NASA TECHNICAL MEMORANDUM

N 73-24933

NASA TM X-2800

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EFFECT OF FUEL VAPOR CONCENTRATIONS ON COMBUSTOR EMISSIONS AND PERFORMANCE

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1973

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM X-2800		

4. Title and Subtitle	5. Report Date
EFFECT OF FUEL VAPOR CONCENTRATIONS ON COMBUSTOR EMISSIONS AND PERFORMANCE	June 1973
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Carl T. Norgren and Robert D. Ingebo	E-7336
9. Performing Organization Name and Address	10. Work Unit No.
Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135	501-24
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
National Aeronautics and Space Administration Washington, D.C. 20546	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Effects of fuel vaporization on the exhaust emission levels of oxides of nitrogen (NO_x), carbon monoxide, total hydrocarbons, and smoke number were obtained in an experimental turbojet combustor segment. Two different fuel injectors were used in which liquid ASTM A-1 jet fuel and vapor propane fuel were independently controlled to simulate varying degrees of vaporization. Tests were conducted over a range of inlet-air temperatures from 478 to 700 K (860° to 1260° R), pressures from 4 to 20 atm, and combustor reference velocities from 15.3 to 27.4 m/sec (50 to 90 ft/sec). Converting from liquid to complete vapor fuel resulted in NO_x reductions of as much as 22 percent and smoke number reductions up to 51 percent. Supplement data are also presented on flame emissivity, flame temperature, and primary-zone liner wall temperatures.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Exhaust emissions Vapor-liquid fuel mixtures Primary-zone radiance	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	34	$3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

Effects of fuel vaporization on the exhaust emission levels of an experimental combustor segment were determined. Test conditions were inlet-air temperatures from 478 to 700 K (860° to 1260° R), pressures from 4 to 20 atmospheres, combustor reference velocities from 15.3 to 27.4 meters per second (50 to 90 ft/sec), and degrees of vaporization from 0 to 100 percent. Various degrees of vaporization were simulated by varying the ratio of liquid ASTM A-1 jet fuel to vapor propane fuel introduced into the combustor through dual concentric fuel injectors. Two different dual fuel injector designs were investigated. In the first configuration the liquid fuel was introduced through a simplex nozzle located at the center of the assembly, and vapor fuel was injected through a series of eight evenly spaced holes located on a diameter concentric with the simplex orifice. The second configuration was a commercial duplex nozzle with liquid fuel in the small center orifice and vapor fuel in the larger annular ring.

Exhaust emission levels were compared for all-liquid-fuel and all-vapor-fuel operation. Results using the first fuel nozzle injector indicate that (1) the emission index for oxides of nitrogen was reduced by as much as 22 percent at high inlet-air temperatures; (2) at conditions corresponding to engine idling the emission indexes for both carbon monoxide and total hydrocarbons were reduced 36 percent; (3) at the most severe smoking condition (20-atm pressure) the smoke number was reduced 51 percent; (4) the apparent gray-body flame emissivity was reduced 39 percent for an inlet-air temperature of 589 K (1060° R), pressure of 10 atmospheres, and fuel-air ratio of 0.014; and (5) the primary-zone liner wall temperature decreased 100 K (180° R) for the most severe cooling conditions (i.e., high inlet-air temperature, low pressure, and low reference velocity).

Similar reductions in emission levels were observed with the second fuel nozzle geometry as the proportion of propane vapor was varied from 0 to 100 percent. Although substantial reductions in exhaust emission levels were experienced, the decrease was not as large as anticipated, probably because of inadequate control of the effective primary-zone equivalence ratio. Careful control of the mixing process will be required to obtain low emission levels with vaporized fuel.

INTRODUCTION

An experimental investigation was undertaken at the NASA Lewis Research Center to determine the effect of substituting vapor fuel for liquid fuel on the emission level of an experimental gas turbine combustor.

The turbojet combustor emission products that are of primary concern for hydrocarbon fuels are the oxides of nitrogen (NO_x), carbon monoxide (CO), total hydrocarbons (THC), and smoke (ref. 1). The relative level of these emission products depends on many factors, including the fuel preparation, distribution, mixing, and recirculation patterns within the reaction zone. The combustion characteristics are affected by the inlet combustor conditions, which are dependent on the engine compressor pressure ratio, power output, flight speed, and altitude.

At idle and low power output (low combustor inlet-air temperature and pressure) the CO and THC are highest because of low combustion efficiency but improve as the power level is increased. At high power output (high combustor inlet-air temperature and pressure) the NO_x and smoke number levels increase and become the predominating pollutants. In a turbojet combustor the formation of CO, THC, and smoke are the result of incomplete reaction, whereas the formation of NO_x is primarily dependent on the flame temperature and residence time. At high power output (high pressure) combustion depends primarily on the mixing process between fuel and air rather than on kinetic limitations (ref. 2). Thus, techniques which improve mixing should reduce emissions of CO and THC by enhancing complete reaction between fuel and air. The oxides of nitrogen can be reduced by providing a lean uniform primary-zone equivalence ratio. One technique for obtaining a more uniform equivalence ratio is to prevaporize the fuel to eliminate hot zones which are associated with localized liquid droplet burning.

In order to determine effects of fuel vaporization on performance a segment of an experimental combustor was operated at inlet temperature levels to 700 K (1260° R) and pressures to 20 atmospheres. The combustor operates with intense primary-zone mixing obtained by introducing most of the air through swirlers concentric with the fuel nozzles, as described in reference 3. Vaporized propane was used to simulate vaporized liquid jet fuel. Propane was chosen since it is relatively easy to handle, and burning characteristics are similar to those of the majority of the constituents of jet fuel. Two different fuel nozzles were used to introduce liquid ATSM A-1 jet fuel and propane vapor either separately or in combination into the combustor. Data obtained for various percentages of vapor fuel included exhaust emission levels of NO_x, CO, THC, and smoke, as well as combustor flame emissivity, flame temperature, and liner wall temperature.

APPARATUS AND PROCEDURE

Test Facility and Instrumentation

The test combustor was mounted in the closed-duct facility described in reference 3 and shown in figure 1. Tests were conducted at pressure levels up to 20 atmospheres. Combustion air drawn from the laboratory high-pressure supply system was indirectly heated to 700 K (1260° R) in a counterflow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold bypassed air. The airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet airflow were regulated by remotely controlled valves.

Combustor instrumentation stations are also shown in figure 1. The inlet-air temperature was measured at station A with eight Chromel-Alumel thermocouples. Inlet total pressures were measured at the same station by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential-pressure strain-gage transducers that were balanced by wall static-pressure taps located at the top and bottom of the duct. Combustor outlet temperatures, pressure, and smoke sample were obtained with a traversing exhaust probe mounted at station C. The probe consisted of 12 elements: 5 aspirating platinum - platinum-13-percent-rhodium total-temperature thermocouples, 5 total-pressure probes, and 2 wedge-shaped static-pressure probes. A portion of the aspirated exhaust was bypassed for use as a smoke sample. At station D a four-point air-cooled probe was located to provide the exhaust emission gas sample. Station D was located 0.914 meter (36 in.) downstream of the combustor exhaust in a circular pipe with a diameter of 0.508 meter (20 in.).

Test Hardware

Combustor. - The combustor liner used in this investigation was similar to combustor model 3 of reference 3 with the faceplate slightly modified to accommodate different fuel nozzle injectors. A schematic of the combustor is shown in figure 2. The combustor liner was composed of a series of panels which are independently supported from the outer wall as shown in figure 2(a). The combustor has an inlet snout area which was 40 percent of the combustor inlet area. The main portion of the airflow entering the snout passed through air swirlers. A small portion, approximately 6 percent of the total flow, was used to film cool the sides of the combustor. The combustor

liner walls were film cooled by means of continuous slots. The dilution air was admitted by means of external scoops. The mass flow distribution in the combustor, also shown in figure 2(a), was calculated by means of a computer program for the analysis of annular combustors, as described in reference 4. Provision was made in the combustor side plates to allow direct observation of the primary flame zone through sapphire windows located 0.05 meter (2 in.) downstream of the combustor faceplate.

Fuel nozzle injectors. - Two different fuel nozzle injectors were used in this investigation and are shown in figure 2(b). Configuration 1 consisted of two separate passages in which liquid fuel was injected through a simplex nozzle located in the center of the assembly and vapor fuel was injected through a series of eight evenly spaced 0.94-millimeter- (0.037-in.-) diameter holes (with a 60° included angle) located on a 1.75-centimeter- (0.69-in.-) diameter concentric with the simplex orifice. Configuration 2 was a commercial duplex nozzle with liquid fuel in the small center orifice and vapor fuel in the larger annular ring. Typical flow rates for a given pressure drop across the nozzle are shown in figure 3 for liquid fuel and vapor fuel.

Gas Sample Technique

Gas samples. - The exhaust gas sample is withdrawn through the four-point air-cooled stationary probe shown in figure 4. The gas sample probe was located downstream of the traversing probe and in the center of the exhaust gas stream at station D, as shown in figure 1. The gas sample at a pressure of approximately 2 atmospheres was passed through an electrically heated sampling line at a temperature of approximately 423 K (760° R) to the gas analyzer. To prevent contamination in the sample line, a nitrogen purge was used prior to and during combustor ignition.

Gas sample analysis. - The exhaust gas was analyzed for oxides of nitrogen, carbon monoxide, and total hydrocarbons. Carbon dioxide was also included to determine and cross-check the fuel-air ratio of the sample. The gas analysis equipment is shown in figure 5 and is in accord with the recommendations set forth in reference 5.

Oxides of nitrogen were analyzed with a chemiluminescent meter. The meter included a converter for reducing nitrogen dioxide (NO_2) to nitric oxide (NO), which was measured. Measurement with and without the converter allows determination of both NO and NO_2 content. The carbon monoxide (CO) and carbon dioxide (CO_2) instruments were of the nondispersive infrared type. The total hydrocarbon content was determined by a flame ionization detector in which a portion of the sample gas was passed through a hydrogen flame. Concentrations of the oxides of nitrogen, carbon monoxide, and total hydrocarbons are reported on a wet basis. The emission index for oxides of nitro-

gen is expressed as grams of NO_2 per kilogram of fuel and that for total hydrocarbons as grams of CH_2 per kilogram of fuel.

Since practical considerations limited exhaust gas sampling to only four positions across the exhaust duct, attempts were made to verify that the gas sampling was representative of the average concentration levels at the combustor exit. Two fuel-air ratios were calculated. The first value was computed from measured quantities of carbon dioxide, carbon monoxide, and unburned hydrocarbons. The second fuel-air ratio was obtained from metered values of fuel and air. All of the data presented in this report, for which both values of fuel-air ratio were available, produced gas sample fuel-air ratios within ±15 percent of metered values.

Smoke sample. - The exhaust smoke sample was withdrawn through the movable exhaust probe which traverses the combustor exit at station C, as shown in figure 1. The sample line was heated by means of steam tracing, and the smoke number was determined with the smoke meter shown in figure 6. The sample was analyzed in accord with SAE practice, as discussed in reference 6. The gas flow rate at standard conditions was 2.36×10^{-4} cubic meter per second (0.50 ft^3/min), and four samples were obtained at each test condition for time durations of 12, 22, 36, and 72 seconds. From a plot of smoke number against weight of gas samples per square centimeter of filter area, the smoke number at 1.623 grams of gas per square centimeter of filter (0.023 lb of gas/in.^{2} of filter) was determined.

