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Ultra-Lean Combustion at High Inlet Temperatures

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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Energy
Office of Transportation Programs

Prepared for
Twenty-sixth Annual International Gas Turbine Conference
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E-677

INTRODUCTION

This report presents emissions data for combustion with ultra-lean fuel-air ratios at inlet-air temperatures of 1100 to 1250 K. The experiments were performed without a flameholder in a flame-tube test section by using a multiple-source fuel injector of the type often employed for premixed-prevaporized combustion tests.

The NASA Lewis Research Center has been doing supporting research for the Department of Energy's Gas Turbine Highway Vehicle Systems project for several years. One of the research areas has been the evaluation of ultra-low emissions combustion concepts suitable for use at advanced automotive gas turbine engine (AGT) conditions. Both catalytic and premixed-prevaporized combustion have been studied experimentally to determine useful operating ranges and potential problem areas. Catalytic combustion has been demonstrated with nitrogen oxides (NO_x) emissions of less than 1 ppm (for nitrogen-free fuels) (1) along with high combustion efficiency at combustion temperatures between 1220 and 1500 K (2). Catalyst durability for extended operation at the temperatures required in the AGT (up to 1650 K) has not been successfully demonstrated, however. Premixed-prevaporized combustion, unlike catalytic combustion, must have combustion temperatures above the lean flammability limit. According to theoretical analyses this limit is about 1600 K, independent of inlet-air temperature (3). Several experimental studies at inlet-air temperatures up to 800 K have reported lean limits of around 1700 to 1800 K for premixed combustion of typical hydrocarbon fuels (4,5). To insure good combustion stability, then, it has been proposed that premixed combustors should be designed so that the combustion temperature is about 1900 K (3). The thermal NO_x formed at this temperature is only about 10 ppm, but because NO_x formation is nearly exponentially dependent on combustion temperature, the maximum temperatures cannot be permitted to be much higher than 1900 K. To maintain the combustion temperature close to 1900 K while the turbine inlet temperature varies over a typical AGT range of 1400 to 1650 K variable geometry or fuel staging will be required (3,6). These features complicate the design. Furthermore the premixed-prevaporized combustor will be susceptible to autoignition in the premixing zone at the high inlet-air temperatures (up to 1340 K) of the AGT combustor.

The ability to react ultra-lean fuel-air mixtures to give combustion temperatures no higher than those at the turbine inlet could result in a simplified combustion system without the variable geometry or fuel staging of the premixed combustor. The elimination of the durability questions concerning the catalytic combustor requires that reactions take place entirely in the gas phase. Obviously, gas-phase combustion cannot occur in the temperature range 1400 to 1650 K if the lean flammability limit really is between 1600 and 1800 K as low-inlet-air-temperature evidence suggests. For the inlet-air temperatures of the AGT combustor lean flammability limits have not been experimentally established; however, there is some evidence that it might be possible to react ultra-lean fuel-air mixtures at inlet-air temperatures higher than 1100 K. Catalytic combustion studies, for example, have shown that gas-phase reactions are initiated at a temperature of about 1100 K to complete the combustion started by the catalyst (7). Studies of reaction rates in combustion systems also show that ultra-lean mixtures will react and proceed to completion if sufficient time is allowed (8).

Most premixed and catalytic combustion studies in the past have been limited to a maximum inlet-air temperature of 1000 K, at which temperature the gas-phase reactions begin only after unacceptably long delays or with assistance from a catalyst. The present study made use of a new combustion test facility that can supply air to the test section at temperatures as high as 1250 K. This report describes the tests that were performed to establish the residence times needed to achieve acceptable emissions with ultra-lean fuel-air ratios. Carbon monoxide and nitrogen oxides emissions are reported for the combustion of no. 2 diesel fuel in a 12-cm-diameter test section at inlet-air temperatures of 1100 to 1250 K, a pressure of 2.5×10^5 Pa, reference velocities of 32 to 60 m/s, adiabatic combustion temperatures of 1340 to 1830 K, and combustion-zone lengths of 29 to 44 cm. These conditions were chosen to simulate those of advanced automotive gas turbine engines.

DESCRIPTION OF EXPERIMENT

The experiment was designed to provide emissions data for ultra-lean combustion with idealized conditions. The fuel injector was built to give a uniform dispersion of fuel in the airstream. To avoid any flameholding surfaces, the test section had no steps or discontinuities. The duct was internally lined with insulation to prevent heat loss and to minimize cold-wall effects. Finally, sampling of the combustion gases was done at the centerline to further eliminate any wall effects on the results. This idealized approach should make the data generally more useful for combustor design than would be the results from testing a specific combustor concept.

Test Section

The main features of the test section are illustrated in figure 1. Fiberfrax tube insulation 1.6 cm thick was placed inside the duct. The insulation was protected from erosion by a 12-cm-inside-diameter Hastelloy liner. Inlet air was indirectly preheated, and the temperature was measured with an array of 12 Chromel-Alumel thermocouples. The test-section pressure was controlled to 2.5×10^5 Pa, and it was measured at a tap approximately 29 cm downstream of the fuel injector. A pitot-static probe (not shown in fig. 1) was located just upstream of the inlet-thermocouple plane to measure the airflow entering the test section. The test-section fuel flow rate was obtained from a Flo-tron linear mass flowmeter.

Fuel Injector

Fuel was introduced into the airstream by means of the multiple-passage fuel injector shown in figure 2. This device was developed by Tacina (9,10) to provide a good dispersion of fuel in the airstream by injecting equal quantities of fuel into each of several airflow passages. The configuration used in these tests had nineteen 2.5-cm hexagonal bars arranged as shown in figure 2(a). The outside dimension of this grouping of hexagonal bars was 12.7 cm. To give an exit flow diameter of 12 cm to match that of the duct, a sheet-metal shroud with a tapered extension was wrapped around the hexagonal bars (figs. 2(a) and (b)). Each bar was bored with a taper to provide 19 individual airflow passages (fig. 2(b)). The upstream diameter of each passage was 1.25 cm. The resulting 79-percent blockage helped to insure a uniform velocity profile over the duct cross section but it resulted in pressure drops of 7 percent at 32-m/s and 23 percent at 60-m/s reference velocity. The passage diameter increased to 2.5 cm at the downstream plane of the hexagonal-bar array.

Fuel was discharged from a 25-cm-long, 0.5-mm-diameter tube into a 1.25-cm-diameter tubular extension of the upstream end of each air passage (figs. 2(b) and (c)). These tubular extensions formed a flow passage for the combustion air through a plenum. The fuel tubes were also routed through this plenum, and the plenum was air cooled to prevent the fuel from heating and coking within the fuel tubes. The individual fuel tubes entered the plenum in two bundles: one with 9 tubes and the other with 10. Each bundle was soldered into a 1.25-cm-diameter tube, and one of these large tubes entered the fuel injector body from each side (fig. 2(c)).

Combustion Zone

Ignition. No external igniter was used. The inlet air, with temperatures of 1100 to 1250 K, was probably hot enough to initiate the combustion reactions, although hot surfaces of the fuel injector and duct could also have acted as ignition sources. Thus combustion could have started as soon as the fuel was injected into the airstream.

Flameholding. No flameholder was used to stabilize a flame. On the downstream face of the fuel injector, however, small recirculation zones could have been established in the flat areas between the intersecting air passages.

Combustion was free to continue in the duct until cooling occurred in a water spray. This water quench was located downstream of the region pictured in figure 1. Reactions were also quenched in the samples of combustion gas withdrawn by the sampling probes.

