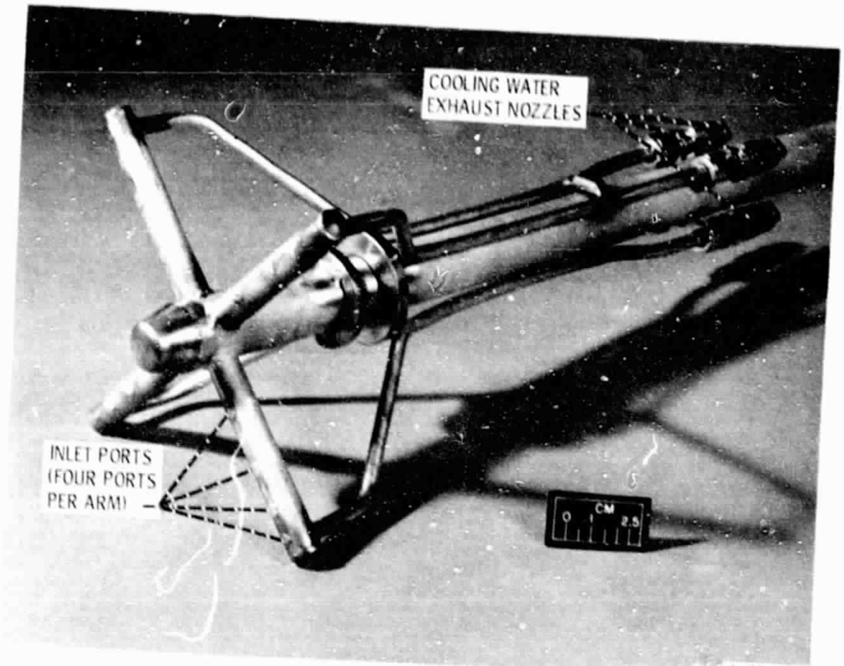


Figure 9. - Exhaust gas sample probe.

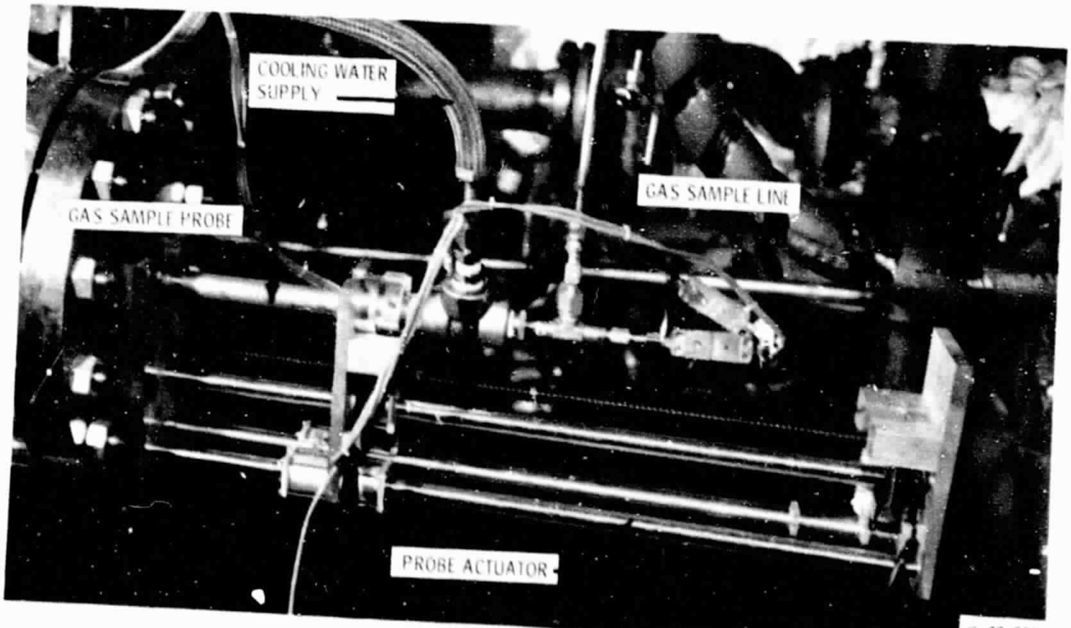


Figure 10. - Gas sample probe actuator.

