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EFFECT OF OPERATING CONDITIONS ON THE EXHAUST EMISSIONS FROM A GAS TURBINE COMBUSTOR

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APPENDIX A - ANALYTICAL METHODS by Albert Evans, Jr., and Gilbert M. Boyd

16. Abstract

Exhaust concentrations of total unburned hydrocarbons, carbon monoxide, and nitric oxide were measured from a single J-57 combustor liner installed in a 30-cm- (12-in. -) diameter test section. Tests were conducted over a range of inlet total pressures from 1 to 20 atmospheres, inlet total temperatures from 310 to 590 K (100° to 600° F), reference velocities from 8 to 46 m/sec (25 to 150 ft/sec), and fuel-air ratios from 0.004 to 0.015. Most of the data were obtained using ASTM A-1 fuel; however, a limited number of tests was performed with natural gas fuel. Combustion efficiency and emission levels are correlated with operating conditions. Sampling error at operating conditions for which combustion efficiency was below about 90 percent resulted in abnormally low readings for hydrocarbon emissions.

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SUMMARY

Exhaust concentrations of total unburned hydrocarbons, carbon monoxide, and nitric oxide were measured from a single J-57 combustor liner installed in a 30-centimeter- (12-in. -) diameter test section. A range of operating conditions was studied that is representative of idle, takeoff, and cruise for a variety of gas turbine engines with different compressor pressure ratios and different flight speed and altitude requirements. Tests were conducted over a range of inlet total pressures from 1 to 20 atmospheres, inlet total temperatures from 310 to 590 K (100° to 600° F), reference velocities from 8 to 46 meters per second (25 to 150 ft/sec), and fuel-air ratios from 0.004 to 0.015. Most of the data were obtained using ASTM A-1 fuel; however, a limited number of tests was performed with natural gas fuel.

Emission indexes expressed in terms of grams of pollutant per kilogram of fuel burned and combustion efficiency calculated from thermocouple measurements were determined at different operating conditions and were correlated with a combustor operating parameter that included the combined effect of inlet total pressure, inlet total temperature, and reference velocity. At low fuel flows, poor fuel atomization has a predominant influence on producing low combustion efficiency and high hydrocarbon and carbon monoxide emissions. Higher nitric oxide emissions were obtained at conditions yielding high reaction zone temperature and long dwell time. Sampling error at operating conditions for which combustion efficiency was below about 90 percent resulted in abnormally low readings for hydrocarbon emissions thought to be caused by fuel droplets passing through the combustor along the liner and not being drawn into the gas sample probe.

Appendix A by Albert Evans, Jr., and Gilbert M. Boyd describes the analytical methods used to analyze exhaust gas samples for total hydrocarbon, carbon monoxide, oxides of nitrogen, carbon dioxide, and hydrogen.

INTRODUCTION

The purpose of this investigation was to study the effect of operating conditions on the gaseous emissions of a typical aircraft gas turbine combustor. References 1 to 3 indicate that the highest hydrocarbon and carbon monoxide emissions occur during idle and that the highest nitric oxide emissions occur during takeoff. The relatively high hydrocarbon and carbon monoxide emissions during idle are, of course, due to lower combustion efficiency at this operating condition. Lower combustion efficiency at idle may be caused by (1) lower combustor inlet pressure and temperature, (2) lower fuel-air ratio, and (3) poor fuel atomization. The higher nitric oxide emission during takeoff is known to be caused by a higher combustor inlet temperature which effects its rate of formation (refs. 3 and 4).

Previous investigations (refs. 2 and 5) have already established the concentrations of hydrocarbons, carbon monoxide, and nitric oxide in jet engine exhaust, together with their dependence on engine operating conditions. Most of these data have been obtained from either (1) turbojet engine tests in which detailed combustor operating or performance data were not presented, or from (2) laboratory combustor tests over a limited range of operating conditions. The intent of the effort described in this report was to expand on these previous exhaust emission results by testing an aircraft gas turbine combustor over a wide range of operating conditions.

In addition, the exhaust emission measurements were compared with combustion efficiency determined from temperature measurements. Sampling validity was checked by comparing combustion efficiency determined from thermocouple measurements and fuel-air ratios determined from fuel and airflow measurements with combustion efficiency and fuel-air ratio determined from gas sampling measurements.

Exhaust emission data were obtained from a single J-57 combustor liner that was installed in a 30-centimeter- (12-in. -) diameter test section. This combustor has a relatively rich primary zone fuel-air ratio at takeoff conditions, whereas current combustor designs have relatively lean primary zone fuel-air ratios in order to reduce smoke emissions. The observed emission trends are probably similar for both combustors with lean and rich primary zone designs; however, the emission levels may be considerably different for combustors with widely different primary zone designs. Furthermore, this combustor uses pressure atomizing fuel nozzles; therefore, the emission levels of combustors with either air atomizing, carbureting, or vaporizing fuel nozzles may also be widely different.

Tests were performed over as wide a range of operating conditions as permitted by the capacity of the test facility and were not necessarily limited to the actual engine operating conditions of the combustor that was chosen for this study. Inlet total pressure was varied from 1 to 20 atmospheres, inlet total temperature from 310 to 590 K (100° to 600° F), reference velocity from 8 to 46 meters per second (25 to 150 ft/sec),

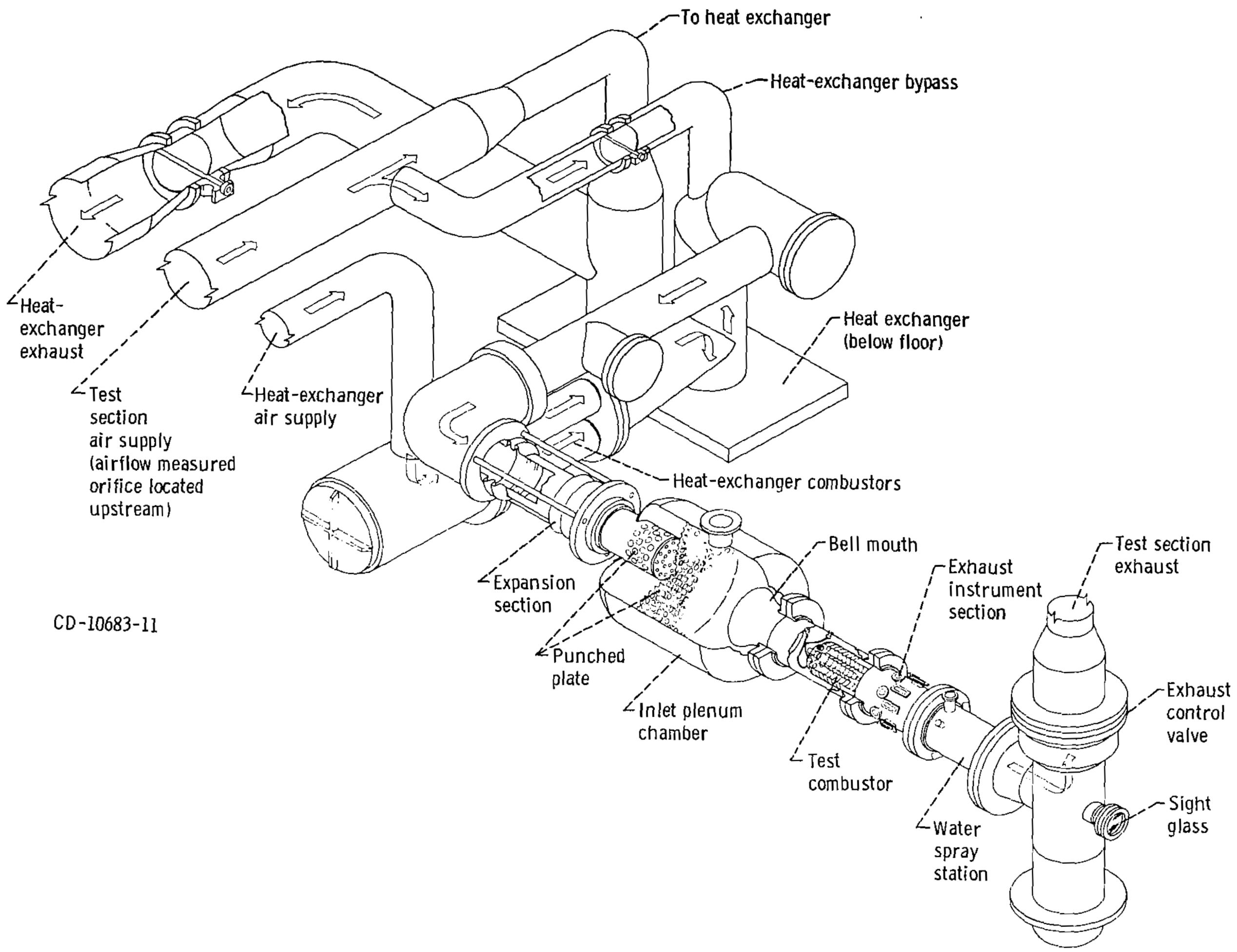


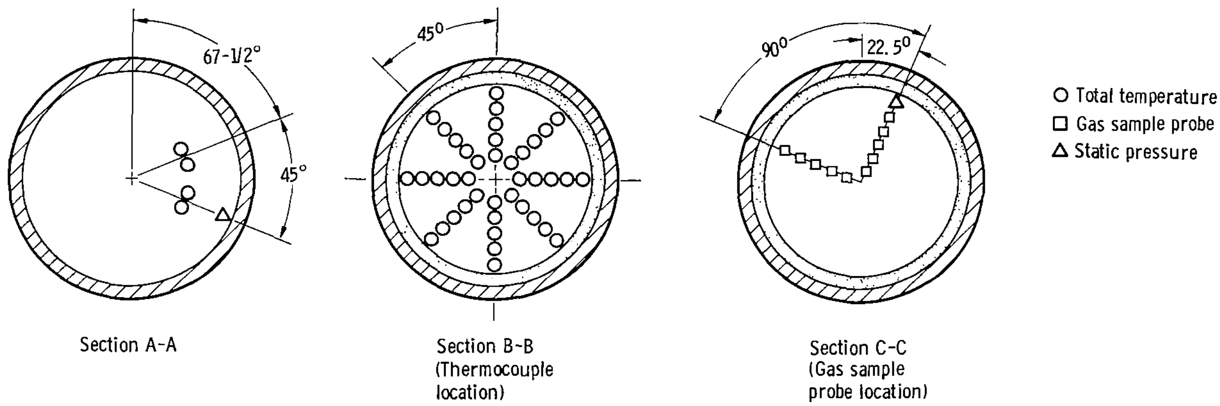
Figure 1. - Test installation.

and fuel-air ratio from 0.004 to 0.015. Emission indexes for total hydrocarbons, carbon monoxide, and nitric oxide expressed in terms of grams of pollutant per kilogram of fuel burned are compared with combustion efficiency over the range of operating conditions that were studied.

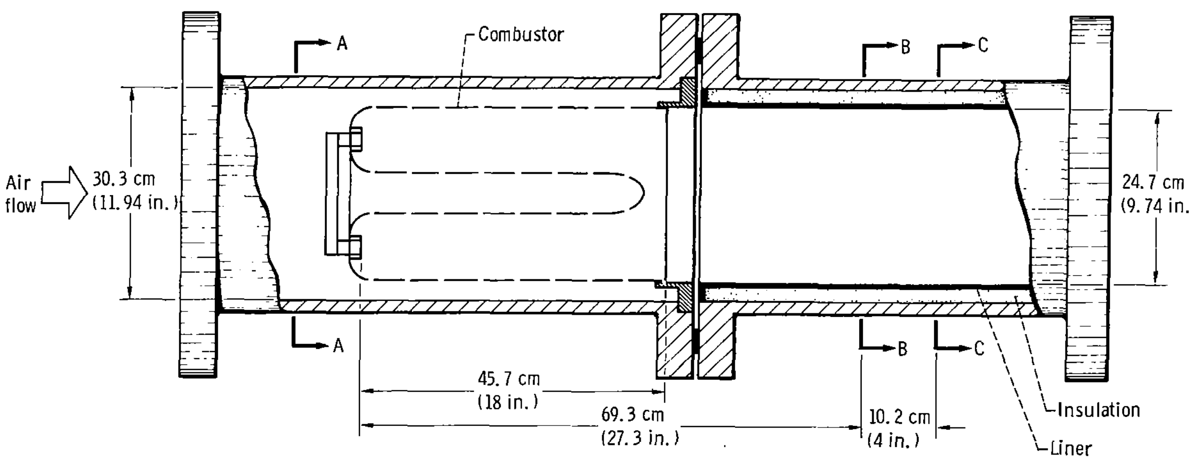
APPARATUS AND PROCEDURE

Facility

The test facility is shown in figure 1 and is described in reference 6. The test com-



(a) Instrumentation stations.



(b) Location of instrumentation at each station.

Figure 2. - Combustor test duct.

bustor is housed in a 30-centimeter- (12-in. -) diameter pipe. A nonvitiating preheater was used to supply conditioned combustion air at temperatures up to 590 K (600° F). The test facility was connected to the laboratory air supply. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

Test Section

A cross section of the test section is shown in figure 2. The combustor reference area was defined as the cross-sectional area inside the 30-centimeter- (12-in. -) test section which is 7.2×10^{-2} square meter (0.775 ft^2) or approximately one-eighth the annular cross-sectional area of the combustor housing in the J-57 engine which contains eight combustor liners. To simplify fabrication the inlet diffuser and the exit transition were made of constant area ducting of circular cross-section.

Test Combustor

Tests were performed with the standard fuel nozzle manifold from the J-57 engine which consists of six dual-orifice nozzles as shown in figure 3. The combustor liner

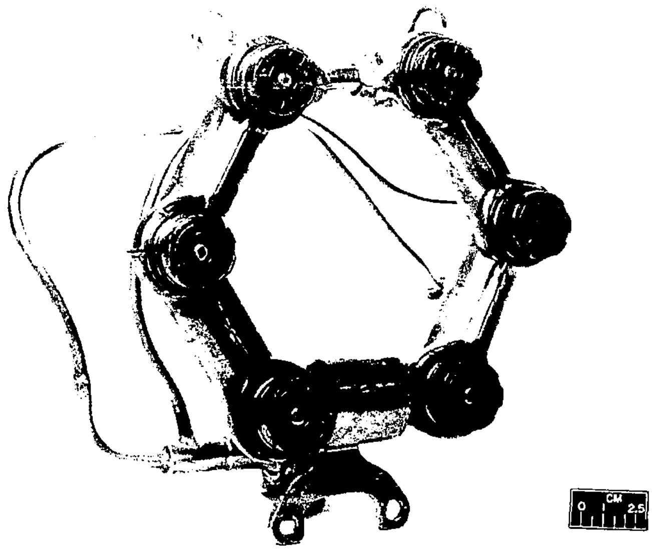


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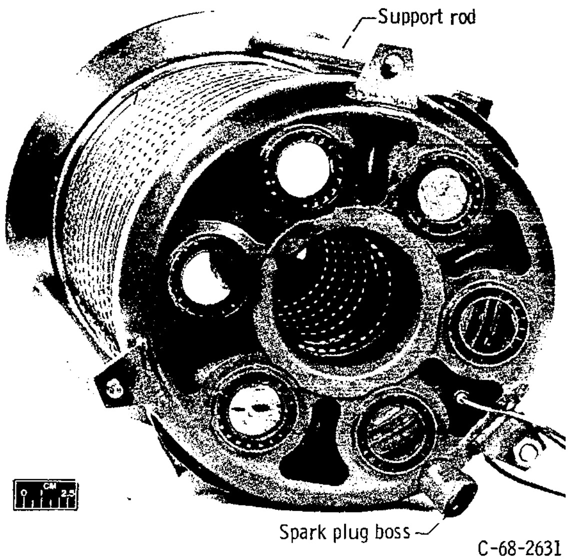
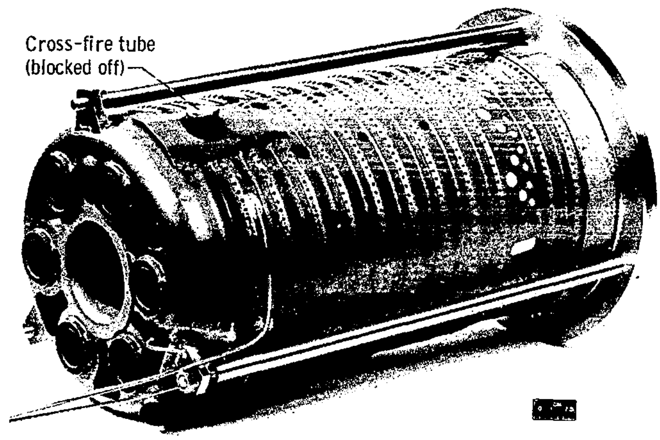
Figure 3. - Fuel nozzle manifold for test combustor.



(a) Upstream view.



(b) Side view.

Figure 4. - Combustor liner.

is shown in figures 4(a) and (b). Fuel flows to the primary and secondary chambers of the dual-orifice nozzles were controlled by separate throttle valves. Flow calibrations for the primary and secondary chamber of a set of six fuel nozzles are shown in figure 5. Low pressure drop fuel nozzles were used for natural gas fueled operations.

Instrumentation

Airflows were measured by square-edged orifices installed according to ASME specifications. Fuel flows were measured by turbine flowmeters. Pressures were measured by strain gage transducers.

The axial location of the test instrumentation planes are shown in figure 2(b). The cross-sectional positions of the gas sampling probes, thermocouples, and combustor static pressure taps are shown in figure 2(a). Exit temperatures were measured by 40 bare junction Chromel-Alumel thermocouples positioned at the center of equal areas as shown in figure 2(a).

Exhaust Emission Probe

The water-cooled exhaust emission probe is shown in figure 6. The probe was de-

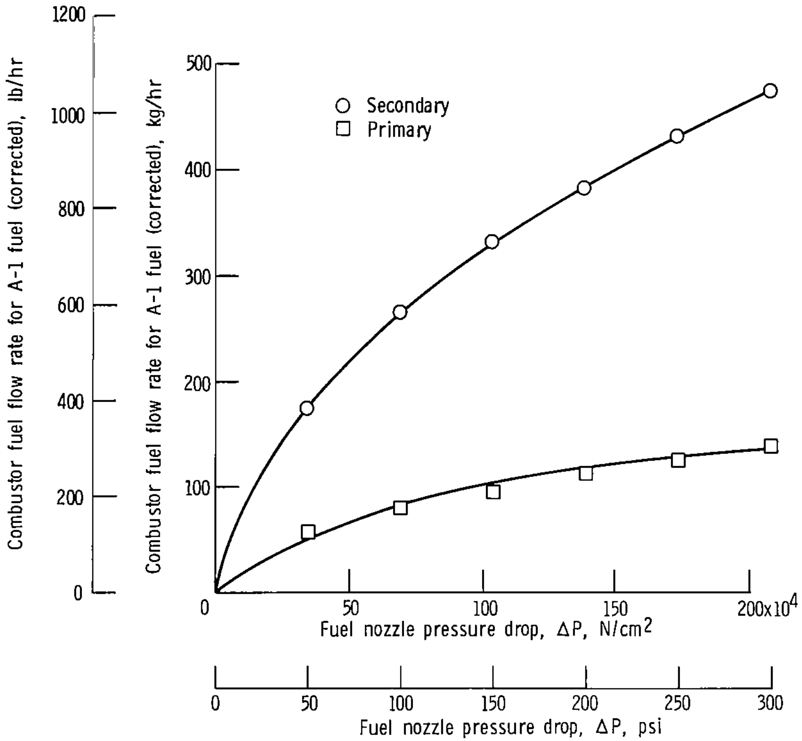


Figure 5. - Typical flow calibration for a set of six J-57 duplex fuel nozzles; calibration with water corrected to ASTM A-1 fuel density.

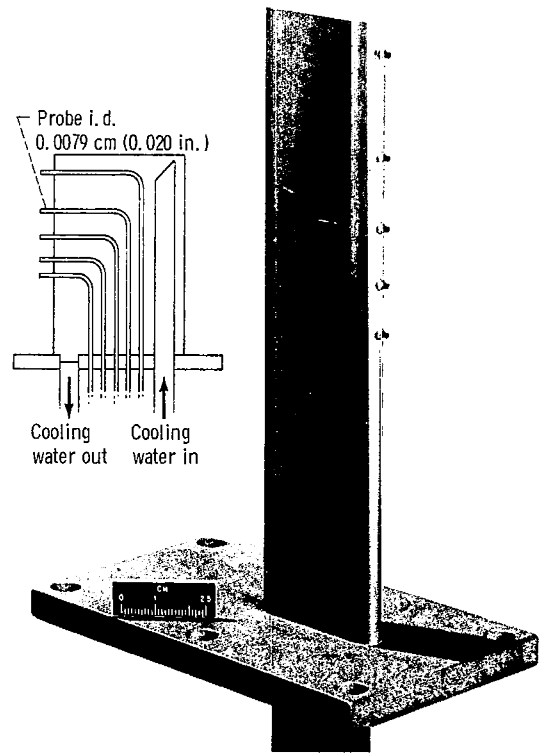


Figure 6. - Exhaust emission probe.

signed to sample the exhaust stream at five positions on the centers of equal areas. Two probes were used to gather a sample as shown in figure 2(a). All five positions were connected together outside the test section and the sample flow of the two probes were manifolded together. The sampling line length was 9 meters (30 ft). The temperature of the sample line was maintained at an average temperature of 390 K (250° F) with electrical heating tape. The exhaust sample was analyzed for total unburned hydrocarbon content by an online flame ionization detector. Batch samples for gas analysis were taken in 150- or 300-milliliter stainless-steel vessels for carbon monoxide analysis and for nitric oxide analysis in 250- or 500-milliliter glass vessels. The content of these vessels was analyzed at a later time. Carbon monoxide content of the exhaust sample was determined using a Beckman GC4 gas chromatograph. Nitric oxide content of the exhaust sample was determined by the Saltzman technique. A limited number of grab samples was also analyzed for carbon dioxide and hydrogen. Analytic techniques used to determine exhaust emissions are described in appendix A.

