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EFFECT OF PRIMARY-ZONE EQUIVALENCE RATIO AND HYDROGEN ADDITION ON EXHAUST EMISSION IN A HYDROCARBON-FUELED COMBUSTOR

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SUMMARY

The effects of reducing the primary-zone equivalence ratio on the exhaust emission levels of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons in experimental hydrocarbon-fueled combustor segments at simulated supersonic cruise and idle conditions were investigated. In addition, the effects of the injection of hydrogen fuel (up to 4 percent of the total weight of fuel) on the stability of the hydrocarbon flame and exhaust emissions were studied and compared with results obtained without hydrogen addition. The emissions of oxides of nitrogen were decreased 18 percent as the calculated value of the primary zone equivalence ratio was reduced from 0.75 to 0.34 at a supersonic cruise condition. The addition of hydrogen in concentrations to 4 percent of the total fuel weight flow did not appreciably affect the emission level of nitrogen oxides. At idle conditions, emissions of carbon monoxide and unburned hydrocarbons increased as the primary zone was leaned out; however, the addition of 4 percent hydrogen enhanced combustion to compensate for the leaner flame. The result was that the CO and HC emissions were reduced nearly to levels originally measured in the richer flame. The investigation indicated that making simple changes in airflow distribution patterns and injecting additional hydrogen fuel into the primary zone of an existing combustor did not produce large reductions in oxides-of-nitrogen emissions. Basic changes in combustor design are needed to fully realize the benefits of leaning out the primary zone and of injecting additional hydrogen fuel as a means of extending lean combustion limits and thereby reducing nitrogen oxides.

INTRODUCTION

An investigation was conducted on the possibility of reducing oxides-of-nitrogen emissions at supersonic cruise by reducing the primary-zone equivalence ratio. Exhaust emissions with and without the addition of a small amount of hydrogen to stabilize combustion and to improve exhaust pollutant emissions at idle were compared. Flame temperature is one of the most critical factors affecting the formation of oxides of nitrogen in a gas turbine combustor. It is shown in reference 1 that a significant reduction in the formation of nitrogen oxides is possible for a combustor burning a uniformly premixed-prevaporized fuel by operating at a lean equivalence ratio and thus a relatively low flame temperature. The minimum nitrogen oxide emissions measured in reference 1 was limited by the lean stability limit of the prevaporized fuel-air mixture. Further reduction in nitrogen oxides might be possible by operating at equivalence ratios below the flammability limits of the hydrocarbon fuel-air mixture. It is proposed in reference 2 that the addition of hydrogen can be used to extend the lean flammability limit of a premixed hydrocarbon flame.

The emissions of carbon monoxide and unburned hydrocarbons are greatest during low power requirements, such as idle, because of the reduced combustion efficiency. If the combustion air is proportioned to establish a lean primary zone under maximum power conditions, as the power is reduced, an even leaner primary zone will result from the excess air in relation to the reduced fuel flow. The net result at low power conditions could be increased carbon monoxide and hydrocarbon emissions as well as the degradation of the combustion stability to the point of blowout. Consequently, for idle, not only must the flame be stabilized to prevent blowout, but also combustion must be enhanced to reduce carbon monoxide and unburned hydrocarbons. A variable combustor geometry to control airflow and/or fuel distribution might be necessary to provide flame stability and high combustion efficiency. An alternative approach would be to add a small amount of highly reactive fuel, such as hydrogen, to stabilize the combustion.

In order to determine the feasibility of using a leaner primary zone to reduce nitrogen oxide emissions, the combustor of reference 3 was selected as the basic model configuration. This combustor features a high-intensity primary mixing zone and has previously been used to burn a liquid and a vaporized fuel either separately or simultaneously. Additional holes were added to increase recirculation of air into the primary zone for one modification; and finally in a second modification, all secondary dilution holes were blocked. A total of three configurations with calculated primary-zone equivalence ratios of 0.75, 0.52, and 0.34 were constructed. Test conditions were selected to simulate supersonic cruise and idle. Tests were conducted by injecting hydrogen at rates from 0 to 4 percent of total fuel weight flow into Jet A fuel while keeping the temperature rise across the combustor constant. The concentrations of oxides of nitrogen, carbon monoxide, and unburned hydrocarbons were measured.

APPARATUS AND PROCEDURE

Test Facility and Instrumentation

The test combustor was mounted in the closed-duct facility described in reference 3 and shown in figure 1. Tests were conducted at pressures of 207 and 414 kN/m^2 (30 and 60 psia). Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to give inlet-air temperatures as high as 810 K (1460° R) in a counterflow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold bypassed air. The airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves.

The inlet-air temperature was measured in the diffuser with eight Chromel-Alumel thermocouples. Inlet total pressures were measured at the same location by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential pressure strain-gage transducers that were referenced to the static pressure obtained by manifolding static taps located at the top and bottom of the duct. Combustor outlet temperatures and pressures were obtained with a traversing exhaust probe. The probe consisted of 12 elements: five aspirating platinum/platinum - 13-percent-rhodium total-temperature thermocouples, five total-pressure probes, and two wedge-shaped static-pressure probes. A stationary four-point air-cooled gas sample probe was located 91.4 centimeters (36 in.) downstream of the combustor exhaust in a circular pipe with a diameter of 50.8 centimeters (20 in.). Details of the gas sampling procedure are discussed in the section Gas Sampling Technique.