Exhaust-Gas Sampling and Gas Analysis

The combustion products were sampled with four water-cooled probes located at the axial positions shown in figure 1: 29.2, 34.3, 39.4, and 44.4 cm downstream of the plane of fuel injection. The sampling port of each probe was located at the duct centerline. The probes were 0.95 cm in outside diameter with a 0.375-cm-diameter sampling tube. Remotely operated solenoid valves permitted the selection of the sample gas from one probe at a time so that the effect of reaction distance (residence time) on emissions could be studied. The 0.625-cm-diameter sample line was electrically heated to maintain a gas temperature of 400 to 450 K. Carbon monoxide and carbon dioxide concentrations were measured with nondispersive infrared analyzers, unburned hydrocarbons with a flame-ionization detector, and total nitrogen oxides ($NO + NO_2$) with a chemiluminescent analyzer.

CALCULATED QUANTITIES

Reference Velocity

The reference velocity is the velocity in the duct referenced to test-section inlet conditions. For this experiment the reference velocity was based on the test-section, rather than the inlet, pressure because the fuel injector produced a high pressure drop. In a practical combustor there would be little difference between the inlet and the test-section pressure.

Reference Residence Time

Because the temperature history of the combustion gases was unknown, a reference residence time was calculated for a constant temperature (the inlet-air temperature). The reference residence time was determined by integrating the local length-velocity quotient from the plane of fuel injection to the gas-sampling probe location. The resulting expression was

$$\tau_{ref} = 1000\left(\frac{K}{V_{ref}} + \frac{L_2}{V_{ref}}\right)$$

where

τ_{ref}	reference residence time, ms
K	0.023 m
V_{ref}	reference velocity, m/s
L_2	length from exit plane of fuel injector to gas-sampling probe: 0.233 m (probe 1), 0.284 m (probe 2), 0.335 m (probe 3), 0.385 m (probe 4)

The first term represents the time spent within the tapered air passages of the fuel injector; the second term gives the time in the constant-diameter duct of the test section.

Fuel-Air Ratio

The fuel-air ratio was determined by two methods: (1) by dividing the metered test-section fuel flow rate by the metered airflow rate, and (2) by summing the carbon atoms in the measured concentrations of CO, CO_2, and unburned hydrocarbons. The two fuel-air ratios generally agreed within ±5 percent. The carbon-summation fuel-air ratio f_c represents the local fuel-air ratio at the sampling location, and it was used to calculate the emission index of emittants and the adiabatic combustion temperature.

Adiabatic Combustion Temperature

Equilibrium combustion temperatures were calculated for adiabatic conditions for a range of inlet-air temperatures and fuel-air ratios using the computer program of reference 11. A curve-fit equation was evolved, and it was found to agree with the computer program within less than 10 K for the conditions of this study. This curve-fit expression was used to calculate the adiabatic combustion temperature for the present study. It is

$$T_{ad} = T_{in}\left[1 - \frac{f_c}{0.068}\left(0.4525 - 0.3118\,\frac{f_c}{0.068}\right)\right] + \frac{f_c}{0.068}\left(2947.34 - 1011.44\,\frac{f_c}{0.068}\right)$$

where

T_{ad}	adiabatic combustion temperature, K
T_{in}	inlet-air temperature, K
f_c	carbon-summation fuel-air ratio

RESULTS AND DISCUSSION

Emissions of CO, CO_2, NO_x, and unburned hydrocarbons were continuously monitored at each test condition. Data were recorded when steady-state conditions were reached, and results were found to be repeatable from day to day.

Temperatures measured at the four probe positions showed no change with distance. This result indicated that all the significant heat release occurred upstream of the first gas-sampling station.

The most stringent proposed automotive emissions standards of 0.25 g HC/km, 2.1 g CO/km, and 0.25 g NO_2/km were converted to emission-index goals for this project. A no. 2 diesel fuel density of 847 kg/m^3 was used, and it was assumed that an advanced automotive gas turbine engine in a compact vehicle would have a fuel consumption of 7.7×10^{-5} m^3/km (equivalent to about 30 mpg) over the urban driving cycle. The resulting emission indexes were divided by 2 to provide a margin for error. In this way the goals for this project were established as 1.9 g HC/kg fuel, 16 g CO/kg fuel, and 1.9 g NO_2/kg fuel. Because the combustion efficiency is related to the emissions of unburned hydrocarbons and carbon monoxide, the achievement of these goals will assure combustion efficiencies greater than 99.4 percent.

Unburned Hydrocarbons

Unburned hydrocarbons emissions were always well within the goal of 1.9 g HC/kg fuel. This result indicated that all the fuel had been converted to CO and CO_2 before the first probe position.

Nitrogen Oxides and Carbon Monoxide

The NO_x and CO emission indexes for each inlet-air temperature and reference velocity tested are given in figure 3. Data were taken at reference velocities of 32 to 60 m/s for each inlet-air temperature except 1100 K. At the 1100 K inlet-air temperature performance deteriorated so badly when the reference velocity was increased from 32 to 45 m/s that no data were taken for velocities higher than 32 m/s.

The emission index is plotted as a function of the adiabatic combustion temperature for all four probe positions on each figure. Measured temperatures near the duct centerline, where the emissions were sampled, were never more than 50 to 60 K below the adiabatic combustion temperature. Because conduction and radiation errors affect the measured temperatures, the calculated adiabatic combustion temperature may represent the true temperature better than the measured values. For this reason the adiabatic combustion temperature was used in the presentation of all results for this study.

The NO_x emissions in figure 3 are represented by solid symbols and the CO emissions by open symbols. The goals for each pollutant are also indicated on the figure.

Nitrogen oxides emissions. Total NO_x emissions increased exponentially with the adiabatic combustion temperature but were independent of the probe position (residence time). The minimum NO_x emission was about 0.4 g NO_2/kg fuel, which corresponds with complete conversion of about 120 ppm of fuel nitrogen. This is the approximate concentration of nitrogen in the no. 2 diesel fuel used. Emissions of NO_x higher than 0.4 g NO_2/kg fuel were the result of thermal NO_x formation. For combustion temperatures below 1680 K, NO_x was always within the goal of 1.9 g NO_2/kg fuel.

The absence of a residence-time effect on the thermal NO_x can be explained by supposing that a flame front was stationed near the point of fuel injection. If the fuel and air were incompletely mixed upon entering the flame, the NO_x formation rate in the flame would be significantly greater than that in the well-mixed plug-flow regime downstream of the flame. With most of the NO_x formed in the flame zone the downstream residence time would have little effect on the final NO_x concentration.

Further evidence that combustion began before complete mixing and vaporization occurred was seen in the effect of reference velocity on NO_x emissions. A comparison of figures 3(b) and (c) shows that at an inlet-air temperature of 1150 K NO_x emissions decreased by about a factor of 2 when the reference velocity was increased from 32 m/s to 45 m/s. A decrease in NO_x was also observed at inlet-air temperatures of 1200 and 1250 K when the velocity was increased from 32 m/s to 60 m/s (compare fig. 3(e) with 3(f) and fig. 3(g) with 3(h)). An increase in reference velocity will decrease the initial fuel droplet size and therefore reduce the fraction of fuel entering the flame zone as a liquid. Cooper (12) has shown that a lower NO_x concentration will result when the liquid fuel fraction is reduced. If complete vaporization and mixing had occurred before combustion, this effect of initial fuel drop size would not have been observed.

NO_x emissions at reference velocities of 45 m/s (fig. 3(c)) and 60 m/s (fig. 3(d)) were essentially the same. Apparently injected fuel droplets were sufficiently small at 45 m/s that the effect of a further reduction in size was insignificant.

Finally, the effect of inlet-air temperature on NO_x emissions also indicates incomplete mixing prior to initiation of combustion. Figure 3 shows that an increase in inlet temperature tended to reduce NO_x. The effect can be seen by comparing the results at a reference velocity of 32 m/s and an adiabatic combustion temperature of 1700 K, for example. The NO_x emissions at 1100, 1150, 1200, and 1250 K inlet-air temperatures were 2.1, 2.0, 1.6, and 1.4 g NO_2/kg fuel, respectively (figs. 3(a), (b), (e), and (g)). An increase in inlet-air temperature will produce more rapid fuel vaporization and thereby result in a more uniform fuel-air mixture entering the flame front.

