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Work performed for
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EFFECTS OF FUEL-INJECTOR DESIGN ON ULTRA-LEAN COMBUSTION PERFORMANCE

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ABSTRACT

Emissions data were obtained for six fuel-injector configurations tested with ultra-lean combustion at an inlet-air temperature of 1200 K, a pressure of 250 kPa, and a reference (inlet) velocity of 32 m/s. Fuel injectors included three multiple-source designs and three configurations using a single air-assist injector. Only the multiple-source fuel injectors provided acceptable emissions. Values below the program goals of 16 g CO/kg fuel, 1.9 g HC/kg fuel, and 1.9 g NO_2/kg fuel were obtained for the combustion temperature range of 1450 to 1700 K for both a high-blockage (20.2-percent open area) 19-source injector and a low-blockage (41.1-percent open area) 41-source injector. The study thus showed that high fuel-injector pressure drop may not be required to achieve low-emissions performance at high inlet-air temperatures when the fuel is well-dispersed in the airstream. Further evaluation of both single-source and multiple-source fuel injection systems is required.

INTRODUCTION

This paper presents the results of a study of the effects of fuel-injector design on ultra-lean gas-phase combustion at an inlet-air temperature of 1200 K. The work was performed as supporting research under the DOE Gas Turbine Highway Vehicle Systems Project.

The advanced automotive gas-turbine engine (AGT) currently being developed under DOE contracts will operate with combustor inlet-air temperatures which are significantly higher than those in current gas-turbine engines. Values will typically range from approximately 1100 to 1300 K. Combustor-exit (turbine-inlet) temperatures will be as high as 1650 K. Combustors will be required not only to provide stable combustion but also to operate with low emissions at these conditions.

Low-emissions combustors have traditionally been of the lean premixed type (1-3). Recent combustion tests with inlet-air temperatures of 1100-1250 K (4) concluded, however, that at AGT conditions, premixing will probably be impossible because ignition delay times are so short. That study demonstrated low emissions using a multiple-source fuel injector with a high pressure drop (7 percent at a reference (inlet) velocity of 32 m/s).

The present study was a preliminary look at whether either the multiple-source feature or the high pressure drop is essential to achieving low emissions at high inlet-air temperatures. Emissions of CO, NO_x, and UHC were measured for six NASA-designed fuel injector configurations in a 12-cm diameter flame tube test section. Three multiple-source fuel injectors were tested to compare designs with large and small open airflow areas (low and high pressure drops) and different numbers of sources (19 and 41). A single-source air-assist fuel injector was also evaluated with three different duct area restrictions to determine the potential of relatively simple injector configurations. The tests were made with no. 2 diesel fuel. The inlet air was indirectly preheated to 1200 K, the reference velocity was 32 m/s, and the pressure was 250 kPa.

DESCRIPTION OF EXPERIMENT

Test Section

The test section is illustrated in Fig. 1. The test duct was circular in cross section and lined internally with 1.6-cm-thick Fiberfrax tube insulation to avoid heat loss. The insulation was protected from erosion by a 12-cm-inside-diameter Hastelloy sheet-metal liner. Inlet air was indirectly preheated to a temperature of 1200 K. This temperature was monitored with an array of 12 Chromel-Alumel thermocouples located approximately 34 cm upstream of the fuel injector. Inlet temperatures measured near the duct wall were typically less than 40 K below those at the duct centerline.

Fuel Injectors

The fuel-injector concepts tested are shown in Figs. 2(a) to (f). The three multiple-source air-blast fuel injectors were designed by R. Tacina at NASA Lewis. They are variations of injectors developed for premixing-prevaporizing-type combustors (5). The single-source injectors were simple air-assist designs constructed at NASA Lewis.

The first multiple-source injector was used in the study of Ref. 4. It had 19 air passages as shown in Fig. 2(a). The objective of this design was to split the airflow into 19 equal flowrates. Equal quantities of fuel entered each passage by flowing through 25-cm-long, 0.5-mm-diameter open-ended tubes. Each tube discharged into a 1.27-cm-diameter tubular extension of the upstream end of each air passage. The air-passages were conical diffusers with a half angle of 7 degrees. The reduced diameter at the plane of fuel injection not only tended to distribute the airflow, but also increased the air velocity to improve the fuel atomization. The fuel drop size was estimated from Lorenzetto and Lefebvre (6) to be about 15 μm for a reference velocity of 32 m/s. The open area seen by the combustion airflow was 20.2 percent of the test-section cross-sectional area (see Table I). At a reference velocity of 32 m/s, the pressure drop of the airflow was 7 percent of the upstream total pressure.