Experimental Combustors

The three combustor configurations used in this investigation to provide primary-zone equivalence ratios of 0.75, 0.52, and 0.34 are described in the following table:

Combustor model	Primary-zone equivalence ratio, φ	Comments
A	0.75	See figure 2(a).
B	0.52	Model A converted by six additional holes 2.2 centimeters (0.875 in.) in diameter in top liner wall, 6.7 centimeters (2.63 in.) from the combustor faceplate. Fifty percent recirculation assumed. Film cooling from snout blocked.
C	0.34	Model B converted by blocking all secondary dilution holes and adding thirty-six 0.64-centimeter- (0.25-in.-) diameter holes symmetrically around the swirlers in the combustor faceplate.

The basic combustor used in this investigation, model A, was similar to the combustor of reference 3 with the model 1 fuel injector and is shown in figure 2(a). The inlet air from the diffuser was split into three streams. The main stream, comprising 40 percent of the total airflow, was directed into the inlet snout. The remaining two streams provided for film cooling of the liner walls and dilution of the hot gases. A small portion of air, approximately 6 percent of the total flow, was diverted from the inlet snout to film cool the sides of the combustor. The calculated primary-zone equivalence ratio of this reference combustor was based on 34 percent of the air entering the snout and 9 percent supplied by 50 percent recirculation from the five holes in the lower primary wall (fig. 2(a)). The effective discharge coefficient C_d of the snout was assumed to be 0.98 and the C_d for the hole was 0.6. A primary-zone equivalence ratio of 0.75 was calculated for an overall fuel-air ratio of 0.022. Film cooling air was assumed not to enter into the reaction.

The fuel nozzles (fig. 2(b)) for all three combustors were identical and provided for the simultaneous injection of a liquid and a vapor fuel. In this study, liquid Jet A fuel was injected through the center simplex nozzles, and hydrogen was injected through the series of eight 0.094-centimeter- (0.037-in.-) diameter holes (60° included angle) evenly spaced on a 1.75-centimeter- (0.69-in.-) diameter around each of the four simplex nozzles.

Gas Sample Technique

The exhaust gas sample was withdrawn through the four-point, air-cooled, stationary probe shown in figure 3. The gas sample probe was located downstream of the traversing probe and in the center of the exhaust stream as shown in figure 1. The gas sample was passed through an electrically heated sampling line at a temperature of approximately 423 K ($760^{\circ}R$) and a pressure of 207 kN/m^2 (30 psia) to the gas analyzer. In order to prevent contamination in the sample line, a nitrogen purge was used prior to and during combustor ignition.

The exhaust gas was analyzed for oxides of nitrogen by means of a chemiluminescent meter. The meter included a converter for reducing NO_2 to NO. The carbon monoxide analyzing instrument was of the nondispersive infrared type. The total hydrocarbon content was determined by a flame ionization detector in which a portion of the sample gas was passed through a hydrogen flame. Concentrations of oxides of nitrogen, carbon monoxide, and total hydrocarbons are reported on a wet basis. The emission index for oxides of nitrogen is expressed as grams of NO_2 per kilogram of fuel and that for total hydrocarbons as grams of CH_2 per kilogram of fuel. Since hydrogen fuel has about three times the heating value of Jet A fuel, a correction to the emission index per kilogram of fuel was made to compare the data for liquid fuel and the data for liquid fuel plus hydrogen on an equal heat input basis. Emission index is normally defined as

$$EI = 10^{-3} \frac{M_x}{M_e} \left(\frac{1 + f}{f}\right) (x) \tag{1}$$

where EI is the pollutant emission index in grams per kilogram of fuel burned, M_x is the molecular weight of the pollutant, M_e is the average molecular weight of the exhaust gases, f is the total fuel-air weight ratio, and x is the total concentration of the pollutant in ppm. In this study the heating value per kilogram of fuel varied. The emission index was therefore corrected to the basis of an equivalent weight of Jet A fuel by multiplying the EI of equation (1) by the ratio of the heating value of Jet A fuel to that of the fuel mixture. For the mixture of Jet A and hydrogen the heating value HV can be expressed as

$$HV_{\text{Fuel mixture}} = (1 - \alpha)\left[HV_{\text{Jet A}} + \left(\frac{\alpha}{1 - \alpha}\right) HV_{H_2}\right] \tag{2}$$

where α is the fraction of hydrogen in the total fuel weight flow. The ratio by which the emission index of equation (1) is multiplied is then

$$\frac{HV_{\text{Jet A}}}{HV_{\text{Fuel mixture}}} = \frac{1}{(1 - \alpha)\left(\frac{HV_{H_2}}{HV_{\text{Jet A}}}\right)} \tag{3}$$

Combustor Test Conditions

The combustor was operated with Jet A fuel at the test conditions shown in the following table:

Test condition	Pressure		Inlet-air temperature		Overall equivalence ratio, φ_o	Reference velocity		Outlet temperature (combustion efficiency, percent)	
	kN/m^2	psia	K	^oR		m/sec	ft/sec	K	^oR
Supersonic cruise simulation[a]	414	60	810	1460	0.14, 0.209, and 0.269	21.3	70	[b]1460	[b]2630
Idle I	414	60	478	860	.119	21.3	70	800	1440
Idle II	207	30	367	660	.119	21.3	70	690	1240

[a]Supersonic cruise is simulated for an overall equivalence ratio of 0.269.