Test Conditions

Tests were conducted over a range of fuel-air ratios, inlet temperatures, pressures, and reference velocities. The fuel used was ASTM A-1 with an average hydrogen-carbon ratio of 0.161 and a lower heating value of 43 200 joules per gram (18 600 Btu/lb). A limited amount of data was also obtained using natural gas fuel with an average hydrogen-carbon ratio of 0.327 and a lower heating value of 47 800 joules per gram (20 531 Btu/lb).

RESULTS AND DISCUSSION

A summary of the test data is presented in table I. For purposes of comparison with other air pollution sources, and for comparison at different engine operating conditions, it is important that consideration be given to fuel-air ratio. To overcome the difficulty of comparing engines operating at different fuel-air ratios, recent practice has been to relate the emission levels to the fuel consumption. A convenient parameter is an emission index expressed in grams of species per kilogram of fuel. The emission data in the figures in the body of the report are given in emission index. The method of calculating emission index is found in appendix B. Data plots for emission concentration in parts per million by volume (ppm) corresponding to figures 8 to 12 in the body of the report are given in appendix C.

Effect of Improving Fuel Atomization

Prior to examining the effect of pressure, temperature, reference velocity, and fuel-air ratio on combustion efficiency and exhaust emissions, it is instructive to consider the effect of the fuel nozzle on these results. Variations in fuel atomization may result in differences in fuel penetration. Poor fuel atomization leads to large fuel droplets that require increased time for vaporization. As droplet size increases, the vaporization step becomes controlling and thus combustion efficiency may be reduced for a given reactor volume.

The production J-57 dual-orifice fuel nozzle assembly (fig. 3) was used with ASTM A-1 fuel to obtain the majority of the test data reported herein. Many of the reductions in combustion efficiency and increases in hydrocarbon and carbon monoxide emissions that occurred during variation in operating conditions may be traced to poor fuel atomization. Data from reference 8 are presented in figures 7(a) to (d) to illustrate the effect of improving fuel atomization. The model 4 combustor of reference 8 was equipped with air-assist fuel nozzles consisting of the standard dual-orifice fuel nozzle with fuel flowing through the primary side and high pressure air at 144 newtons per square centimeter (166 psi) flowing through the secondary side. Figure 7(a) illustrates the improvement in combustion efficiency obtained with the use of the air-assist fuel nozzle. Combustion efficiency is defined as the ratio of actual temperature rise as determined by averaging 40 exit thermocouples to the theoretical temperature rise determined by the fuel-air ratio and the inlet total temperature and pressure. The accuracy of the combustion efficiency determined in this manner is believed to be within ±3 percent. The improvement in combustion efficiency is greatest at the reduced fuel flows required at low fuel-air ratios. The reduction in hydrocarbon production is shown in figure 7(b). The flame ionization detector used to measure unburned hydrocarbons is calibrated to count carbon atoms, and the result is expressed as parts per million carbon. Some assumption must be made as to the structure of the unburned hydrocarbon molecule to determine the emission index. The assumed form of unburned hydrocarbon was CH_2. At the lower values of the fuel-air ratio and consequent low primary nozzle pressure differential, the reduction in hydrocarbons is greatest. Figure 7(c) shows the reduction in carbon monoxide obtained with the air-assist fuel nozzle. The improvement in fuel atomization with resulting increased combustion efficiency causes the nitric oxide emission to increase as shown in figure 7(d). Nearly all of the oxides of nitrogen produced by turbojet combustors is in the form of nitric oxide with the balance being nitrogen dioxide. However, in time the nitric oxide oxidizes into nitrogen dioxide so current investigators sometimes express nitric oxide emission indexes in terms of equivalent nitrogen dioxide. The oxides of nitrogen data in this report are expressed in terms of equivalent nitric oxide. In order to obtain these data in terms of equivalent nitrogen dioxide one must multiply

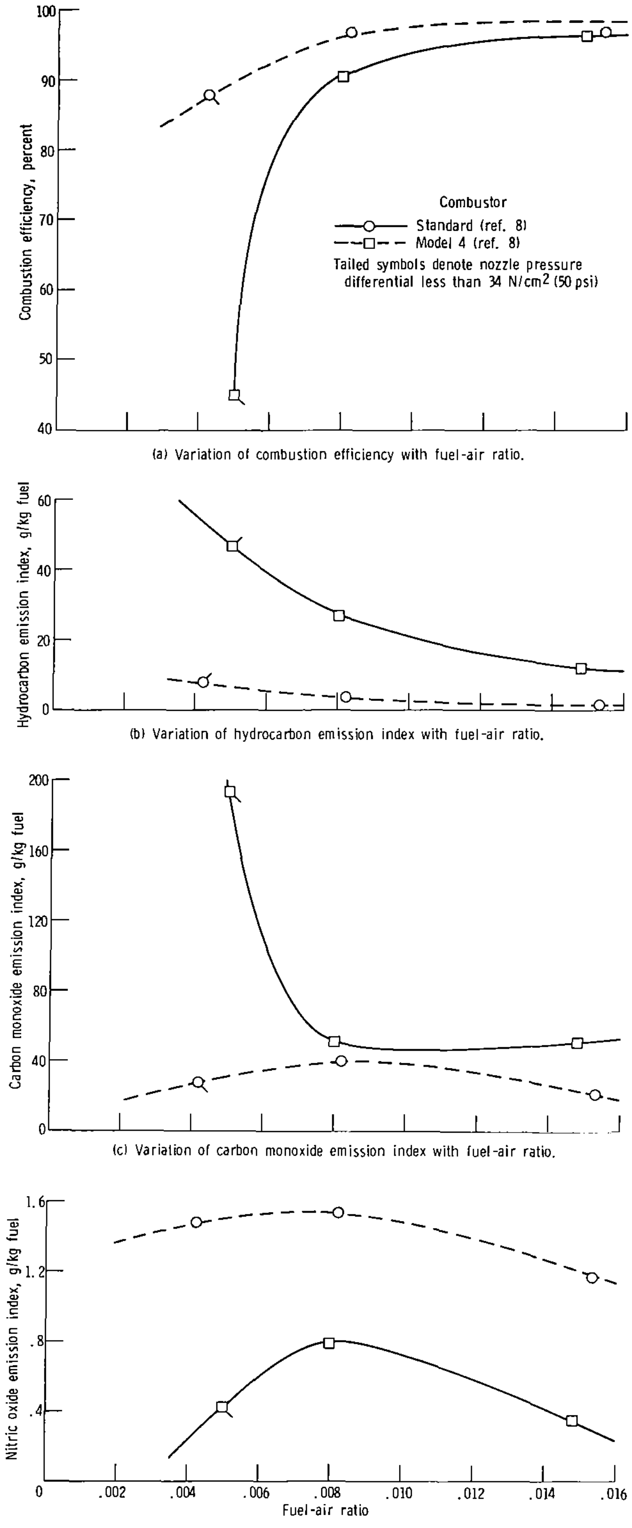


Figure 7. - Data from reference 8 to illustrate effect of improving fuel atomization. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres; inlet total temperature, 420 K (300° F).

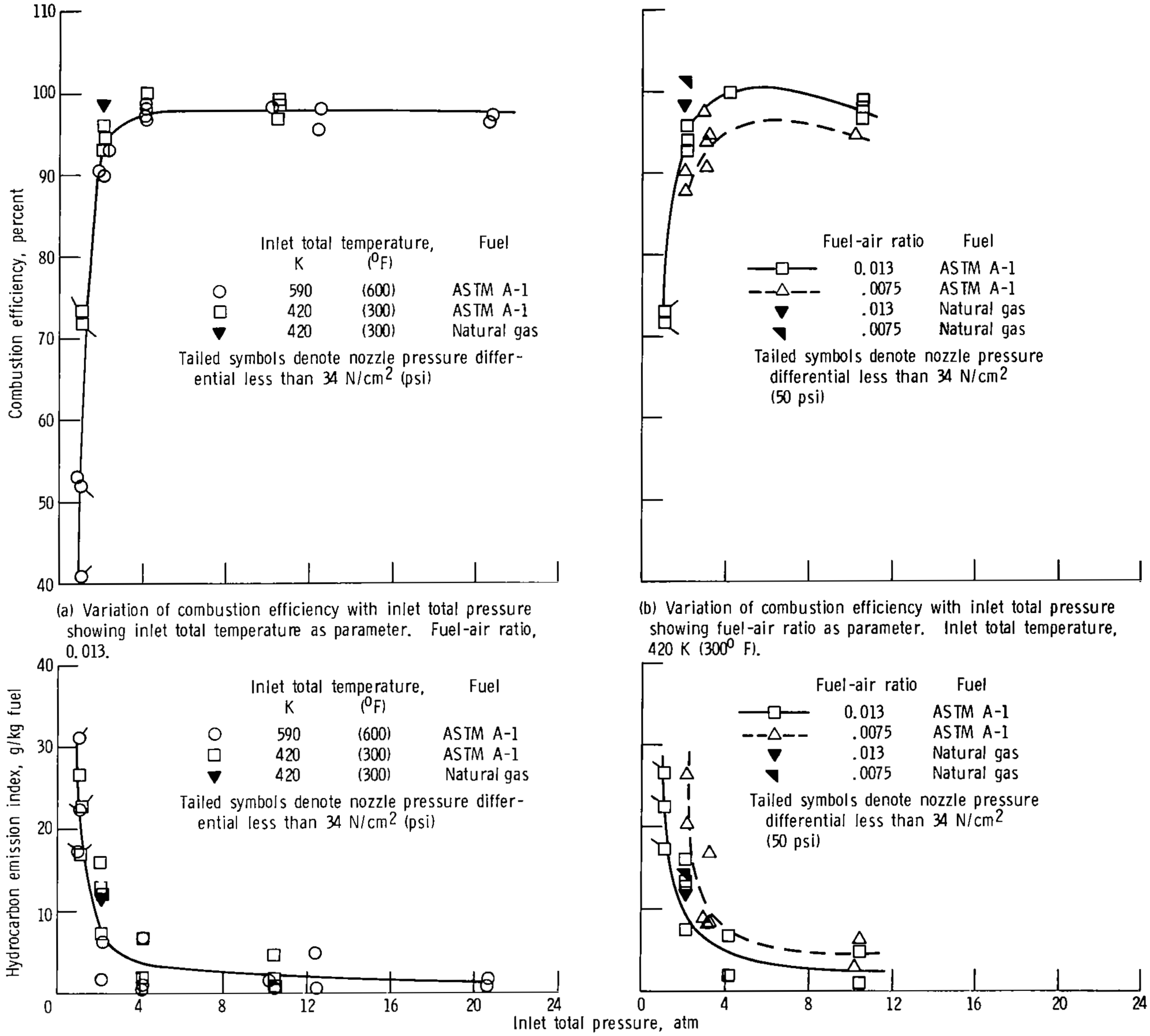
the nitric oxide emission data in this report by the ratio of the molecular weight of nitrogen dioxide to the molecular weight of nitric oxide which is 1.53.

Effect of Combustor Inlet Total Pressure

The effect of combustor inlet total pressure on combustion efficiency and exhaust emissions is shown in figures 8(a) to (h). The data are shown for a 15 meter per second (50 ft/sec) reference velocity. The tailed symbols indicate a nozzle pressure differential of less than 34 newtons per square centimeter (50 psi) and are marked so the effect on combustor performance of poor fuel atomization may be taken into account. Combustion efficiency as a function of inlet total pressure showing the effect of inlet total temperature is plotted in figure 8(a). Fuel-air ratio is 0.013, and data are shown for two inlet total temperatures, 590 and 420 K (600° and 300° F). The low efficiencies at a pressure of 1 atmosphere are due to low nozzle pressure differential as explained in the previous section. The pressure effect on combustion efficiency is not shown to be great except perhaps at pressures below 2 atmospheres where there is a slight downward trend; however, it is difficult to separate the effects of nozzle pressure differential and data scatter from the effects of inlet total pressure. The single data point for natural gas fuel adds further evidence that the effect of inlet total pressure is small above 2 atmospheres when fuel atomization and vaporization are not limiting steps. Variations in combustion efficiency with inlet total pressure showing fuel-air ratio as a parameter are shown in figure 8(b). Inlet total temperature is 420 K (300° F). The data at 0.0075 fuel-air ratio have a somewhat lower combustion efficiency trend than the data at 0.013 fuel-air ratio; however, the effect of inlet total pressure for these data is still not great. The single data point for natural gas fuel at a 0.0075 fuel-air ratio is considerably higher than the corresponding ASTM A-1 fuel data at the same fuel-air ratio.

The effect of inlet total pressure on combustion efficiency at values below a pressure of 1 atmosphere was not investigated since present day aircraft gas turbine combustors are generally not required to operate at subatmospheric pressures except during altitude windmill relight. Previous results such as presented in reference 7 indicate that the reduction in combustion efficiency becomes more significant as the inlet total pressure is lowered below 1 atmosphere.

As would be expected from the combustion efficiency data, the hydrocarbon emission data presented in figure 8(c) show the opposite trend as that shown in figures 8(a) and (b). The fuel-air ratio in figure 8(c) is 0.013 and the inlet total temperatures are 590 and 420 K (600° and 300° F). There is no apparent difference noted in hydrocarbon emission for this temperature range. High values of hydrocarbon emission index at low pressures are thought due to poor fuel atomization as shown by the tailed symbols. At an inlet total



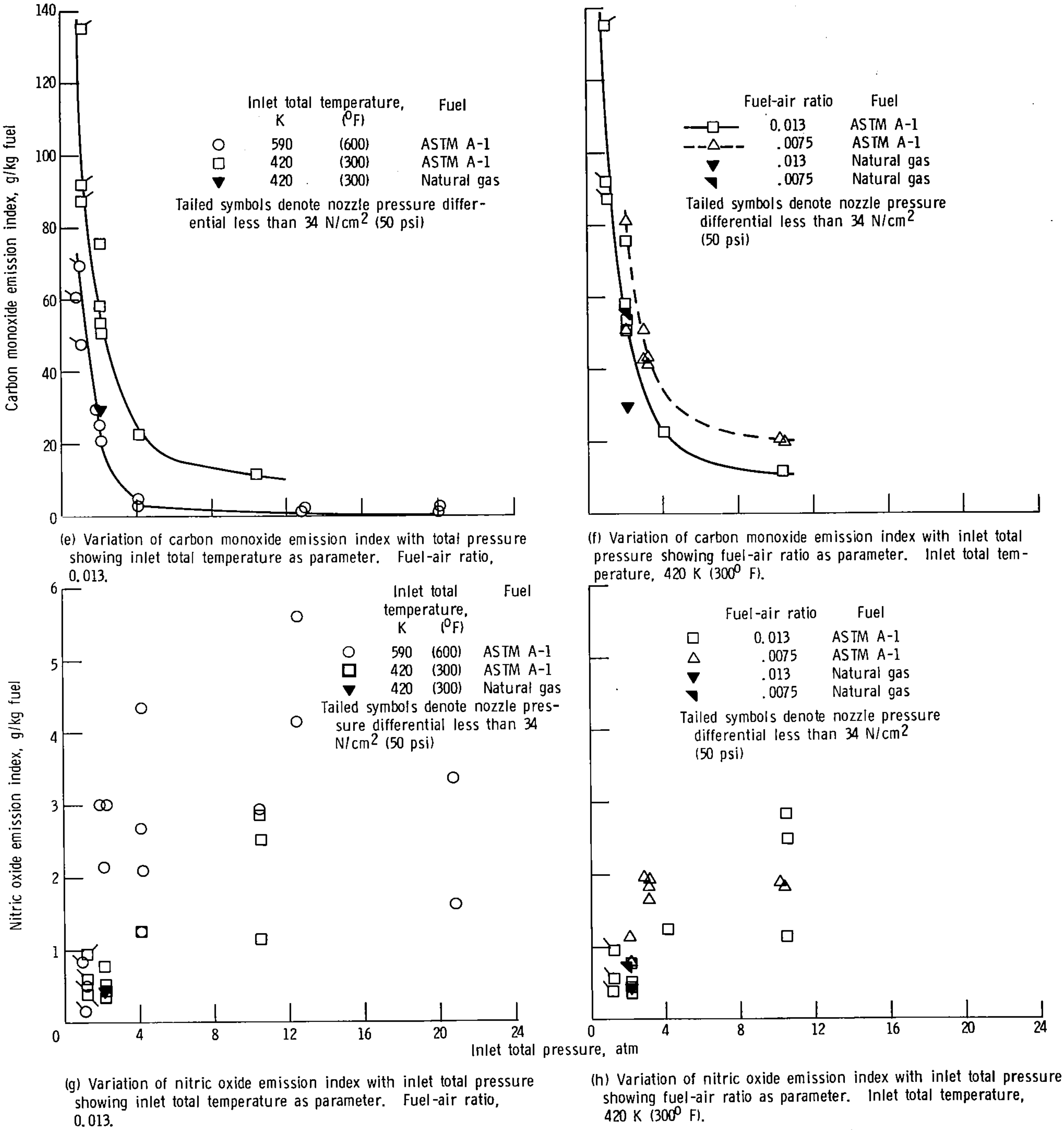
(a) Variation of combustion efficiency with inlet total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(b) Variation of combustion efficiency with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

(c) Variation of hydrocarbon emission index with inlet total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(d) Variation of hydrocarbon emission index with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

Figure 8. - Effect of combustor inlet total pressure on combustion efficiency and exhaust emissions. Reference velocity, 15 meters per second (50 ft/sec).



(e) Variation of carbon monoxide emission index with total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(f) Variation of carbon monoxide emission index with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

(g) Variation of nitric oxide emission index with inlet total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(h) Variation of nitric oxide emission index with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

Figure 8. - Concluded.

pressure of 20 atmospheres, hydrocarbon emissions are less than 3 grams per kilogram fuel at an inlet total temperature of 590 K (600° F). Figure 8(d) shows the effect of variations in hydrocarbon emissions as a function of inlet total pressure with fuel-air ratio as a parameter. Inlet total temperature is 420 K (300° F). The hydrocarbon emissions are reduced sharply as inlet total pressure is increased from 1 to 4 atmospheres partly because of poor fuel atomization as indicated by the tailed symbols. There is a slight trend for the hydrocarbon emissions to increase as the fuel-air ratio is reduced to 0.0075 corresponding to the trend shown in figure 8(b). The natural gas fuel results fall into the same general trend as the ASTM A-1 fueled combustor data.

Carbon monoxide emission data as functions of combustor inlet total pressure are shown in figure 8(e). Fuel-air ratio is 0.013 and inlet temperatures are 590 and 420 K (600° and 300° F). The data follow the same sharp downward trend as the hydrocarbon emission data as the inlet total pressure is increased from 1 to 4 atmospheres. At the higher inlet total temperature of 590 K (600° F), less carbon monoxide is emitted than for the data at 420 K (300° F) at any constant pressure. Values of carbon monoxide emission index are below 2 grams per kilogram fuel at inlet total pressure above 4 atmospheres for the data taken at the higher inlet total temperature. Figure 8(f) shows that a variation in fuel-air ratio with the inlet total temperature fixed at 420 K (300° F) produces little change in carbon monoxide emission with inlet total pressure. It may be expected that the lower fuel-air ratio data will show higher carbon monoxide levels. This is likely due to the lean burning conditions.

The nitric oxide emission data described in this report suffer from a high degree of random variation causing uncertainties in making a clear-cut correlation with combustor operating conditions. The low nitric oxide emissions encountered in the data cause the analytic techniques used to be somewhat compromised in accuracy. Better methods of analysis and improved sampling accuracy are required to improve the quality of the nitric oxide emission data.