A 19-source fuel injector with 51.7 percent open area was also built to determine if the small open area of the first 19-source injector was necessary to its low-emissions performance. Figure 2(b) describes this fuel injector. The air passages had an entrance diameter of 2.06 cm and a diffuser half angle of 1.4 degrees. The pressure drop was 0.3 percent at 32-m/s reference velocity (Table I). To insure that equal quantities of fuel were discharged into each air passage, 0.5-mm-diameter fuel tubes with a length of 25 cm were again used. Fuel cooling was provided by a flow of shop air in a concentric 0.165-cm-inside diameter tube surrounding each fuel tube. This cooling airflow was about 10 percent of the combustion airflow rate. It discharged into the airstream along with the fuel and would have provided some air assist to help atomize the fuel. The initial fuel drop size was estimated from Ref. 6 to be about 15 μm.

The third injector tested had 41 fuel sources discharging into an equal number of diffusing air passages as shown in Fig. 2(c). Each air-passage entrance was

1.27 cm in diameter with a diffuser half angle of 3.5 degrees. The open airflow area of 41.1 percent resulted in a pressure drop of 0.5 percent at a 32-m/s reference velocity (see Table I). Fuel tubes were 0.069 cm in inside diameter and the concentric air-cooling tubes were 0.155 cm in inside diameter. The correlation of Ref. 6 again predicted a drop size of about 15 μm. The cooling air flow was about 15 percent of the combustion airflow rate and provided air assist for fuel atomization.

In addition to tests with these three multiple-source fuel injectors, a single air-assist injector was evaluated. It is illustrated in Fig. 2(d). Eight-hundred-kPa atomizing air flowed through a central 4.8-mm-outside-diameter tube. The atomizing air flowrate was about 4 percent of the combustion air flow. Surrounding the atomizing-air tube was a concentric 6.4-mm-outside-diameter, 5.6-mm-inside-diameter tube. Fuel flowed through the annular passage between these two concentric tubes. As shown in Fig. 2(d), the fuel flow was directed across the atomizing-air path to break the fuel stream into fine droplets. A 3.2-mm-diameter-by-6.4-mm-long cylinder was placed 3.2 mm from the end of the fuel tube to help to shatter the fuel stream. The drop size was estimated from the correlation of Ref. 6 to be about 20 μm. This basic injector design was tested in 3 configurations which differed primarily in the restriction given to the combustion airflow passage.

The first of the three air-assist configurations was mounted in the duct as shown in Fig. 2(d). There was no restriction in the duct passage except for the blockage of the fuel injector tube itself. The open area for the combustion airflow was 96.6 percent and the pressure drop was 0.1 percent of the upstream total pressure at a reference velocity of 32 m/s (Table I).

The remaining two air-assist configurations used a restriction in the duct area so that fuel was injected into a reduced-diameter section. Figure 2(e) shows the 7.5-cm-diameter restriction, and Fig. 2(f) shows the 5-cm-diameter restriction. These restrictions provided flow open areas of 37.8 and 16.3 percent, respectively, and the corresponding pressure drops were 0.7 and 5 percent at a reference velocity of 32 m/s. Three to five cm downstream of the fuel-injection point, the airflow area increased suddenly to the full 12-cm diameter of the test duct. This sudden dump of the flow could be expected to assist in flame stabilization.

No igniter was used because combustion reactions occurred spontaneously when fuel was injected into the high-temperature airstream for all fuel injector configurations tested. Combustion products were sampled at a single centerline location approximately 45 cm downstream of the plane of fuel injection. This distance varied for each injector configuration due to slight differences in the hardware used. The sampling probe was water cooled to quench the reactions and freeze the sampled concentrations. A 0.625-cm diameter stainless steel sampling line was electrically heated to maintain a temperature of 400 to 450 K. Through this line, the sampled gases flowed to the emissions analyzers to provide a continuous monitoring of the concentrations of CO, CO_2, unburned hydrocarbons, and nitrogen oxides.

RESULTS AND DISCUSSION

All data reported were obtained with an inlet-air temperature of 1200 K, a pressure of 250 kPa, and a reference (inlet) velocity of 32 m/s.

For this preliminary assessment, emissions were measured only at the duct centerline. This centerline measurement will give an accurate representation of the conditions in the duct only for a homogeneous mixture. An indication of how well the sample represents the conditions in the duct can be obtained by comparing the fuel-air ratio of the sampled gases with the average (metered) fuel-air ratio in the duct. The sample fuel-air ratio is obtained by summing the carbon atoms in the measured CO, CO_2, and UHC emissions.

The most representative sample was obtained with the high-pressure-drop 19-source fuel injector. Sample fuel-air ratios were only 1.3 to 7.1 percent higher than those in the bulk stream. This result suggests that a fairly homogeneous mixture was obtained with this fuel injector. The 41-source injector gave sample fuel-air ratios as much as 14 percent lower than the metered values; typical values were about 10 percent lower. These numbers indicate that this mixture was also fairly uniform. The low-pressure-drop 19-source fuel injector apparently produced a somewhat less homogeneous mixture: sampled fuel-air ratios were typically about 25 percent below the metered fuel-air ratios. The least representative samples were obtained with the three single-source air-assist injectors.