[b]At an overall equivalence ratio of 0.269.

At each test condition the outlet temperature was held constant and emission data with 0, 1, 2, 3, and 4 percent by weight of hydrogen were obtained for primary-zone equivalence ratios of 0.75, 0.52, and 0.34. The weight of hydrogen is expressed as

$$\text{Percent } H_2 = \frac{\text{Weight of hydrogen}}{\text{Weight of hydrogen + Weight of Jet A fuel}} \times 100 \tag{4}$$

Two test conditions were selected for idle. Idle I is representative of current high-bypass-ratio turbofan engines; idle II is probably more typical of proposed advanced supersonic engines.

RESULTS AND DISCUSSION

The effects of reducing the primary-zone equivalence ratio on the exhaust emission level for Jet A fuel in experimental combustor segments are presented. The oxides-of-nitrogen emission levels are presented for three overall calculated equivalence ratios based on Jet A fuel for a simulated supersonic cruise condition, and emission levels of carbon monoxide and unburned hydrocarbons are presented for two simulated idle conditions (see table on preceding page). In addition the hydrocarbon reaction was stabilized by the injection of as much as 4 percent by weight of hydrogen. Emission levels are compared with and without the addition of hydrogen at the simulated supersonic cruise condition and at the idle conditions.

The experimental combustor designated model A in this study has been previously used in fuel prevaporization and hydrogen fuel programs (refs. 3 and 4). In this study, however, the emission levels obtained with the model A configuration using Jet A fuel did not check with those previously reported. Emission data obtained by using only the vapor ports of the dual nozzle and vaporized propane did check within 3 percent of those previously reported in reference 3 for similar conditions. It was concluded that the liquid spray nozzles, rather than the combustor, had probably deteriorated. Differences in pressure-atomizing nozzles are shown in reference 3 to contribute to marked differences in emission levels in this combustor. Since the objective of this report was to establish trends rather than to demonstrate an absolute level of emission, the liquid-fuel simplex nozzles were not replaced, and a new base line was established for comparative purposes. At the conclusion of the program the new base line was found to be reproducible by using combustor model A.

Effect of Reducing Primary-Zone Equivalence Ratio

The basic combustor configuration, model A (primary-zone equivalence ratio φ of 0.75), was selected to provide an intense mixing of the fuel and air. If the fuel and air were completely mixed, combustor model C ($\varphi = 0.34$) could not have maintained combustion because of the lean flammability limit of Jet A fuel, which is of the order of $\varphi = 0.4$ at 800 K. In order for a flame to stabilize under these conditions, local pockets of a combustible mixture must exist. This is possible under certain conditions as a result of fuel distribution, recirculation patterns, and/or liquid-fuel droplet burning.

Some background on the stability of combustion in the configuration tested would be in order at this point. The experimental combustor was originally designed for a relatively lean primary zone ($\varphi = 0.75$), and all of the primary air was brought into the combustor by means of swirlers concentric with the fuel nozzles (ref. 5). It soon became apparent that in addition to the swirl, a reinforcement of the recirculation pattern by means of relatively large primary holes in the lower liner wall (fig. 2(a)) improved combustion stability. The basic combustor operated with high efficiency over a wide range of fuel flows.

Apparently, the same principles which resulted in improved performance during the combustor evolution are responsible for the lean stability with combustor model C. In all three configurations, large-flow simplex fuel nozzles were used. The study reported in reference 3 shows the pressure drop across the fuel nozzles to be approximately 100 kN/m^2 (14.7 psia) differential, which corresponds to the fuel flow requirements of the simulated supersonic cruise condition; consequently, a rather coarse fuel spray primarily along the nozzle centerline would be expected. In addition, all the combustion air except for liner-wall film cooling enters the primary zone because of the blockage of the secondary dilution ports. The pressure drop across the combustor in turn is increased, which is reflected in an increase in airflow through the primary swirlers, thus intensifying the swirl. The result is that a higher mass distribution of air exists at the periphery of the swirl in model C. This higher mass distribution of air at the periphery coupled with the fact that fuel is introduced at the center of the vortex could cause the localized mixture to be rich enough and the dwell time to be sufficient to maintain combustion. As a result the effective primary zone is not as lean as would be expected from calculations.

Oxides-of-nitrogen emissions.- The emission levels of the oxides of nitrogen for combustor models A, B, and C are presented in figure 4 for three values of overall equivalence ratio. For an overall equivalence ratio of 0.27, corresponding to the simulated supersonic cruise condition, a reduction of 18 percent in the level of the oxides of nitrogen was obtained with combustor model C ($\varphi = 0.34$) as compared with model A ($\varphi = 0.75$; reference NO_x emission index = 15). As the overall equivalence ratio was decreased, there was a sharp dropoff in NO_x emission. For an overall equivalence ratio of 0.15, which would indicate a reduction in primary-zone equivalence ratio, the NO_x was reduced 40 percent with combustor model C as compared to model A (reference NO_x

emission index = 11.6). The combustion efficiency as calculated from the emission index indicated an efficiency level in excess of 99 percent. Thus, as leaner primary combustion zones were achieved, larger reductions in NO_x were experienced, as would be expected from theoretical calculations (ref. 1).