The trends shown by the NO_x data suggest that combustion reactions were initiated very soon after fuel injection. This observation indicates that it may not be possible to fully premix fuel and air for AGT combustors. The magnitude of the NO_x emissions suggests, however, that low NO_x emissions can be achieved if ultra-lean fuel-air mixtures are used with a well-dispersed fuel injection system.

Carbon monoxide emissions. The carbon monoxide emissions decreased with increasing adiabatic combustion temperature until levels approached equilibrium, as can be seen in figure 3(b), for example. The measured CO emissions then began to increase to follow the equilibrium curve upward for temperatures around 1800 K. Because measured CO emissions did not fall below the equilbrium level, it can be concluded that the CO reactions were quenched in the water-cooled probes rapidly enough to prevent appreciable oxidation in the sampling line.

Figure 3 also shows how the CO emissions decreased with increasing distance from the fuel injector. The effect of upstream probes on downstream samples was not studied in this experiment; however, a similar study using multiple probes downstream of a catalytic combustor (13) showed that the presence of water-cooled probes upstream had no measurable effect on the results.

Carbon Monoxide Relaxation with Time

The effect of residence time on the CO emissions can be seen directly from figure 4, which gives the CO emission index as a function of the reference residence time for constant adiabatic combustion temperatures. This figure was prepared by cross-plotting the data from figure 3. Figure 4(a) is for an inlet-air temperature of 1100 K, figure 4(b) for 1150 K, figure 4(c) for 1200 K, and figure 4(d) for 1250 K. Figure 4 includes results for more than one velocity and shows that within the data scatter the effect of residence time was independent of reference velocity for velocities in the range 32 to 60 m/s.

An increase in the inlet-air temperature made it possible to achieve the CO emissions goal at lower reference residence times. For example, at an adiabatic combustion temperature of 1600 K the CO goal was achieved for reference residence times greater than about 7 ms when the inlet temperature was 1100 K, 4 ms when it was 1150 to 1200 K, and about 3 ms when it was 1250 K. The time required to reduce the CO from one level to another at any adiabatic combustion temperature was independent of inlet temperature, however. Thus, at an adiabatic combustion temperature of 1600 K, the CO decreased from 10 g CO/kg fuel to 2 g CO/kg fuel in about 4 ms for all four inlet-air temperatures. This result suggests that the reaction rates at the different inlet temperatures were the same for any given adiabatic combustion temperature.

It is interesting that a reduction in residence time of about 3.2 ms for 1100 K inlet-air temperature (fig. 4(a)) and about 0.8 ms for 1150 and 1200 K inlet-air temperatures (figs. 4(b) and (c)) would make the lower temperature results agree with those at 1250 K within experimental error. The reference times of figure 4 were calculated from the total distance between the fuel injection plane and each gas-sampling probe. If combustion were not initiated at the point of fuel injection, the actual residence time would of course be less than the reference value. An explanation for these results is therefore that the ignition delay time is approximately 3.2 ms greater at 1100 K than at 1250 K and about 0.8 ms greater at 1150 to 1200 K than at 1250 K.

Minimum Operating Temperature

The minimum combustor operating temperature is the adiabatic combustion temperature required to achieve the emissions goals for each inlet-air temperature and residence time. The minimum operating temperature was determined for the present experiments from figure 3 by noting the adiabatic combustion temperature at which the CO emissions curve crossed the 16-g/kg level. The resulting minimum operating temperatures are plotted in figure 5 as a function of the reference residence time for each reference velocity and inlet-air temperature tested.

The minimum operating temperature decreased with increasing residence time. With inlet-air temperatures of 1150 to 1200 K the operating temperature could be reduced from 1600 K to 1420 K when the residence time was increased from 4.3 ms to 12.7 ms, for example.

The minimum operating temperature was highest at the 1100 K inlet temperature. For any reference residence time the CO emissions goal could be achieved at combustion temperatures 40 to 50 K lower when the inlet-air temperature was increased from 1100 to 1150 K. Minimum operating temperatures at 1200 K were no different from those at 1150 K, but an increase in inlet-air temperature to 1250 K resulted in an additional reduction of about 40 K in the minimum required temperatures at short residence times. As the residence time increased toward 14 ms the minimum operating temperatures for the 1250 K inlet temperature approached those at 1150 to 1200 K.

Maximum Allowable Temperature

Nitrogen oxides emissions increased with combustion temperature; therefore, for each operating condition there was a maximum allowable combustion temperature above which NO_x emissions were higher than 1.9 g NO_2/kg fuel. The maximum operating temperature was independent of residence time. Figure 6 gives the maximum operating temperature for the experimental results of figure 3. It is presented as a function of inlet-air temperature.

Maximum permissible combustion temperatures increased with increasing inlet-air temperature and with increasing reference velocity. For a reference velocity of 32 m/s at 1100 K inlet-air temperature, combustion temperatures had to be below 1680 K for NO_x to be less than the goal of 1.9 g NO_2/kg fuel. With an inlet-air temperature of 1250 K, however, combustion temperatures could be as high as 1760 K without exceeding the NO_x goal. An increase in reference velocity from 32 m/s to 45 to 60 m/s permitted an increase in operating temperature to at least 1800 K for inlet-air temperatures of 1150 to 1250 K.

Operating Range

The minimum required adiabatic combustion temperatures from figure 5 and the maximum allowable adiabatic combustion temperatures from figure 6 have been replotted in figure 7 as a function of the reference residence time. Results are shown for inlet-air temperatures of 1100 and 1250 K and reference velocities of 32 and 60 m/s. For an inlet-air temperature of 1100 K and a reference residence time of 8 ms, low emissions were achieved over a range of adiabatic combustion temperatures of 1540 to 1680 K. An increase in residence time to 12.7 ms broadened this low-emissions operating range to between 1460 and 1680 K. An increase in inlet-air temperature to 1250 K with a 12.7-ms residence time permitted operation between 1410 and 1760 K. These results show that at high inlet-air temperatures, stable gas-phase combustion can provide low emissions at combustion temperatures equal to the turbine inlet temperatures of advanced automotive gas turbine engines.

CONCLUDING REMARKS

Ultra-lean combustion with inlet-air temperatures of 1100 to 1250 K was studied in a 12-cm-diameter duct at a pressure of 2.5×10^5 Pa. No flameholder or igniter was used; combustion was initiated as a result of the high-temperature environment.

The results of this study showed that for inlet-air temperatures of 1150 to 1200 K, CO emissions could be limited to 16 g CO/kg fuel at a combustion temperature of 1600 K. This result was achieved with a reference residence time of 4.3 ms. The combustion temperature required to achieve the CO goal decreased with increasing residence time to a value of 1420 K for a reference residence time of 12.7 ms. The required combustion temperature was about 50 K higher than these values when the inlet-air temperature was reduced to 1100 K, and it was slightly lower for an inlet-air temperature of 1250 K.

Operation at such low combustion temperatures insured low NO_x emissions. The NO_x goal for the program was 1.9 g NO_2/kg fuel, and this goal was always achieved when combustion temperatures were below 1680 K. NO_x emissions were found to be independent of residence time, but an increase in reference velocity from 32 m/s to 45 m/s caused a reduction in NO_x. These observations led to the conclusion that a flame front existed in which combustion began before fuel and air could mix thoroughly. Most of the thermal NO_x was probably formed within this flame front. This result suggests that it may not be possible to fully premix fuel and air before combustion occurs at high inlet-air temperatures.