The air-assist injector with no duct restriction had sample fuel-air ratios typically 35 percent higher than those metered; the addition of the 7.5-cm diameter restriction produced sampled values 77-104 percent higher than the metered values; and sampled values with the 5-cm diameter restriction were about 48 percent higher than the metered. These results suggest that the air-assist injectors produced a highly center-peaked fuel-air ratio profile while the multiple-source injectors tended to achieve a much more uniform fuel-air ratio profile.

For five of the fuel injectors tested and at all test conditions evaluated, unburned hydrocarbons (UHC) emissions at the duct centerline were less than 0.5 g HC/kg fuel. The single-air-assist injector with the 5-cm-diameter flow restriction, however, produced UHC emissions of 15-17 g HC/kg fuel. The program goal was 1.9 g HC/kg fuel (4).

The CO emissions measured at the duct centerline for each of the six injectors are compared in Fig. 3. The CO emission index is plotted as a function of the adiabatic combustion temperature. This temperature was determined from the sample fuel-air ratio. Similar levels of centerline CO were observed with each of the three multiple-source fuel injectors. CO levels decreased with increasing combustion temperature. The goal for this program was 16 g CO/kg fuel (4), and this goal was achieved for each of the three multiple-source injectors for combustion temperatures of 1400-1450 K. The low-pressure-drop 19-passage injector was not operated at temperatures higher than 1400 K because of concern that the carbon-steel fuel injector might be damaged by combustion within the passages; however, the CO emissions appeared to follow the same curve as those measured with the high-pressure-drop 19-source injector.

The single-air-assist injector with no duct restriction produced centerline CO emissions which were higher at first than those from the multiple-source injectors. At a combustion temperature of just under 1500 K, however, CO emissions suddenly decreased from 30 g CO/kg fuel to about 8 to 9 g CO/kg fuel. At the same time, centerline NO_x increased from 0.8 to about 18 g NO_2/kg fuel as will be shown in Fig. 4. The ratio of the centerline-sample fuel-air ratio to the metered fuel-air ratio did not change significantly. when this shift in emissions levels occurred. A possible explanation of the emissions changes is that the location at which combustion began moved upstream toward the fuel injector. Combustion which originally started in a relatively well-mixed environment would now begin in a poorer-mixed region with higher local flame temperatures. The higher local temperatures would result in greater rates of NO_x formation and lower CO emissions. Subsequent testing resulted in CO emissions very similar to those from the multiple-source injector (see Fig. 3).

The single-air-assist injector with the 7.5-cm-diameter restriction also gave centerline emissions which suddenly changed during the course of testing. CO increased from about 10 g CO/kg fuel at a combustion temperature of 1570 K to 54 g CO/kg fuel at 1615 K (Fig. 3) while NO_x decreased from about 37 g NO_2/kg fuel to about 23 g NO_2/kg fuel (Fig. 4). Emissions then stabilized, defining new curves of emissions vs. temperature. The emissions shift, opposite to that observed for the single-air-assist injector with no duct restriction, could have been caused by a flow perturbation which moved the start of combustion from a poorly-mixed region to a somewhat more uniform location. For example, combustion may have started initially at the fuel injector but later stabilized at the step just downstream of the fuel injector. The CO for this fuel injector (see Fig. 3) decreased with increasing combustion temperature but was always higher than that observed with the multiple-source injectors for any combustion temperature.

The centerline CO emissions for the air-assist injector with a 5-cm-diameter restriction were about 2 orders of magnitude above the comparable levels for the multiple-source injectors. Only limited testing was performed with this configuration because very high temperatures would have been required to obtain much improvement in performance. It is likely that a high-velocity core of reacting flow was created by the duct restrictions used with the air-assist injectors. The residence times in this core would have been significantly less than that of the bulk flow, and this effect may explain the poorer performance of these injectors.

The centerline nitrogen oxides emission indexes for the six fuel-injector configurations are given in Fig. 4 as a function of the adiabatic combustion temperature. The NO_x goal for the study was 1.9 g NO_2/kg fuel (4). The lowest centerline NO_x emissions were obtained with the high-pressure-drop 19-source fuel injector and the 41-source injector. For these injectors, NO_x emissions increased exponentially with combustion temperature. The low-pressure-drop 19-source injector produced NO_x emissions which were nearly an order of magnitude higher than those for the other multiple-source injectors. Apparently, the fuel-air ratio profile was not sufficiently uniform to avoid the high-temperature regions which produce large concentrations of NO_x.

The single-air-assist injector without a duct area restriction initially gave centerline NO_x emissions of about 0.8 g NO_2/kg fuel at a combustion temperature of 1500 K (see Fig. 4). As noted in the discussion of Fig. 3, with test conditions held constant, the CO was observed to drop while the NO_x climbed to values around 18 g NO_2/kg fuel. NO_x emissions then ranged from 9.5 g NO_2/kg fuel at a combustion temperature of 1390 K to 29 g NO_2/kg fuel at 1550 K.

When the emissions shift occurred for the single-air-assist injector with the 7.5-cm-diameter duct restriction, centerline NO_x emissions approached the goal as shown in Fig. 4. The NO_x was at least double that from either the 41-source or the high-pressure-drop 19-source injectors. Typical values were 2.3 g NO_2/kg fuel at a combuston temperature of 1620 K and 15 g NO_2/kg fuel at 1810 K.