Carbon monoxide and unburned hydrocarbon emissions.- At supersonic cruise conditions the combustion efficiency is approximately 100 percent so that carbon monoxide and unburned hydrocarbon emissions are negligible. The carbon monoxide and unburned hydrocarbon emission index levels for the two idle conditions are shown in figures 5 and 6 for three combustor models corresponding to calculated primary-zone equivalence ratios of 0.75, 0.52, and 0.34, respectively. As a general trend the emission levels of carbon monoxide and unburned hydrocarbons increased markedly as the inlet-air temperature and pressure decreased, as exemplified by idle II as compared to the less severe idle I.

At idle I the carbon monoxide level decreased as the primary zone was initially leaned out (model B). As the primary zone was leaned out further (model C) the carbon monoxide increased to a level comparable to that originally obtained with model A (reference emission index = 108). The unburned hydrocarbons increased for all reductions in primary-zone equivalence ratio. The unburned hydrocarbon emission level increased 108 percent with model C as compared to model A (reference emission index = 63).

At idle II the carbon monoxide emissions decreased with decreasing primary-zone equivalence ratio. The carbon monoxide emission level decreased 14 percent with model C as compared to model A (reference emission index = 151). The unburned hydrocarbon level at idle II decreased as the primary zone was initially leaned out (model B). As the primary zone was leaned out further (model C) the hydrocarbon emissions increased to a level 20 percent higher than model A (reference emission index = 152).

It would be expected that as the idle conditions become more severe (i.e., lower inlet-air temperature and pressure) exhaust emissions would increase for all primary-zone equivalence ratios. The results obtained did not necessarily bear this out. The carbon monoxide level reached a minimum with combustor model B ($\varphi = 0.52$) at idle I, in addition to the observed reduction with decreasing primary-zone equivalence ratio at idle II. The unburned hydrocarbon level reached a minimum at idle II with combustor model B and increased at idle I with decreasing primary-zone equivalence ratio. Repeating the tests confirmed these trends. These results are probably related to the more rapid mixing as a result of increased recirculation as the primary zone is leaned out.

Effect of Hydrogen Addition on Emissions

The emission levels of oxides of nitrogen for combustor models A, B, and C are presented in figure 7 for a range of hydrogen weight flows from 0 to 4 percent at the simulated cruise condition. As shown in figure 7 there was no appreciable effect of hydrogen addition on NO_x emissions over the range of hydrogen flows investigated.

The carbon monoxide and unburned hydrocarbon emission levels for the two idle conditions are shown in figures 8 and 9, respectively, for combustor models A, B, and C with 0 to 4 percent hydrogen addition. The addition of hydrogen improved the performance at idle. The carbon monoxide level of combustor model C with 4 percent hydrogen addition was reduced 35 percent at idle I (fig. 8(a)) from an emission index level of 107 and was reduced 11 percent at idle II (fig. 9(a)) from an emission index level of 130. The unburned hydrocarbon level of combustor model C with 4 percent hydrogen addition was reduced 44 percent at idle I (fig. 8(b)) from an emission index level of 132 and was reduced 7 percent at idle II (fig. 9(b)) from an emission index level of 180.

Hydrogen was most effective in reducing the carbon monoxide and unburned hydrocarbons at idle I, which is typical of many current high-bypass-ratio turbofan engines. At idle II, which would correspond more closely to idle for a supersonic turbojet engine, the addition of hydrogen was less effective.

CONCLUDING REMARKS

The investigation of combustion at low primary-zone equivalence ratios indicated that making minor changes in airflow distribution patterns and injecting additional hydrogen fuel into the primary zone of an existing combustor did not produce large reductions in oxides-of-nitrogen emissions. The combustor used in this investigation is similar in concept to those of present-day turbojets in that a pressure-atomizing fuel system is used. Basic changes in combustor design are needed to fully realize the benefits of leaning out the primary zone and injecting additional fuel as a means of extending lean combustion limits and thereby reducing nitrogen oxides. It is likely that greater reduction in NO_x could be achieved in a lean-burning premixed-prevaporizing type of combustor with hydrogen injection to improve stability. However, these preliminary data are useful in showing that NO_x can be reduced by using a leaner primary zone and in pointing out the need to direct effort toward this area of research.