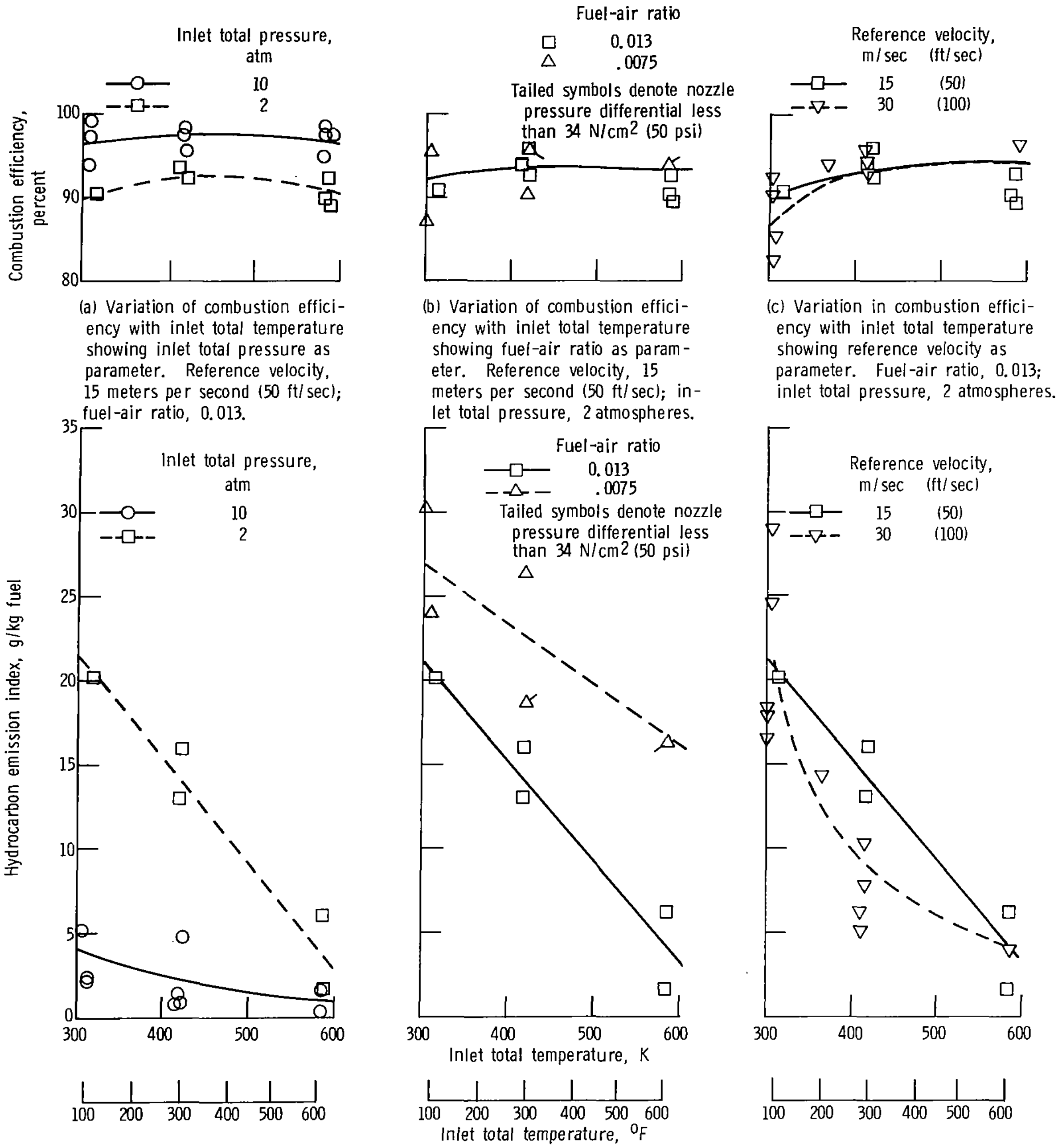
There is considerable scatter in the nitric oxide emission data shown plotted in figure 8(g) for a fuel-air ratio of 0.013 and inlet total temperatures of 590 and 420 K (600° and 300° F). Part of the scatter may be attributed to sampling error in measuring concentrations as low as 10 ppm or less. An exhaust concentration of 10 ppm corresponds to an emission index of 0.82 at a fuel-air ratio of 0.013. The data are always below an emission index of 1 at an inlet pressure of 1 atmosphere. As the inlet total pressure is increased above 2 atmospheres, the emission index shows a generally increasing trend reaching a maximum of 5.6 for an inlet total temperature of 590 K (600° F) at an inlet total pressure of 12 atmospheres. The 590 K (600° F) inlet total temperature data exhibit a higher nitric oxide emission trend than the data at 420 K (300° F). The upward trend in the nitric oxide emission data with increasing inlet total pressure may be partly attributed to improved combustion efficiencies as a result of better fuel atomization due to higher fuel nozzle pressure differentials. Varying the fuel-air ratio from 0.0075 to 0.013 has little effect on nitric oxide emission as shown in figure 8(h).

Effect of Inlet Total Temperature

Variations in combustion efficiency and exhaust emission with combustor inlet total temperature are shown in figures 9(a) to (k). Combustion efficiency does not show a very great variation with increasing combustor inlet total temperature for inlet total pressures of 2 and 10 atmospheres as shown in figure 9(a). Fuel-air ratio is 0.013 and reference velocity is 15 meters per second (50 ft/sec). The combustion efficiency was almost 5 percent higher at an inlet total pressure of 10 atmospheres than at 2 atmospheres. Combustion efficiency as a function of inlet total temperature showing fuel-air ratio as a parameter is shown in figure 9(b). Inlet total pressure is 2 atmospheres and reference velocity is 15 meters per second (50 ft/sec). Changes in fuel-air ratio had a negligible effect on combustion efficiency. Increases in reference velocity have a slight effect on combustion efficiency as illustrated by figure 9(c). The data shown are for a fuel-air ratio of 0.013 and an inlet total pressure of 2 atmospheres. The combination of low inlet total temperatures and low residence times caused by relatively high reference velocities is shown to cause reductions in combustion efficiency at the lower inlet total temperatures.

Variation in hydrocarbon emission index with combustor inlet total temperature is plotted in figure 9(d). Reference velocity is 15 meters per second (50 ft/sec) and fuel-air ratio is 0.013. The data show a linear decrease in hydrocarbon emission as the inlet-total temperature is increased. The data at an inlet total pressure of 2 atmospheres is four to six times higher than the data at 10 atmospheres, and the data have a steeper slope as inlet total temperature is reduced. Variations in hydrocarbon emission with inlet total temperature showing fuel-air ratio as a parameter are shown in figure 9(e). Reference velocity is 15 meters per second (50 ft/sec) and inlet total pressure is 2 atmospheres. The data at a fuel-air ratio of 0.0075 are higher than the data at 0.013; however, the data exhibit similar trends. As expected from figure 9(d), they both decrease with increasing inlet air temperature. Figure 9(f) demonstrates the effect of reference velocity on hydrocarbon emissions with inlet total temperature. Inlet total pressure is 2 atmospheres and fuel-air ratio is 0.013 for these data. The difference in the curves is perhaps due to improved mixing at the higher reference velocity.

Changes in carbon monoxide emission with combustor inlet total temperature are shown in figure 9(g). The fuel-air ratio for this plot is 0.013 and the reference velocity 15 meters per second (50 ft/sec). As with the hydrocarbon data, carbon monoxide emission decreases markedly as the inlet total temperature is increased. The data at an



(a) Variation of combustion efficiency with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(b) Variation of combustion efficiency with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

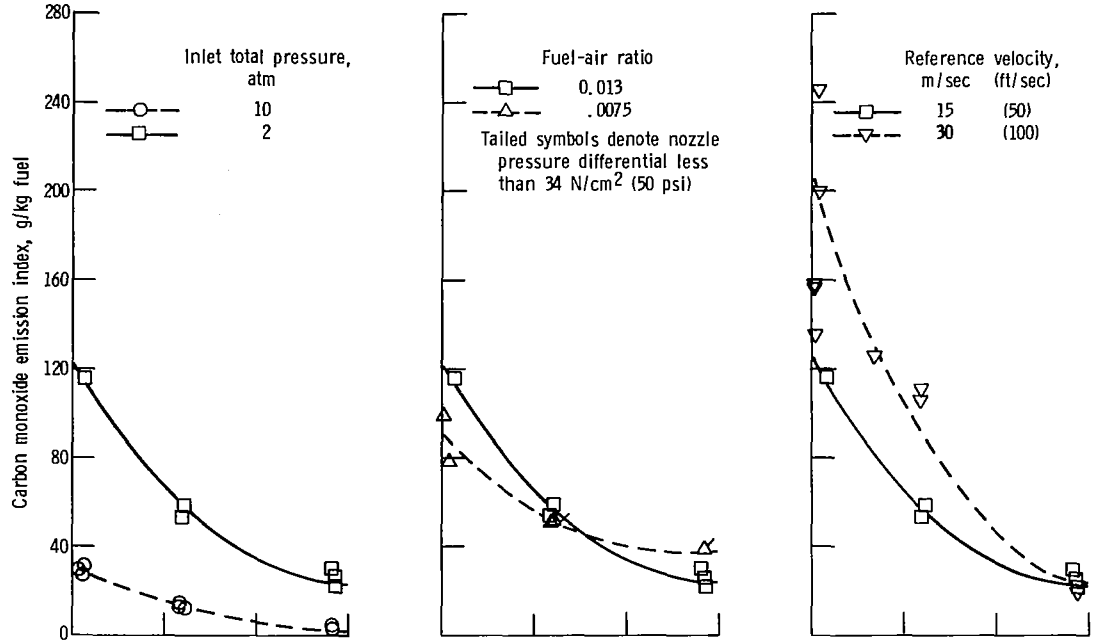
(c) Variation in combustion efficiency with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(d) Variation of hydrocarbon emission index with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(e) Variation of hydrocarbon emission index with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

(f) Variation of hydrocarbon emission index with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

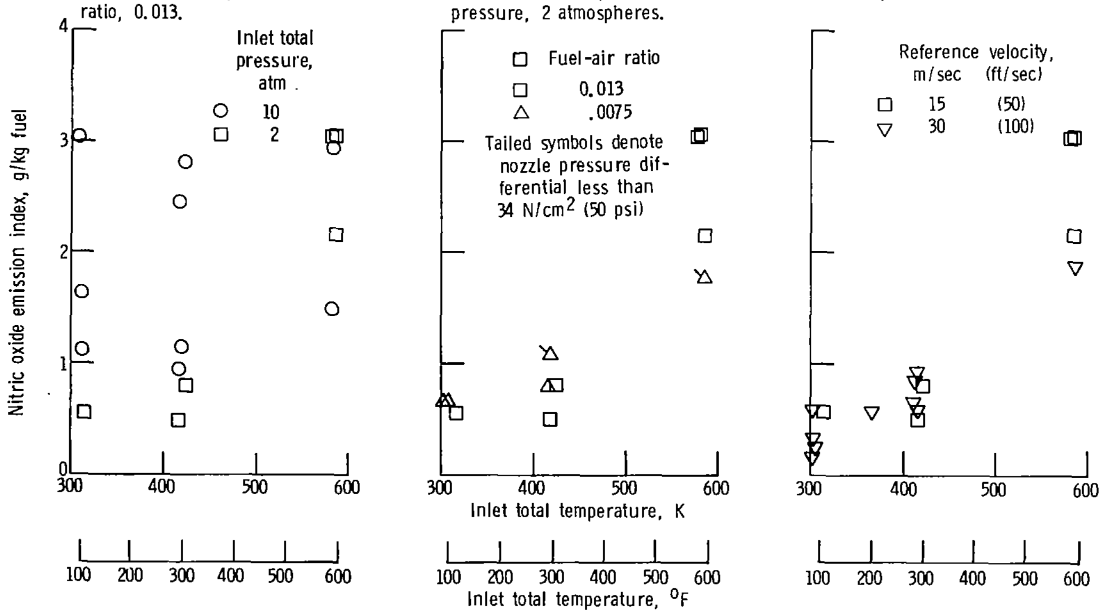
Figure 9. - Variations in combustion efficiency and exhaust emissions with inlet total temperature.



(g) Variation of carbon monoxide emission index with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(h) Variation of carbon monoxide emission index with inlet total temperature showing effect of fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

(i) Variation of carbon monoxide emission index with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.



(j) Variation of nitric oxide emission index with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(k) Variation of nitric oxide emission index with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

(l) Variation of nitric oxide emission index with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

Figure 9. - Concluded.

inlet total pressure of 2 atmospheres are shown to be higher in magnitude and to have a steeper slope than the data at an inlet total pressure of 10 atmospheres. Fuel-air ratio variation on the plot of carbon monoxide emissions with combustor inlet total temperature is shown in figure 9(h). For these data, inlet total pressure is 2 atmospheres and reference velocity is 15 meters per second (50 ft/sec). Unlike the hydrocarbon emission data, the carbon monoxide emission in this plot is not strongly effected by fuel-air ratio. The effect of variations in reference velocity on carbon monoxide emission with inlet total temperature is shown in figure 9(i). Inlet total pressure is 2 atmospheres and fuel-air ratio is 0.013. The data at the higher reference velocity (30 m/sec (100 ft/sec)) show a higher level of carbon monoxide emission than the data at the lower reference velocity (15 m/sec (50 ft/sec)) thus providing a good correlation with the combustion efficiency data.

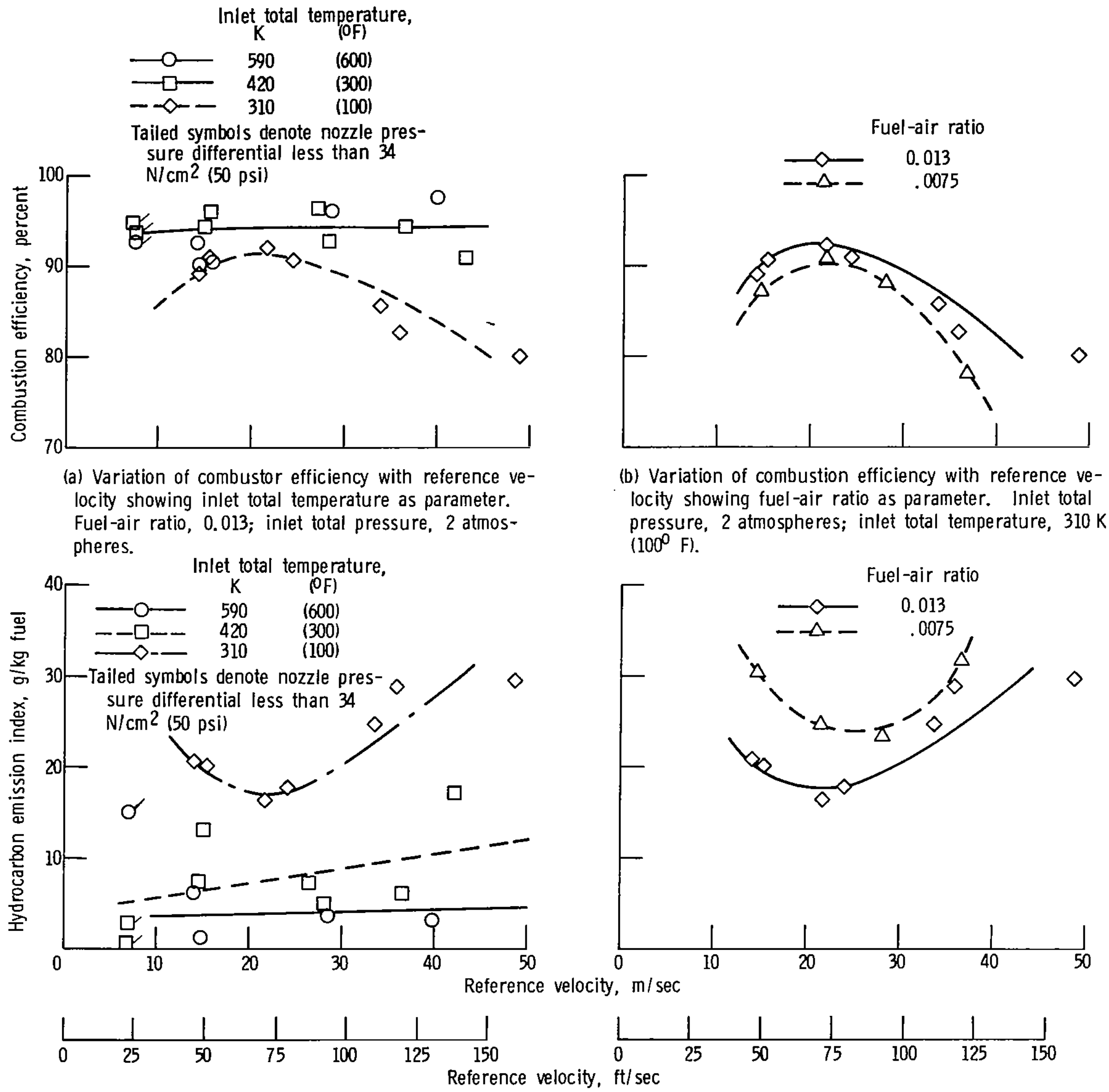
Variation of nitric oxide emission index with inlet total temperature is shown in figure 9(j). Fuel-air ratio is 0.013 and reference velocity is 15 meters per second (50 ft/sec). There is a distinct upward trend in the data at an inlet total pressure of 2 atmospheres, which confirms the findings of reference 10. The data at an inlet total pressure of 10 atmospheres tend to be higher than the data at an inlet total pressure of 2 atmospheres and they do not appear to have any variation with inlet total temperature. This may be attributed to higher primary zone temperatures due to higher combustion efficiency. Variations in fuel-air ratio in the plot of nitric oxide emission with combustor inlet total temperature are shown in figure 9(k). Reference velocity is 15 meters per second (50 ft/sec) and inlet total pressure is 2 atmospheres. There is an increase in nitric oxide formation as fuel-air ratio is increased at the 590 K (600° F) inlet air condition as expected. This is because of the higher primary zone temperature. However, at lower inlet air temperatures, the lower fuel-air ratio produced more nitric oxide than the higher fuel-air ratio. This is an unexpected result. The little effect of fuel-air ratio may be obscured by the data accuracy. The effect of changes in reference velocity on nitric oxide formation with inlet total temperature is shown in figure 9(l). The fuel-air ratio is 0.013 and the inlet total pressure is 2 atmospheres. At a reference velocity of 30 meters per second (100 ft/sec) the formation of nitric oxide is reduced from the amount formed at 15 meters per second (50 ft/sec) especially as the inlet total temperature is increased to 590 K (600° F). This may be attributed to the adverse effect on formation rate because of a decrease in primary zone dwell time caused by the increased reference velocity.

Effect of Reference Velocity

The effect of reference velocity on combustion efficiency and exhaust emissions is shown in figures 10(a) to (h). Reference velocity is defined as the total combustor airflow divided by the product of the combustor inlet density and maximum cross-sectional area. Figure 10(a) shows a plot of the variation in combustion efficiency with reference velocity with inlet total temperature as a parameter for a fuel-air ratio of 0.013 and a combustor inlet pressure of 2 atmospheres. No significant effect of reference velocity on combustion efficiency is apparent at inlet total temperatures of 590 and 420 K (600° and 300° F). However, at an inlet total temperature of 310 K (100° F), there appears to be a relatively strong effect of reference velocity on combustion efficiency. Combustion efficiency decreases from about 90 to 80 percent as reference velocity is increased from about 23 to 46 meters per second (75 to 150 ft/sec). Also, the data at 310 K (100° F) indicate that the combustion efficiency falls off slightly as reference velocity is reduced from 23 to 15 meters per second (75 to 50 ft/sec). Previous results have shown that for most combustors combustion efficiency decreases with increasing reference velocity; however, for some combustors, a maximum value of combustion efficiency occurs at a specific value of reference velocity and will then decrease as reference velocity is either increased or decreased. A reduction in combustion efficiency with increasing reference velocity may be attributed to a reduction in flame stability and dwell time, while a reduction in combustion efficiency with decreasing reference velocity may be attributed to either poor mixing as the result of a lowering in combustor pressure drop or to poor fuel atomization as a result of a lowering in fuel nozzle pressure differential as fuel flow is lowered. Figure 10(b) shows the effect of fuel-air ratio on the data at 310 K (100° F) with an inlet total pressure of 2 atmospheres. The curve for a fuel-air ratio of 0.0075 has a similar shape to the curve for a fuel air ratio of 0.013; however, the efficiency at a fuel-air ratio of 0.0075 is generally lower.

Hydrocarbon emission data with reference velocity are shown in figure 10(c) for an inlet total pressure of 2 atmospheres and a fuel-air ratio of 0.013. Hydrocarbon emissions increase with a decreasing inlet total temperature. The data at 590 and 420 K (600° and 300° F) show a slight upward trend as reference velocity is increased. The curve for the data at 310 K (100° F) has the reverse shape as the combustion efficiency for the same inlet total temperature and shows a minimum value at the same value of reference velocity where a maximum in the combustion efficiency occurred. Figure 10(d) shows the effect of varying the fuel-air ratio on the data taken at 310 K (100° F) inlet total temperature. Although the curve for the data at a fuel-air ratio of 0.0075 has the same shape as the curve for the data at a fuel-air ratio of 0.013, the 0.0075 fuel-air ratio data has a higher emission trend.

Carbon monoxide emissions with reference velocity for a fuel-air ratio of 0.013 and an inlet total pressure of 2 atmospheres are shown in figure 10(e). The data are similar to the hydrocarbon emission data because the emissions increase with decreasing inlet total temperature. However, the rate of increase in carbon monoxide emission with increasing reference velocity is greater than for the hydrocarbon emission data. Also, the data at 310 K (100° F) continuously increase with increasing reference velocity in-



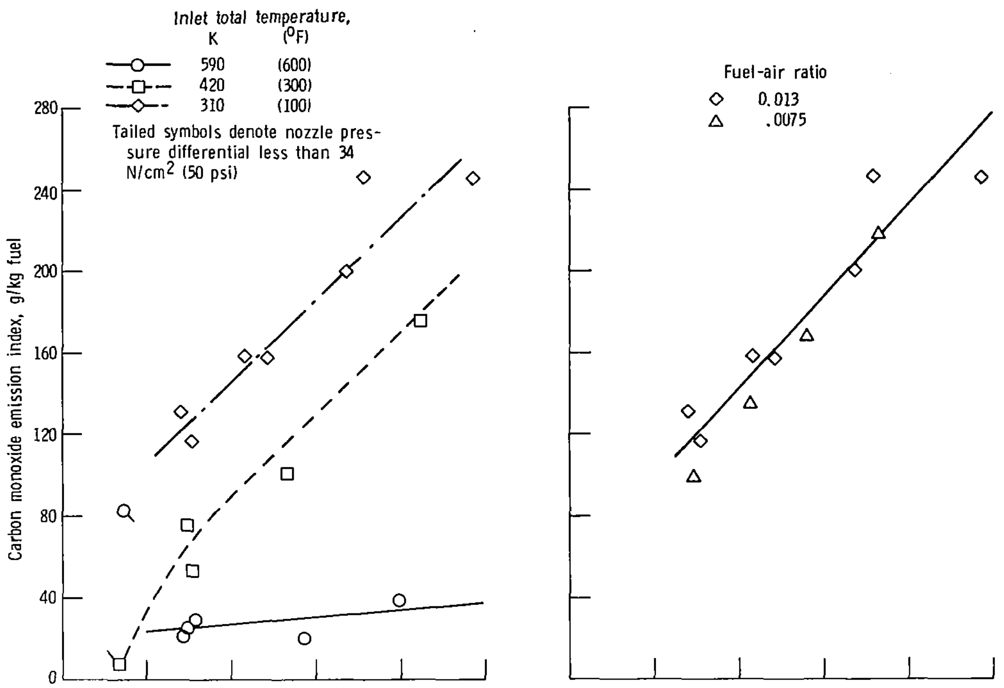
(a) Variation of combustor efficiency with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(b) Variation of combustion efficiency with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet total temperature, 310 K (100° F).