Liner Temperature Measurement

Nine Chromel-Alumel thermocouples were installed in the combustor liner walls. The 0.15-centimeter- (0.06-in.-) diameter thermocouple sheaths were imbedded in liner-wall groves, and the thermocouple junctions were filled with high-temperature braze. Figure 2 shows the location of the thermocouples. Three thermocouples were placed in a single row in line with the fuel nozzles and three in a row between nozzles for the upper wall. On the lower wall three thermocouples were installed in a row in line with the fuel nozzles. The three thermocouples located 0.05 meter (2 in.) downstream of the combustor at station B (see fig. 1) gave consistently higher readings than the other thermocouples because they were farthest from a cooling slot. The experimental liner temperatures presented were the average of these highest temperature indications.

Flame Temperature and Emissivity

Measurement of optical properties of the flame were obtained from a radiometric observation of the flame as viewed through sapphire windows located 0.05 meter (2 in.) downstream of the combustor faceplate in line with three liner wall thermocouples. Two radiometric determinations were taken: in the first, the effective flame temperature was calculated from a narrow band region where the flame can be considered to be a black body; and in the second, the total radiance was calculated from the observed radiance. An indium antimonide detector was used for the narrow-band spectrum (2.608- to 2.789-μm half-width), and an unimmersed bolometer thermal detector was used for the "total" spectral band (0.025- to 6-μm half-width, cutoff due to sapphire windows). Details of the radiometer and calculation procedure are presented in reference 7. The equivalent gray-body emissivity was calculated from the Stephan-Boltzmann equation by using the values of effective flame temperature and total flame radiance.

Combustor Test Conditions

The combustor was operated at the test conditions shown in table I. Data for three fuel-air ratio values of 0.010, 0.014, and 0.018 were obtained for each fuel nozzle injector by using liquid ASTM A-1 jet fuel, vapor fuel, and combinations of 25-percent-liquid - 75-percent-vapor fuel, 50-percent-liquid - 50-percent-vapor fuel, and 75-percent-liquid - 25-percent-vapor fuel. Not all conditions could be obtained because of fuel flow limitations of the injectors.

Fuel Selection

Selected properties of ASTM A-1 jet fuel and propane are listed in table II. Propane was used to simulate vaporized jet fuel because (1) it is easier to vaporize and handle than liquid jet fuel, and (2) the combustion properties are similar to those of distillate jet fuels.

As shown in table II the lower heating value, flammability limits, flame velocity, and flame temperature of propane compare favorably with those of ASTM A-1 jet liquid fuel. The slight difference in combustion characteristics which might occur would probably not be experienced in this program. That is, the test conditions were primarily at high inlet-air temperatures and pressures, where combustion is limited by the

mixing process rather than chemical kinetics. Experiments in which the proportions of isoparaffins, cycloparaffins, and normal paraffins were varied over a wide range in vaporized jet fuel did not produce any appreciable difference in the NO_x, NO, and CO emissions, as shown in reference 8.

The difference in the percent of hydrogen between the two fuels could possibly have an effect on the smoke number. In reference 9 it was shown that for a constant pressure both the percentage of hydrogen in the fuel and the inlet-air temperature can affect the smoke number. In reference 8 smoke emissions were shown to decrease as the hydrogen content increased for inlet-air temperatures up to 700 K (1260° R); however, at higher inlet-air temperatures the effect of fuel type was minor. Although ASTM A-1 jet fuels can comprise a wide variety of hydrocarbon types, the largest proportion is usually of the normal-paraffin type. In reference 2 it is shown that normal paraffins containing two or more carbon atoms have somewhat similar smoking criteria. Therefore, considering the percentage of hydrocarbon in the fuel, the inlet-air temperature, and the hydrocarbon type, it would be expected that the smoke number might be less with propane fuel than with vaporized ASTM A-1 jet fuel at lower inlet-air temperatures. At inlet-air temperature levels of 700 K (1260° R) or more the two fuels would be expected to be similar.

RESULTS AND DISCUSSION

Effects of the percent of fuel vaporization on exhaust emission levels of oxides of nitrogen, carbon monoxide, total hydrocarbons, and smoke and on gray-body flame emissivity, effective flame temperature, and primary-zone liner wall temperature are presented. Combustion efficiencies are not presented since levels were of the order of 100 percent at all test conditions. To establish trends of fuel vaporization effects independent of injector geometry, data from two different types of fuel nozzle injectors are included.

Effect of Fuel Vaporization on Emission of Oxides of Nitrogen

Effects of fuel vaporization on NO_x emission for three different fuel-air ratios are presented in figures 7 to 9 for variations in inlet-air temperature, inlet pressure, and combustor reference velocity.

Effect of fuel-air ratio. - As shown in figure 7(a), there was a general trend for the NO_x emission index to increase as the fuel-air ratio was increased. For example,

for an inlet-air temperature of 700 K (1260° R) the NO_x emission index increased from 16.8 to 23.7 as the fuel-air ratio was increased from 0.010 to 0.018 for fuel nozzle injector 1 operating with only liquid ASTM A-1 jet fuel. In figure 8 for an inlet-air temperature of 589 K (1060° R) and a combustor reference velocity of 21.3 meter per second (70 ft/sec) the emission index at higher pressure levels went through a maximum for variations in fuel-air ratio. The NO_x increased from 12.8 to 13.7 at a pressure of 20 atmospheres as the fuel-air ratio was increased from 0.010 to 0.018 for fuel nozzle injector 1 operating with only liquid A-1 fuel, as shown in figure 8, but the highest NO_x emission index level (14.8) was obtained at an intermediate fuel-air ratio of 0.014.

In order to facilitate comparison of the effects of fuel vaporization during changes in the operating parameters of inlet-air temperature, pressure, and reference velocity a fuel-air ratio of 0.014 was selected.

Effect of inlet-air temperature. - A cross plot of figure 7 is presented in figure 10 to illustrate better the effect of inlet-air temperature on NO_x emission index for various proportions of vapor fuel. Test results using fuel nozzle injector 1 indicate that as the inlet-air temperature was increased from 478 to 700 K (860° to 1260° R) the NO_x emission index increased from 5 to 22 for 0 percent vapor fuel injection at a pressure of 10 atmospheres and a reference velocity of 21.3 meters per second (70 ft/sec). The effect of vapor fuel was negligible for an inlet-air temperature of 478 K (860° R). The reduction in NO_x that occurred as the proportion of vapor fuel was increased became more significant at higher inlet-air temperatures. A 22-percent decrease in NO_x at 589 and 700 K (1060° and 1260° R) was obtained as the fraction of vapor was increased from 0 to 100 percent. Fuel nozzle injector 2 results were similar except that the level of NO_x reduction was not as large. Fuel flows that were 100 percent vapor were not attainable with fuel nozzle injector 2 because of fuel flow limitations.

Factors which affect the NO_x emission index include primary-zone equivalence ratio and dwell time, which in turn can be affected by the reaction-zone volume. An increase in NO_x with increasing inlet-air temperature such as shown in figure 10 would be expected, since the overall fuel-air ratio (primary-zone equivalence ratio) and combustor reference velocity (dwell time) remained constant. Therefore, the flame temperature was primarily dependent on the inlet-air temperature. The reduction of NO_x for a constant inlet-air temperature, various degrees of fuel vaporization, and various fuel nozzle geometries could be attributed to variation in the effective primary-zone equivalence ratio. The primary-zone equivalence ratio was determined by the proportioning of fuel and air. At an operating overall fuel-air ratio of 0.014 the primary-zone equivalence ratio was calculated to be 0.75. However, the local equivalence ratio determines the maximum flame temperature. If the system is well mixed, the minimum NO_x emission level will be established; however, local stoichiometric regions can lead

to higher NO_x emission. In this combustor primary air was introduced through air swirlers concentric with the fuel nozzles. In the case of fuel nozzle injector 1 a rather coarse liquid spray was obtained which could penetrate to the primary airstream. The vapor fuel was injected directly into the airstream by means of eight jets inclined 30° into the airstream. With this configuration relatively intense mixing was established. The higher NO_x emission with liquid fuel as compared to vapor fuel was probably due to local stoichiometric burning associated with liquid fuel droplets. It is also quite possible that even with vapor fuel locally rich zones were present because fuel and air did not mix instantaneously. Additional study would be required to determine the minimum NO_x level with a premixed system.

An additional reduction of approximately 20 percent in NO_x level was obtained with fuel nozzle injector 2 as compared to injector 1. This reduction in NO_x is attributed not to an improvement in mixing but to poorer mixing as a result of the fuel distribution. Fuel injector 2 has a much higher pressure drop for a given flow than injector 1. This results in a more finely atomized fuel spray for a fixed fuel flow. Because of the finer spray and the placement of the spray (in the center of the air swirler vortex) a richer local primary zone was established. The flame temperature went through a maximum near an equivalence ratio of 1 so that lower flame temperatures were associated with rich mixtures. A rich misture is also very susceptible to smoke formation, whereas lean mixtures usually burn smoke free. Operation with fuel nozzle injector 2 produced a great deal of smoke (as discussed in the section Effect of Fuel Vaporization on Smoke Number), which indicated insufficient primary-zone mixing.

Effect of inlet pressure. - A cross plot of figure 8 is presented in figure 11 to illustrate better the effect of inlet pressure on NO_x emission for various proportions of vapor fuel with fuel nozzle injector 1 for an inlet-air temperature of 589 K (1060° R) and a combustor reference velocity of 21.3 meters per second (70 ft/sec). Results show that, as the inlet pressure was increased from 4 to 20 atmospheres, the NO_x emission index increased from 7.5 to 15 for 0 percent vapor fuel. A reduction in the NO_x emission index of 36 percent was obtained by converting to 100 percent vapor at a pressure level of 20 atmospheres. The NO_x emission index was not obtained at higher inlet-air temperatures because of facility limitations. Results with fuel nozzle injector 2 indicate that there was no appreciable effect of pressure or degree of fuel vaporization. Normally it would be expected that an increase in the NO_x emission index would be observed, as was the case with fuel nozzle injector 1. The fact that no increase in NO_x emission occurred with injector 2 can be attributed to a lower flame temperature as a result of poor primary-zone mixing, indicated by excessive smoke.

Effect of reference velocity. - A cross plot of figure 9 is presented in figure 12 to illustrate better the effect of combustor reference velocity on NO_x emission for various proportions of vapor fuel for each fuel injector at an inlet-air temperature of 589 K

(1060° R) and a pressure of 10 atmospheres. As the reference velocity increased from 15.3 to 27.4 meters per second (50 to 90 ft/sec), the NO_x emission index decreased 7 percent with fuel nozzle injector 1 for 0 percent vapor fuel. As the proportion of vapor fuel was increased to 100 percent, a reduction in NO_x of about 16 percent was obtained at a reference velocity of 27.4 meters per second (90 ft/sec). A reduction in NO_x of approximately 53 percent over the same range of reference velocity was observed with injector 2. However, there was no appreciable effect due to vapor fuel injection. The reduction in NO_x with increased reference velocity was anticipated, since the dwell time in the primary combustion zone is less.

Effect of Fuel Vaporization on Emission of Carbon Monoxide

Effects of fuel vaporization on CO emission index are presented in figure 13 for variation in inlet-air temperature for fuel nozzle injector 1. As shown in figure 13, the CO emission index decreased as the fuel-air ratio increased. This trend is opposite that previously shown for NO_x, for which the emission index increased with increasing fuel-air ratio. This indicates that a more intense flame was established at the higher fuel-air ratios.