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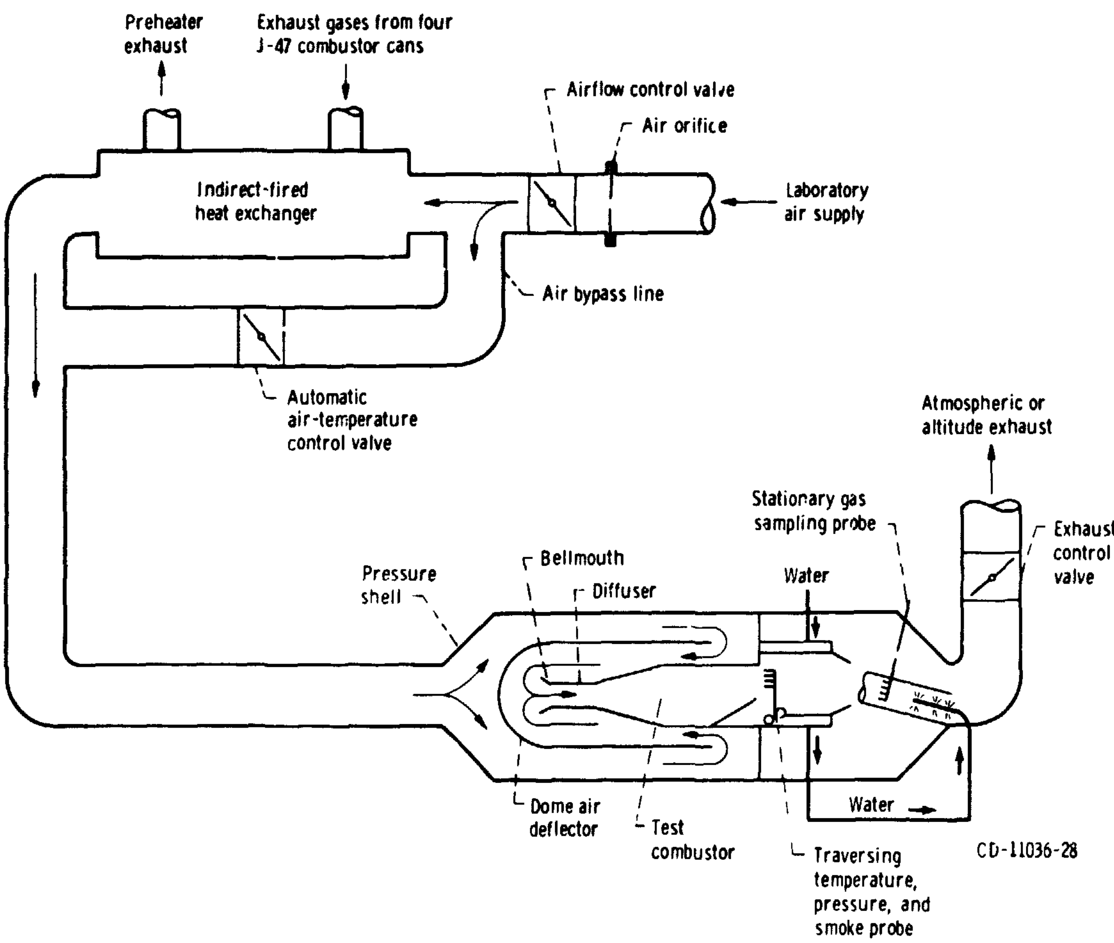
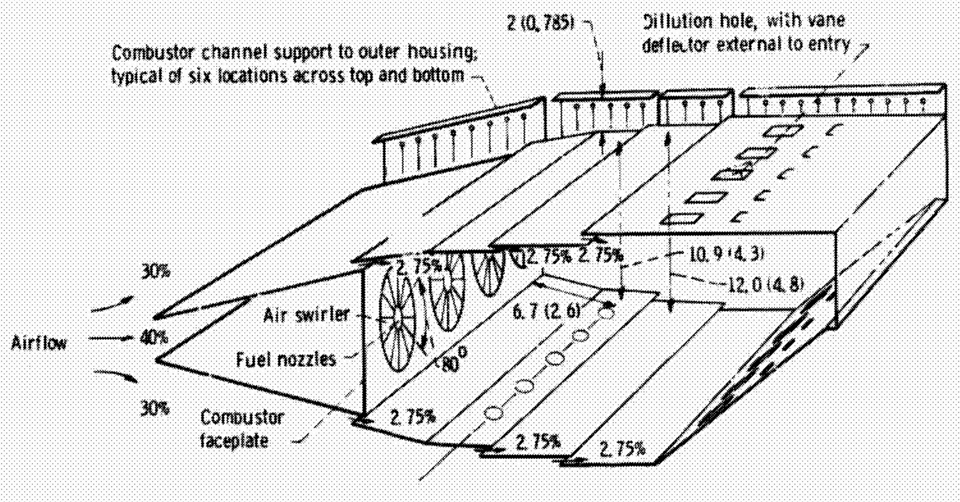
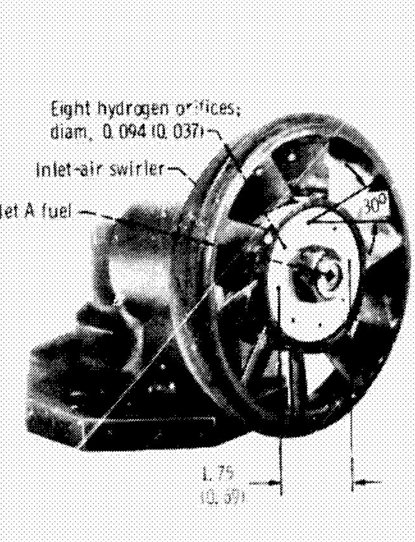


Figure 1. - Test facility and auxiliary equipment.