(c) Variation of hydrocarbon emission index with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

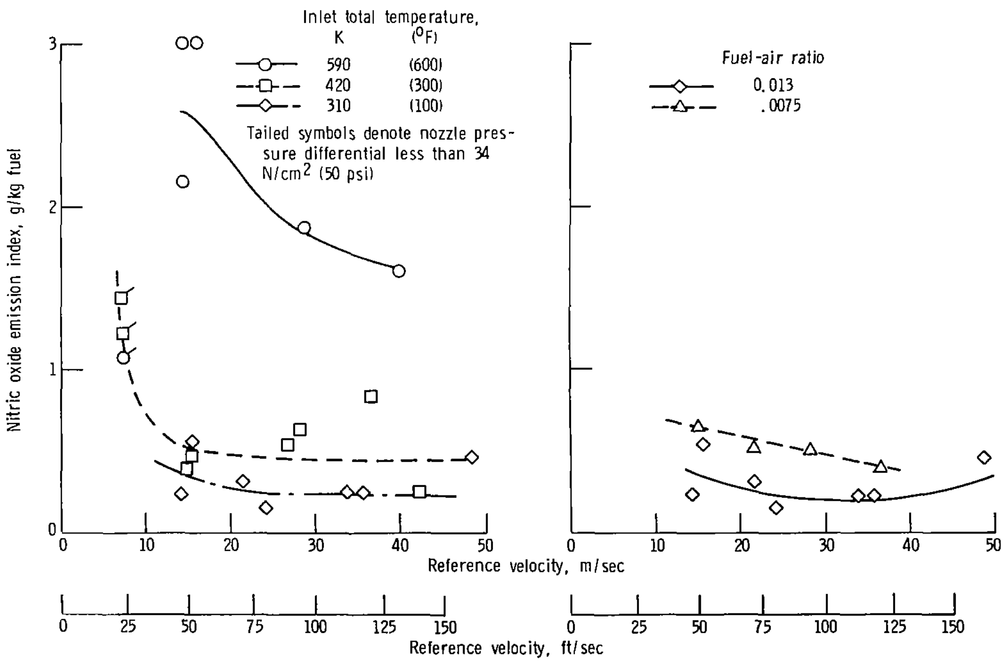
(d) Variation of hydrocarbon emission index with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet temperature, 310 K (100° F).

Figure 10. - Effect of reference velocity on combustion efficiency and exhaust emissions.



(e) Variation of carbon monoxide emission index with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(f) Variation of carbon monoxide emission index with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet total temperature, 310 K (100° F).



(g) Variation of nitric oxide emission index with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(h) Variation of nitric oxide emission index with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet total temperature, 310 K (100° F).

Figure 10. - Concluded.

stead of reaching a minimum value as in the hydrocarbon emission data. This may be attributed to the strong effect that combustor dwell time has on the oxidation of carbon monoxide formed in the primary zone. As combustor dwell time is reduced, lesser amounts of carbon monoxide are oxidized to carbon dioxide. As shown in figure 10(f), reductions in fuel-air ratio for the data at 310 K (100° F) have no discernible effect on carbon monoxide emissions.

The effect of reference velocity on emissions of nitric oxide is shown in figure 10(g). Combustor inlet total pressure is 2 atmospheres and fuel-air ratio is 0.013. Combustor inlet total temperature is shown to strongly effect the nitric oxide formation rate with the higher inlet total temperatures showing increased formation rate. A single flagged data point at 590 K (600° F) inlet total temperature was not used in drawing the curve. As the reference velocity is increased, combustor dwell time is reduced and nitric oxide emission decreases for all the values of combustor inlet total temperatures shown in figure 10(g). The data at an inlet total temperature of 590 K (600° F) show a steeper reduction in nitric oxide emission as reference velocity is increased than the data at an inlet total temperature of 420 or 310 K (300° or 100° F). The effect of a reduction in fuel-air ratio on the nitric oxide emission at an inlet total temperature of 310 K (100° F) is shown in figure 10(h). Reducing the fuel-air ratio from 0.013 to 0.0075 increases the nitric oxide emission. It would be expected that a reduction in fuel-air ratios would result in reduced nitric oxide formation because of the decrease in primary zone temperature. This anomaly may be due to errors in measuring nitric oxide concentrations below 10 ppm.

Effect of Fuel-Air Ratio

Variations in combustion efficiency and exhaust emissions with fuel-air ratio are shown plotted in figure 11(a) to (h). Combustion efficiency variations with fuel-air ratio for inlet total pressures of 2 and 10 atmospheres are plotted in figure 11(a). Inlet total temperature is 420 K (300° F) and reference velocity is 15 meters per second (50 ft/sec). The data for an inlet total pressure of 10 atmospheres give higher efficiencies than the data at 2 atmospheres. Also, with the higher inlet pressure, combustion efficiency does not decrease rapidly as fuel-air ratio is reduced below 0.010. At an inlet total pressure of 2 atmospheres, the reduction in combustion efficiency with decreasing fuel-air ratio is partially due to reducing nozzle pressure differentials causing poor fuel atomization. The natural gas data at an inlet total pressure of 2 atmospheres and an inlet total temperature of 420 K (300° F), which is not affected by fuel atomization or vaporization controlling steps, are considerably higher in combustion efficiency than the data for ASTM A-1 fuel at corresponding conditions. The reduction in combustion efficiency as fuel-air ratio is reduced may be attributed to the formation of fuel-air mixtures in the primary zone that are too lean to burn in addition to the influence of poor fuel atomization. Data were not obtained beyond a fuel-air ratio of 0.0155; however, it would be expected that as the fuel-air ratio is further increased, a fuel-air ratio would be eventually reached at which combustion efficiency would start to decline because of either fuel enrichment or volumetric heat release limits. Figure 11(b) shows the effect of inlet total temperature on combustion efficiency with fuel-air ratio. Reference velocity is 15 meters per second (50 ft/sec) and inlet total pressure is 2 atmospheres. Within the accuracy of the combustion efficiency data (±3 percent), there is no significant increase in efficiency with fuel-air ratio as the inlet total temperature is increased from 370 to 590 K (200° to 600° F).

Variations of hydrocarbon emission index with fuel-air ratio are shown in figure 11(c). Reference velocity is 15 meters per second (50 ft/sec) and inlet total temperature is 420 K (300° F). The hydrocarbon emissions correlated with the combustion efficiency data are strongly a function of inlet total pressure with the data at 2 atmospheres exhibiting a much higher trend than the data at 10 atmospheres. The hydrocarbon emission data at an inlet total pressure of 10 atmospheres is not a function of fuel-air ratio, while the data at an inlet total pressure of 2 atmospheres is a strong inverse function of fuel-air ratio. The data on hydrocarbon emissions as a function of fuel-air ratio in figure 11(d) show that as inlet total temperature is increased the hydrocarbon emissions decrease.

The effect of fuel-air ratio on carbon monoxide emissions with inlet total pressure as a parameter is shown in figure 11(e). Reference velocity is 15 meters per second (50 ft/sec) and inlet total temperature is 420 K (300° F). As was the case with the hydrocarbon emission data, the carbon monoxide data for conditions of high inlet pressure were lower than the data for low inlet pressure. Carbon monoxide emission is not a function of fuel-air ratio for the range of conditions tested. This is not unexpected since the effect of lower fuel-air ratios should be poor fuel atomization and formation of lean mixtures below the flammability limit. Lower fuel-air ratios should not necessarily affect the rate of oxidation of carbon monoxide to carbon dioxide except by a reduction of the reaction zone temperature because of lower combustion efficiency. An illustration of the effect of the combustor inlet temperature parameter on the variations of carbon monoxide with fuel-air ratio is found in figure 11(f). As the inlet temperature is increased to 590 K (600° F), the carbon monoxide emissions are reduced from their level at the lower inlet total temperatures and are a slight inverse function of fuel-air ratio.

Variation in nitric oxide emission index as a function of fuel-air ratio with inlet total pressure as the parameter is plotted in figure 11(g). Reference velocity is 15 meters per second (50 ft/sec) and inlet total temperature is 420 K (300° F). As with the previous nitric oxide emission data presented, the scatter in the data may be partially attributed to sampling error in measuring concentrations of 10 ppm or less. The data

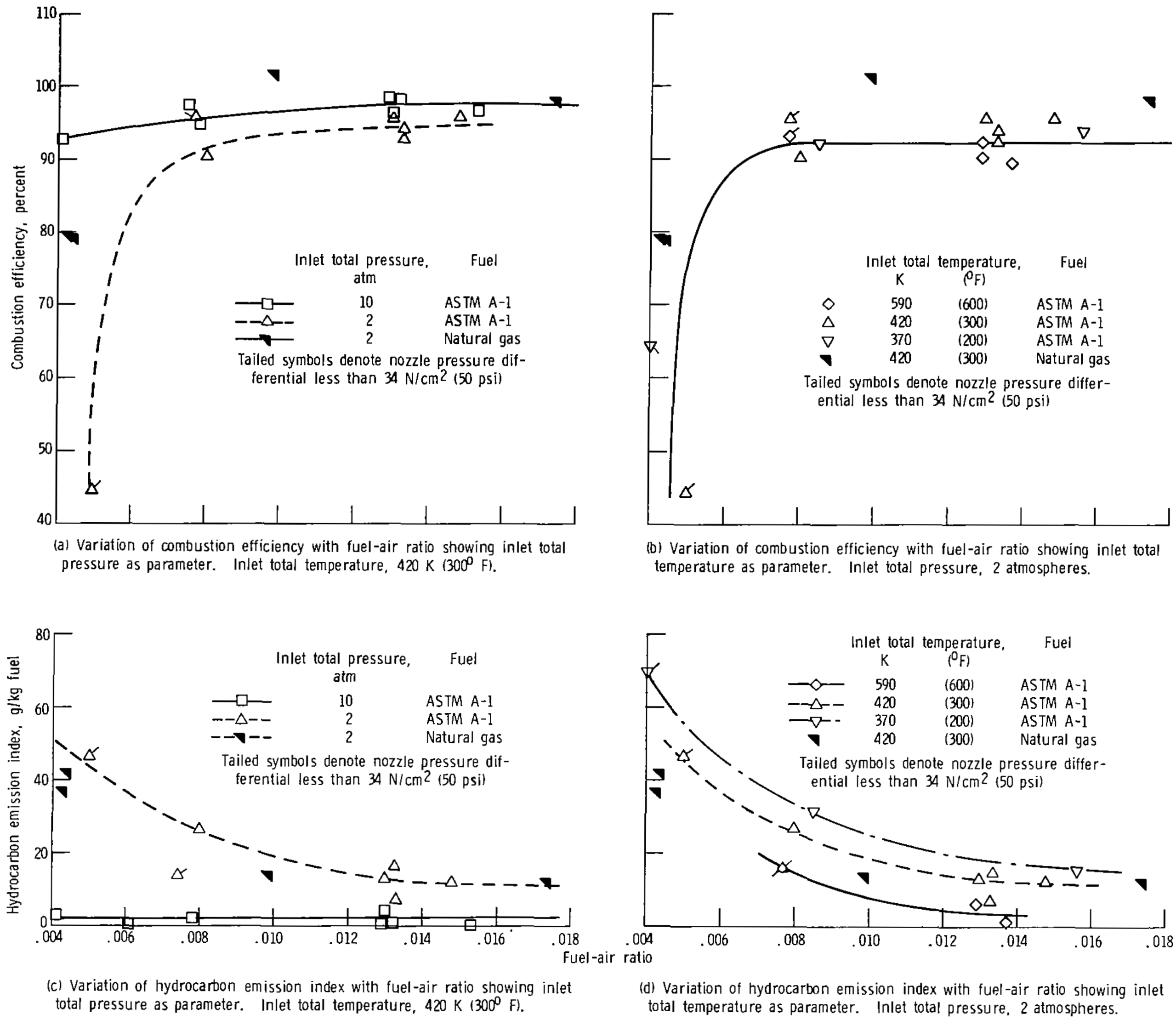
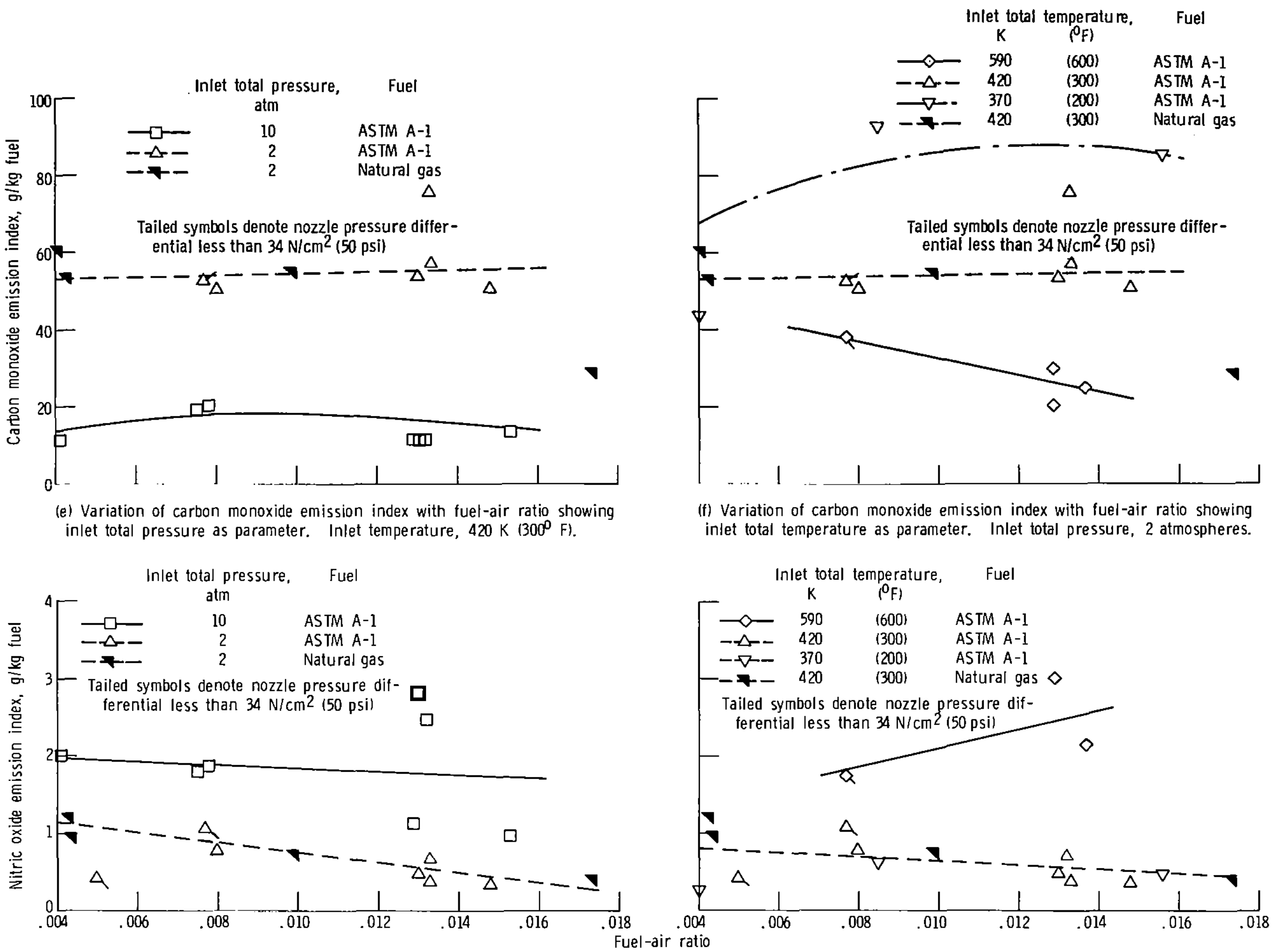


Figure 11. - Variations in combustion efficiency and exhaust emissions with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec).



(e) Variation of carbon monoxide emission index with fuel-air ratio showing inlet total pressure as parameter. Inlet temperature, 420 K (300° F).

(f) Variation of carbon monoxide emission index with fuel-air ratio showing inlet total temperature as parameter. Inlet total pressure, 2 atmospheres.

(g) Variation of nitric oxide emission index with fuel-air ratio showing inlet total pressure as parameter. Inlet total temperature, 420 K (300° F).

(h) Variation of nitric oxide emission index with fuel-air ratio showing inlet total temperature as parameter. Inlet total pressure, 2 atmospheres.

Figure 11. - Concluded.

exhibit the reverse trend when compared to the hydrocarbon and carbon monoxide emission data. More efficient burning (i. e., high efficiency and low emissions in unburned products) means higher primary zone temperatures with resulting increases in nitric oxide formation. In most cases, high combustor loading (i. e., high inlet pressure) resulted in nitric oxide emission above 2.0 grams per kilogram fuel. At the lower inlet total pressures (2 atmospheres) the data were below 1 gram per kilogram fuel. Figure 11(h) has plotted nitric oxide emission with fuel-air ratio, inlet total temperature being a parameter. Reference velocity is 15 meters per second (50 ft/sec) and inlet total pressure is 2 atmospheres. Nitric oxide is formed in higher levels and is a slight function of fuel-air ratio as the inlet total temperature is increased to 590 K (600° F). The data at an inlet total temperature of 370 K (200° F) are grouped with the data at 420 K (300° F). These data are generally below 1 gram per kilogram fuel.

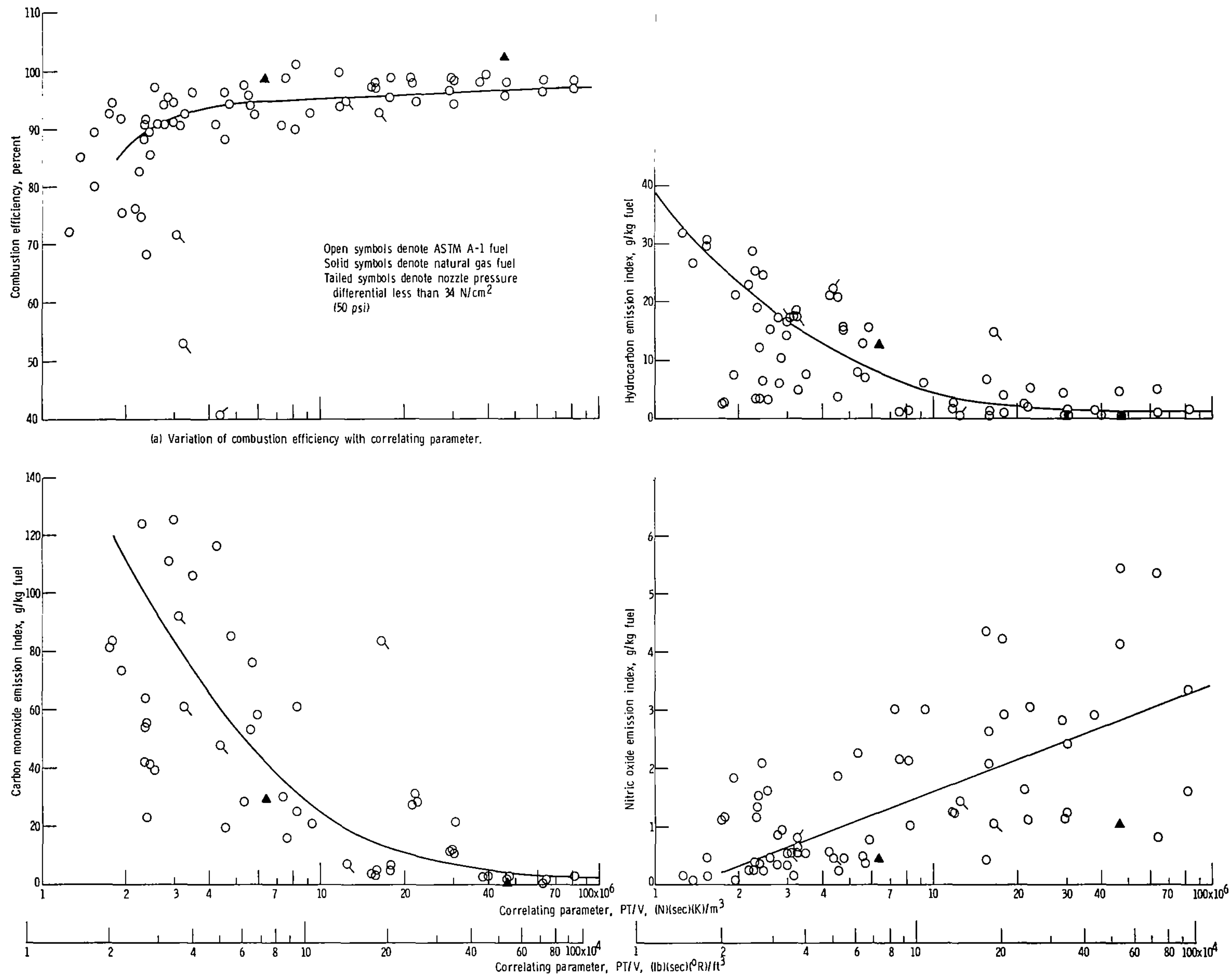
Effect of Correlating Parameter (PT/V)

Combustion efficiency is plotted in figure 12(a) against a correlating parameter made up of inlet pressure (P) multiplied by inlet temperature (T) and the result divided by reference velocity (V). Previous reports (ref. 9) have used this parameter to correlate combustor efficiency data. All combustors display a similar trend with this parameter; however, only the data for a given combustor design operating at a given fuel-air ratio may be represented by a single curve. There is a trend for the data to group together with the lower values of efficiency falling at the lower values of the correlating parameter. In some cases, the drop in efficiency at low values of correlating parameter is due to poor fuel atomization because of low fuel nozzle pressure differentials as indicated by the tailed symbols. The data affected by poor fuel atomization would not be expected to follow the trend of the correlation.