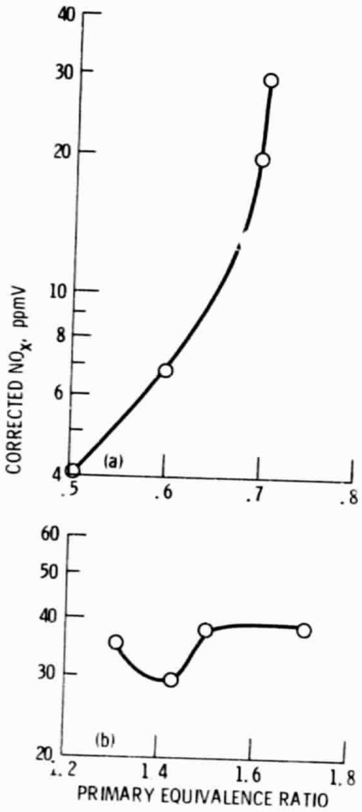


Figure 11. - Corrected NO_x versus primary equivalence ratio for propane. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~0.5 secondary φ.

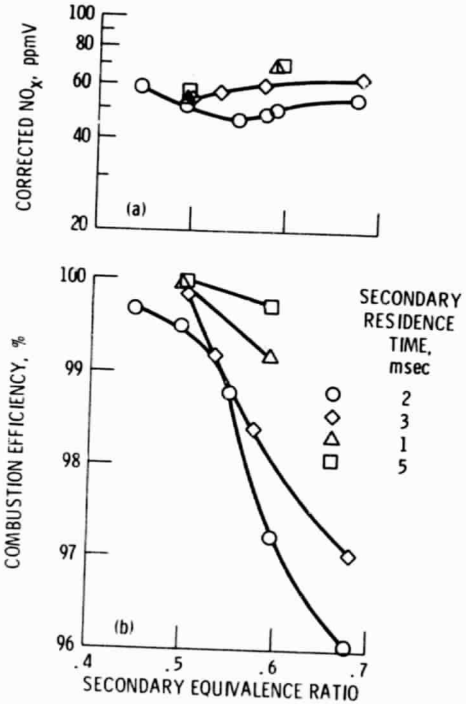
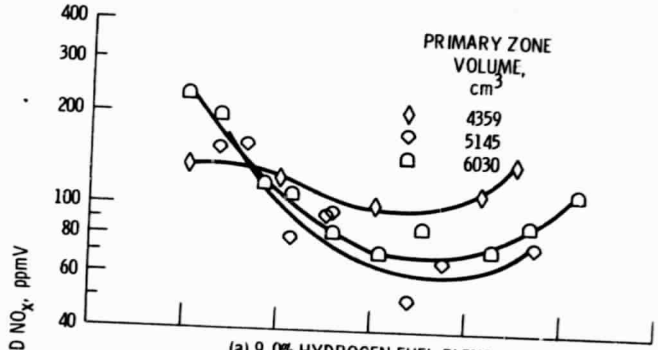
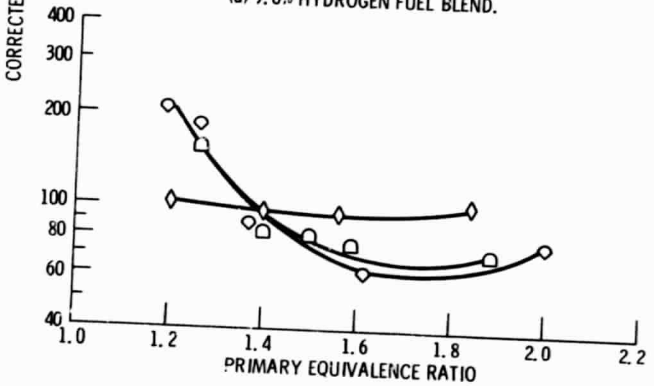


Figure 12. - Combustion efficiency versus secondary equivalence ratio for an 11.3% hydrogen fuel blend. Inlet air at 672 K and 0.48 MPa; 5145 cm^3 primary volume; 1.5 primary φ.