(a) Combustor liner - model A.



(b) Fuel nozzle injector 1.

Figure 2. - Schematic of combustor assembly. Combustor width, 31 centimeters (12 in.); combustor length, 32 centimeters (12.5 in.); maximum combustor housing height, 15 centimeters (6 in.). (Dimensions are in cm (in.).)

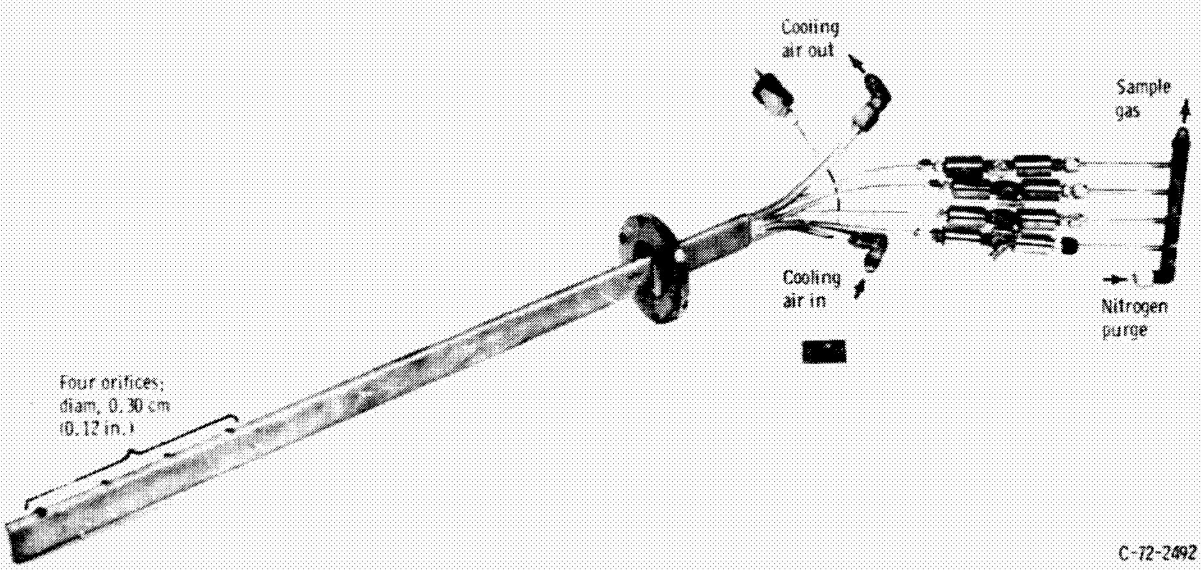


Figure 3. - Stationary gas sampling probe.

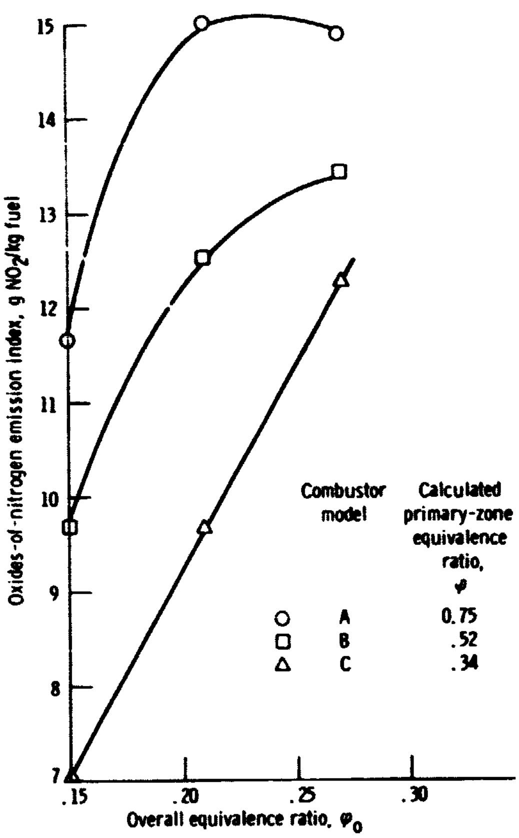


Figure 4. - Effect of overall equivalence ratio on total oxides-of-nitrogen emissions for three combustor models. Jet A Fuel: inlet-air temperature, 810 K (1460° R); inlet-air pressure, 414 kN/m^2 (60 psia); reference velocity, 21.3 m/sec (70 ft/sec).