Variation of hydrocarbon emission with the correlating parameter is presented in figure 12(b). As expected, these data reflect the reverse trend of the efficiency data variation with the correlating parameter. Although considerable scatter exists in the data, especially at low values of the correlating parameter, the hydrocarbon emissions increase markedly as the correlating parameter is reduced below about 10×10^{6} newtons-seconds - degrees K per cubic meter (11.4×10^{4} (lb)(sec)($^{\circ}$R)/ft^{3}).

Carbon monoxide emission against the correlating parameter is shown in figure 12(c). The same discussion applies to these data as those of figure 12(b). There is less scatter in the data at high values of correlating parameter.

Emission data for nitric oxide variation with the correlation parameter is shown in figure 12(d). There is scatter in these data throughout the range of correlating parameters shown. One trend is nevertheless apparent. At values of correlating parameter



(a) Variation of combustion efficiency with correlating parameter.

(c) Variation of carbon monoxide emission index with correlating parameter.

(d) Variation of nitric oxide emission index with correlating parameter.

Figure 12. - Variation of combustion efficiency and exhaust emission with correlating parameter PT/V. Fuel-air ratio, 0.013.

below 10×10^6 newtons-seconds - degrees K per cubic meter (11.4×10^4 (lb)(sec)($^{\circ}$R)/ft^3), nitric oxide emission is in most cases below 1.5 grams per kilogram fuel. At higher values of correlating parameter, corresponding to higher combustion efficiencies and inlet temperatures, the nitric oxide emissions generally fall above 1.5 grams per kilogram fuel. These data show the reverse of the trend observed in the plots of unburned product emissions.

Sample Validity

On a portion of the data taken, the exhaust concentrations of carbon dioxide and hydrogen were also measured. A check can be made on sampling validity by calculating the fuel-air ratio based on a mass balance of exhaust constituents containing carbon. A ratio can then be made of the fuel-air ratio obtained by this method $(F/A)_{GS}$ called the gas sample fuel-air ratio and the fuel-air ratio determined by measured flow rates of fuel and air $(F/A)_m$. This ratio should be close to unity if the sample of combustion products taken by the sampling probes is a valid representation of the exhaust products. Calculation can also be made as to the percent inefficiency caused by exhaust concentrations of carbon monoxide, hydrogen, and unburned hydrocarbons. A component efficiency based on the individual concentrations of hydrocarbons, carbon monoxide, and hydrogen were calculated for each data point. The efficiency based on the exit thermocouples η_{TC} can then be compared to the efficiency as determined by the gas sampling. The ratio η_{TC}/η_{GS} is shown plotted against the ratio of local to measured fuel-air ratio in figure 13. Data are shown plotted for various ranges of η_{TC}. When the effi-

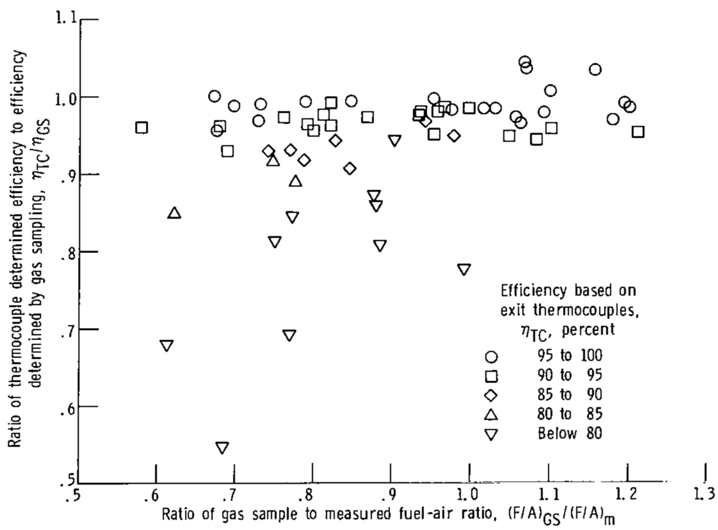


Figure 13. - Variation of ratio of thermocouple determined efficiency to efficiency determined by gas sampling with gas sample to measured fuel-air ratio.

ciency ratio is less than unity, the sample is not representative. As can be seen, while the efficiency ratio is seldom greater than unity, the ratio of gas sample to measured fuel-air has a range of about 0.65 to 1.2. Thus, the fuel-air ratio determined by gas sampling is not always representative of the fuel-air ratio as determined from fuel and airflow measurements. These data indicate that the combustion efficiency as determined by the gas sampling and the combustion efficiency determined by the thermocouple agree only at the higher values of combustion efficiency. As the combustion efficiency is reduced below 90 percent, the agreement becomes poor. This discrepancy may be attributed to liquid fuel droplets passing through the combustor along the liner and not being drawn into the gas sample probe, thus leading to erroneous hydrocarbon emission concentrations. Because of this effect, the trends in the hydrocarbon emission data may be in error, especially at low values of combustion efficiency. The carbon monoxide emission data do not suffer from this effect and should, therefore, be a good indication of combustor performance even at low values of combustion efficiency. Other possible explanation for poor sample representation include variations in sample density throughout the exhaust plane and nonisokinetic sampling.

SUMMARY OF RESULTS

A J-57 combustor liner was tested at various operating conditions in a closed duct test facility in order to evaluate combustion efficiency and exhaust emission of unburned hydrocarbons, carbon monoxide, and nitric oxide. Inlet total pressure was varied from 1 to 20 atmospheres, inlet total temperature was varied from 310 to 590 K (100° to 600° F), reference velocity ranged from 8 to 46 meters per second (25 to 150 ft/sec), and fuel-air ratio was varied from 0.004 to 0.015. The effect on combustion efficiency and exhaust emissions of primary fuel nozzle pressure differential, inlet total pressure, inlet total temperature, reference velocity, fuel-air ratio, and correlating parameter was investigated and the following results were obtained:

1. At low fuel nozzle pressure differentials (below 50 N/cm^2 (73 psi)), poor fuel atomization resulted in low combustion efficiencies and consequently high emissions of hydrocarbon and carbon monoxide. Nitric oxide emissions are slightly reduced by this effect.

2. Reducing inlet total pressure below 2 atmospheres reduced combustion efficiency and increased hydrocarbon and carbon monoxide emissions. However, the effect of inlet total pressure was overshadowed by the effect of lower nozzle pressure differential. Carbon monoxide emissions are below 2 grams per kilogram fuel at inlet pressures above 4 atmospheres and inlet temperatures greater than 590 K (600° F). As the inlet pressure increases from 1 to 20 atmospheres, the nitric oxide emission index ranges

from 0.15 to 5.6, indicating an upward trend as the inlet pressure is increased. The effect of increasing inlet pressure on increasing nitric oxide emissions is attributed to higher reaction zone temperature because of improved combustion efficiency.

3. The effect of reducing inlet total temperature on combustion efficiency appeared slight except at higher reference velocities; however, hydrocarbon and carbon monoxide emissions increased with reduced inlet total temperature. The rate of increase of hydrocarbon and carbon monoxide emissions with reduced inlet total temperature was larger at lower inlet total pressure and higher reference velocities. Emission of nitric oxide increased markedly with increasing inlet total temperature.

4. The effect of reference velocity on combustion efficiency is not strong except at the lowest inlet temperature of 310 K (100° F) where there is a marked downward trend in combustion efficiency with increasing reference velocity, likely caused by insufficient dwell time for the reaction to go to completion. At an inlet temperature of 310 K (100° F), both the hydrocarbons and carbon monoxide emissions increased markedly with increasing reference velocity; but the rate of increase of the emission index for carbon monoxide was much greater than that for the hydrocarbon emission index. Nitric oxide emissions were significantly reduced by increased reference velocity at the high inlet temperature of 590 K (600° F).

5. Combustion efficiency fell off sharply as fuel-air ratio was reduced to values below about 0.008 at lower values of inlet total pressure and temperature. There was a corresponding increase in the hydrocarbon emission index; however, the effect on the carbon monoxide emission index appeared to be negligible. These effects are due partly to poor fuel atomization and partly to the formation of fuel-air mixtures in the primary zone below the flammability limit. A slight increase in nitric oxide emissions with increasing fuel-air ratio at an inlet total temperature of 590 K (600° F) was attributed to increased reaction zone temperature due to improved combustion efficiency.

6. Combustion efficiency decreases and hydrocarbon and carbon monoxide increase markedly as the correlating parameter (PT/V) is decreased below a value of about 10×10^{6} newtons-seconds - degrees K per cubic meter (11.4×10^{4} (lb)(sec)($^{\circ}$R)/ft^{3}), at a fuel-air ratio of 0.013. Nitric oxide emissions tended to increase with increases in the correlating parameter.

7. Sampling error resulted in low readings for hydrocarbons emission as combustion efficiency was reduced below about 90 percent. This was attributed to the presence of significant quantities of liquid fuel in the exhaust that was not collected by the gas sample probe.

For this reason, the combustion efficiency as determined by the thermocouples is a much more accurate indication of combustor performance than the amount of inefficiency as determined by the hydrocarbon emission data. When the combustion efficiency is above 90 percent, the inefficiency as determined by the hydrocarbon and carbon monoxide emission data is a better indication of combustor performance than the thermocouples which have an accuracy of only ±3 percent. Some of the scatter in the data presented in this report may be due to inaccuracies caused by an insufficient number of exhaust gas sampling points.

CONCLUDING REMARKS

The purpose of this investigation was to gain a better understanding of the effect of operating conditions on emissions and determine what modifications were necessary to reduce emissions. The largest emissions of carbon monoxide and hydrocarbons have been at idle which represents low values of inlet total pressure and temperature and low fuel flows. The results reported herein have pointed out the importance of the influence of fuel atomization on combustion efficiency and hydrocarbon and carbon monoxide emissions at idle. It would be expected that low compression ratio engines will have higher emissions of unburned products than high compression ratio engines. It can therefore be assumed that the most important factor determining emissions will be either the compression ratio or the type of fuel nozzle employed. Reference 8 indicates that an air-assist nozzle was effective in reducing unburned products and increasing combustion efficiency at idle operating conditions.

It is to be expected that with the trend toward higher compression ratios or with regeneration (higher inlet temperatures), the emissions of nitric oxide will increase (ref. 10). One approach to reduce nitric oxide emission is to reduce combustor dwell time.

At the lower combustion efficiencies (below 90 percent), the exit thermocouples are a better indirect indication of hydrocarbon emissions than the gas sampling technique because of the effect of fuel droplets by-passing the gas sample probe.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 8, 1971,
132-86.

APPENDIX A

ANALYTICAL METHODS

by Albert Evans, Jr., and Gilbert M. Boyd

Each exhaust gas sample was analyzed for total hydrocarbon, carbon monoxide, and oxides of nitrogen. A selected number of samples was also analyzed for carbon dioxide and hydrogen. Standard instruments and methods were used for the analyses with only slight modifications in technique.

TOTAL HYDROCARBONS

Total hydrocarbons were determined with a flame ionization detector (FID) Beckman Model 106E. In principle, this method involves a hydrogen diffusion flame into which the hydrocarbon vapor is introduced along with the hydrogen fuel. In general, hydrocarbons of any molecular configurations are thermally dissociated into single carbon ions. An electric potential between the burner and an electrode located just above the flame causes the carbon ions to migrate to the electrode, thus producing a current. The collecting electrode is part of an electrometer amplifier. The burner and associated controls were contained in a compartment heated at 370 K (206^{o} F). Fuel was high purity (99.999 percent) hydrogen, burned at a rate of 35 cubic centimeters per minute (2.14 $in.^3/min$). Burner air was supplied at 400 cubic centimeters per minute (25.4 $in.^3/min$). Sample flow was maintained at 2 liters per minute (122 $in.^3/min$) to a stream splitter located close to the burner where the flow was divided, 3 to 5 cubic centimeters per minute (0.18 to 0.30 $in.^3/min$) being fed to the burner. Output signal from the electrometer amplifier was fed to a 5 millivolt strip chart recorder. The instrument was capable of rapid response (less than 1 min for full scale) and was free from drift when calibration gases were used. With sample gases it was necessary to monitor for 10 to 20 minutes because of drifting, which was attributed to slight fluctuations in combustor operation. A portion of the chart record showing a steady reading for at least 2 minutes was used for the data point. Full scale sensitivity was set with standard gas mixtures obtained commercially. Two mixtures containing 0.05 and 0.50 percent ethylene were available for low and medium standards. A third mixture containing 1.0 percent ethylene and 1.0 percent methane (equivalent to 3.0 percent CH_2) was available for the high concentration range. These mixtures were certified accurate to 2 percent of the components. Response of the FID is linear, so calibration with these mixtures serve equally well for low concentration of hydrocarbons.

NITRIC OXIDE

Although the only oxide of nitrogen produced in significant quantity by the combustion process in the gas turbine engine is nitric oxide, in the presence of excess oxygen this is oxidized to nitrogen dioxide. A wet chemical method based on the Saltzman reagent (ref. 11) which is specific for nitrogen dioxide was used for the analysis. Saltzman reagent is an aqueous solution of nitrogen-(1-naphthyl)-ethylenediamine dihydrochloride (NEDA) in sulfanilic and acetic acids, which absorbs nitrogen dioxide to form an intense red-purple color, having its maximum absorption at 5.5×10^{-7} meter (1.8×10^{-6} ft). Sample bottles were allowed to reach ambient temperature in the laboratory. Unless a bottle was known to be at reduced pressure, a stopcock was opened momentarily to equilibrate the sample pressure with barometric pressure. Bottles were then weighted and cooled slightly with dry ice to create a partial vacuum before the Saltzman reagent was drawn into the bottle by immersing the tip in liquid reagent and carefully opening the stopcock. Bottles were brought to room temperature, wiped dry if necessary, and weighted again. The volume of reagent added was calculated from the increase in weight and density of the reagent. Amount of reagent used varied from 10 to 20 milliliters (0.34 to 0.68 fl. oz). Bottles were rotated and shaken to ensure good contact between sample and reagent. At least 15 minutes were allowed for color development. Liquid was then drained into a smaller beaker through the same stopcock used for filling to ensure mixing with any reagent retained in the stopcock bore. Percent transmittance was measured at 5.5×10^{-7} meter (1.8×10^{-6} ft) with a spectrophotometer using a 1-centimeter (0.4-in.) cell. The amount of nitrogen dioxide was determined by reference to a calibration chart prepared previously with standard samples of sodium nitrite. The following equation was used to calculate percent nitrogen dioxide (NO_2):

$$\text{Percent } NO_2 = \frac{M v_r D}{V_s \frac{p}{760} \frac{298}{t}} 100$$

where

M milliliter of NO_2 (298 K, 760 torr) per liter of Saltzman reagent, from calibration plot

v_r volume of Saltzman reagent used, liters

D dilution factor

V_s volume gas sample bottle, milliliters p pressure of sample in bottle, torr

t temperature at which pressure of sample in bottle was measured, K

The sensitivity of the method for a 500-milliliter (16.9-fl.-oz) sample, 20-milliliter (0.68-fl.-oz) Saltzman reagent, and 1-centimeter (0.4-in.) absorption cell (path length) is about 1 ppm. However, the method may give low results with exhaust gas samples because at low concentration of nitric oxide the reaction with oxygen to form nitrogen dioxide is very slow. Reference 12 gives an equation for calculating the fraction of nitric oxide converted. At the 10 ppm level 5.6 hours would be required for 50 percent conversion. In this work, approximately 15 hours elapsed between sampling and analysis, which should be sufficient for at least 75 percent conversion at the 10 ppm level and virtually 100 percent at 100 ppm. Although the data reported herein may be 10 percent low, the trends indicated should be valid.

CARBON MONOXIDE, HYDROGEN, AND CARBON DIOXIDE

A Beckman GC4 gas chromatograph was used to determine the quantity of carbon monoxide, hydrogen, and carbon dioxide in the sample bottles. An oven whose operating temperature was 370 K (200° F) accommodates three columns at one time. The instrument oven contains a helium ionization detector, a thermal conductivity detector, and a flame ionization detector.

The sample flow was through a Carle valve with 2-cubic-centimeter (0.21-$in.^3$-) sample loops into a molecular sieve column, then into the helium ionization detector, and from there to the atmosphere. A second portion of the sample was passed through a Carle sample valve with 0.1-cubic-centimeter (0.0061-$in.^3$-) sample loops into a Porapak Q column, then into a thermal conductivity detector, and from there to the atmosphere. The molecular sieve column length was 3.7 meters (12 ft) with a 0.48-centimeter (3/16-in.) outside diameter. The Porapak Q length was 6.7 meters (22 ft) with a 0.32-centimeter (1/8-in.) outside diameter. The helium carrier gas flow rate was 34 cubic centimeters per minute (2.1 $in.^3$/min). The carrier gas sweeps the sample from the sample loop of the sample valve into the columns and then out of the columns into the detectors.

The constituents of the sample are all absorbed on the surfaces of the column packing material where they are retained for a specific time period. The retention times of the constituent gases in the molecular sieve column were as follows: neon, 1.3 minutes; hydrogen, 1.4 minutes; oxygen, 2.0 minutes; nitrogen, 2.6 minutes; methane, 4.0 minutes; carbon monoxide, 5.2 minutes.

The molecular sieve column is not suitable for detection of carbon dioxide. The Porapak Q column is used for the quantitative detection of carbon dioxide. The retention times of the constituent gases in the Porapak Q column are 1. 4 minutes for nitrogen, oxygen, and carbon monoxide and 2. 5 minutes for carbon dioxide. Note that this column does not separate carbon monoxide from air at the operating temperature.

The various constituents, as they are released by the molecular sieve at the times indicated, are carried into the helium ionization detector. The response of this detector to any gas except helium is directly proportional to the concentration of that gas in the sample being analyzed. Therefore, quantitative results are obtained. The detector will measure gases in the fractional ppm range. Within this detector helium is ionized by establishing a high potential difference between two electrodes. Electrons and photons result from the ionization of the helium. The photons are permitted to enter a measuring chamber within the detector where they, in turn, ionize the sample gas components as they enter the measuring chamber. The electrons resulting from the photoionization of the component gas migrate to the collector electrode within the measuring chamber. The voltage resulting from the current generated in the collector circuit is amplified and used to actuate a strip chart recorder of an electronic digital integrator.

The various constituents which are released by the Porapak Q column enter a thermal conductivity detector. This detector has four filaments connected in a wheatstone bridge arrangement. The filaments are exposed initially to the helium carrier gas. A current of 200 milliamperes flows through the bridge raising all four filaments to a steady temperature. Two of the filaments are housed in one side of the detector which sees only pure helium. When a sample component enters the side of the detector in which the other two filaments are housed, the temperature and resistance of those two filaments are changed because of the difference in the thermal conductivity of the sample gas. The change in resistance unbalances the wheatstone bridge and the resulting voltage is measured with a strip chart recorder or an electronic digital integrator. The extent of the unbalance is directly proportional to the concentration of the component gas in the sample. Qualitative results are also obtained because the constituents of interest are released by the columns at known times.