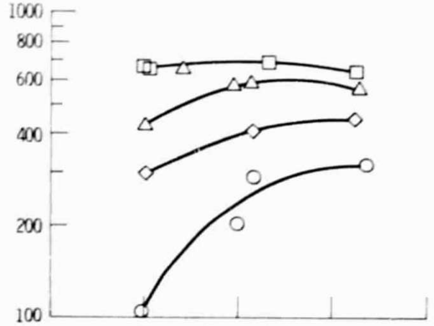


(a) 9.0% HYDROGEN FUEL BLEND.

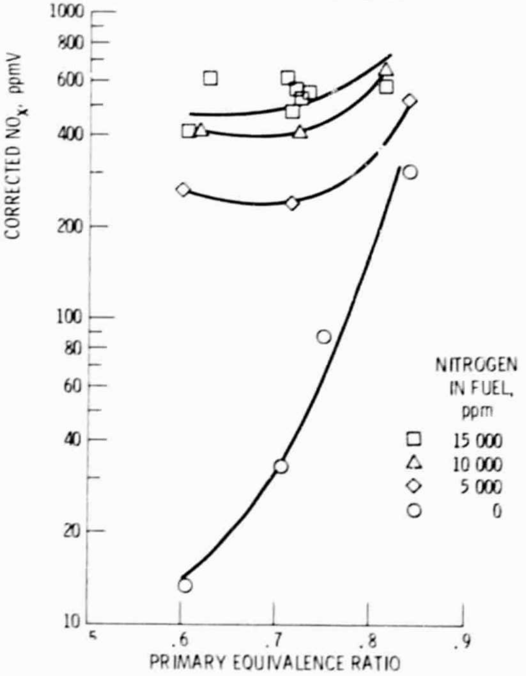


(b) 11.3% HYDROGEN FUEL BLEND.

Figure 13. - Corrected NO_x values for different primary volumes and for two different hydrogen fuel blends. Inlet air at 672 K and 0.48 MPa; 2 msec secondary residence time ~ 0.5 secondary φ.

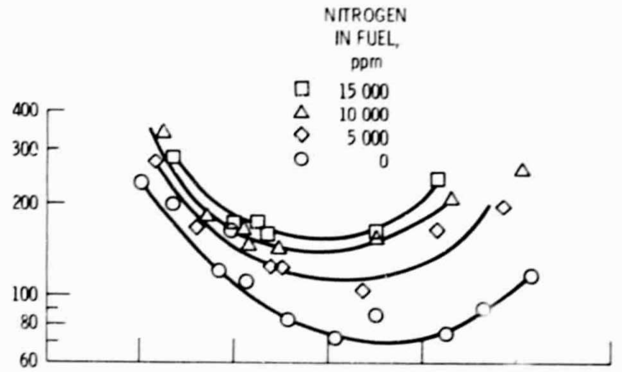


(a) 9% HYDROGEN FUEL BLEND.

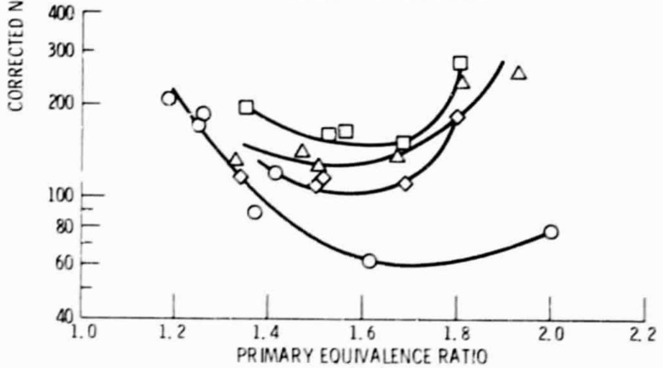


(b) 13.6% HYDROGEN FUEL BLEND.

Figure 14. - Corrected NO_x versus primary equivalence ratio for two different hydrogen fuel blends. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~ 0.5 secondary φ.



(a) 9% HYDROGEN FUEL BLEND.



(b) 11.3% HYDROGEN FUEL BLEND.