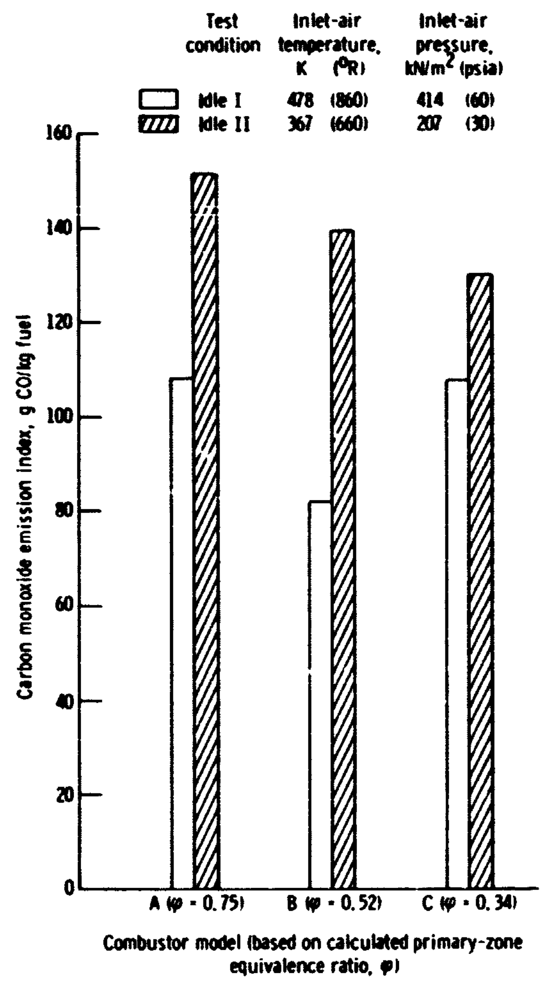


Figure 5. - Effect of combustor model on carbon monoxide emissions for two idle conditions. Jet A fuel; overall equivalence ratio, φ_0, 0.119; reference velocity, 21.3 m/sec (70 ft/sec).

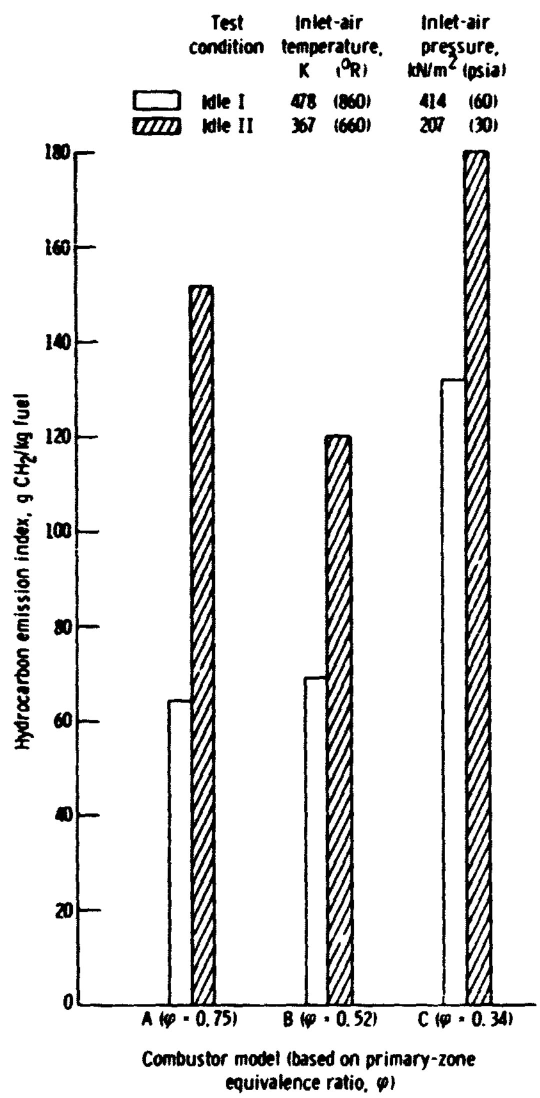


Figure 6. - Effect of combustor model on unburned hydrocarbon emissions for two idle conditions. Jet A fuel; overall equivalence ratio, φ_0, 0.119; reference velocity, 21.3 m/sec (70 ft/sec).