APPENDIX B

CALCULATION OF EMISSION INDEX

The emission index is defined as the ratio of the number of grams of pollutant formed divided by the number of kilograms of fuel consumed. The amount of pollutant formed can be expressed by the equation

$$\frac{MW_P}{MW_E} \times \dot{m} \times \text{ppm}$$

where MW_P is the molecular weight of the pollutant, MW_E the molecular weight of the exhaust products, $\dot{m}$ the total mass flow rate through the combustor composed of the sum of the air and the fuel flows, and ppm the concentration of the pollutant in parts per million. When dividing by kilograms of fuel and simplifying the equation becomes

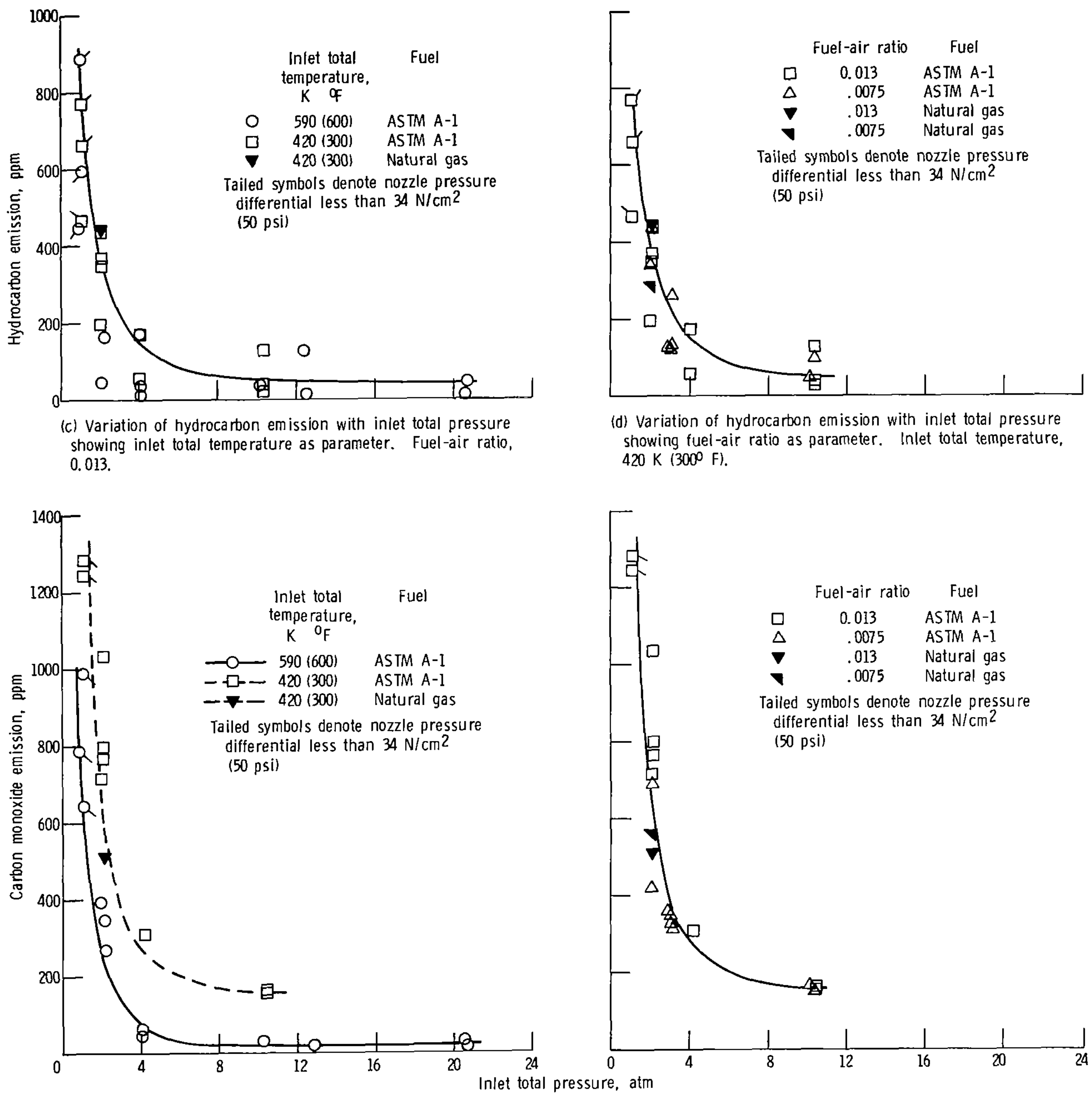
$$EI = \frac{MW_P}{29} \times 10^{-3} \times \frac{1 + \frac{F}{A}}{F/A} \times \text{ppm}$$

where F/A is the fuel-air ratio and EI is the emission index. Values used for the molecular weight of the pollutant were 30 for nitric oxide, 28 for carbon monoxide, and 14 for hydrocarbons. The assumed molecular weight of the exhaust products is 29.

APPENDIX C

EMISSION DATA IN PPM

The figures discussed in the body of the report have emissions of hydrocarbons, carbon monoxide, and nitric oxide presented in terms of emission index. For the convenience of the reader who might desire to see the emission results in terms of parts per million by volume (ppm), figures 8 to 12 in the body of the report are replotted in this appendix. The figure numbers are the same for the ppm figures with the exception of the prefix C: for example, figure 8(c) is given in appendix C as C8(c).



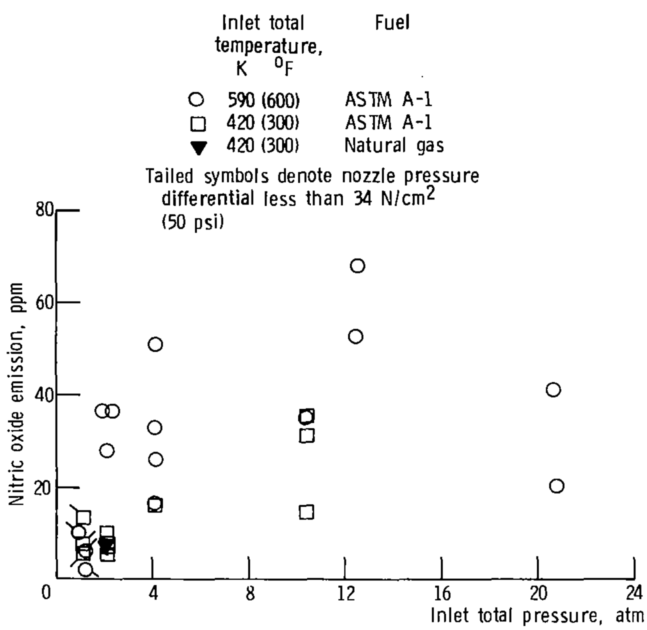
(c) Variation of hydrocarbon emission with inlet total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(d) Variation of hydrocarbon emission with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

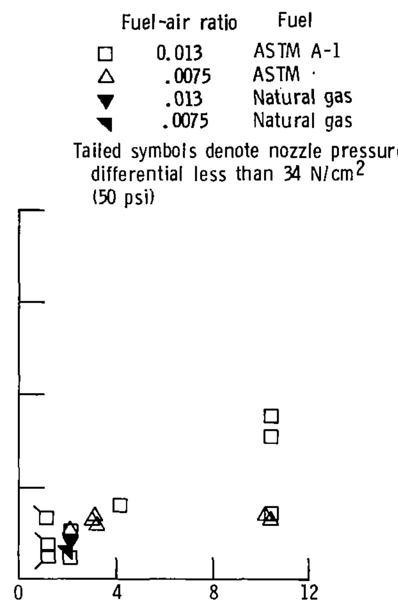
(e) Variation of carbon monoxide emission with inlet total pressure showing inlet total temperature as parameter. Fuel-air ratio, 0.013.

(f) Variation of carbon monoxide emission with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

Figure C8. - Effect of combustor inlet total pressure on exhaust emissions. Reference velocity, 15 meters per second (50 ft/sec).

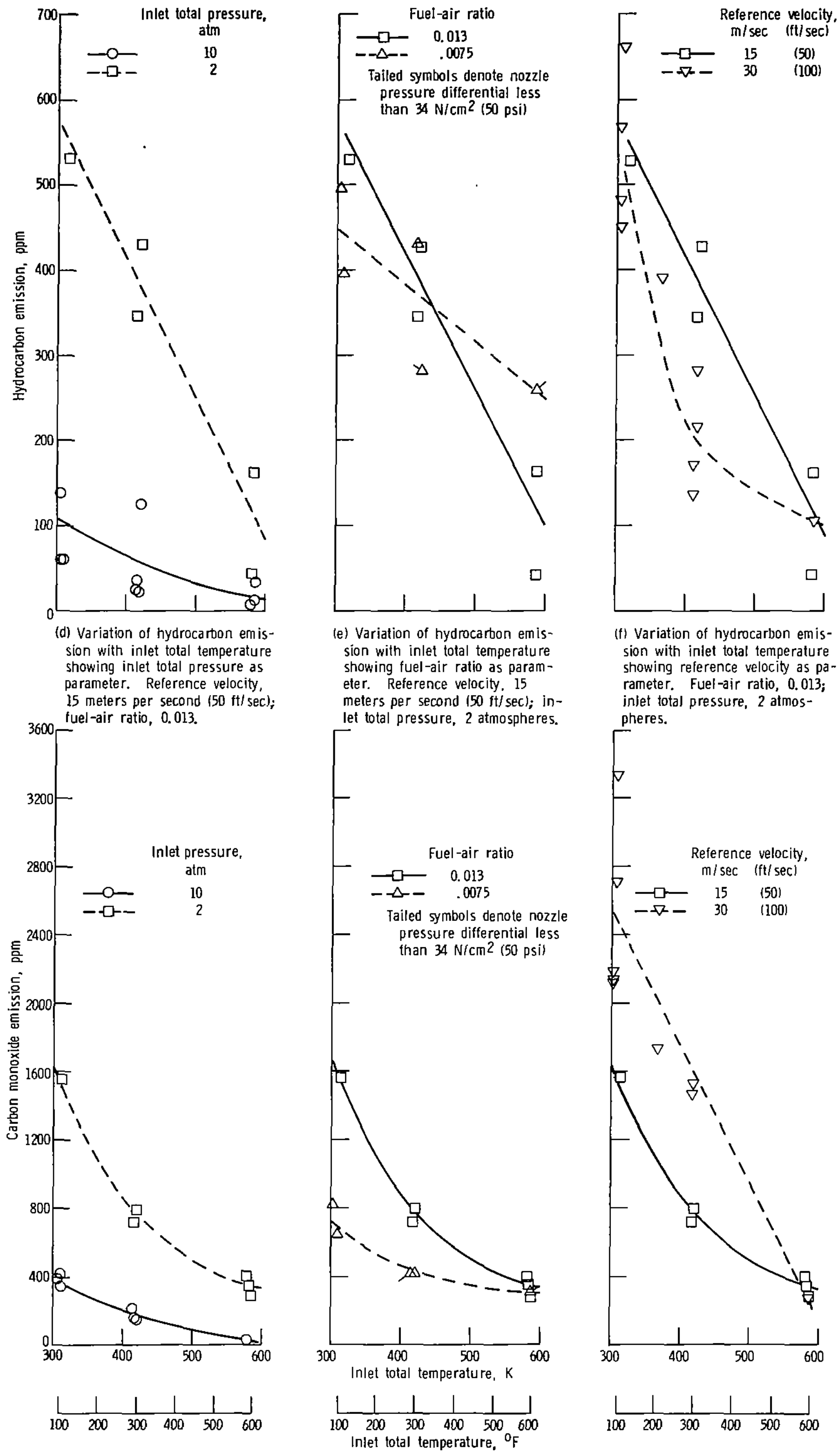


(g) Variation of nitric oxide emission with inlet total pressure showing inlet total temperature as parameter. Fuel air ratio, 0.013.



(h) Variation of nitric oxide emission with inlet total pressure showing fuel-air ratio as parameter. Inlet total temperature, 420 K (300° F).

Figure C8. - Concluded.



(d) Variation of hydrocarbon emission with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(e) Variation of hydrocarbon emission with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

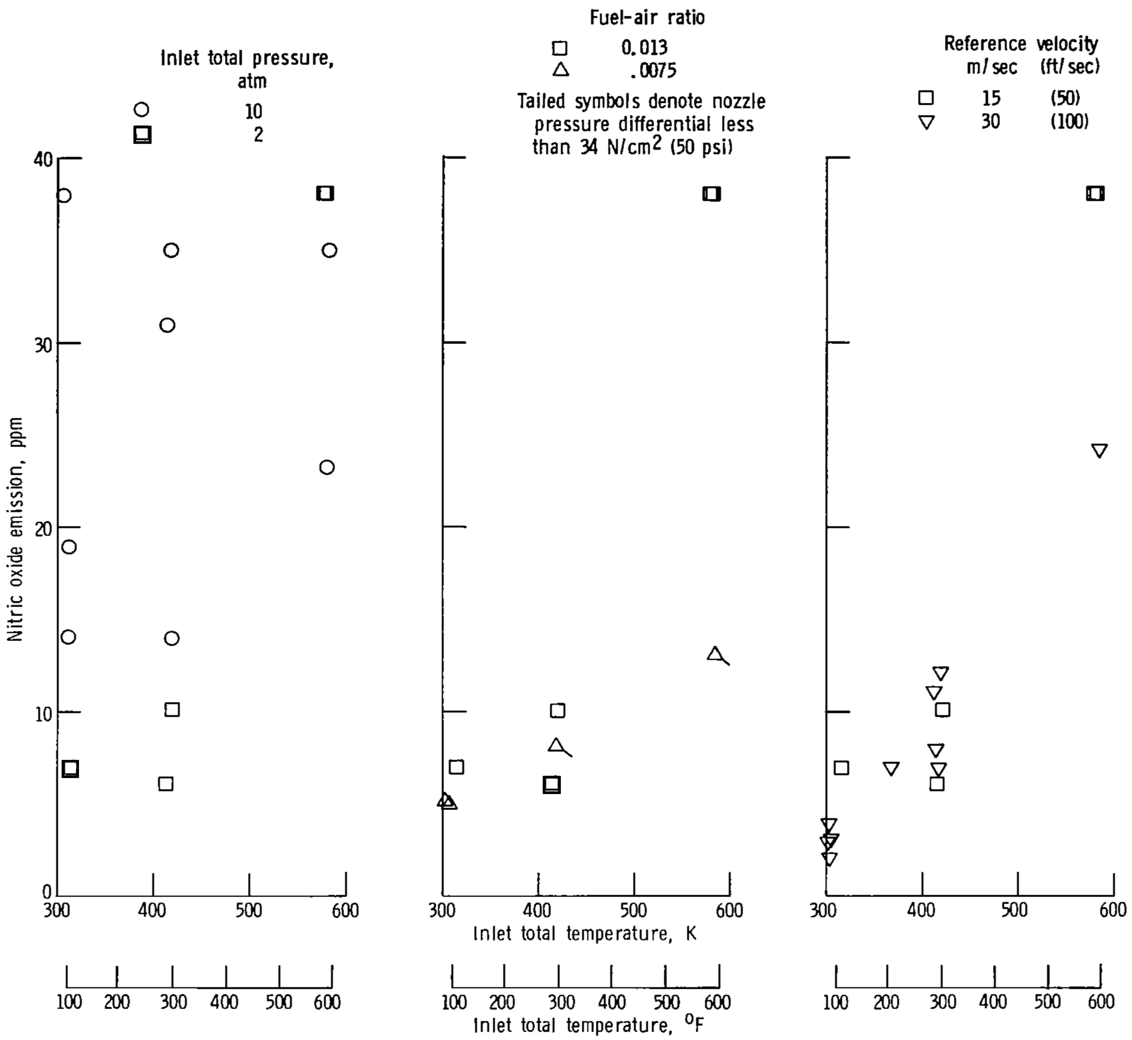
(f) Variation of hydrocarbon emission with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(g) Variation of carbon monoxide emission with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(h) Variation of carbon monoxide emission with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmospheres.

(i) Variation of carbon monoxide emission with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

Figure C9. - Variations in exhaust emission with inlet total temperature.

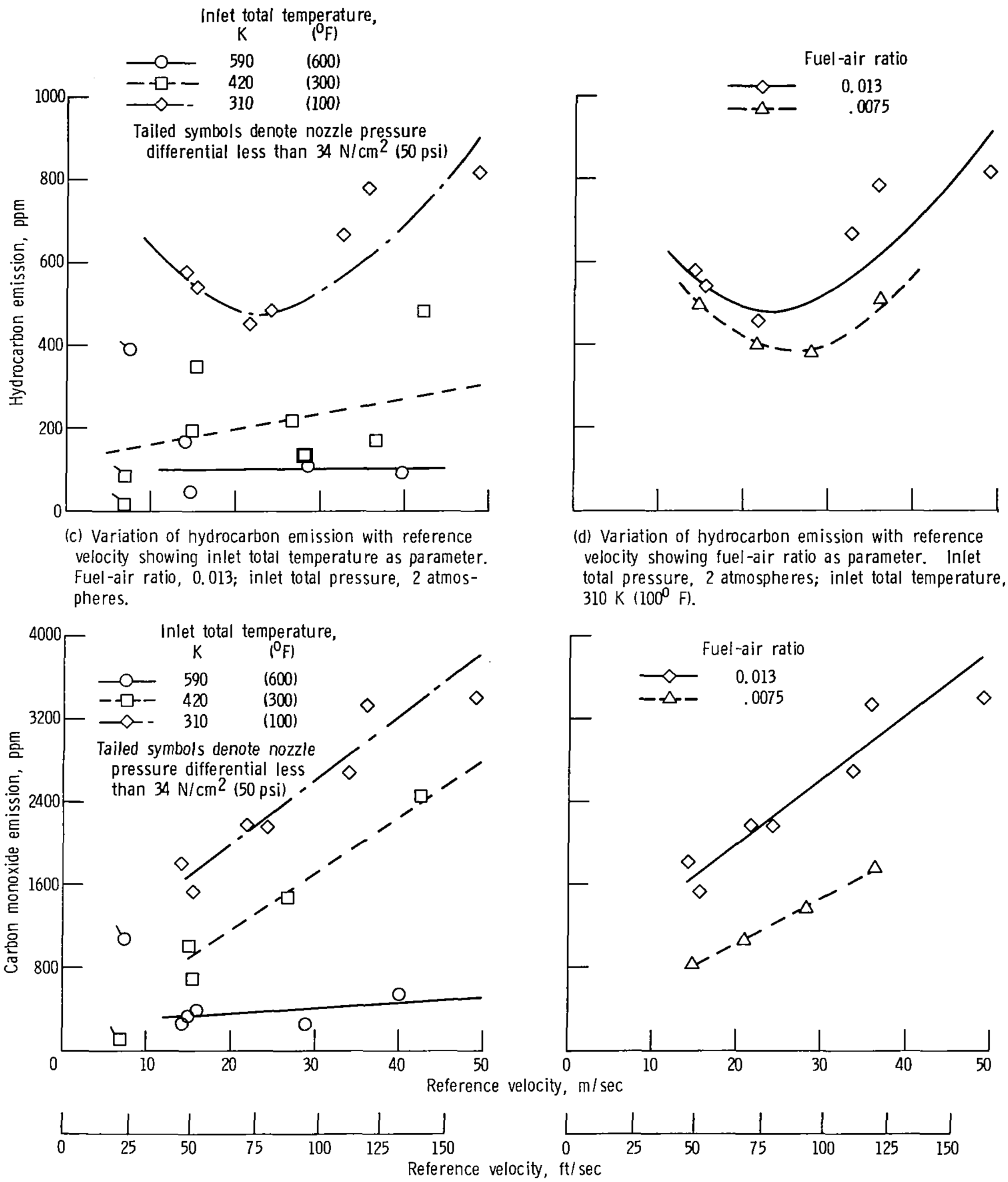


(j) Variation of nitric oxide emission with inlet total temperature showing inlet total pressure as parameter. Reference velocity, 15 meters per second (50 ft/sec); fuel-air ratio, 0.013.

(k) Variation of nitric oxide emission with inlet total temperature showing fuel-air ratio as parameter. Reference velocity, 15 meters per second (50 ft/sec); inlet total pressure, 2 atmosheres.

(l) Variation of nitric oxide emission with inlet total temperature showing reference velocity as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

Figure C9. - Concluded.



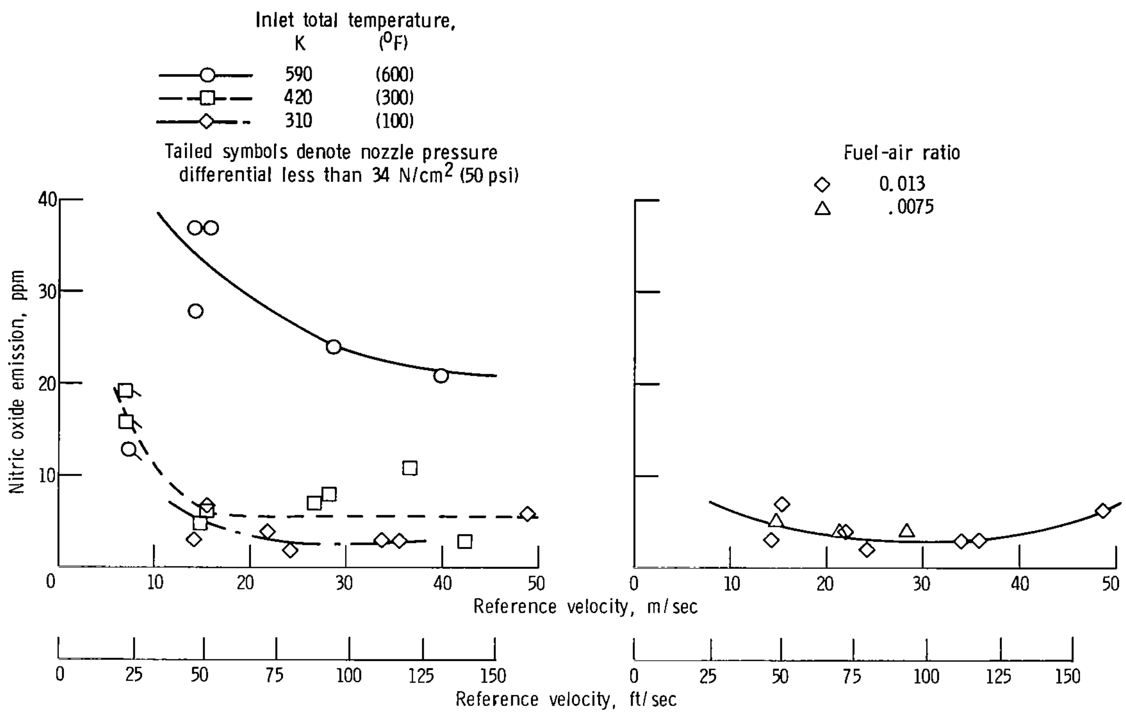
(c) Variation of hydrocarbon emission with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(d) Variation of hydrocarbon emission with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet total temperature, 310 K (100° F).