The last set of centerline NO_x data were obtained from tests of the single-air-assist injector with the 5-cm-diameter duct area reduction. As can be seen from Fig. 4, NO_x emissions were of the same magnitude as those from the best mutliple-source injector. However, in view of the high UHC and CO emissions for this air-assist configuration, it can be concluded that the low NO_x in this case resulted simply from incomplete combustion rather than from the combustion of a uniform fuel-air mixture.

For a combustion system to be satisfactory, it must provide low CO and low NO_x simultaneously. Frequently, there is a trade-off between CO and NO_x such that operating conditions which give low NO_x also produce high CO. Conversely, low CO is achieved when NO_x is high. For this reason, it is helpful to compare the different fuel injector configurations by charting the CO-NO_x trade-off. This has been done in Fig. 5 where the centerline CO emission index is plotted as the ordinate and the centerline NO_x as the abscissa. The CO and NO_x goals define a low-emissions operating box as shown on the figure.

Only for the high-pressure-drop 19-source injector and the 41-source injector was there an appreciable body of data for which CO and NO_x were simultaneously within the acceptable range. From Figs. 3 and 4 it can be seen that within the combustion temperature range of 1450 to 1700 K both CO and NO_x would be acceptable for these injectors. The first two data points obtained for the single-air-assist injector without a duct restriction show low NO_x emissions, and the CO was only about 10-15 g CO/kg fuel higher than the goal. This result suggests that this type of injector with proper design may have potential for low emissions operation.

It's noteworthy that the low-pressure-drop, 41-source fuel injector performed nearly as well as the high-pressure-drop, 19-source injector. Clearly, high pressure drop was not essential to acceptable performance in this study. However, for some applications, higher pressure drops may be required to distribute the incoming airflow to provide a uniform velocity profile. Uniform velocity profiles are important, along with good fuel dispersion, to insure that the fuel-air ratio is constant over the duct cross section when combustion begins.

SUMMARY AND CONCLUDING REMARKS

Tests were performed to compare the emissions for six NASA-designed fuel injector configurations at ultra-lean gas-phase combustion conditions in a 12-cm-diameter flame tube. Test conditions included a non-vitiated inlet-air temperature of 1200 K, a reference (inlet) velocity of 32 m/s, and a pressure of 250 kPa. Three multiple-source fuel injectors were evaluated to determine the effects of different pressure drops and different numbers of sources (19 and 41). Three single-air-assist injectors were tested as well so that data for fairly simple injectors used the same injector design but different duct-area restrictions to establish if performance was affected by an area reduction at the injection point.

Centerline CO and NO_x emissions were simultaneously below program goals over a range of combustion temperatures from 1450 to 1700 K for both a 19-source fuel injector with 20-percent open area (high pressure drop) and a 41-source fuel injector with 41-percent open area (low pressure drop). A second 19-source injector with 52 percent open area (low pressure drop) produced significantly higher NO_x emissions, apparently because of a less-uniform fuel-air ratio profile.

Three single-source air-assist fuel injector configurations gave generally higher NO_x emissions than the multiple-source injectors. Although CO emissions for one single-air-assist-injector were acceptable, low CO and NO_x could not be achieved simultaneously.

For this study, then, multiple-source fuel injection was required to achieve low emissions ultra-lean combustion while high fuel-injector pressure drop was not. Single-source injector designs different from those tested in this study need to be evaluated further to determine their potential for low-emissions performance at AGT conditions. Additional tests of multiple-source injectors with a smaller number of sources are also required to detemine if simpler designs might provide acceptable performance.

This study demonstrated that the achievement of low emissions with high-inlet-air-temperature combustion is very sensitive to fuel injector design. The development of practical combustors to operate at high inlet-air temperatures will therefore require extensive fuel injector development.

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TABLE I. - FUEL INJECTOR OPEN AREA AND PRESSURE DROP

Fuel injector	Open area, percent of duct area	Pressure drop, percent of upstream total pressure, V_r, m/s*	
		32	60
High-pressure-drop 19-source	20.2	7.0	23
Low-pressure-drop 19-source	51.7	0.3	0.9
41-source	41.1	.5	2.2
Single air-assist with no duct restriction	96.6	.1	.4
Single air-assist with 7.5-cm-diameter restriction	37.8	.7	3
Single air-assist with 5-cm-diameter restriction	16.3	5.0	----

*V_r = Reference Velocity, Velocity based on test-section-inlet conditions and 12-cm diameter.