Combustor operating conditions corresponding to an engine idling would produce the highest level of CO emissions because of poorer fuel spray and lowered inlet-air temperature. A dashed curve is also included in figure 13(a) to indicate the CO emission index level for a simulated idle condition with an inlet-air temperature of 478 K (860° R), a pressure of 4 atmospheres, a reference velocity of 21.3 meters per second (70 ft/sec), and a fuel-air ratio of 0.008. A somewhat lower combustion efficiency corresponding to approximately 95 percent was obtained at idle. Results indicate that, as the percentage of vapor fuel was increased from 0 to 100 percent, the CO emission index decreased from 110 to 70 (improved 36 percent). The high CO emission level is reflected in the lower operating combustion efficiency level. Comparison of the CO emission index at idle with fuel nozzle injector 2 was not made because of operational difficulties.

Effect of inlet-air temperature. - A cross plot of figure 13 is presented in figure 14 to summarize the effect of variation of inlet-air temperature on the CO emission index for various proportions of vapor fuel for each fuel injector for a pressure of 10 atmospheres and a combustor reference velocity of 21.3 meters per second (70 ft/sec). The results obtained by using fuel nozzle injector 1 indicate that, as the inlet-air temperature was increased from 478 to 700 K (860° to 1260° R), the CO emission index decreased from 60 to 8 for 0 percent vapor fuel. With 100 percent vapor fuel injection

CO was decreased 33 percent at the most severe condition, which corresponded to an inlet-air temperature of 478 K (860° R). Use of fuel nozzle injector 2 resulted in about the same level of CO. The effect of vapor fuel was more pronounced in reducing CO with fuel nozzle injector 2 than with fuel nozzle injector 1.

Higher CO emission index levels were evident at the lower inlet-air temperatures and indicated incomplete combustion. Even though combustion was incomplete, the combustion efficiency was nearly 100 percent, since a loss in efficiency of only 1 percent due to carbon monoxide for liquid A-1 would result in a CO emission index level of 43. The inlet-air temperature of 478 K (860° R) was below the boiling point of the liquid fuel (final boiling point, 532 K (956° R), and coupled with intense mixing the fuel vaporization and burning processes were probably somewhat delayed as compared to combustion with higher inlet-air temperature or 100 percent vapor fuel. As the inlet-air temperature was increased, a sharp drop in CO was observed which reflected the improved reaction environment. The largest absolute gain in CO reduction was at the lower inlet-air temperatures. At the higher inlet-air temperatures the CO levels were low so that large percentage gains did not amount to much of an actual decrease in absolute CO level.

Effect of inlet pressure. - The effects of inlet pressure on the CO emission index for various proportions of vapor fuel are shown in figure 15 for the two fuel nozzle injectors for an inlet-air temperature of 589 K (1060° R) and a combustor reference velocity of 21.3 meters per second (70 ft/sec). Results using fuel nozzle injector 1 indicate that, as the inlet pressure was increased from 4 to 20 atmospheres, the CO emission index decreased from 46 to 26 for 0 percent vapor fuel. The effect of 100 percent vapor fuel was to decrease the CO further by approximately 28 percent at a pressure of 4 atmospheres. When fuel nozzle injector 2 was used, the CO emission index was reduced from 32 to 12 at a pressure level of 4 atmospheres as the proportion of vapor was increased from 0 to 50 percent.

Effect of inlet velocity. - The effects of combustor reference velocity on CO emission index for various proportions of vapor fuel are shown in figure 16 for the two fuel nozzle injectors for an inlet-air temperature of 589 K (1060° R) and a pressure of 10 atmospheres. Results using fuel nozzle injector 1 indicate that, as the reference velocity was increased from 15.3 to 27.4 meters per second (50 to 90 ft/sec), the CO emission index increased from 25 to 39 for 0 percent vapor fuel. Proportions of vapor fuel up to 50 percent did not significantly influence CO formation; however, 100 percent vapor fuel operation did decrease the CO emission index approximately 27 percent at a reference velocity of 27.4 meters per second (90 ft/sec). The trends shown in figure 16 are consistent in that at the lower reference velocity the dwell time was increased and the CO emission reduced.

Effect of Fuel Vaporization on Emission of Hydrocarbons

The effect of fuel vaporization on the THC emission index for variation in inlet-air temperatures is shown in figure 17 for the two fuel nozzle injectors for a pressure of 4 atmospheres and a reference velocity of 21.3 meters per second (70 ft/sec). Also included for fuel nozzle injector 1 is the THC emission level corresponding to that for engine idling. As shown in figure 17, for the simulated idle condition the THC emission index was reduced from 21 to 13.5 (36 percent reduction) for injector 1 as combustion was converted from 0 to 100 percent vapor fuel. The level of unburned hydrocarbons decreased as the fuel-air ratio was increased for both fuel injectors for an inlet-air temperature of 589 K (1060° R). The THC emission index was of the order of 1 for a fuel-air ratio of 0.014 over a range of vapor fuel flows from 0 to 100 percent. The THC emission index at higher inlet-air temperatures and pressures was so low (generally less than 1) that trends were ambiguous.

Effect of Fuel Vaporization on Smoke Number

Effects of fuel vaporization on smoke number are presented in figure 18 for variations in inlet pressure for an inlet-air temperature of 589 K (1060° R), a combustor reference velocity of 21.3 meters per second (70 ft/sec), and a fuel-air ratio of 0.010. The data from figure 18 are cross-plotted in figure 19. In figure 19 the effect of inlet pressure on smoke number is presented for various proportions of vapor fuel for two fuel nozzle injectors, an inlet-air temperature of 589 K (1060° R), and a combustor reference velocity of 21.3 meters pers second (70 ft/sec). As shown in figure 19, the smoke number increased from 12 to 27 as the inlet pressure was increased from 4 to 2 atmospheres for fuel nozzle injector 1 with 0 percent vapor fuel. Operation with 100 percent vapor fuel decreased the smoke number 51 percent at the most severe condition of 20 atmospheres. Fuel nozzle injector 2 produced a very sharp increase in smoke number as the pressure was increased. Values over 80 were indicated at a pressure level of 20 atmospheres and 0 percent vapor fuel. Operation at 100 percent vapor was not obtained with fuel nozzle injector 2; however, at a pressure of 10 atmospheres and 75 percent vapor a decrease in smoke number of 25 percent was obtained with injector 2, compared to a decrease of 66 percent with injector 1.

The differences in smoke number between the two fuel injectors are consistent with the emission index levels previously presented. For example, the NO_x emission index was lower with injector 2; this was attributed to lower flame temperature resulting from an overly rich local condition in the primary zone. An overly rich primary would be susceptible to producing a smoking condition.

Effect of Fuel Vaporization on Gray-Body Flame Emissivity

The effect of fuel vaporization on the apparent gray-body flame emissivity is shown in figure 20 for a range of inlet-air temperatures, a pressure of 10 atmospheres, a combustor reference velocity of 21.3 meters per second (70 ft/sec), and a fuel-air ratio of 0.014 for fuel nozzle injector 1. The apparent gray-body emissivity increased from 0.48 to 0.77 as the inlet-air temperature was increased from 478 to 700 K (860° to 1260° R) with 0 percent vapor fuel. With 100 percent vapor fuel, emissivity levels of 0.25, 0.45, and 0.38 were indicated for inlet-air temperatures of 478, 589, and 700 K (860°, 1060°, and 1260° R), respectively. For an inlet-air temperature of 589 K (1060° R) a 39-percent decrease in apparent gray-body flame emissivity was observed as combustion conditions were converted from 0 to 100 percent vapor fuel.

The apparent gray-body flame emissivity is a convenient way to approximate radiance from the various emitting species in a flame. At high pressures entrained smoke particles are the primary contributors to the flame emissivity. With 0 percent vapor fuel the emissivity increased for the higher inlet-air temperatures and indicated that more smoke was formed, which could be attributed to pyrolysis of the liquid fuel droplets at the higher temperature level. This additional smoke was consumed more rapidly with the combustor because of the higher flame temperature, however, so that at the exhaust the smoke number generally was slightly reduced for an increase in operating inlet-air temperature. As combustion was converted to 100 percent vapor fuel, there was less possibility of smoke formation (providing the reactants are well stirred) and the flame emissivity decreased as expected.

Effect of Fuel Vaporization on Apparent Flame Temperature

The effect of fuel vaporization on apparent flame temperature is shown in figure 21 for a range of inlet-air temperature, a pressure of 10 atmospheres, a combustor reference velocity of 21.3 meters per second (70 ft/sec), and a fuel-air ratio of 0.014 for fuel nozzle injector 1. The apparent flame temperature was relatively unaffected by the addition of vapor fuel at an inlet-air temperature of 478 K (860° R), whereas at higher inlet-air temperatures a peaking in apparent flame temperature was observed with increasing proportions of vapor fuel. For an inlet-air temperature of 589 K (1060° R) the flame temperature was 2395 and 2275 K for vapor fuel percentages of 0 and 75. Since the radiometer location was fixed, it is possible that the peak temperature moved out of the field of view of the radiometer. It has been previously observed, however, that the flame temperature in the primary combustion zone remains relatively constant over a

fairly wide range of observation stations downstream of the fuel injector, as reported in references 7 and 11.

The maximum apparent flame temperature corresponded rather closely to that associated with stoichiometric burning. At the operating equivalence ratio of 0.75 the theoretical flame temperature was about 2170 K, and at an equivalence ratio of 1, about 2450 K, for an inlet-air temperature of 589 K and a pressure of 10 atmospheres. The higher observed temperatures (up to 2420 K for 25 percent vapor fuel) indicated local burning near stoichiometric due to either incomplete mixing in the primary zone or droplet burning or both.

Effect of Fuel Vaporization on Primary-Zone Liner Wall Temperature

The effect of fuel vaporization on primary-zone liner wall temperature for various inlet-air temperatures, pressures, and combustor reference velocities is shown in figure 22 for a fuel-air ratio of 0.014. The liner wall temperature is presented as the difference between the temperature with 0 percent vapor fuel and the temperature with a given percentage of vapor fuel. The base temperature is included for reference. As shown in the figure, the liner wall temperature always decreased with the addition of vapor fuel. The effect of inlet-air temperature is shown in figure 22(a) for a pressure of 10 atmospheres and a combustor reference velocity of 21.3 meters per second (70 ft/sec). A 6.5-percent (104 K; 187° R) decrease in the liner wall temperature was observed as the combustor was converted from 0 to 100 percent vapor fuel operation for an inlet-air temperature of 700 K (1060° R).

The effect of inlet-pressure is shown in figure 22(b) for an inlet-air temperature of 589 K (1060° R) and a combustor reference velocity of 21.3 meters per second (70 ft/sec). A 9-percent (120 K; 216° R) decrease in liner wall temperature was observed as the combustor was converted from 0 to 100 percent vapor fuel operation for an inlet pressure of 4 atmospheres.

The effect of combustor reference velocity is shown in figure 22(c) for an inlet-air temperature of 589 K (1060° R) and a pressure of 10 atmospheres. A 6.7-percent (96 K; 173° R) decrease in liner wall temperature was observed as the combustor was converted from 0 to 100 percent vapor fuel operation for a combustor reference reference velocity of 15.3 meters per second (50 ft/sec).

The heat flux to the liner wall in the primary zone is determined by the flame radiance, which in turn is controlled by flame emissivity and flame temperature. As previously shown in figure 20, the apparent gray-body flame emissivity decreased as the proportion of vapor fuel increased. As shown in figure 21, the apparent flame tem-

perature either remained constant (with an inlet-air temperature of 478 K; 860° R) or decreased (with higher inlet-air temperatures) as the proportion of vapor fuel increased. The overall effect was a reduction in heat flux to the liner wall and a corresponding decrease in liner wall temperature.