Although a flameholder was not purposely provided, the fuel injector probably stabilized small flames at its exit plane. Whether these flame zones were necessary or significant cannot be determined from the present study. Experimentation with different fuel-injector designs could help to answer this question. It is also of interest to determine how well dispersed the fuel needs to be at the time of injection in order to achieve low emissions.

The major limitation of ultra-lean combustion is the need for high inlet-air temperatures. Although this study did not explore inlet-air temperatures below 1100 K, the residence times required for complete combustion are probably too long for most practical applications with lower inlet temperatures. The advanced automotive gas turbine engine (AGT), because of its regenerative cycle, provides the high combustor inlet-air temperatures necessary for ultra-lean combustion. Ultra-lean combustion produces low emissions at combustion temperatures equal to AGT turbine inlet temperatures. Therefore it may be possible to operate without dilution air and to eliminate variable geometry and fuel staging. As with other low-emissions combustors, however, an auxiliary combustor will still be required for engine start.

The ability to combust fuel in the gas phase at very lean fuel-air ratios to achieve low NO_x emissions shows sufficient promise to warrant additional study. The limits of operation with various fuels and fuel injector types and the effects of pressure need to be established to provide practical design information.

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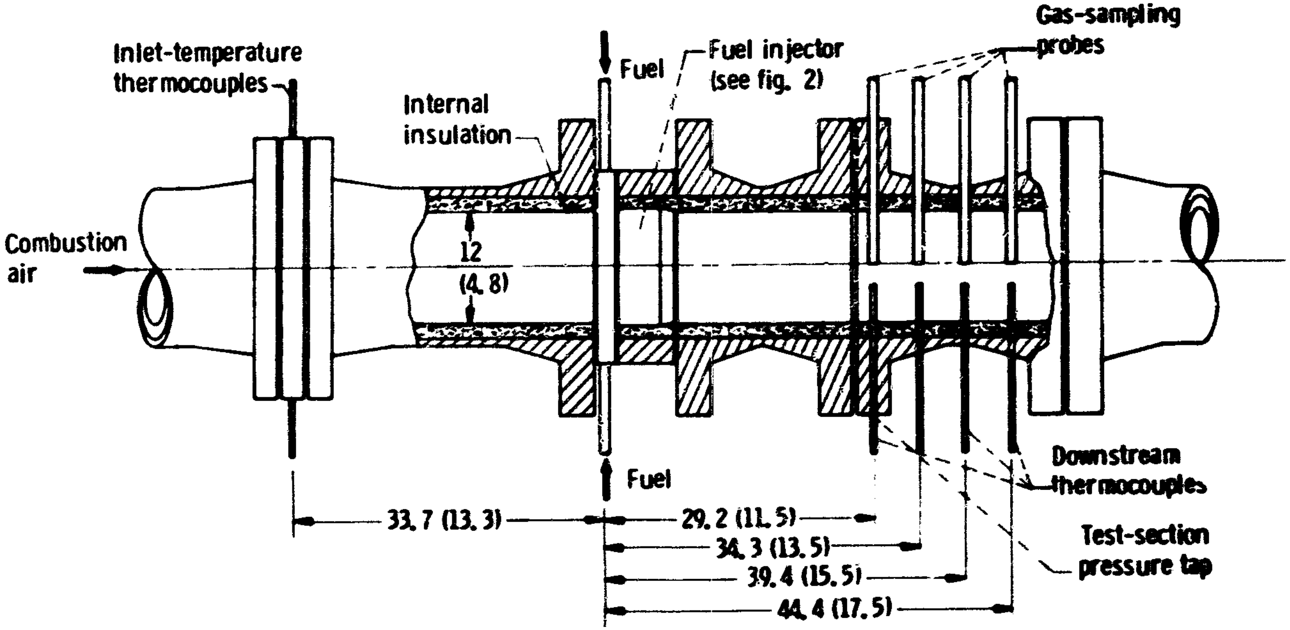
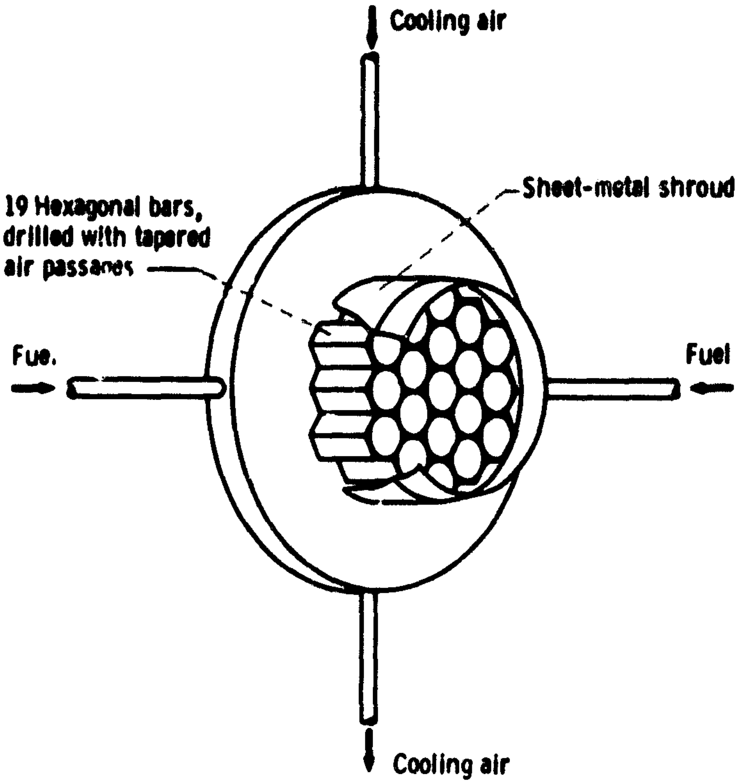
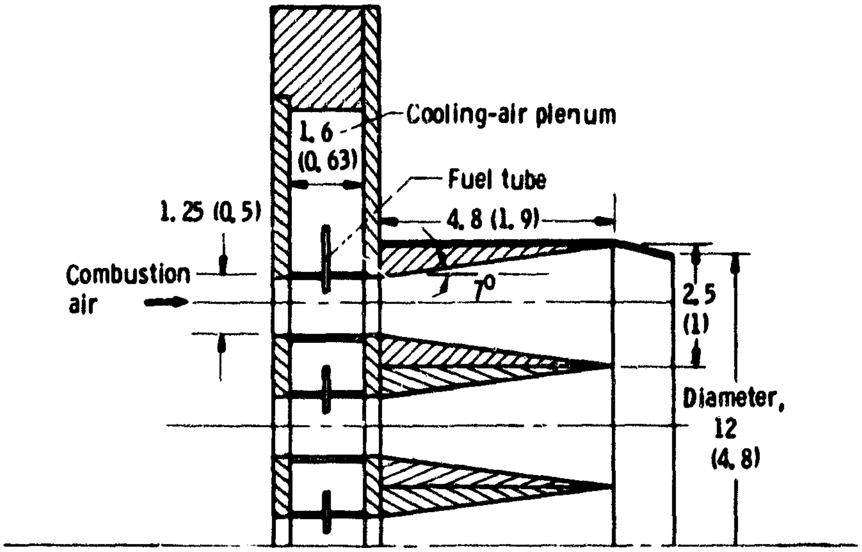


Figure 1. - Test section (all dimensions are in cm (in.)).