(e) Variation of carbon monoxide emission with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet pressure, 2 atmospheres.

(f) Variation of carbon monoxide emission with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet temperature, 310 K (100° F).

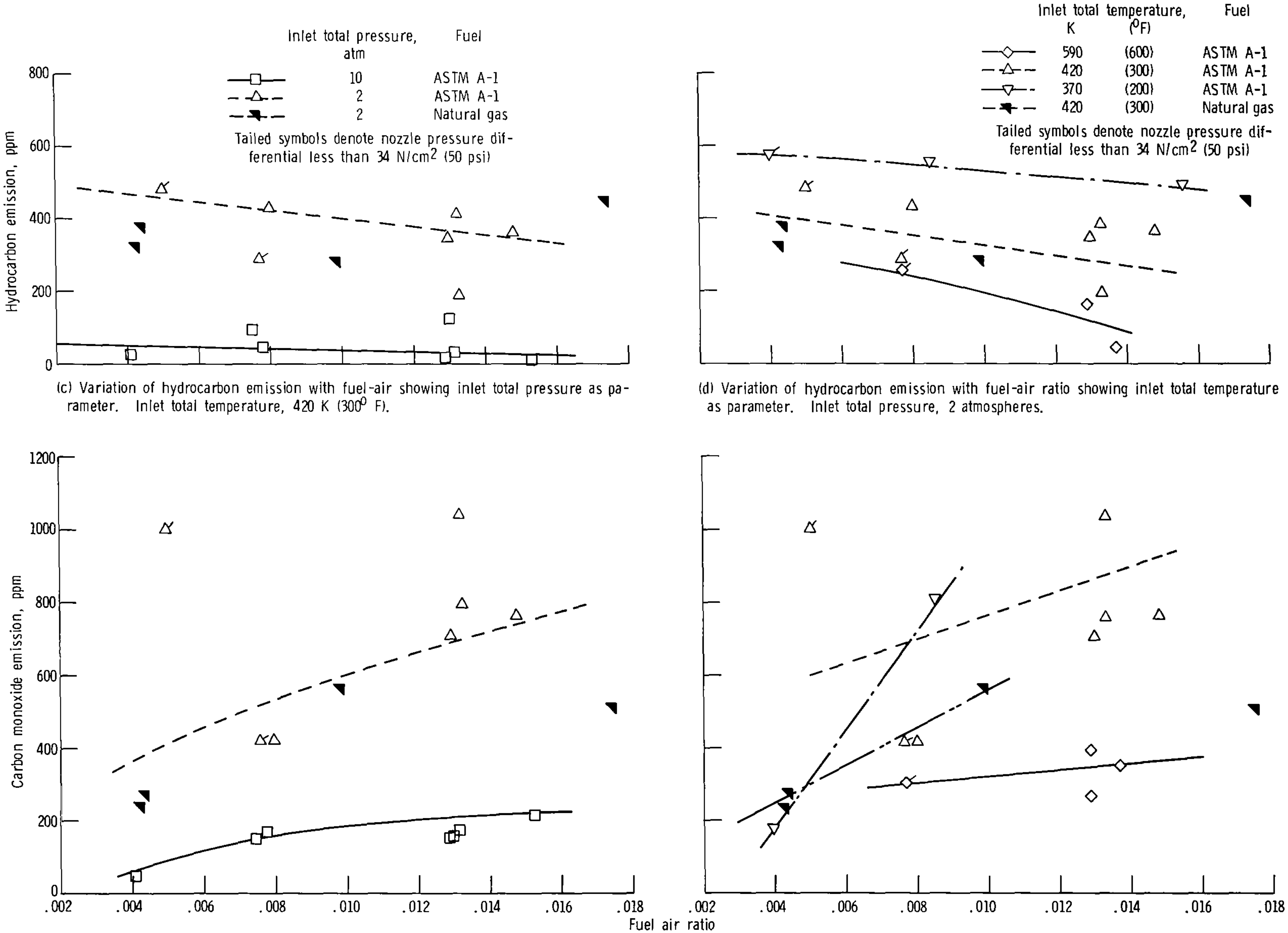
Figure C10. - Effect of reference velocity on exhaust-emissions.



(g) Variation of nitric oxide emission with reference velocity showing inlet total temperature as parameter. Fuel-air ratio, 0.013; inlet total pressure, 2 atmospheres.

(h) Variation of nitric oxide emission with reference velocity showing fuel-air ratio as parameter. Inlet total pressure, 2 atmospheres; inlet temperature, 310 K (100° F).

Figure C10. - Concluded.



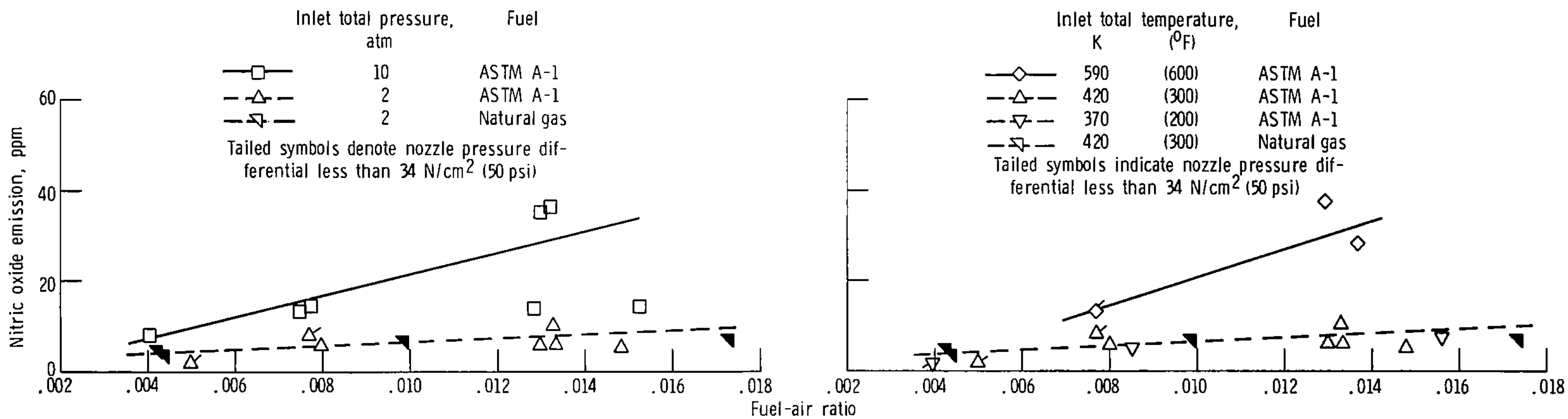
(c) Variation of hydrocarbon emission with fuel-air showing inlet total pressure as parameter. Inlet total temperature, 420 K (300° F).

(d) Variation of hydrocarbon emission with fuel-air ratio showing inlet total temperature as parameter. Inlet total pressure, 2 atmospheres.

(e) Variation of carbon monoxide emission with fuel-air ratio showing inlet total pressure as parameter. Inlet total temperature, 420 K (300° F).

(f) Variation of carbon monoxide emission with fuel-air ratio showing inlet total temperature as parameter. Inlet total pressure, 2 atmospheres.

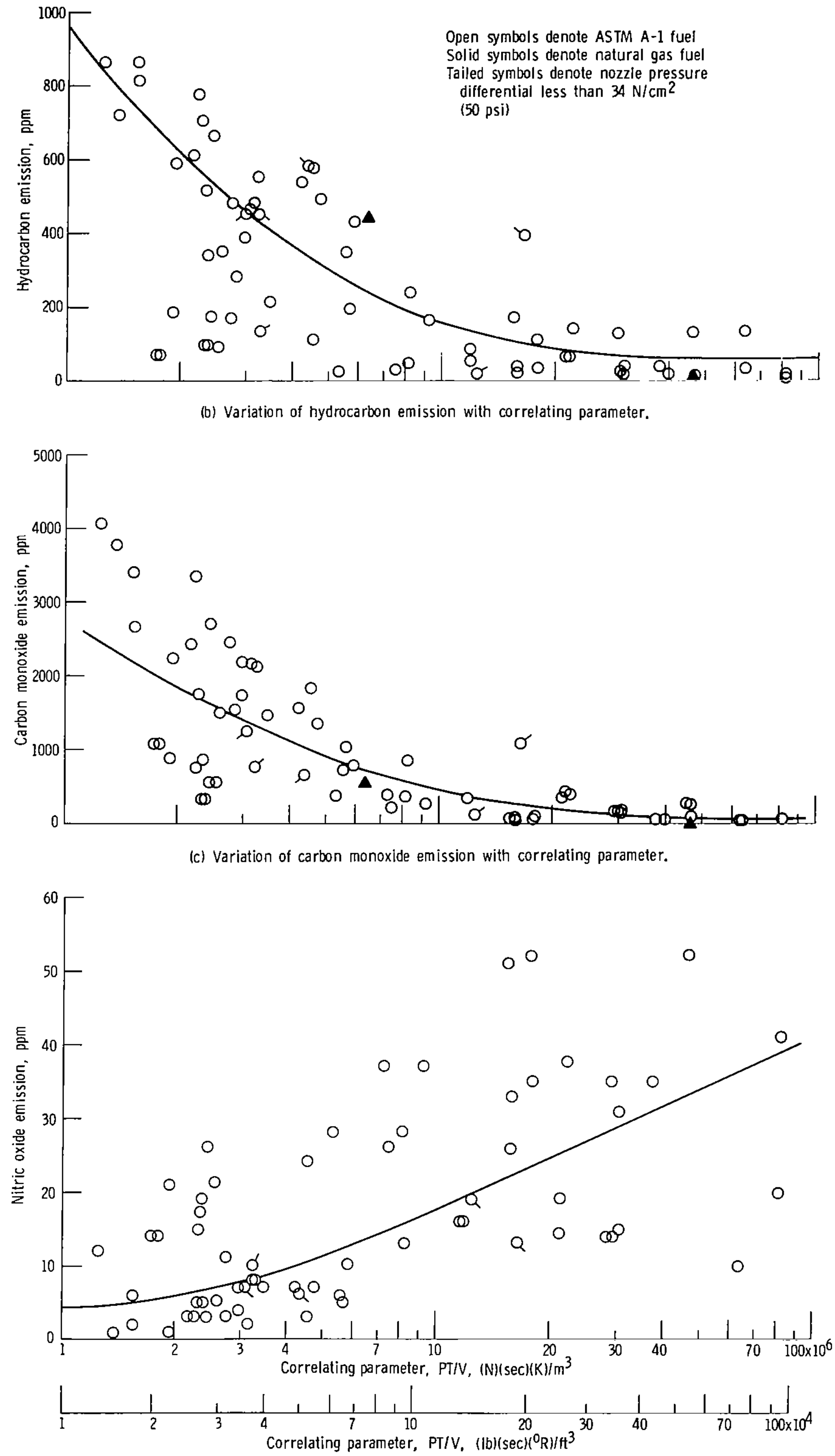
Figure C11. - Variations in exhuast emissions with fuel-air ratio. Reference velocity, 15 meters per second (50 ft/sec).



(g) Variation of nitric oxide emission with fuel-air ratio showing inlet total pressure as parameter. Inlet temperature, 420 K (300° F).

(h) Variation of nitric oxide emission with fuel-air ratio showing inlet total temperature as parameter. Inlet total pressure, 2 atmospheres.

Figure CII. - Concluded.



(b) Variation of hydrocarbon emission with correlating parameter.

(c) Variation of carbon monoxide emission with correlating parameter.

(d) Variation of nitric oxide emission with correlating parameter.

Figure C12. - Variation of exhaust emissions with correlating parameter. Fuel-air ratio, 0.013.

REFERENCES

1. Anon.: Nature and Control of Aircraft Engine Exhaust Emissions. Rep. 1134-1, Northern Res. and Eng. Corp., Nov. 1968.
2. Bristol, C. W., Jr.: Gas Turbine Engine Emission Characteristics and Future Outlook. Proceedings of a Combined Society of Automotive Engineers and U. S. Department of Transportation Conference on Aircraft and the Environment. Part 1. SAE, 1971, pp. 84-92.
3. Odgers, J.: Air Pollution by Gas Turbines - Is Control Possible? Canadian Aeronaut. Space J., vol. 16, no. 8, Oct. 1970, pp. 339-344.
4. Sawyer, R. F.: Fundamental Processes Controlling the Air Pollution Emissions from Turbojet Engines. Paper 69-1040, AIAA, Oct. 1969.
5. Smith, D. S.; Sawyer, R. F.; and Starkman, E. S.: Oxides of Nitrogen from Gas Turbines. J. Air Pollution Control Assoc., vol. 18, no. 1, Jan. 1968, pp. 30-35.
6. Grobman, Jack; and Papathakos, Leonidas C.: Smoke Evaluation of a Modified J-57 Combustor. NASA TM X-2236, 1971.
7. Barnett, Henry C.; and Hibbard, Robert R., eds.: Adaptation of Combustion Principles to Aircraft Propulsion. Vol. II - Combustion in Air-Breathing Jet Engines. NACA RM E55G28, 1956.
8. Briehl, D.; and Papathakos, Leonidas: Use of an Air-Assist Fuel Nozzle to Reduce Exhaust Emissions from a Gas-Turbine Combustor at Idle Conditions. NASA TN D-6404, 1971.
9. Childs, J. Howard; Reynolds, Thaine W.; and Graves, Charles C.: Relation of Turbojet and Ramjet Combustion Efficiency to Second-Order Reaction Kinetics and Fundamental Flame Speed. NACA Rep. 1334, 1957.
10. Cornelius, Walter; and Wade, Wallace R.: The Formation and Control of Nitric Oxide in a Regenerative Gas Turbine Burner. Paper 700708, SAE, Sept. 1970.
11. Saltzman, Bernard E.: Colorimetric Microdetermination of Nitrogen Dioxide in the Atmosphere. Anal. Chem., vol. 26, no. 12, Dec. 1954, pp. 1949-1955.
12. Freedman, Robert W.; Couleban, B. A.; and Lang, H. W.: Kinetic Evaluation of the Factor Used in the Saltzman Analysis of Oxide of Nitrogen. Amer. Ind. Hygiene Assoc. J., vol. 31, no. 1, Jan.-Feb., 1970, pp. 76-80.

TABLE I. -

[ASTM A-1 fuel used except when

Inlet total pressure, atm	Inlet temperature		Reference velocity		Inlet Mach number	Airflow		Fuel-air ratio	Exit temperature		Primary fuel nozzle pressure differential		Secondary fuel nozzle pressure differential		Correlating parameter	
	K	^{o}F	m/sec	ft/sec		kg/sec	lb/sec		K	^{o}F	N/cm^2	psi	N/cm^2	psi	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^{o}R)(sec)}{ft^3}$
0.94	575	575	17.0	55.8	0.0353	0.71	1.57	0.0127	828	1030	14.3	20.8	----	---	3.24×10^6	3.71×10^4
1.11	294	70	13.9	45.5	.0403	1.33	2.93	.0137	667	740	67.8	98.4	----	---	2.38	2.73
1.11	423	302	13.3	43.6	.0322	.89	1.97	.0144	821	1017	33.3	48.3	----	---	3.60	4.12
1.26	586	595	39.0	128	.0805	2.16	4.76	.012	997	1335	135	196	----	---	1.93	2.21
1.13	585	593	27.6	90.6	.0568	1.36	3.00	.013	1024	1384	67.6	98.1	----	---	2.43	2.79
1.02	573	572	14.2	46.7	.0296	.64	1.42	.005	677	759	-----	-----	----	---	4.16	4.77
1.02	573	572	13.8	45.4	.0288	.64	1.42	.008	743	878	3.4	5.0	----	---	4.38	5.02
1.02	574	574	14.6	47.8	.0303	.67	1.48	.015	1058	1495	10.3	15.0	----	---	4.14	4.75
1.08	304	87	14.5	47.6	.0415	1.32	2.91	.0136	708	815	34.7	50.3	----	---	2.29	2.63
1.05	422	299	14.7	48.3	.0357	.94	2.08	.0132	787	957	14.9	21.6	----	---	3.07	3.52
1.07	583	589	14.4	47.4	.0298	.68	1.50	.0132	783	949	2.7	3.9	----	---	4.38	5.02
1.10	591	603	28.1	92.2	.0576	1.33	2.94	.0133	1037	1406	35.5	51.5	----	---	2.35	2.69
1.05	301	81	14.8	48.4	.0424	1.32	2.91	.0131	699	799	42.6	61.8	----	---	2.17	2.49
1.09	591	604	28.2	92.5	.0578	1.32	2.91	.0134	1028	1391	43.5	63.2	----	---	2.32	2.66
1.10	594	609	27.4	89.9	.0571	1.32	2.91	.0132	1034	1401	43.8	63.5	----	---	2.37	2.72
1.18	588	598	40.5	133	.0832	2.07	4.57	.0130	1035	1403	109	158	----	---	1.74	1.99
1.20	587	596	39.9	131	.0824	2.09	4.60	.0127	1032	1398	109	158	----	---	1.78	2.04
.98	302	84	15.5	50.9	.0445	1.29	2.85	.0135	710	818	43.9	63.7	----	---	1.95	2.23
1.05	416	288	13.4	44.1	.0331	.88	1.94	.0147	814	1006	18.7	27.2	----	---	3.29	3.77
1.01	584	591	14.2	46.5	.0292	.63	1.38	.0140	852	1073	6.3	9.2	----	---	4.23	4.85
1.22	306	90	37.2	122	.1060	3.73	8.23	.0080	546	522	123	179	----	---	1.00	1.15
1.11	304	88	27.5	90.1	.0784	2.57	5.66	.0133	689	780	157	228	----	---	1.26	1.44
1.06	302	84	14.4	47.1	.0412	1.29	2.84	.0078	446	343	147	214	----	---	2.26	2.59
1.09	303	86	28.3	92.8	.0809	2.58	5.69	.0078	557	543	57.0	82.7	----	---	1.18	1.35
1.07	366	198	29.2	95.7	.0760	2.19	4.82	.0133	810	998	115	167	----	---	1.37	1.57
1.06	420	296	29.1	95.5	.0708	1.88	4.12	.0139	898	1157	90.3	131	----	---	1.54	1.77
1.96	582	588	15.8	52.0	.0329	1.37	3.03	.0129	1015	1367	59.1	85.8	----	---	7.30	8.36
2.21	586	594	14.2	46.5	.0292	1.37	3.01	.0129	1031	1396	56.6	82.2	----	---	9.25	10.6
2.03	584	592	14.8	48.4	.0304	1.31	2.89	.0137	1041	1414	46.4	67.3	----	---	8.17	9.36
2.09	421	297	15.2	50.0	.0369	1.92	4.24	.0133	897	1155	91.6	133	----	---	5.85	6.70
2.05	315	107	15.5	51.0	.0436	2.58	5.69	.0131	808	995	166	241	1.4	2	4.21	4.83
2.04	416	289	15.2	49.8	.0371	1.92	4.24	.0050	507	452	7.2	10.4	----	---	5.72	6.56
2.10	418	292	15.0	49.2	.0365	1.92	4.24	.0080	707	812	34.7	50.3	----	---	5.93	6.80
2.11	418	293	15.2	50.0	.0371	1.92	4.23	.0148	965	1276	123	178	.7	1	5.75	6.59
2.04	418	293	15.4	50.6	.0376	1.91	4.22	.0130	900	1160	94.4	137	----	---	5.58	6.39
2.04	414	286	7.2	23.7	.0177	.91	2.01	.0137	909	1177	23.0	33.4	----	---	11.9	13.6
2.21	413	284	28.2	92.5	.0691	3.84	8.47	.0130	911	1179	198	288	3.4	5	3.29	3.77
2.42	411	279	36.6	120	.0896	5.44	12.0	.0135	903	1166	212	307	20.7	30	2.76	3.16
2.08	413	284	7.0	23.0	.0172	.90	1.99	.0138	917	1190	23.2	33.6	----	---	12.5	14.3
2.03	412	282	14.9	48.9	.0366	1.88	4.14	.0133	898	1154	92.3	134	----	---	5.69	6.52

:ST RESULTS

ted in inlet total pressure column.]