Effect of Fuel Injector Design

Combustor exhaust emissions were reduced as combustion was converted from liquid fuel to 100 percent vapor fuel. A reduction in emissions was observed with both fuel nozzle injectors. In general, it was necessary to convert to 100 percent vapor before any appreciable decrease in emission index was obtained. Even if 100 percent vapor fuel were available over the entire range of operating conditions, larger reductions in the NO_x emission index would be desired.

The NO_x emission level is strongly dependent on the primary-zone equivalence ratio. The primary-zone equivalence ratio was predicted to be 0.75. As shown in figure 21 for fuel nozzle injector 1, as combustion is converted to 100 percent vapor the effective flame temperature can be extrapolated to approximately 2170 K. (Experimental radiance data were not obtained at all operating conditions because of instrumentation difficulties.) The theoretical flame temperature for an inlet-air temperature of 589 K (1060° R) and a pressure of 10 atmospheres is also of the order of 2170 K. This indicates that, when no liquid fuel droplets were involved, complete mixing may have been attained. No attempt was made to modify the selected fuel nozzles or combustor geometry in this study. It is possible that there may have been local pockets of fuel which burned at a higher temperature and caused the relatively high level of NO_x; however, indications are that the primary-zone equivalence ratio and volume should be further reduced in order to lower the NO_x emission. A further reduction in equivalence ratio might lead to instabilities at the idle condition which could result in increased CO and THC levels. Fuel staging or a variable geometry might possibly minimize these problems, however.

Fuel nozzle injector 2, on the other hand, was shown to be operating with an overly rich primary zone because of the poor arrangement of the fuel admission ports and swirler combination. This arrangement is characteristic of the configuration that would result, however, if vapor fuel were directly substituted for liquid fuel in a conventional combustor system. Obviously, such an arrangement is unsatisfactory, and it would be necessary to provide an alternative primary-zone mixing method.

The design, optimization, and development of the fuel nozzle injector and appropriate primary mixing zone present a difficult task. Lower flame temperatures can be

achieved by operating at lean equivalence ratios; however, careful control of the combustion process is required in order to prevent locally rich regions. Lower flame temperature can also be achieved by operating with a rich equivalence ratio; however, excess smoke is produced which requires additional dwell time at relatively high temperatures in order to be consumed prior to dilution.

SUMMARY OF RESULTS

The following results were obtained in a segment of an experimental combustor operating at inlet-air temperatures of 478 to 700 K (860° to 1260° R), pressures of 40 to 20 atmospheres, and combustor reference velocities of 15.3 to 27.4 meters per second (50 to 90 ft/sec) by using liquid ASTM A-1 jet fuel, propane vapor fuel, and various proportions of vapor fuel while maintaining a fixed fuel-air ratio. Specific results are presented for a dual fuel injector in which the liquid fuel was introduced through a simplex nozzle located in the center of the assembly and the vaopr fuel was injected through a series of eight evenly spaced 0.94-millimeter- (0.037-in.) diameter holes located on a diameter concentric with the simplex orifice. One additional injector was used in which liquid fuel was admitted into the center of a commercial duplex nozzle and vapor fuel was admitted into the annular ring. Increasing the proportion of vapor fuel injected into the combustor from 0 to 100 percent indicated the following trends for a combustor reference velocity of 21.3 meters per second (70 ft/sec):

1. At an inlet total pressure of 10 atmospheres and a fuel-air ratio of 0.014 the emission index for the oxides of nitrogen decreased 22 percent at inlet-air temperatures of 589 and 700 K (1060° and 1260° R) but was not affected at an inlet-air temperature of 478 K (860° R).

2. At an inlet-air temperature of 478 K (860° R), a pressure of 4 atmospheres, and a fuel-air ratio of 4 atmospheres, and a fuel-air ratio of 0.008 the emission index levels for carbon monoxide and total hydrocarbons were decreased 36 percent.

3. At an inlet-air temperature of 589 K (1060° R), a pressure of 20 atmospheres, and a fuel-air ratio of 0.010 the smoke number was decreased 51 percent.

4. At an inlet-air temperature of 589 K (1060° R), a pressure of 10 atmospheres, and a fuel-air ratio of 0.014 the apparent gray-body flame emissivity decreased 39 percent (with 75 percent vapor fuel).

5. The primary-zone liner wall temperature decreased approximately 100 K (180° R) for a temperature of 700 K (1260° R), a pressure of 4 atmospheres, a fuel-air ratio of 0.014, and a combustor reference velocity of 15.3 meters per second (50 ft/sec).

6. Similar reductions in emission levels were observed with fuel nozzle configuration 2 as the proportion of vapor propane was varied from 0 to 100 percent.

7. Results indicate that changing the amount of vapor alone is insufficient to obtain major reductions in emission index levels and that a design optimization of the primary-zone equivalence ratio would be required to achieve further improvement.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 26, 1973,
501-24.

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TABLE I. - COMBUSTOR TEST CONDITIONS

Inlet pressure, atm	Inlet temperature		Reference velocity[a]	
	K	°R	m/sec	ft/sec
10	589	1060	21.3	70
10	487	860	↓	↓
10	700	1260		
4	589	1060		
20	589	1060		
10	589	1060	15.3	50
10	589	1060	27.4	90

[a]Reference velocity is based on total mass flow of air through maximum combustor housing cross-sectional area of 0.0464 m^2 (72 $in.^2$).

TABLE II. - PHYSICAL AND CHEMICAL PROPERTIES OF TEST FUELS

Property	ASTM A-1 jet fuel	Propane[a]
Boiling point, K (°R)		
Initial	334 (800)	---
Final	532 (956)	231 (416)
Lower heating value, J/g (Btu/lb)	43 000 (18 600)	46 024 (19 927)
Hydrogen-carbon ratio	0.160	0.220
Hydrogen, wt.%	14.3	18.2
Spontaneous ignition temperature, K (°R)	523 (940)	778 (1400)
Flammability limits		
Lean fuel-air ratio	0.035	0.034
Rich fuel-air ratio	0.27	0.19
Maximum flame velocity, cm/sec	38	43
Flame temperature, K	2235	2252

[a]Prpoane fuel was commercial grade about 90 to 92 percent pure. Impurities were primarily propylene (about 6 to 8 percent) and traces of ethylene and butane.

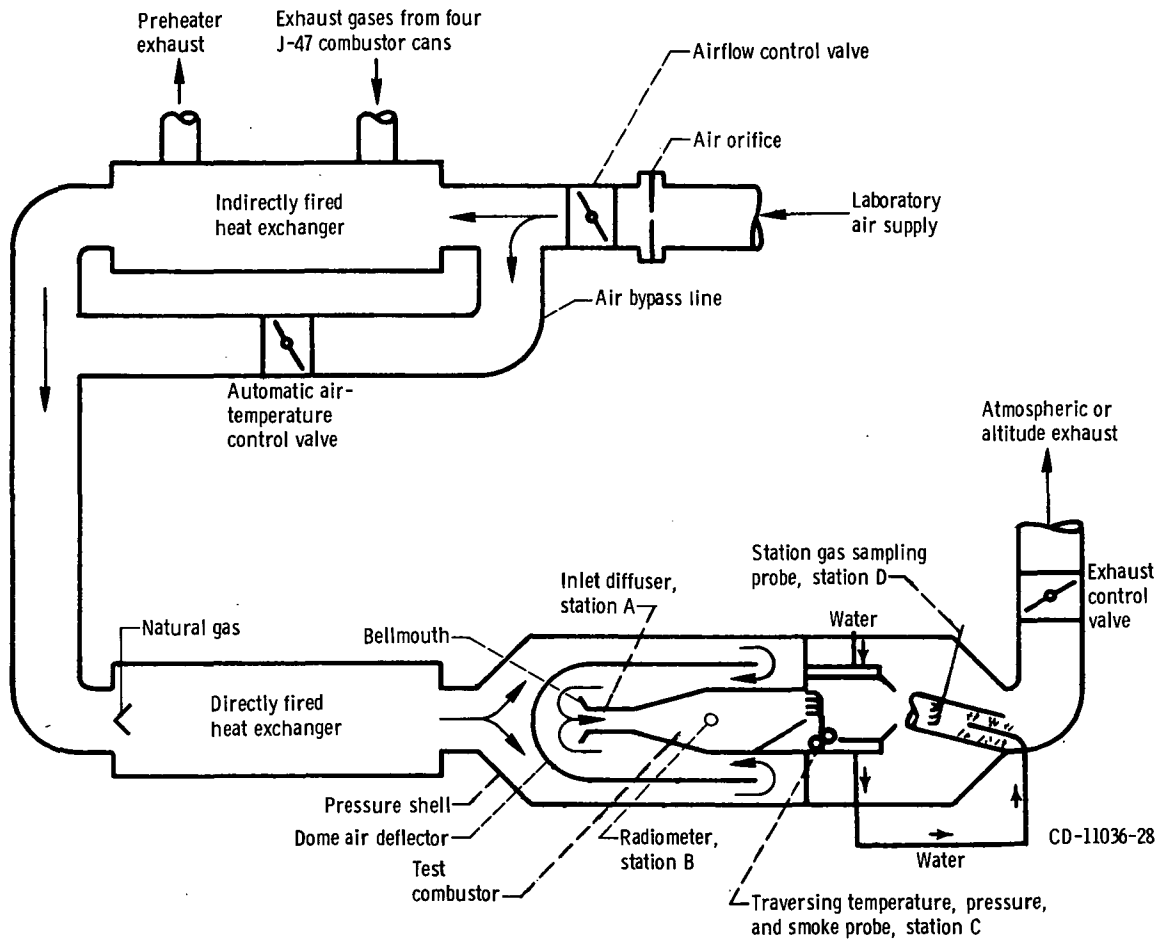
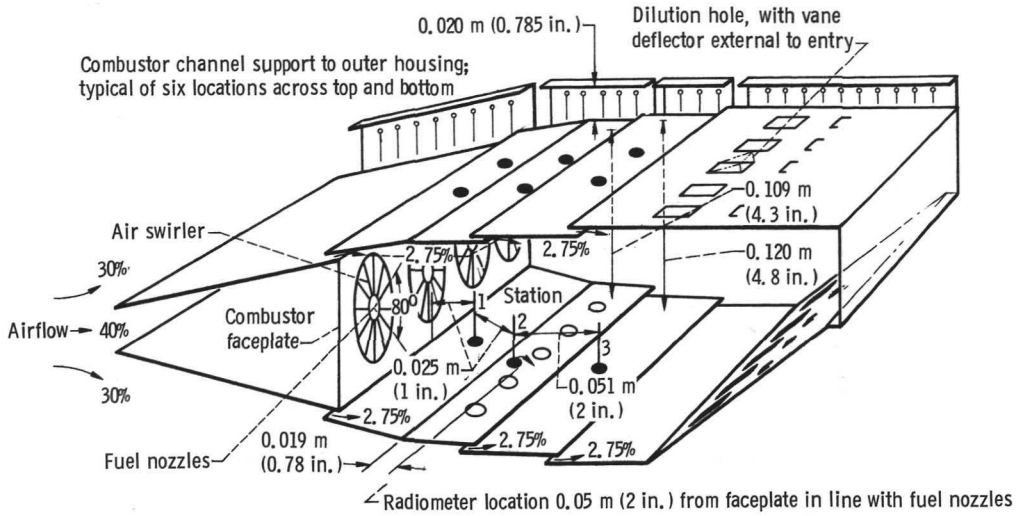
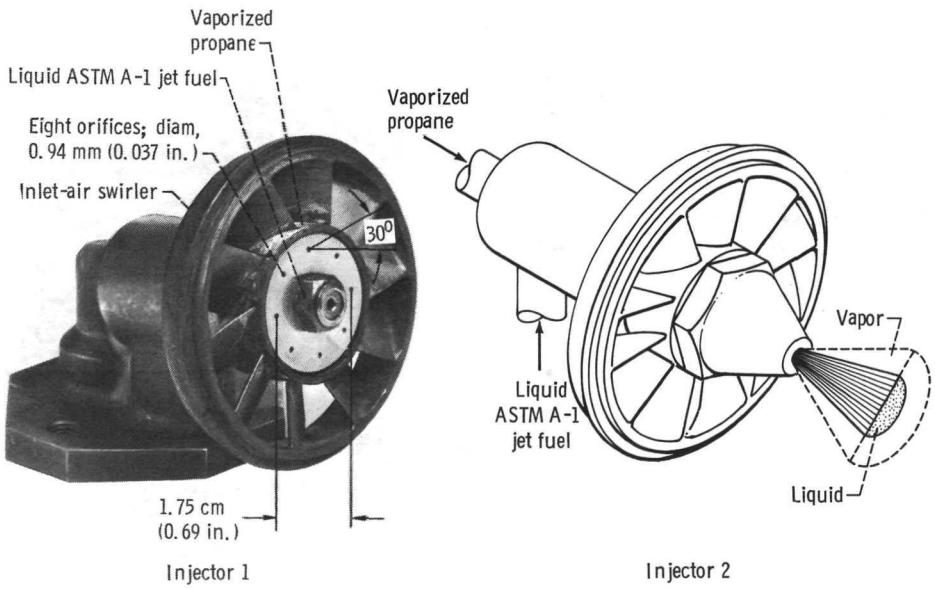