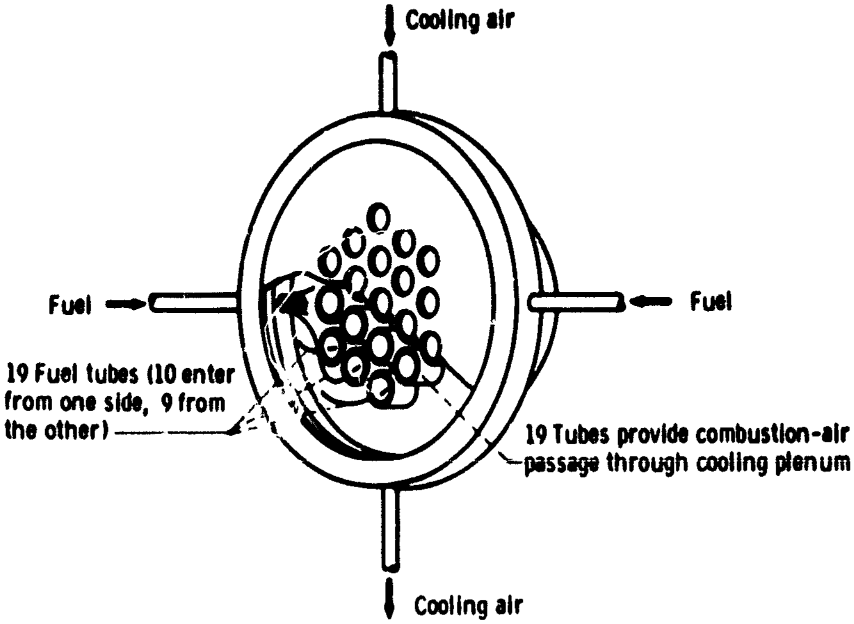


(a) Viewed from downstream.



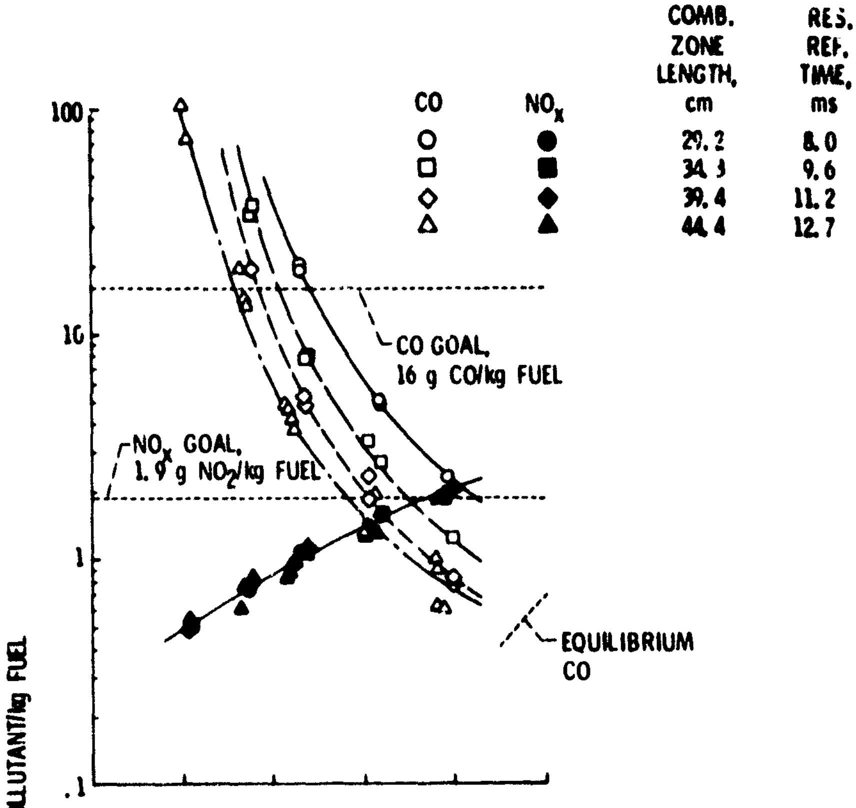
(b) Cross-section view. (All dimensions are in cm (in.).)

Figure 2. - Fuel injector.

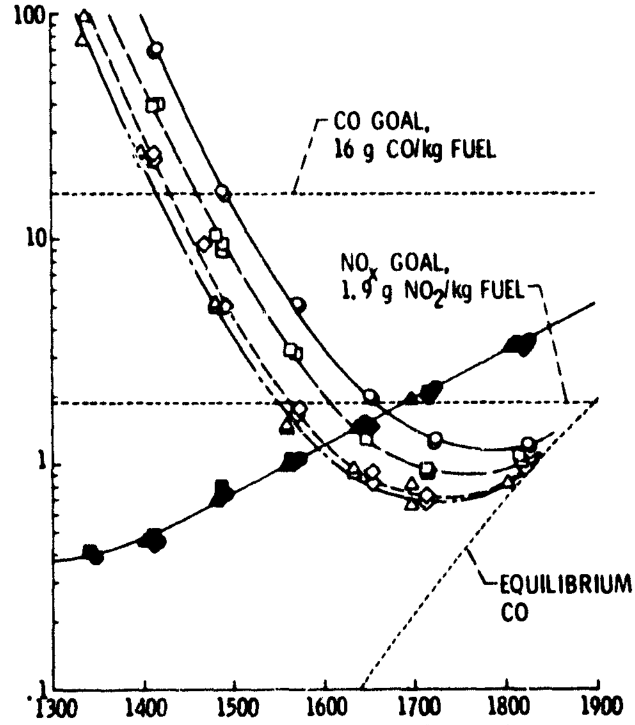


(c) Viewed from upstream.

Figure 2. - Concluded.

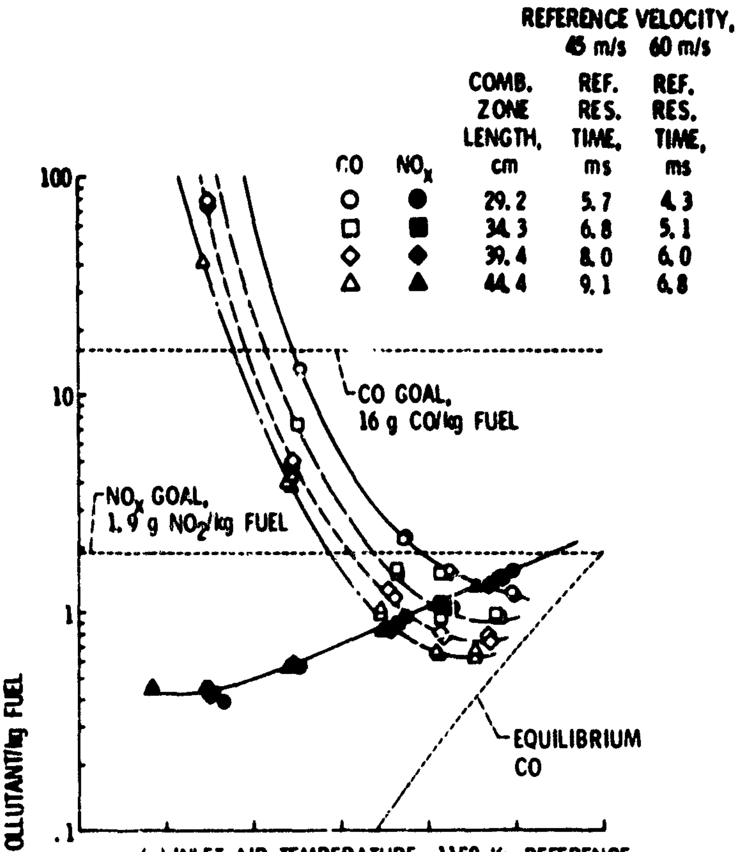


(a) INLET-AIR TEMPERATURE, 1100 K; REFERENCE VELOCITY, 32 m/s.