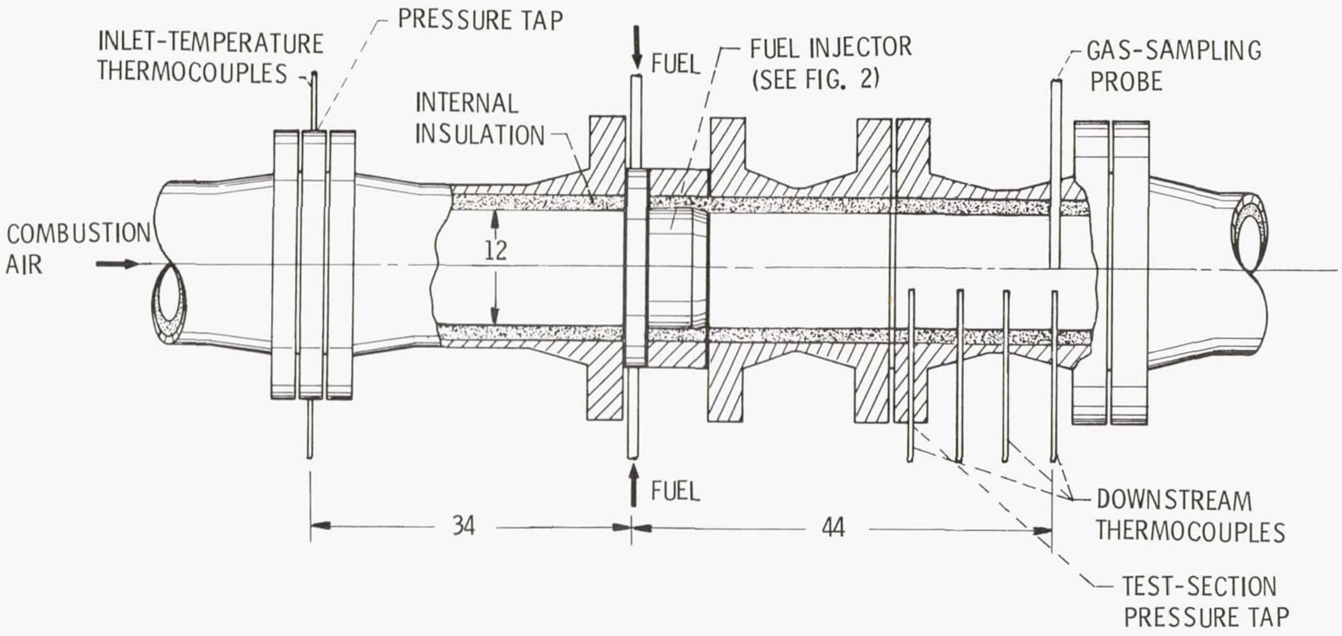
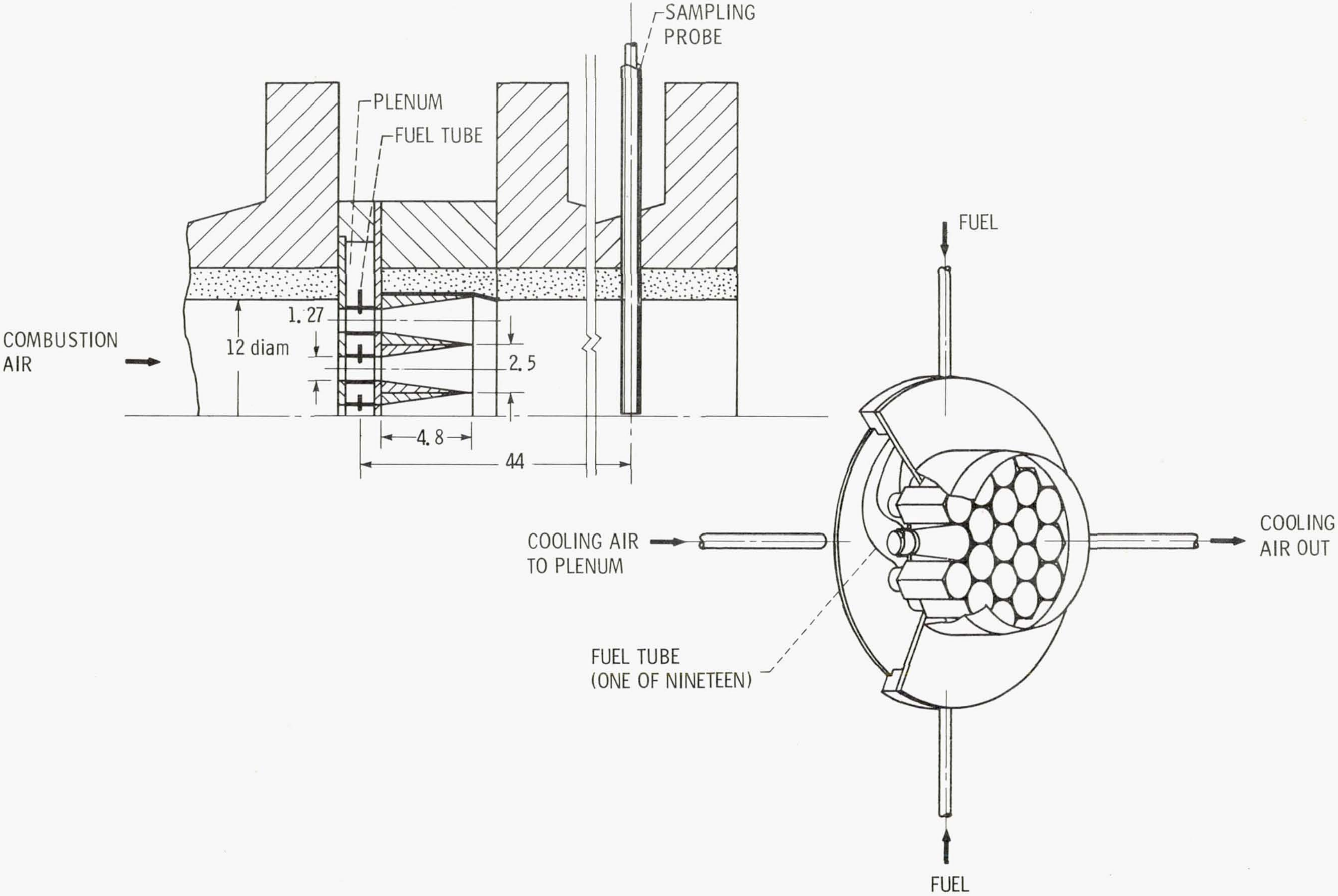