Figure 1. - Test facility and auxiliary equipment.



(a) Combustor liner.



(b) Fuel nozzle injectors.

Figure 2. - Schematic of combustor assembly. Combustor width, 0.31 meter (12 in.); combustor length, 0.32 meter (12.5 in.); maximum combustor housing height, 0.15 meter (6 in.).

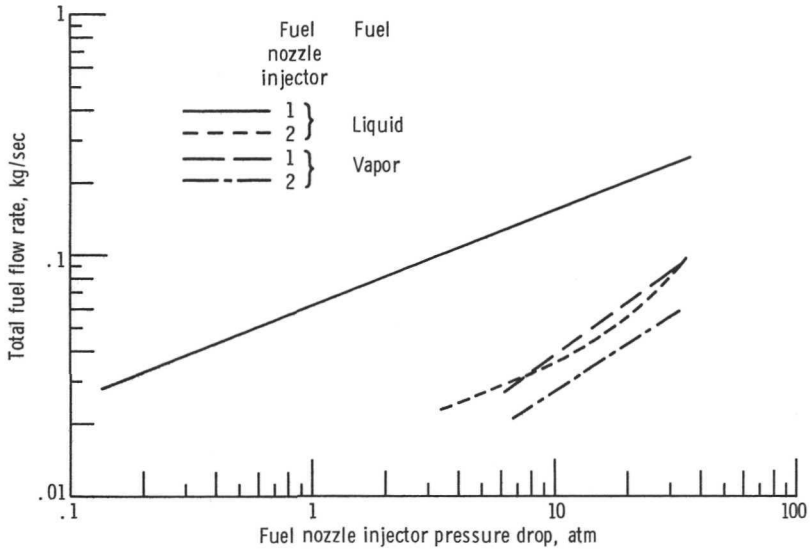


Figure 3. - Comparison of liquid and vapor fuel flows for fuel nozzle injectors 1 and 2. (Total flow equal to summation of flow for four injectors.)

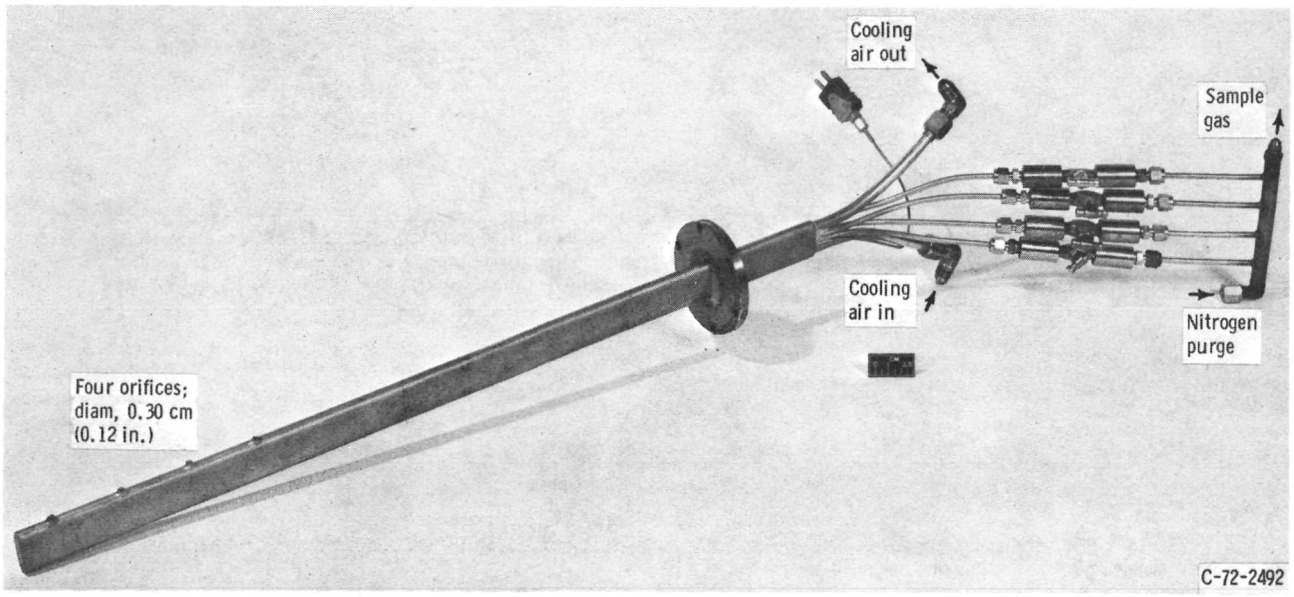


Figure 4. - Stationary gas sampling probe.

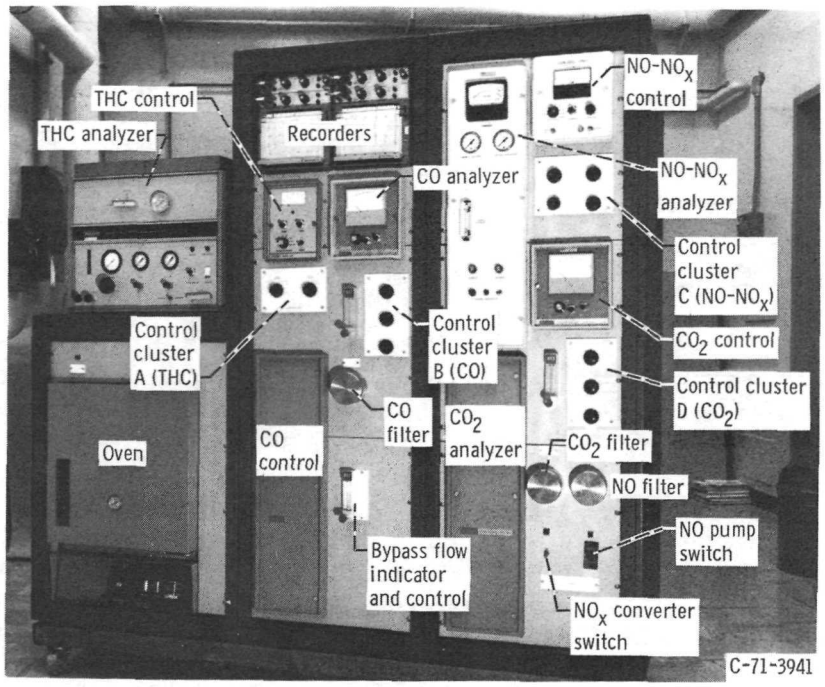


Figure 5. - Gas analysis equipment.

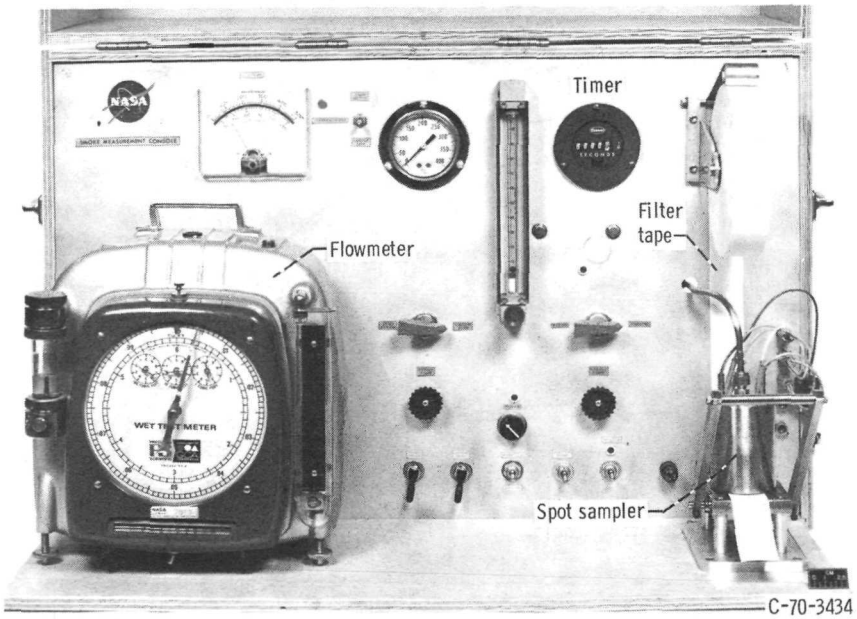
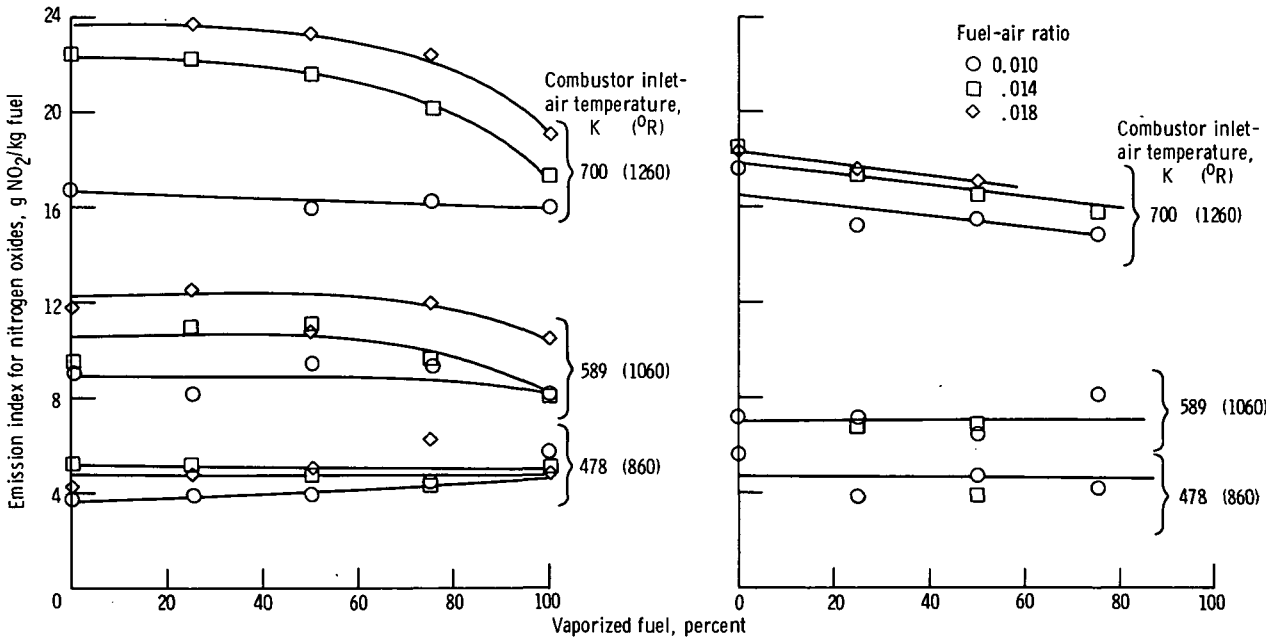


Figure 6. - Smoke meter.