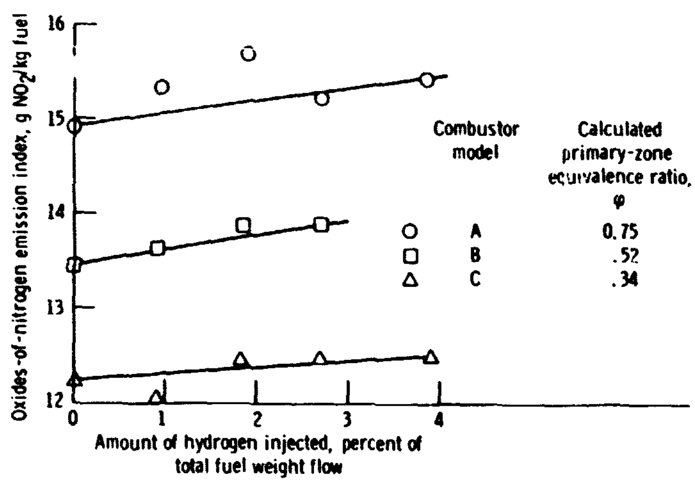
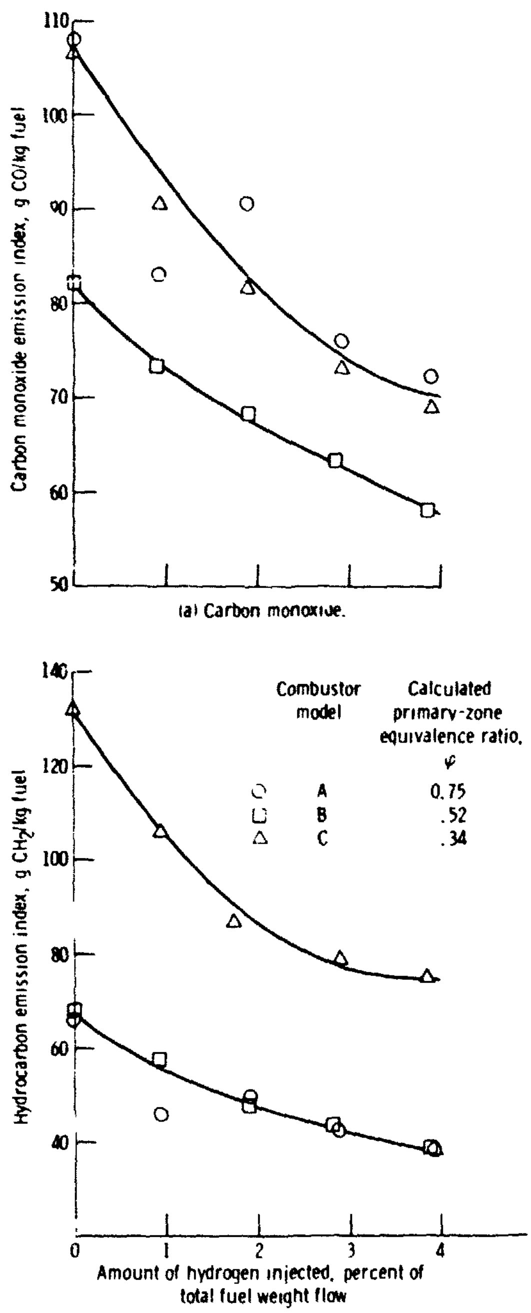
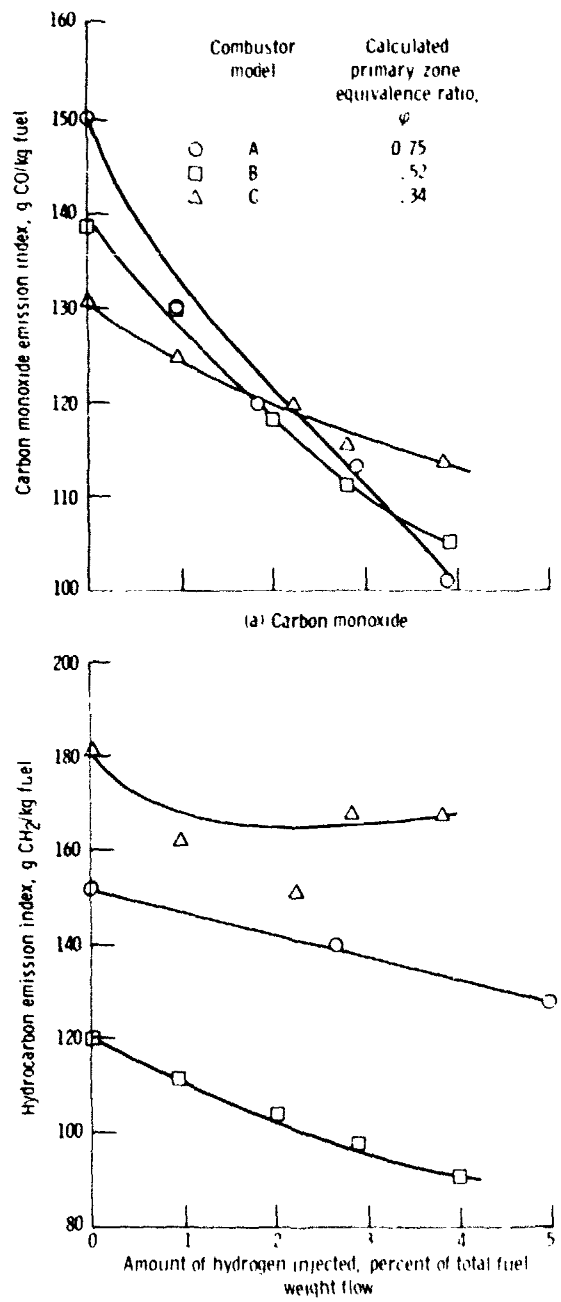


Figure 7. - Effect of hydrogen injection on total oxides-of-nitrogen emissions for three combustor models. Inlet-air temperature, 810 K (1460° R); inlet-air pressure, 414 kN/m^2 (60 psia); overall equivalence ratio, φ_0, 0.267; reference velocity, 21.3 m/sec (70 ft/sec).



(b) Unburned hydrocarbons.

Figure 8. - Effect of hydrogen injection on emissions for three combustor models - idle I. Inlet-air temperature, 478 K (860° R); inlet-air pressure, 414 kN/m^2 (60 psia); overall equivalence ratio, φ_0, 0.119; reference velocity, 21.3 m/sec (70 ft/sec).



(b) Unburned hydrocarbons

Figure 9. Effect of hydrogen injection on emissions for three combustor models - idle II. Inlet air temperature, 367 K (660° R); inlet air pressure, 207 kN/m^2 (30 psia); overall equivalence ratio, φ_0, 0.119; reference velocity, 21.3 m/sec (70 ft/sec).