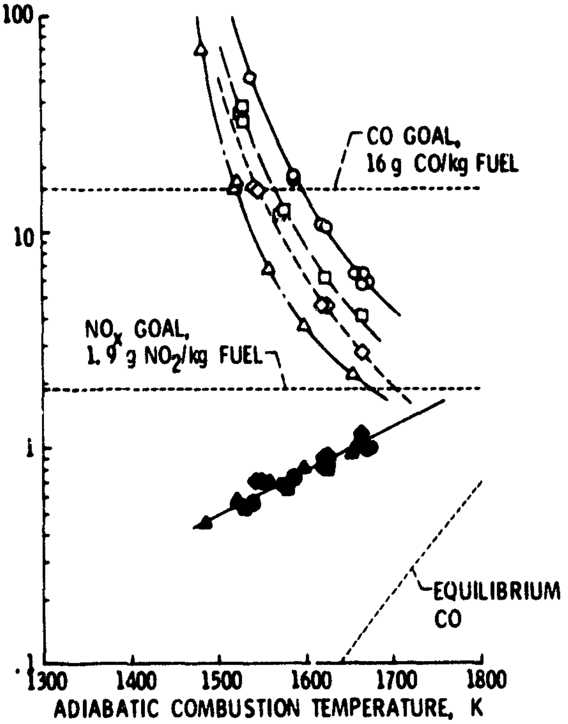


(b) INLET-AIR TEMPERATURE, 1150 K; REFERENCE VELOCITY, 32 m/s.

Figure 3. - Emissions of nitrogen oxides and carbon monoxide. Pressure, 2.5×10^5 Pa.

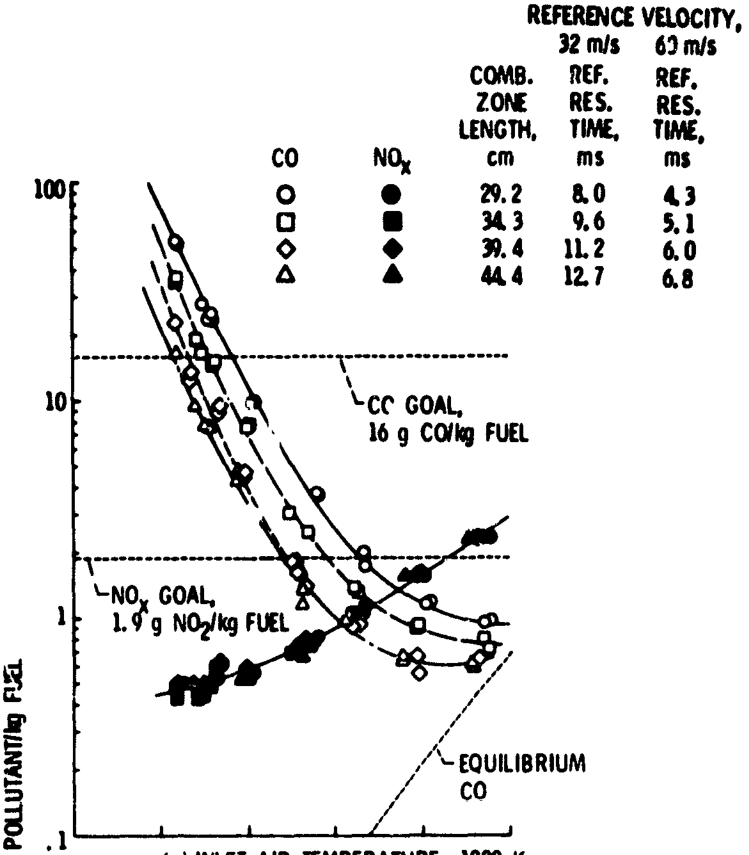


(c) INLET-AIR TEMPERATURE, 1150 K; REFERENCE VELOCITY, 45 m/s.

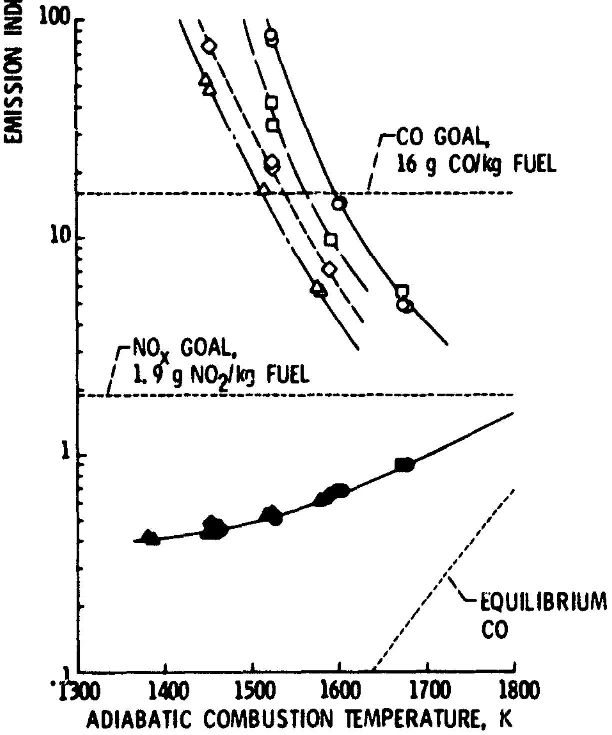


(d) INLET-AIR TEMPERATURE, 1150 K; REFERENCE VELOCITY, 60 m/s.

Figure 3. - Continued.

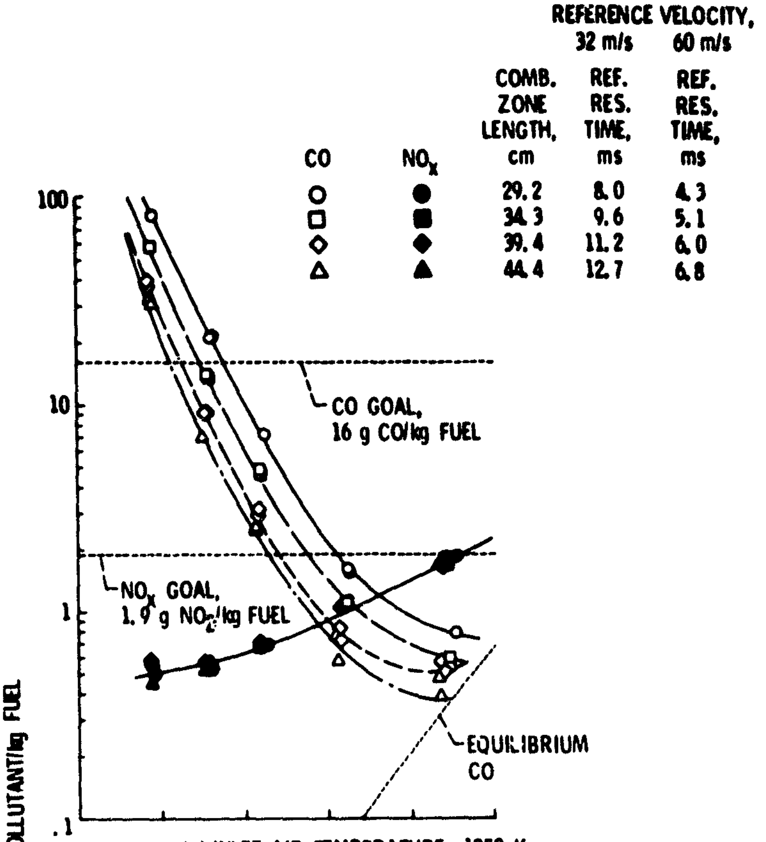


(e) INLET-AIR TEMPERATURE, 1200 K; REFERENCE VELOCITY, 32 m/s.