Figure 15. - Corrected NO_x versus primary equivalence ratio for two different hydrogen fuel blends. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~ 0.5 secondary φ.

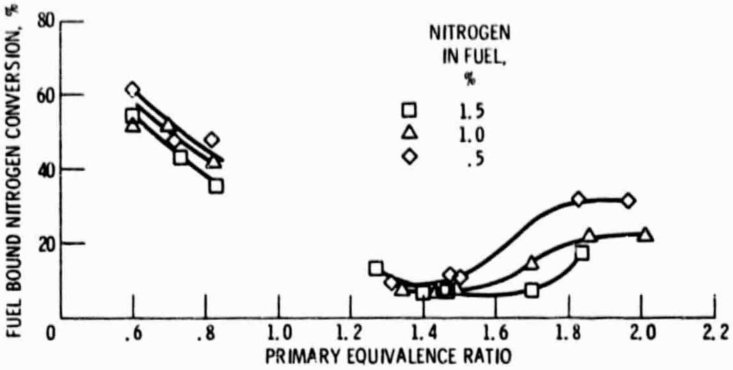


Figure 16. - Fuel bound nitrogen conversion versus primary equivalence ratio for a 9% hydrogen fuel blend. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~ 0.5 secondary φ.

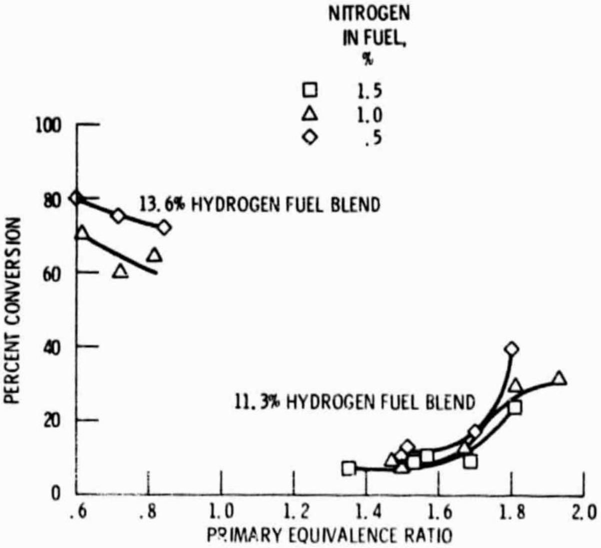


Figure 17. - Fuel bound nitrogen conversion versus primary equivalence ratio for 11.3% and 13.6% hydrogen fuel blends. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~ 0.5 secondary φ.

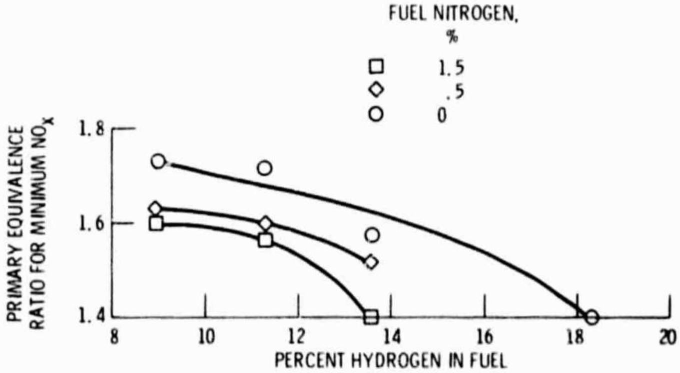


Figure 18. - Optimum primary equivalence ratio versus fuel hydrogen content. Inlet air at 672 K and 0.48 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time ~ 0.5 secondary φ.