(a) Fuel nozzle injector 1.

(b) Fuel nozzle injector 2.

Figure 7. - Effect of fuel vaporization on emission index for nitrogen oxides for three values of combustor inlet-air temperature. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec).

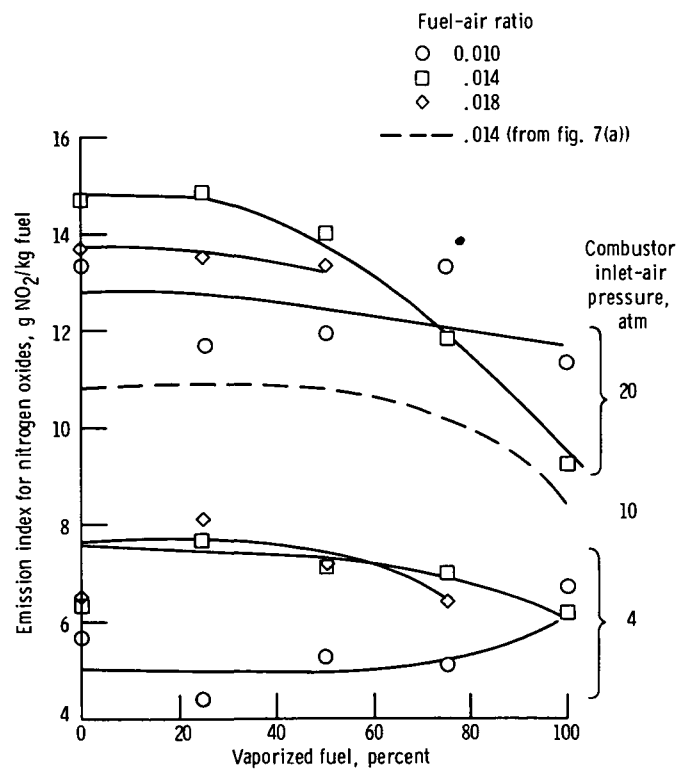
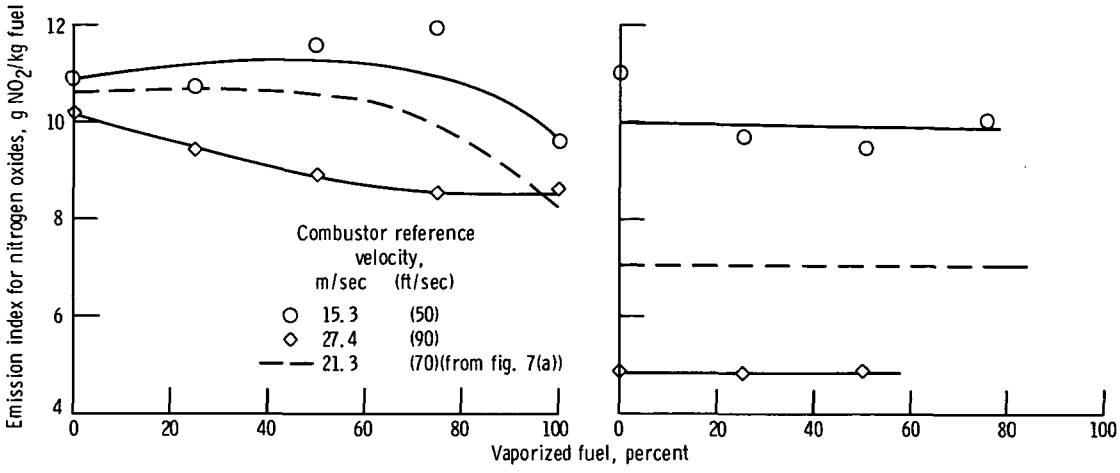


Figure 8. - Effect of fuel vaporization on emission index for nitrogen oxides with fuel nozzle injector 1 for two values of combustor inlet-air pressure. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec).



(a) Fuel nozzle injector 1.

(b) Fuel nozzle injector 2.

Figure 9. - Effect of fuel vaporization on emission index for nitrogen oxides for three values of combustor reference velocity. Inlet-air temperature, 589 K (1060° R); pressure, 10 atmospheres; fuel-air ratio, 0.014.

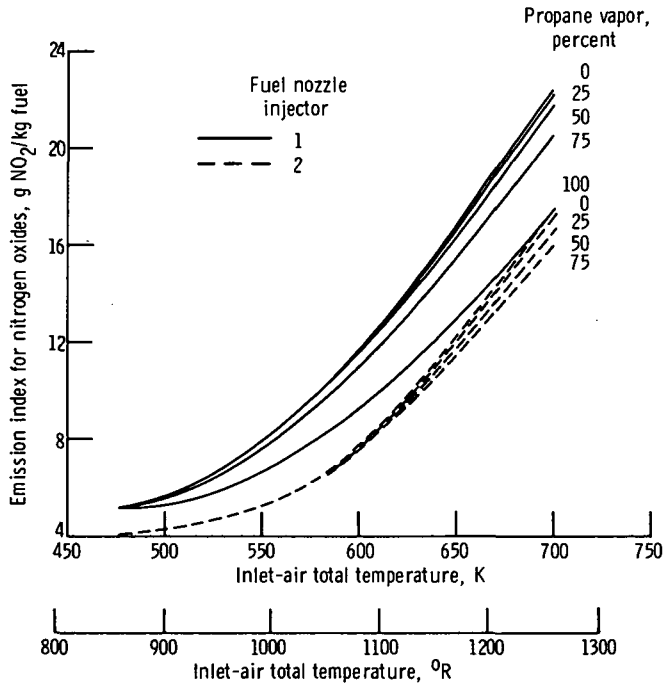


Figure 10. - Summary of effect of combustor inlet-air temperature on emission index for nitrogen oxides over range of vaporized fuel proportions. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.014.

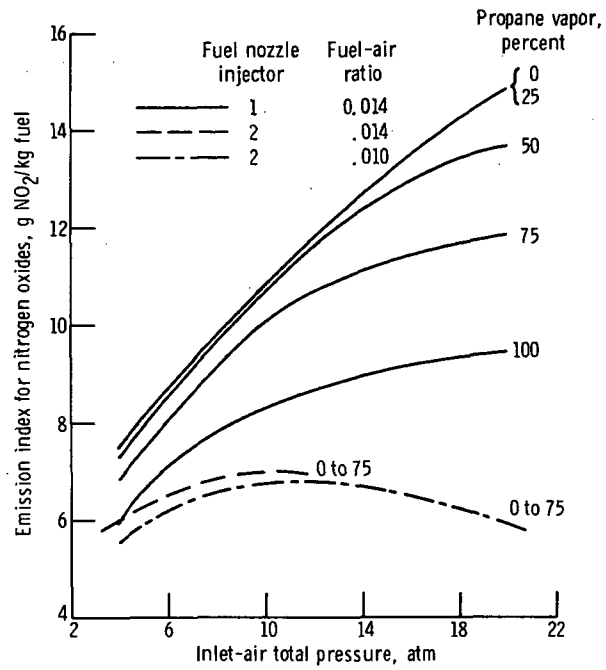


Figure 11. - Summary of effect of combustor inlet-air pressure on emission index for nitrogen oxides over range of vaporized fuel proportions. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec).

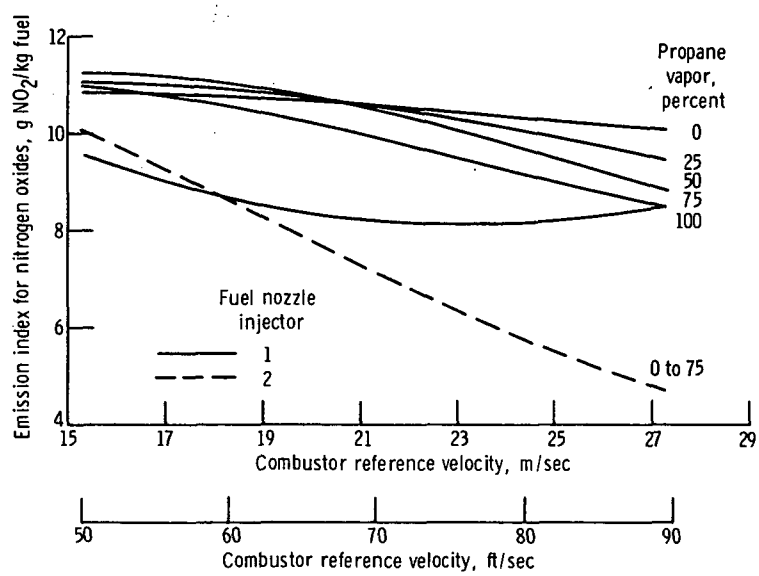
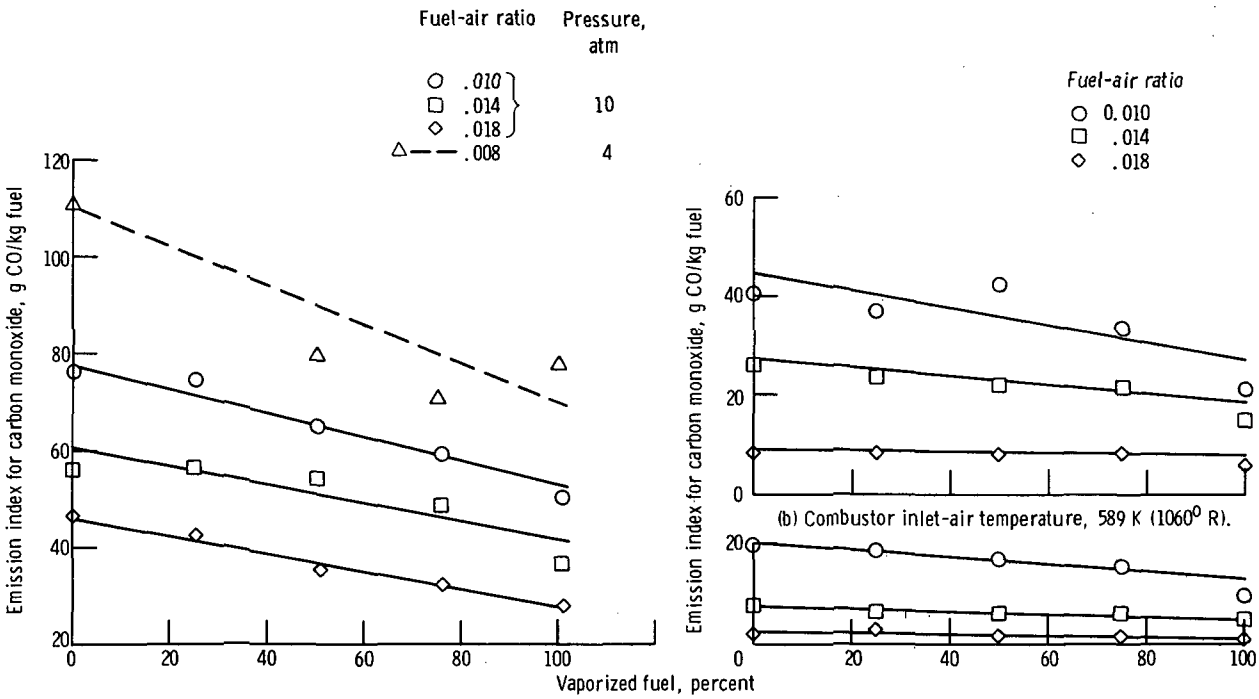


Figure 12. - Summary of effect of combustor reference velocity on emission index for nitrogen oxides over range of vaporized fuel proportions. Inlet-air temperature, 589 K (1060° R); pressure, 10 atmospheres; fuel-air ratio, 0.014.