Exhaust emissions										Combustion efficiency
Hydrocarbons		Carbon monoxide		Nitric oxide		Hydrogen		Carbon dioxide		
g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	
17.3	448	60.7	778	0.82	10	----	---	--------	--------	53.1
12.2	340	23.0	322	.38	5	----	---	--------	--------	68.1
22.3	656	87.1	1280	.36	5	----	---	--------	--------	71.6
7.53	185	73.0	895	1.83	21	----	---	--------	--------	91.8
6.66	177	41.2	548	2.10	26	----	---	--------	--------	89.5
61.4	633	48.7	251	.62	3	----	---	--------	--------	55.9
48.1	791	62.7	515	.52	4	----	---	--------	--------	53.4
19.2	587	77.8	1190	1.33	19	----	---	--------	--------	88.9
25.2	701	125	1740	.39	5	----	---	--------	--------	14.8
17.1	461	91.9	1240	.56	7	----	---	--------	--------	71.7
22.1	597	47.7	644	.48	6	----	---	--------	--------	40.8
19.0	516	63.3	860	1.34	17	----	---	--------	--------	90.8
23.0	612	186	2490	.24	3	----	---	--------	--------	76.1
3.63	99	54.0	740	1.18	15	----	---	--------	--------	88.1
3.68	99	54.8	740	1.52	19	----	---	--------	--------	91.7
2.57	68	81.2	1080	1.13	14	----	---	--------	--------	92.8
2.63	68	83.1	1080	1.16	14	----	---	--------	--------	94.6
21.2	586	161	2220	.08	1	1.10	213	2.46×10^3	21.6×10^3	75.8
25.6	768	135	2030	.93	13	.61	129	2.83	27.0	73.1
31.0	883	69.2	990	.15	2	.40	80	1.95	17.7	51.8
41.9	686	319	2620	.13	1	4.43	510	1.80	9.41	72.9
31.9	863	298	4050	.16	2	3.58	681	1.80	15.5	72.2
42.1	672	69.1	554	.13	1	.50	56	1.26	6.4	45.0
60.2	960	251	2010	.13	1	2.78	312	2.17	11.07	79.1
26.6	720	278	3780	.08	1	2.16	411	2.56	22.1	85.1
30.6	865	187	2650	.15	2	1.07	212	2.57	23.2	89.2
-----	---	29.9	394	3.01	37	----	---	--------	--------	90.3
6.10	161	20.4	269	3.01	37	----	---	--------	--------	92.6
1.50	42	25.0	350	2.15	28	0	0	2.62	23.31	89.9
15.9	431	58.3	793	.79	10	.21	39	3.32	28.7	92.6
20.1	538	116	1550	.56	7	.69	130	3.57	30.35	90.6
46.7	481	193	995	.42	2	.13	9	1.32	4.33	44.5
26.3	432	50.9	418	.78	6	.24	27	2.68	14.0	90.3
12.1	365	50.7	765	.35	5	.20	42	2.95	28.3	95.9
13.0	346	53.4	710	.48	6	.23	42	3.07	25.95	95.7
2.96	83	------	----	1.22	16	----	---	--------	--------	93.7
5.00	133	------	----	.64	8	----	---	--------	--------	92.5
6.05	167	------	----	.85	11	----	---	--------	--------	94.2
.67	19	7.23	102	1.44	19	.01	2	3.28	29.4	94.6
7.10	193	75.8	1030	.39	5	.39	75	2.79	24.1	94.0

TABLE I. - Continued.

[ASTM A-1 fuel used except when

Inlet total pressure, atm	Inlet temperature, K	Inlet temperature, °F	Reference velocity, m/sec	Reference velocity, ft/sec	Inlet Mach number	Airflow, kg/sec	Airflow, lb/sec	Fuel-air ratio	Exit temperature, K	Exit temperature, °F	Primary fuel nozzle pressure differential, N/cm^2	Primary fuel nozzle pressure differential, psi	Secondary fuel nozzle pressure differential, N/cm^2	Secondary fuel nozzle pressure differential, psi	Correlating parameter, $\frac{(N)(K)(sec)}{m^3}$	Correlating parameter, $\frac{(lb)(^oR)(sec)}{ft^3}$
2.21	416	288	26.7	87.5	0.0652	3.62	7.97	0.0135	919	1195	169	246	4.1	6	3.49×10^6	4.00×10^4
2.39	413	283	42.4	139	.0886	5.31	11.7	.0136	889	1140	179	259	23.4	34	2.77	3.17
2.10	412	281	14.2	46.5	.0348	1.84	4.06	.0046	511	459	19.6	28.4	.7	1	6.17	7.07
2.09	415	287	14.4	47.3	.0353	1.85	4.08	.0083	707	813	126	183	-----	---	6.07	6.96
2.20	308	95	13.9	45.6	.0394	2.54	5.59	.0080	599	619	57.4	83.3	-----	---	4.95	5.67
1.97	421	298	15.8	51.7	.0383	1.88	4.14	.0077	718	832	34.3	49.8	-----	---	5.32	6.10
2.03	587	597	15.1	49.6	.0311	1.34	2.95	.0077	862	1092	14.7	21.3	-----	---	7.99	9.16
2.07	584	591	7.44	24.4	.0153	.67	1.48	.0127	1020	1376	11.6	16.8	-----	---	16.5	18.9
2.19	586	595	28.6	93.6	.0587	2.71	5.98	.0134	1066	1457	136	198	-----	---	4.55	5.21
2.28	586	595	39.8	130	.0819	3.95	8.70	.0137	1077	1478	139	201	8.3	12	2.54	2.91
2.11	302	84	14.2	46.6	.0407	2.53	5.58	.0136	778	940	165	240	2.1	3	4.55	5.21
2.11	303	85	21.7	71.1	.0621	3.84	8.47	.0135	796	972	165	239	6.9	10	2.98	3.41
2.48	303	85	24.2	79.5	.0694	5.04	11.1	.0133	782	947	167	242	19.3	28	3.14	3.60
2.70	306	90	33.8	111	.0967	7.62	16.8	.0132	755	899	176	255	66.2	96	2.46	2.82
2.56	305	89	35.7	117	.101	7.58	16.7	.0132	739	870	171	248	57.2	83	2.23	2.55
2.42	305	89	48.8	160	.139	9.71	21.4	.0136	737	866	177	257	135.1	196	1.54	1.76
2.02	301	82	14.8	48.7	.0426	2.54	5.60	.0041	414	286	16.9	24.5	1.4	2	4.16	4.77
2.03	302	83	14.8	48.6	.0424	2.54	5.59	.0080	587	597	59.2	85.9	1.4	2	4.19	4.80
2.01	302	84	15.0	49.3	.0431	2.55	5.62	.0100	661	730	95.1	138	1.4	2	4.09	4.69
2.31	303	86	22.0	72.2	.0630	4.27	9.42	.0152	853	1076	170	246	15.2	22	3.23	3.70
2.23	360	188	27.3	89.6	.0717	4.31	9.50	.0134	857	1083	170	247	8.9	13	2.98	3.42
2.03	417	291	30.1	98.8	.0734	3.72	8.20	.0135	915	1187	172	250	4.8	7	2.84	3.26
2.06	303	85	21.5	70.4	.0615	3.72	8.21	.0079	599	619	123	179	.7	1	2.93	3.36
2.12	304	88	28.1	92.2	.0802	4.99	11.0	.0080	589	601	181	262	2.1	3	2.33	2.67
2.49	307	92	36.3	119	.1033	7.48	16.5	.0079	561	550	169	245	8.9	13	2.13	2.44
2.12	366	198	14.6	47.9	.0380	2.16	4.77	.0040	473	391	13.7	19.9	-----	---	5.39	6.18
2.02	360	188	15.1	49.7	.0397	2.16	4.77	.0085	677	758	58.6	85.0	-----	---	4.88	5.59
1.98	368	202	15.7	51.4	.0406	2.16	4.77	.0156	934	1222	195	283	-----	---	4.74	5.43
2.41	368	202	35.4	116	.0918	5.85	12.9	.0031	491	423	57.4	83.3	-----	---	2.54	2.91
2.42	367	201	35.1	115	.0916	5.90	13.0	.006	600	620	220	319	-----	---	2.55	2.92
[a]2.09	430	314	15.0	49.3	.0361	1.93	4.25	.0043	583	590	-----	-----	-----	---	6.27	7.18
[a]2.08	420	296	15.1	49.4	.0366	1.90	4.19	.0044	577	578	-----	-----	-----	---	5.88	6.74
[a]2.04	418	293	15.1	49.6	.0368	1.88	4.15	.0099	844	1060	-----	-----	-----	---	5.72	6.55
[a]2.16	421	298	14.4	47.4	.0351	1.90	4.18	.0173	1125	1565	-----	-----	-----	---	6.38	7.31
3.01	416	288	14.9	49.0	.0365	2.77	6.10	.0075	687	777	82.7	120	-----	---	8.46	9.70
2.99	416	288	15.1	49.5	.0369	2.77	6.11	.0069	688	778	83.4	121	-----	---	8.34	9.56
3.20	412	282	13.7	45.0	.0336	2.71	5.97	.0075	699	799	81.3	118	-----	---	9.77	11.2
3.14	419	295	14.3	46.8	.0347	2.73	6.02	.0077	711	819	64.4	93.5	-----	---	9.34	10.7
4.06	588	598	15.5	51.0	.0321	2.76	6.09	.0123	1033	1399	193	280	3.4	5	15.5	17.8
4.07	574	594	15.3	50.1	.0315	2.72	6.00	.0130	1057	1442	131	190	.7	1	15.9	18.2

[a]Natural gas fuel.

EST RESULTS

oted in inlet total pressure column.]

Exhaust emissions											Combustion efficiency
Hydrocarbons		Carbon monoxide		Nitric oxide		Hydrogen		Carbon dioxide			
g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm		
7.72	213	106	1460	0.54	7	0.60	115	2.81×10^3	24.6×10^3		96.2
17.3	480	176	2440	.23	3	1.64	318	2.40	21.2		90.7
35.1	333	34.0	161	.68	3	.17	11	1.56	4.7		51.8
20.1	343	80.9	690	1.13	9	.49	58	2.40	13.0		87.8
24.0	395	78.5	645	.65	5	.71	82	1.92	10.0		95.2
17.7	281	52.6	416	1.08	8	.25	25	2.21	10.1		95.8
16.4	260	38.0	301	1.76	13	.16	16	1.88	8.6		93.4
15.0	390	83.9	1090	1.07	13	.24	43	2.32	19.1		92.6
3.91	107	19.2	263	1.88	24	.03	5	2.25	19.6		96.1
3.25	91	38.9	545	1.61	21	.08	15	2.13	18.9		97.1
20.8	576	131	1820	.23	3	.93	180	2.45	21.6		88.0
16.4	451	158	2180	.31	4	1.18	228	2.26	19.8		92.0
17.7	480	157	2140	.16	2	1.15	219	2.28	19.7		90.4
24.6	662	200	2700	.24	3	2.16	408	1.95	16.7		85.5
28.9	778	246	3320	.24	3	2.76	522	1.88	16.1		82.6
29.5	816	245	3400	.47	6	2.68	522	1.97	17.4		80.0
48.6	409	50.4	213	.76	3	.34	20	1.71	4.6		66.2
30.2	495	98.5	810	.65	5	.84	97	2.22	11.6		87.0
24.2	495	117	1195	.52	5	.93	134	2.16	14.1		88.0
18.3	566	136	2110	.56	8	1.00	216	2.12	20.9		92.1
14.1	385	126	1730	.55	7	.73	140	2.35	20.4		94.4
10.2	280	111	1530	.94	12	.62	120	2.46	21.6		95.3
24.4	394	134	1085	.53	4	1.38	157	2.23	11.5		90.6
23.2	379	167	1370	.52	4	1.76	202	2.28	11.9		87.6
31.5	509	217	1760	.40	3	2.44	277	2.33	12.0		77.9
69.2	571	43.4	179	.26	1	.28	16	2.14	5.6		64.4
31.6	552	92.6	808	.61	5	.57	70	2.80	15.5		92.3
15.4	489	85.5	1360	.47	7	.47	105	2.83	28.6		94.1
35.0	224	93.7	300	.67	2	.69	31	2.90	5.9		93.6
16.8	208	102	628	.87	5	.56	48	2.73	10.7		94.1
36.1	320	53.7	238	1.21	5	.90	56	1.88	5.3		79.4
41.8	379	60.4	274	.94	4	.99	63	1.94	5.6		79.0
14.1	286	55.5	563	.74	7	.29	41	2.65	17.1		101.5
12.6	442	29.1	512	.43	7	.19	46	2.83	31.7		98.3
7.78	120	42.4	327	1.81	13	----	---	----	----		90.6
8.87	123	50.4	358	1.96	13	----	---	----	----		97.8
16.9	260	41.0	316	1.95	14	----	---	----	----		94.8
7.94	125	43.1	341	1.63	12	----	---	----	----		94.2
6.71	169	3.81	48	4.34	51	----	---	----	----		97.0
1.20	32	4.59	61	2.10	26	----	---	----	----		97.6

TABLE I. - Concluded.

[ASTM A-1 fuel used except when

Inlet total pressure, atm	Inlet temperature, K	Inlet temperature, °F	Reference velocity, m/sec	Reference velocity, ft/sec	Inlet Mach number	Airflow, kg/sec	Airflow, lb/sec	Fuel-air ratio	Exit temperature, K	Exit temperature, °F	Primary fuel nozzle pressure differential, N/cm^2	Primary fuel nozzle pressure differential, psi	Secondary fuel nozzle pressure differential, N/cm^2	Secondary fuel nozzle pressure differential, psi	Correlating parameter, $\frac{(N)(K)(sec)}{m^3}$	Correlating parameter, $\frac{(lb)(^{o}R)(sec)}{ft^3}$
4.07	308	94	15.3	50.2	0.0434	5.13	11.3	0.0133	844	1059	170	247	23.4	34	8.25×10^6	9.46×10^4
4.07	419	294	14.7	48.2	.0358	3.62	7.98	.0135	938	1229	172	249	6.2	9	11.7	13.4
4.07	586	594	32.0	105	.0656	5.62	12.4	.0126	1050	1430	197	286	22.1	32	7.55	8.65
4.07	553	535	43.0	141	.0909	8.03	17.7	.013	1029	1393	-----	-----	-----	---	5.31	6.08
4.07	585	593	15.5	51.0	.0320	2.74	6.04	.0082	883	1129	75.8	110	-----	---	15.5	17.7
4.07	587	596	15.5	51.0	.0320	2.74	6.03	.0144	1109	1536	169	245	2.8	4	15.5	17.7
4.01	582	587	15.2	49.9	.0314	2.74	6.03	.0130	1051	1432	167	242	.7	1	15.9	18.2
4.07	586	595	7.9	26.0	.0163	1.40	3.08	.0127	1029	1393	47.3	68.7	-----	---	30.2	34.6
8.15	586	595	7.6	25.0	.0158	2.74	6.05	.0123	1026	1387	199	289	-----	---	63.2	72.4
8.15	585	593	7.6	24.8	.0156	2.70	5.95	.0130	1062	1452	125	181	-----	---	64.0	73.4
8.63	582	587	28.6	93.9	.0591	10.8	23.9	.0129	1039	1411	229	333	158.6	230	17.8	20.4
8.71	569	565	28.0	91.9	.0584	10.9	24.1	.0126	1033	1400	187	271	153.1	222	18.0	20.6
10.4	423	302	15.2	50.0	.0369	9.53	21.0	.0130	909	1176	178	258	121.4	176	29.3	33.6
10.7	308	94	15.1	49.2	.0427	13.3	29.3	.0130	795	973	288	418	260.6	378	22.7	25.4
10.4	418	292	14.6	47.9	.0356	9.30	20.5	.0132	921	1197	201	292	108.2	152	30.2	34.6
10.5	312	102	15.7	51.5	.0442	13.5	29.8	.0122	800	980	183	265	248.2	360	21.3	24.4
10.5	312	102	15.4	50.5	.0434	13.3	29.3	.0131	819	1015	245	355	258.6	375	21.7	24.9
10.4	420	296	15.0	49.1	.0364	9.53	21.0	.0129	914	1186	243	352	103.4	150	29.8	34.1
12.4	582	587	15.8	52.0	.0326	8.62	19.0	.0131	1049	1428	184	267	99.3	144	46.6	53.4
12.5	592	605	16.0	52.4	.0327	8.62	19.0	.0131	1069	1464	-----	-----	-----	---	47.0	53.9
10.3	582	587	15.3	50.2	.0316	6.94	15.3	.0126	1047	1424	192	278	40.0	58	39.9	45.7
10.2	583	590	15.9	52.2	.0328	7.08	15.6	.0125	1039	1411	205	298	39.3	57	37.9	43.4
10.5	303	86	14.6	48.1	.0419	12.9	28.5	.0074	592	605	184	267	55.8	81	22.0	25.2
10.4	412	281	14.9	48.8	.0365	9.62	21.2	.0075	704	808	187	272	22.1	32	29.2	33.4
10.4	584	592	15.2	50.0	.0314	6.94	15.3	.0076	863	1094	166	241	13.8	20	40.5	46.4
10.5	417	291	14.8	48.6	.0361	9.53	21.0	.0041	573	572	152	220	-----	---	30.0	34.4
10.2	414	286	15.4	50.5	.0377	9.66	21.3	.0078	712	822	173	251	29.6	43	27.8	31.8
10.3	416	289	14.6	48.0	.0357	9.71	21.4	.0153	983	1310	177	257	164.1	238	27.1	31.1
10.4	581	586	14.4	47.3	.0298	6.62	14.6	.0043	737	867	78.5	114	-----	---	42.5	48.7
10.4	581	586	14.4	47.1	.0296	6.58	14.5	.0084	581	586	163	236	7.6	11	42.9	49.1
10.5	583	589	14.3	47.0	.0296	6.58	14.5	.0155	1140	1592	169	245	66.2	96	43.1	49.4
[a]12.6	587	596	16.0	52.4	.0329	8.80	19.4	.0101	1009	1356	-----	-----	-----	---	46.9	53.8
20.7	547	525	14.0	45.9	.0298	13.5	29.8	.0038	695	793	197	286	1.4	2	81.9	93.9
20.7	553	535	14.1	46.4	.0299	13.5	29.8	.0078	844	1060	183	266	71.0	103	81.9	93.9
20.7	553	535	14.1	46.4	.0299	13.5	29.8	.0130	1027	1389	238	346	242.0	351	82.0	94.0
20.3	543	517	13.7	44.8	.0292	13.1	28.9	.0041	706	810	149	216	11.0	16	81.9	93.9
20.3	536	504	13.8	45.4	.0298	13.4	29.6	.0080	844	1060	149	216	86.9	126	79.9	91.6
20.6	547	525	13.9	45.7	.0297	13.4	29.6	.0129	1017	1370	150	217	149.6	217	82.0	94.0
20.6	549	528	13.9	45.7	.0296	13.4	29.6	.0081	853	1076	146	212	77.2	112	82.5	94.5
20.6	551	531	13.8	45.4	.0294	13.2	29.2	.004	707	814	146	212	1.4	2	83.2	95.4

[a]Natural gas fuel.

'EST RESULTS

oted in inlet total pressure column.]

Exhaust emissions										Combustion efficiency
Hydrocarbons		Carbon monoxide		Nitric oxide		Hydrogen		Carbon dioxide		
g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	g/kg fuel	ppm	
8.83	239	61.0	830	1.03	13	0.31	59	3.24×10^3	28.0×10^3	101
1.89	52	22.5	310	1.25	16	.05	10	3.42	30.0	99.7
1.13	29	15.7	203	2.17	26	.01	2	3.33	27.3	98.8
.79	21	28.3	376	2.27	28	.04	8	3.20	27.0	97.5
.95	16	6.77	57	3.07	24	.02	2	3.29	17.6	94.8
.34	10	3.06	45	1.25	17	0	0	3.64	34.0	98.2
.61	16	3.46	46	2.67	33	0	0	3.32	28.0	97.0
.62	16	10.9	141	1.24	15	.01	1	3.39	28.0	94.0
5.17	130	.40	5	5.36	63	----	----	--------	--------	96.2
1.02	27	1.13	15	.81	10	----	----	--------	--------	98.1
4.06	107	4.93	65	4.22	52	----	----	--------	--------	95.2
1.25	32	6.44	83	2.92	35	----	----	--------	--------	98.7
4.74	126	11.7	155	2.82	35	----	----	--------	--------	96.3
5.19	138	28.7	382	3.06	38	----	----	--------	--------	94.4
1.37	37	11.9	160	2.46	31	----	----	--------	--------	98.2
2.41	60	27.2	340	1.64	19	----	----	--------	--------	99.7
2.25	60	30.8	412	1.13	14	.18	34	3.71	31.6	97.6
.80	21	11.8	156	1.14	14	.01	2	3.74	31.3	98.6
4.74	127	1.79	24	4.16	52	----	----	--------	--------	95.4
.41	11	2.02	27	5.47	68	----	----	--------	--------	97.9
.62	16	2.64	34	----	--	0	0	2.69	22.0	99.0
1.45	37	2.66	34	2.93	35	----	----	--------	--------	97.8
13.3	203	35.4	269	1.13	8	.21	22.5	2.03	9.8	94.1
6.10	94	19.6	151	1.81	13	.04	4.5	2.43	11.9	97.5
1.60	25	3.71	29	2.33	17	Trace	Trace	2.12	10.5	95.5
3.07	26	11.1	47	2.03	8	.03	2	2.12	5.7	92.7
2.93	47	20.5	164	1.87	14	----	----	2.04	10.4	94.9
.83	26	13.8	216	.96	14	----	----	1.90	18.8	96.7
1.80	16	4.06	18	3.14	13	----	----	2.09	5.9	92.5
.70	12	3.59	31	3.10	25	----	----	1.92	10.5	95.8
.28	9	2.15	34	1.49	22	----	----	1.99	20.0	98.2
.48	10	.39	4	1.03	11	.01	1	2.50	16.3	102.3
7.14	56	1.28	5	4.92	18	----	----	--------	--------	98.4
2.62	42	1.75	14	2.00	15	----	----	--------	--------	96.6
1.66	44	2.03	27	1.61	20	----	----	--------	--------	97.0
3.09	26	1.18	5	3.06	12	----	----	--------	--------	100
.98	16	1.82	15	4.19	32	----	----	--------	--------	99.0
.34	9	2.96	39	3.35	41	0	0	3.34	28.0	96.4
.48	8	1.22	10	5.57	43	0	0	3.71	19.6	96.7
.97	8	.48	2	5.74	22	.02	1	3.43	9.0	97.8