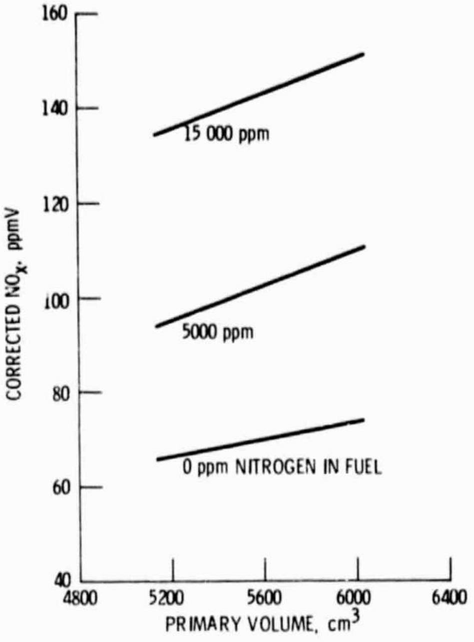


Figure 19. - Corrected NO_x versus primary volume for a 9% hydrogen fuel blend (φ_p = 1.6). Inlet air at 672 K and 0.48 MPa; 2 msec secondary residence time ~ 0.5 secondary φ; 1.6 primary φ.

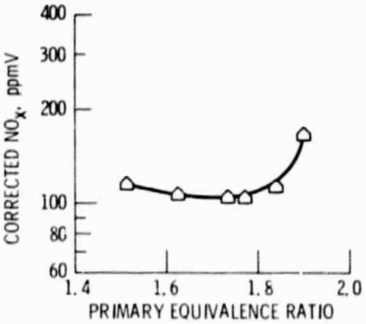


Figure 20. - Corrected NO_x versus primary equivalence ratio for SRC-II naphtha. Inlet air at 672 K and 0.48 MPa; 5145 cm^3 primary volume; 1 msec secondary residence time ~ 0.5 secondary φ.

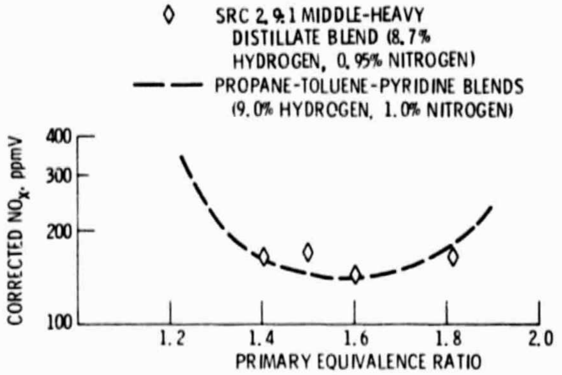


Figure 21. - Corrected NO_x versus primary equivalence ratio for SRC-II and a toluene-pyridine blend. Inlet air at 673 K and 0.58 MPa; 6030 cm^3 primary volume; 2 msec secondary residence time.

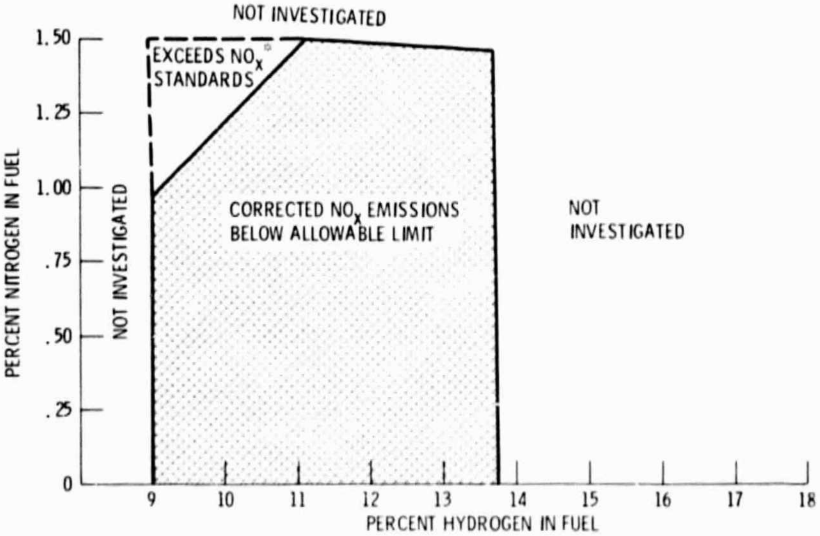


Figure 22. - Fuel blends which met emissions standards. Inlet air at 672 K and 0.48 MPa; 2 msec secondary residence time ~ 0.5 secondary φ.

[a]Metropolitan area.