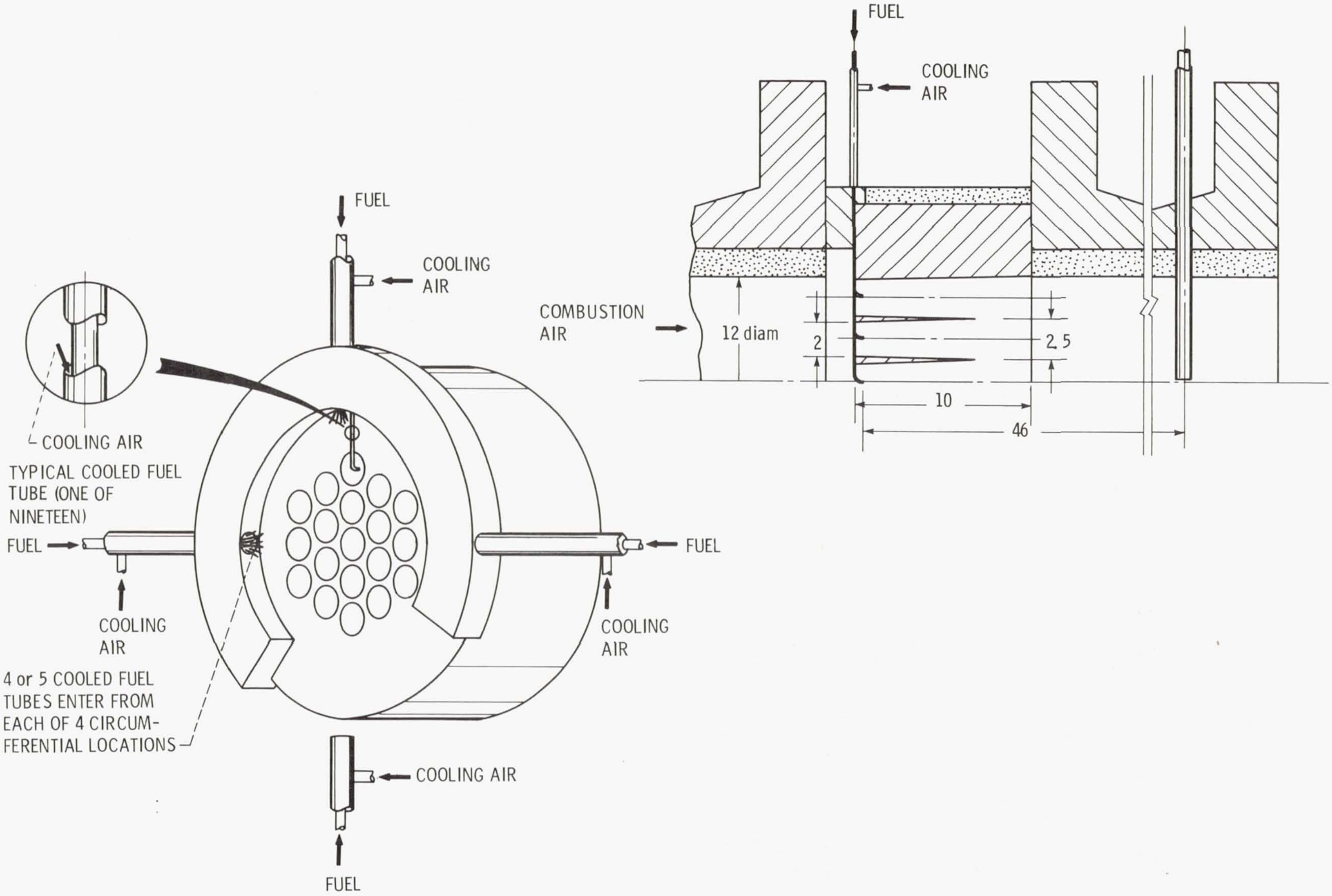