(a) Combustor inlet-air temperature, 478 K (860° R).

(b) Combustor inlet-air temperature, 589 K (1060° R).

(c) Combustor inlet-air temperature, 700 K (1260° R).

Figure 13. - Typical results of effect of fuel vaporization on emission index for carbon monoxide. Reference velocity, 21.3 meters per second (70 ft/sec); fuel nozzle injector 1.

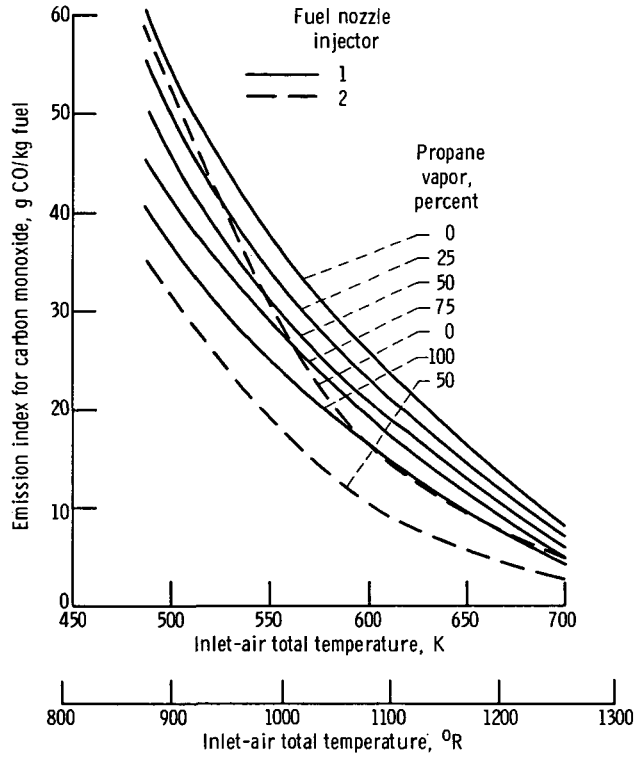


Figure 14. - Summary of effect of combustor inlet-air temperature on emission index for carbon monoxide over range of vaporized fuel proportions. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.014.

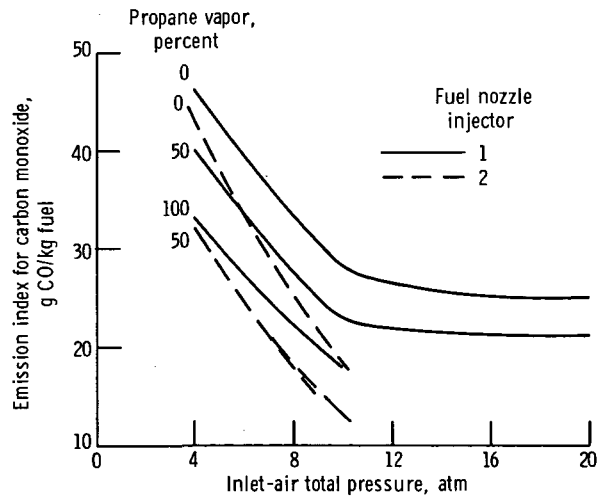


Figure 15. - Summary of effect of combustor inlet-air pressure on emission index for carbon monoxide over range of vaporized fuel proportions. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.014.

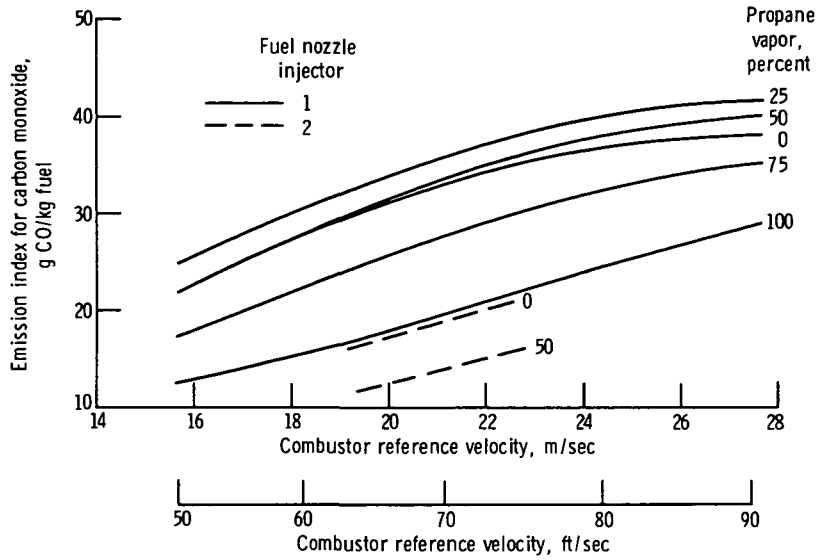
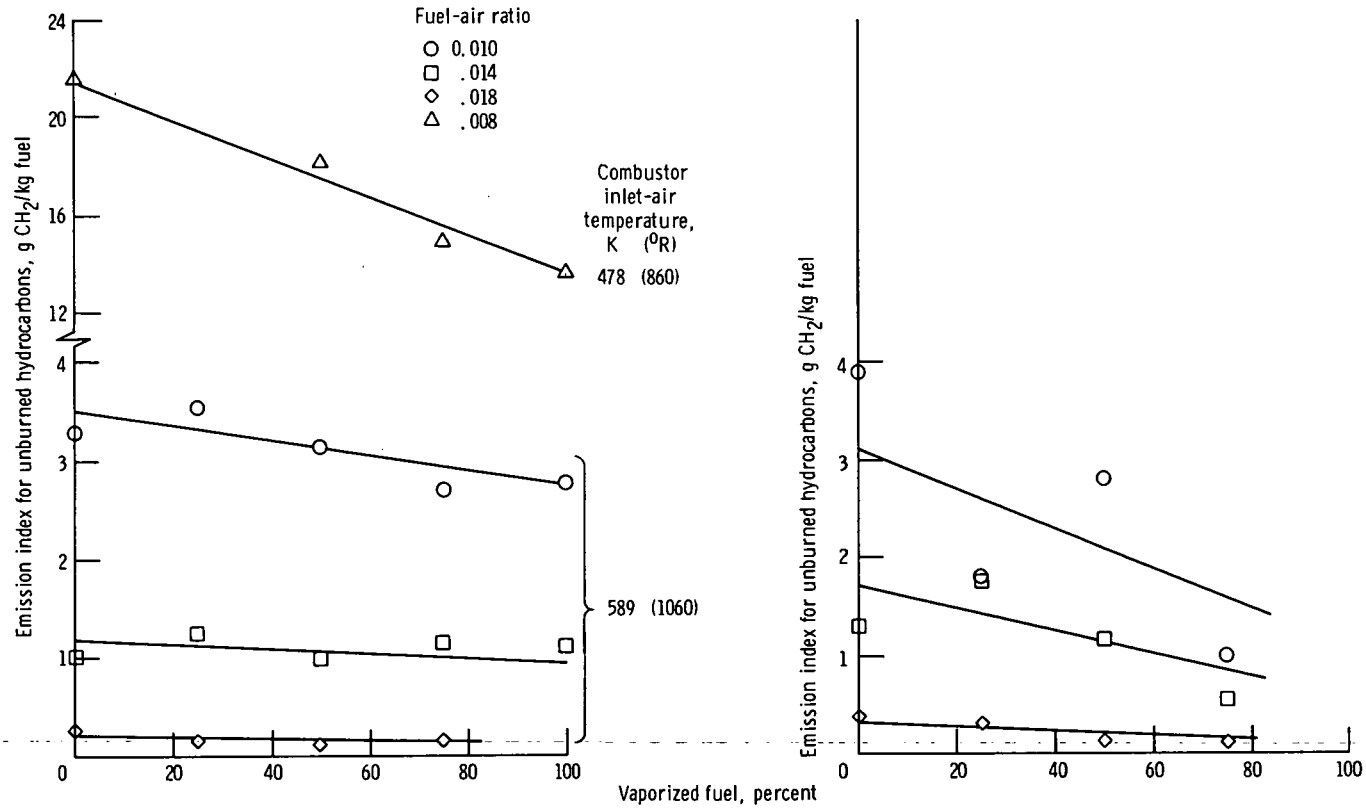