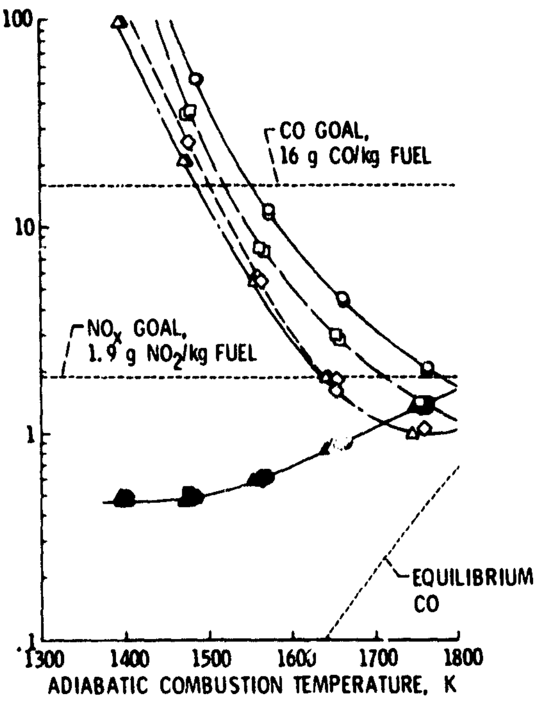


(f) INLET-AIR TEMPERATURE, 1200 K; REFERENCE VELOCITY, 60 m/s.

Figure 3. - Continued.

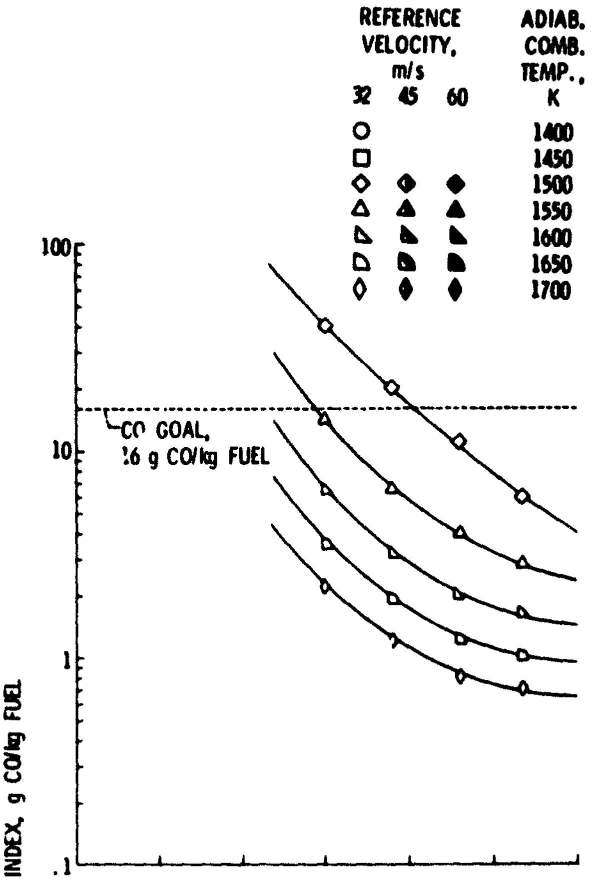


(g) INLET-AIR TEMPERATURE, 1250 K; REFERENCE VELOCITY, 32 m/s.

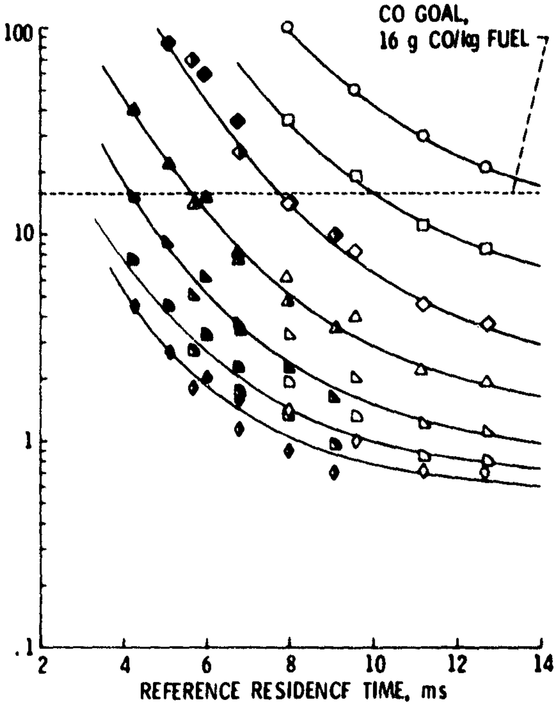


(h) INLET-AIR TEMPERATURE, 1250 K, REFERENCE VELOCITY, 60 m/s.

Figure 3. - Concluded.

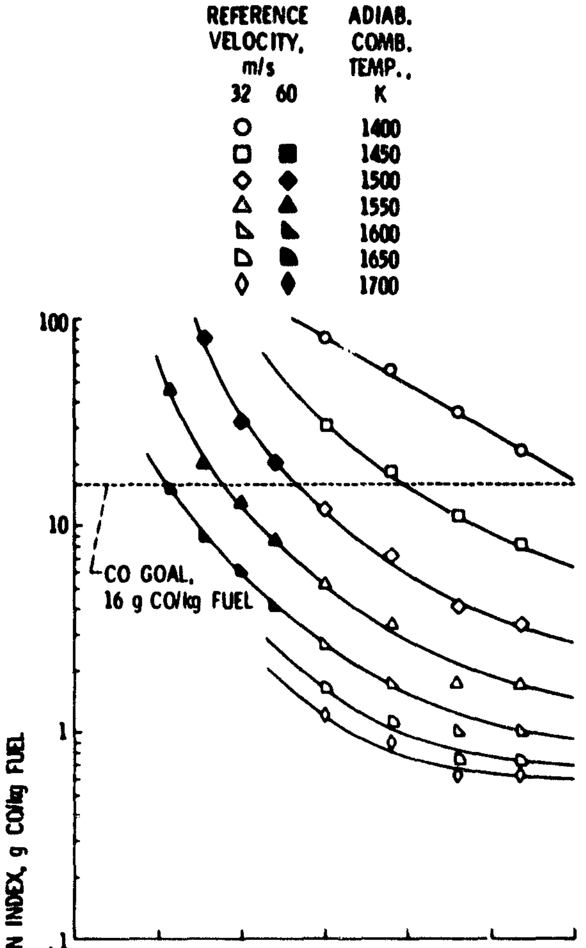


(a) INLET-AIR TEMPERATURE, 1100 K; REFERENCE VELOCITY, 32 m/s.

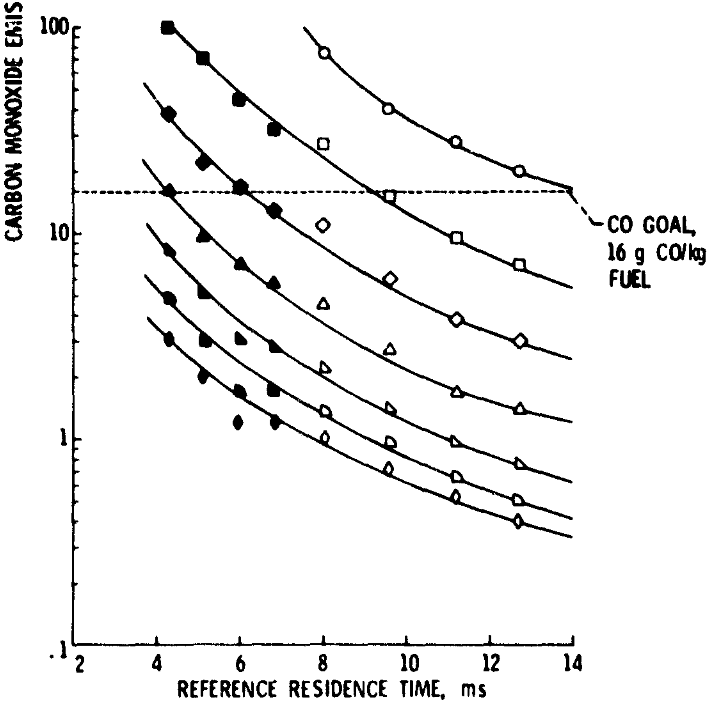


(b) INLET-AIR TEMPERATURE, 1150 K.