Figure 1. - Test section with high-pressure-drop 19-source fuel injector. (Dimensions are in cm.)



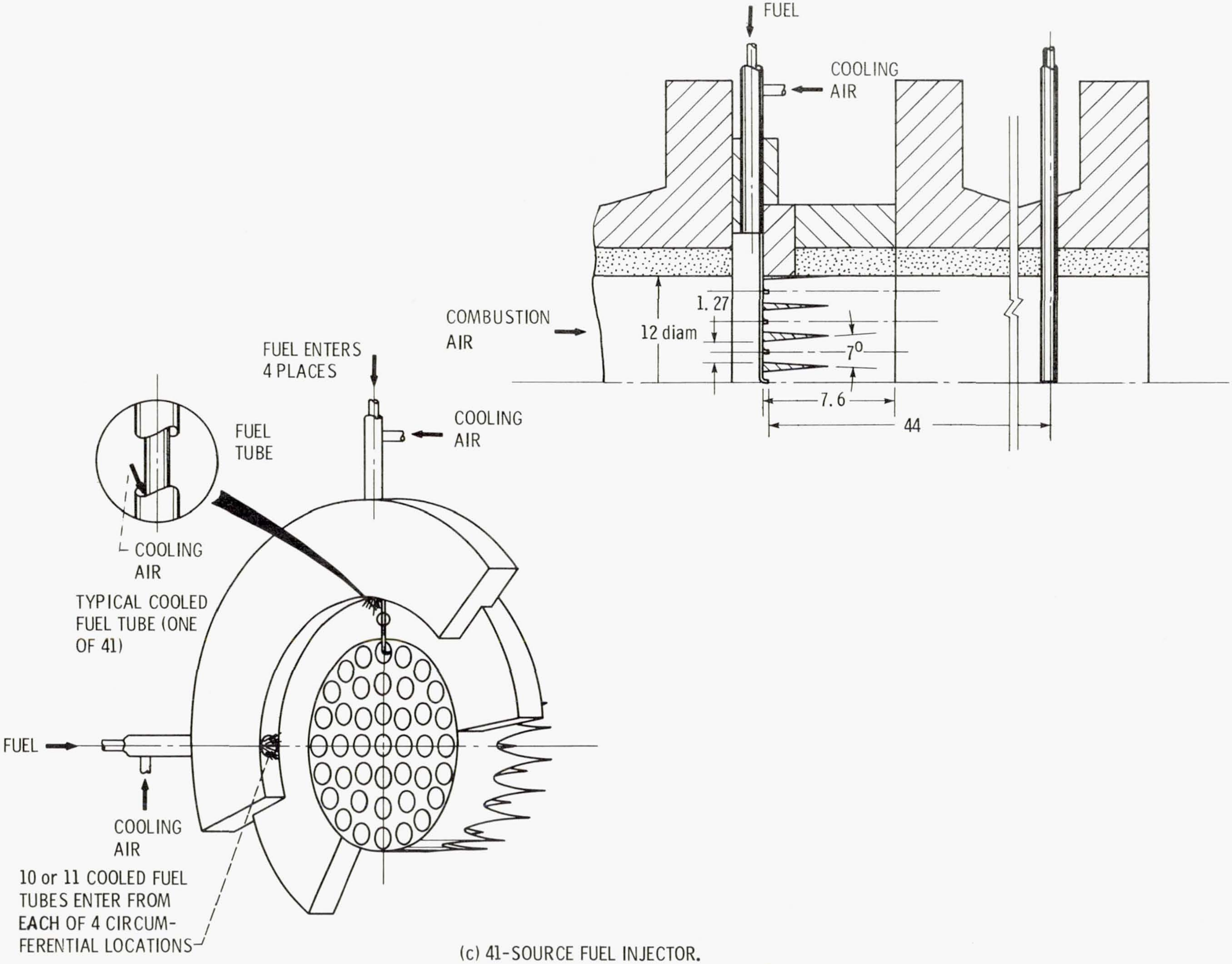
(a) HIGH-PRESSURE-DROP 19-SOURCE FUEL INJECTOR.

Figure 2. - Fuel injectors. (Dimensions in cm.)