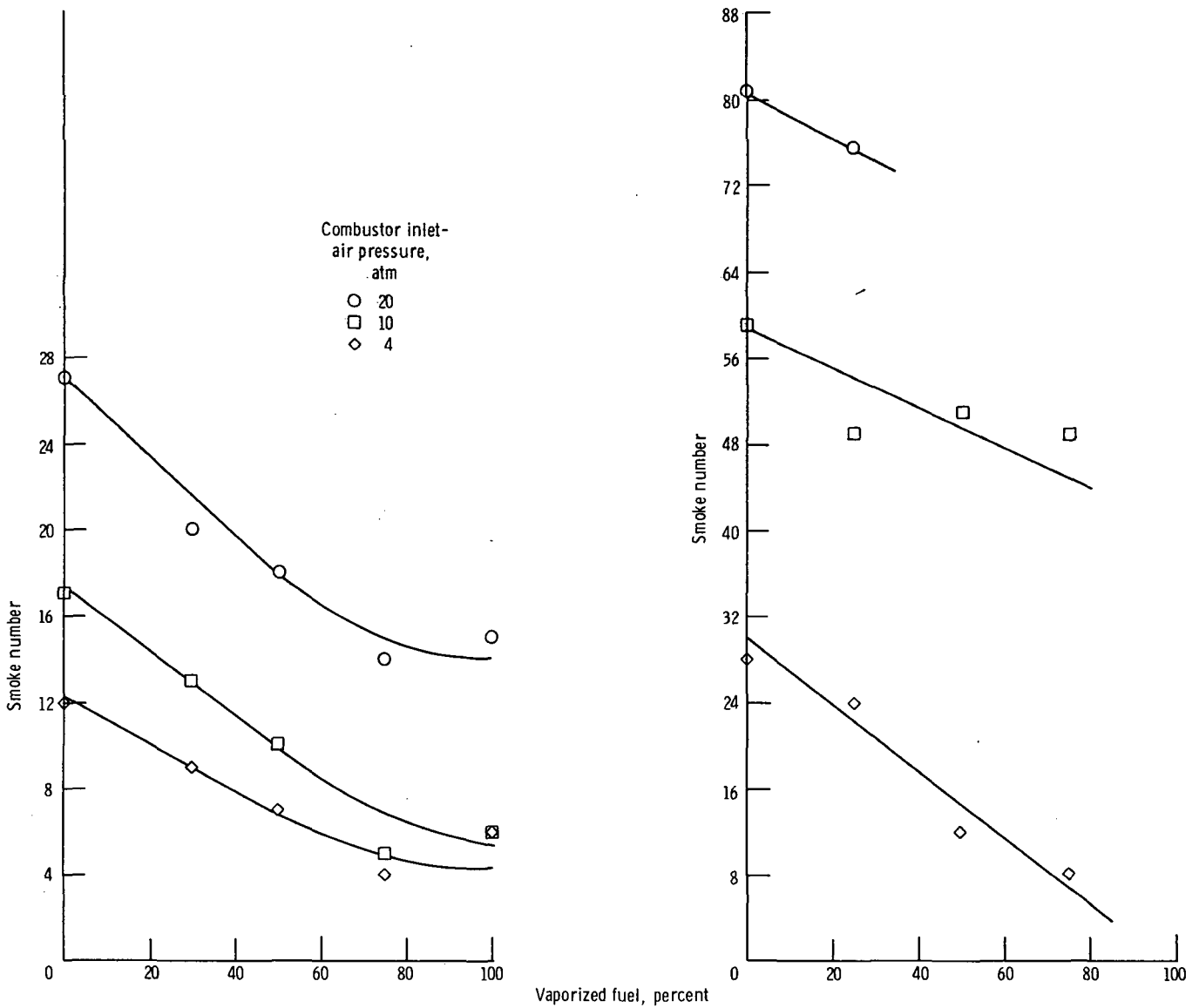
Figure 16. - Summary of effect of combustor reference velocity on emission index for carbon monoxide over range of vaporized fuel proportions. Inlet-air temperature, 589 K (1060° R); pressure, 10 atmospheres; fuel-air ratio, 0.014.



(a) Fuel nozzle injector 1.

(b) Fuel nozzle injector 2.

Figure 17. - Effect of fuel vaporization on emission index for unburned hydrocarbons. Pressure, 4 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec).



(a) Fuel nozzle injector 1.

(b) Fuel nozzle injector 2.

Figure 18. - Effect of fuel vaporization on smoke number. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.010.

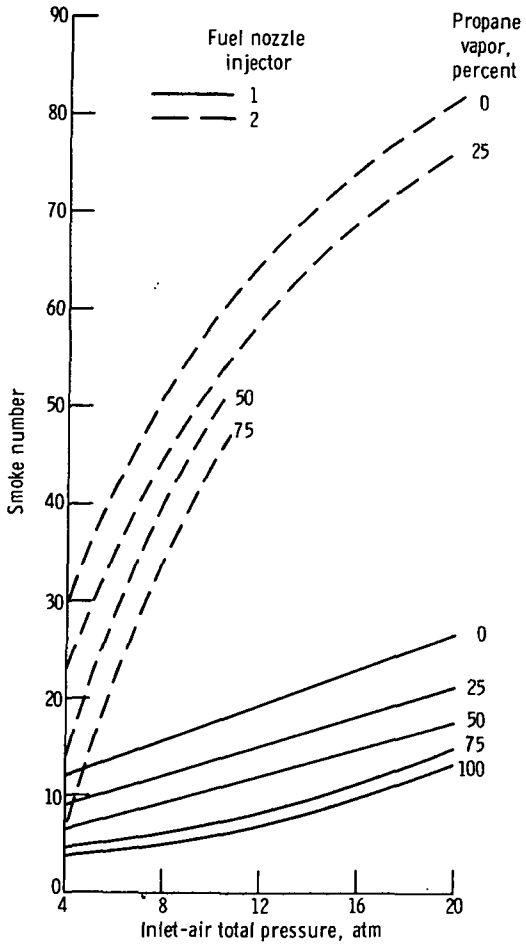


Figure 19. - Summary of effect of combustor inlet-air pressure on smoke number. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.010.

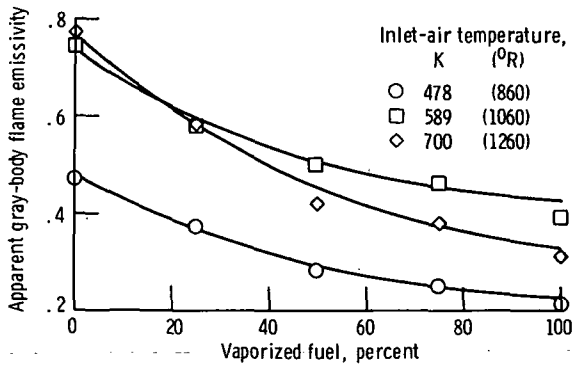


Figure 20. - Effect of fuel vaporization on apparent gray-body flame temperature. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.014; fuel nozzle injector 1.

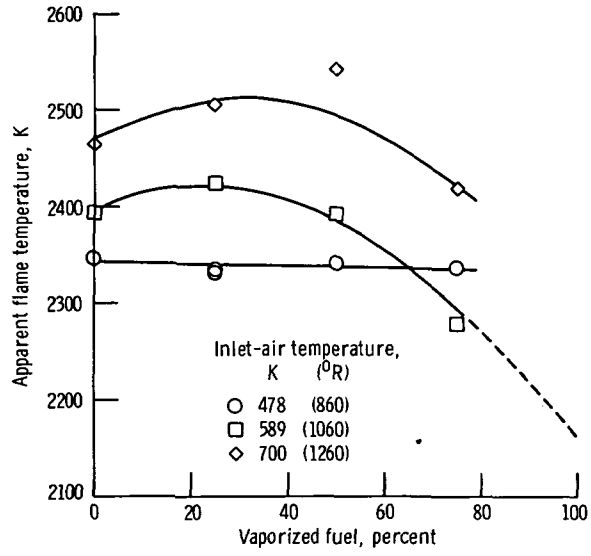
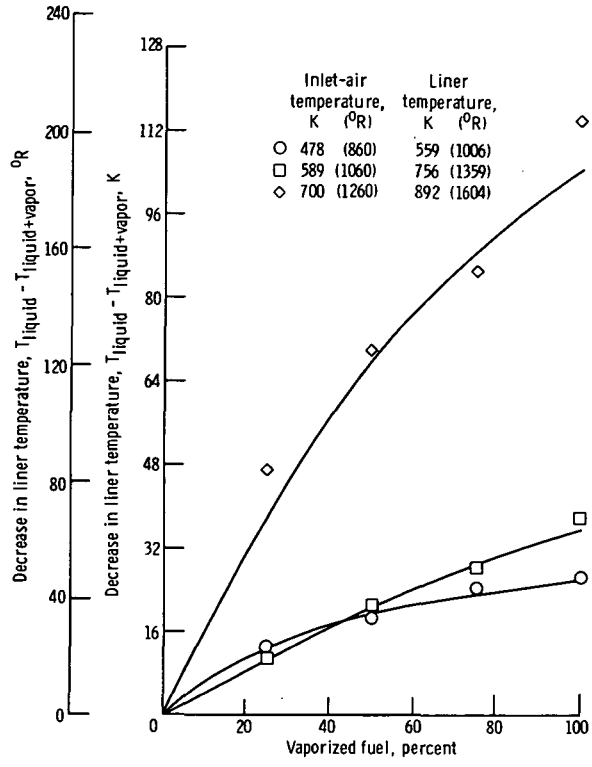
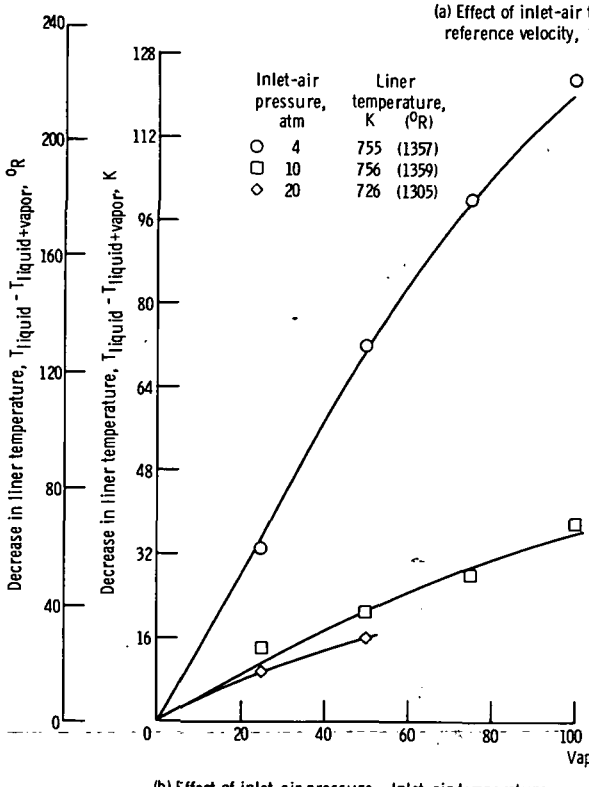


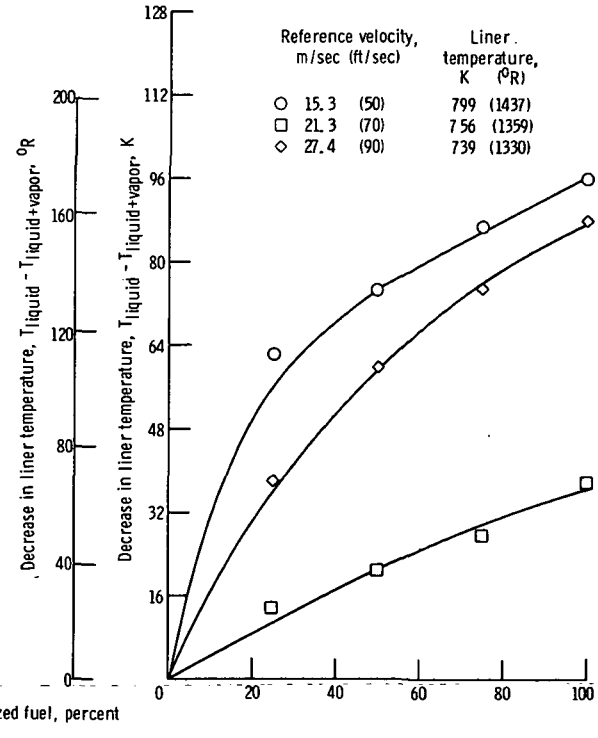
Figure 21. - Effect of fuel vaporization on apparent flame temperature. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec); fuel-air ratio, 0.014; fuel nozzle injector 1.



(a) Effect of inlet-air temperature. Pressure, 10 atmospheres; reference velocity, 21.3 meters per second (70 ft/sec).



(b) Effect of inlet-air pressure. Inlet-air temperature, 589 K (1060° R); reference velocity, 21.3 meters per second (70 ft/sec).



(c) Effect of reference velocity. Inlet-air temperature, 589 K (1060° R); pressure, 10 atmospheres.

Figure 22. - Effect of fuel vaporization on liner temperature. Fuel-air ratio, 0.014; fuel nozzle injector 1.

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