Figure 4. - Carbon monoxide relaxation with time. Pressure, 2.5×10^5 Pa.



(c) INLET-AIR TEMPERATURE, 1200 K.



(d) INLET-AIR TEMPERATURE, 1250 K.

Figure 4. - Concluded.

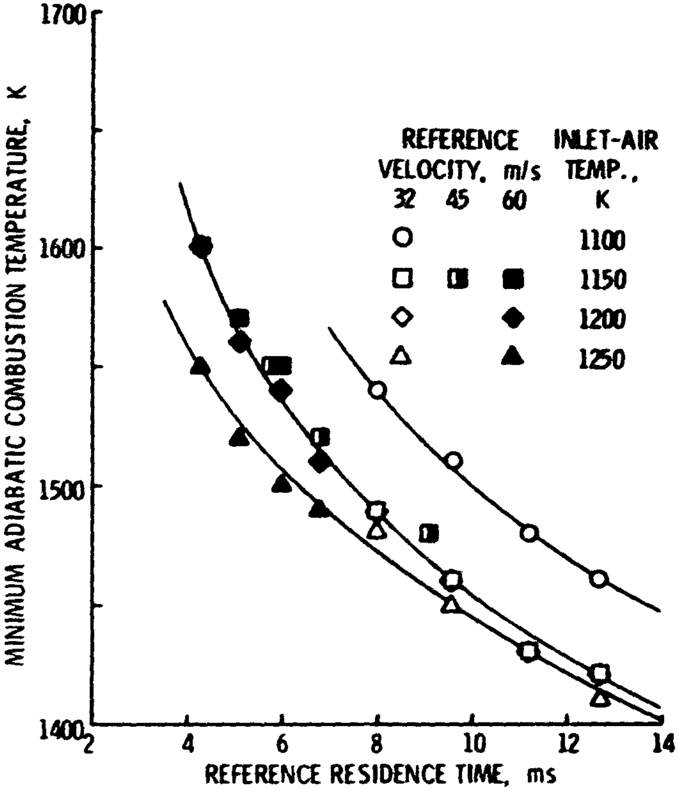


Figure 5. - Minimum operating temperature required to achieve CO emission goal of 16 g/kg. Pressure, 2.5×10^5 Pa.

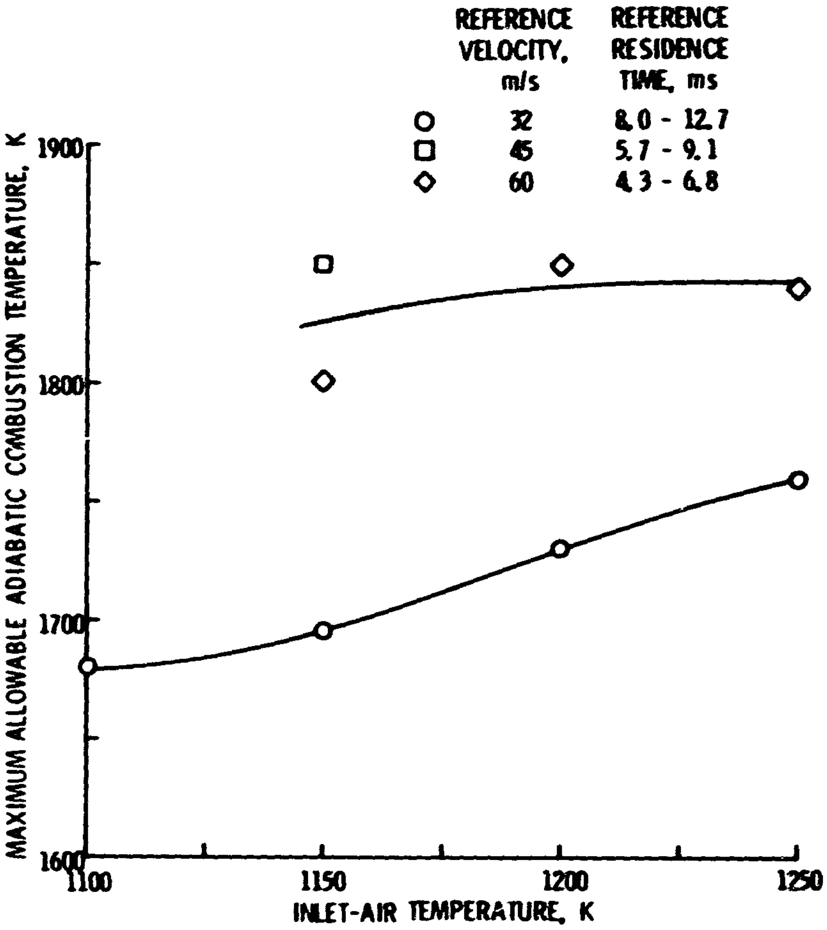


Figure 6. - Maximum allowable operating temperature to maintain NO_x below 1.9 g/kg. Pressure, 2.5×10^5 Pa.

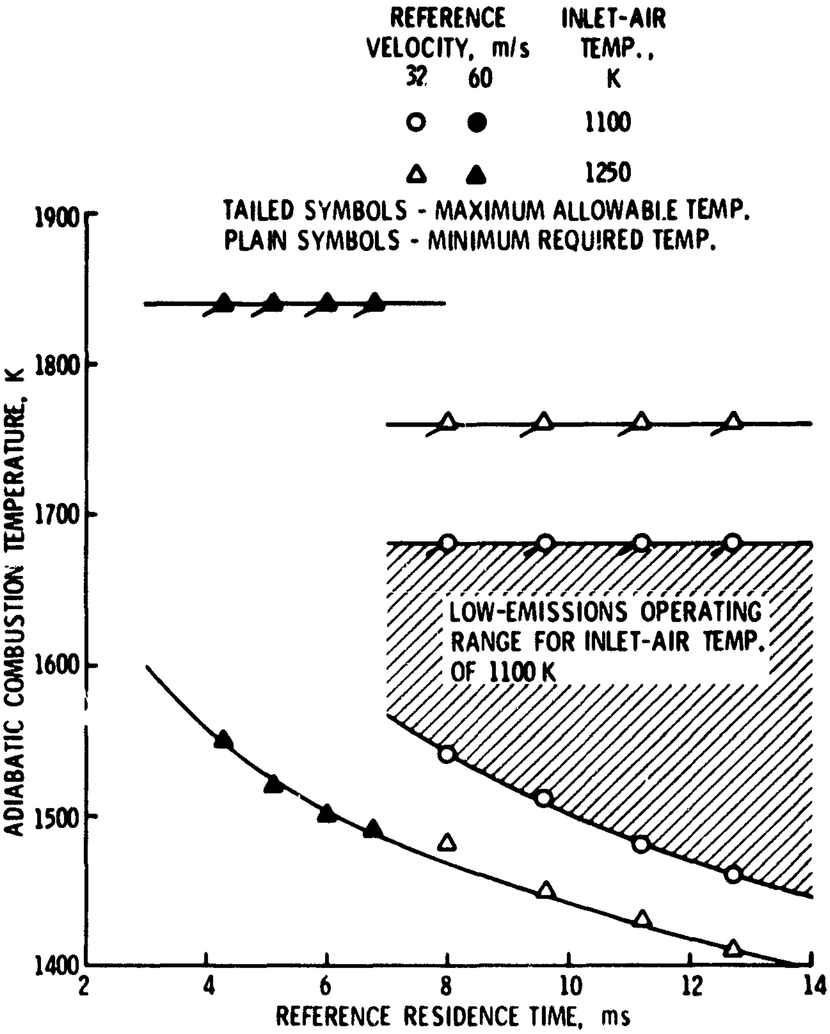


Figure 7. - Operating range. Pressure, 2.5 x 10^5 Pa.