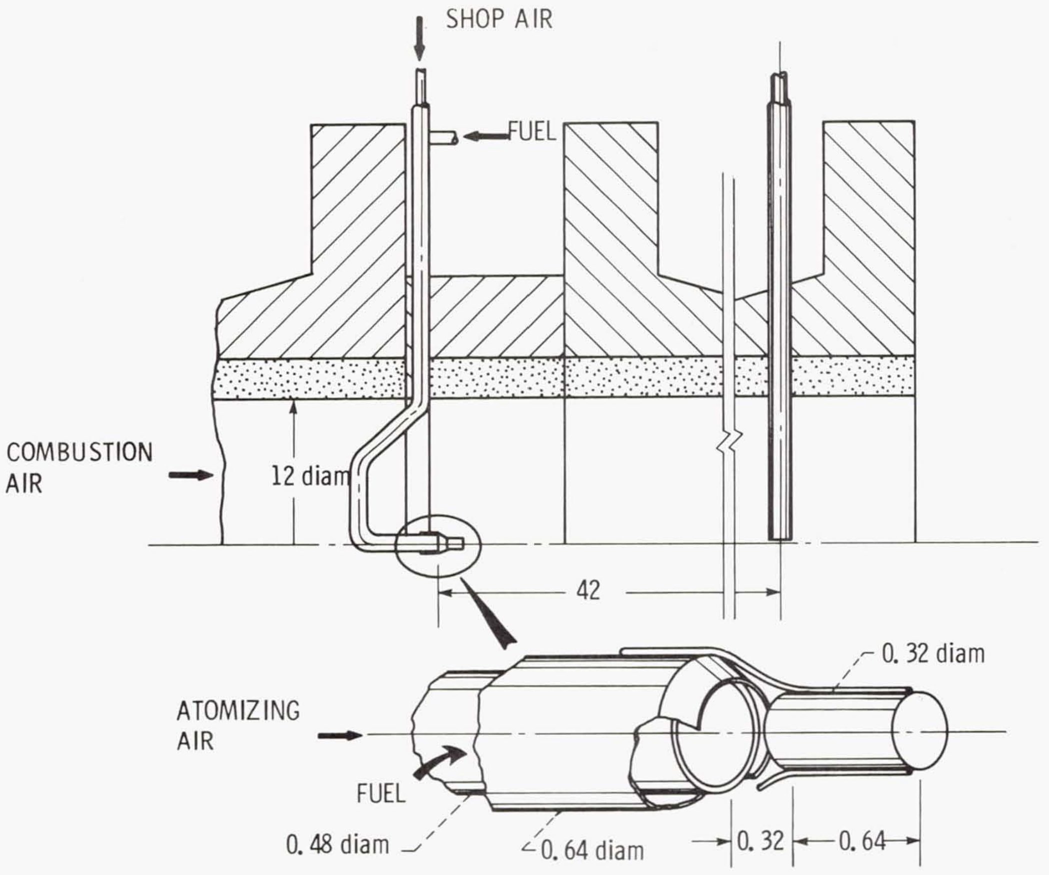
(b) LOW-PRESSURE-DROP 19-SOURCE FUEL INJECTOR.

Figure 2. - Continued.

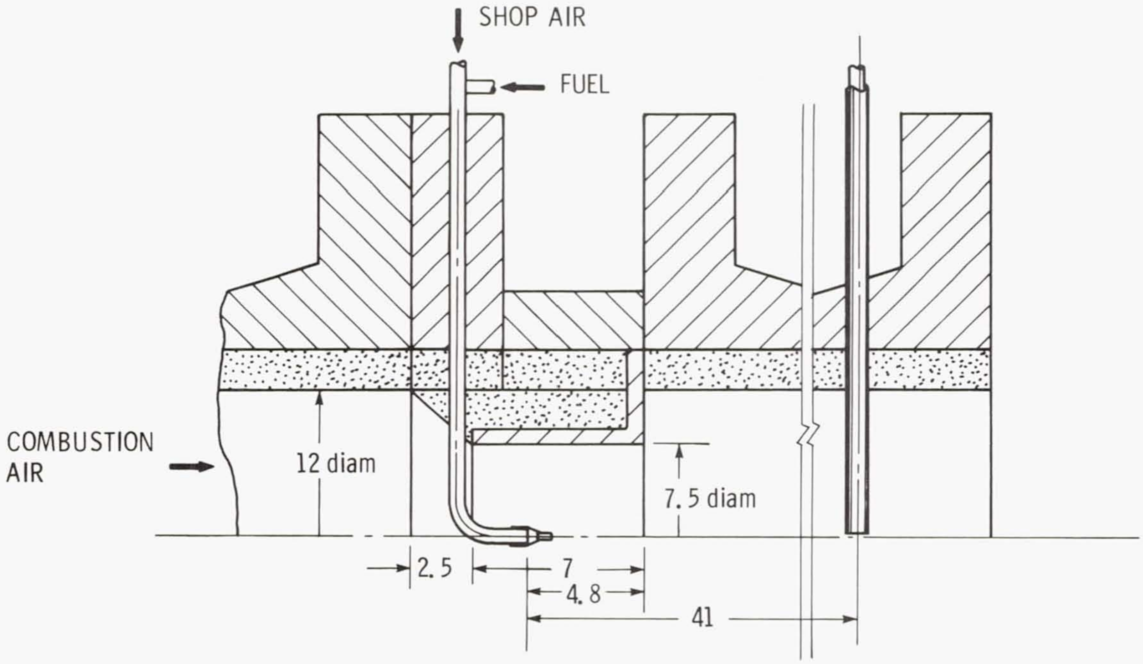


(c) 41-SOURCE FUEL INJECTOR.

Figure 2. - Continued.



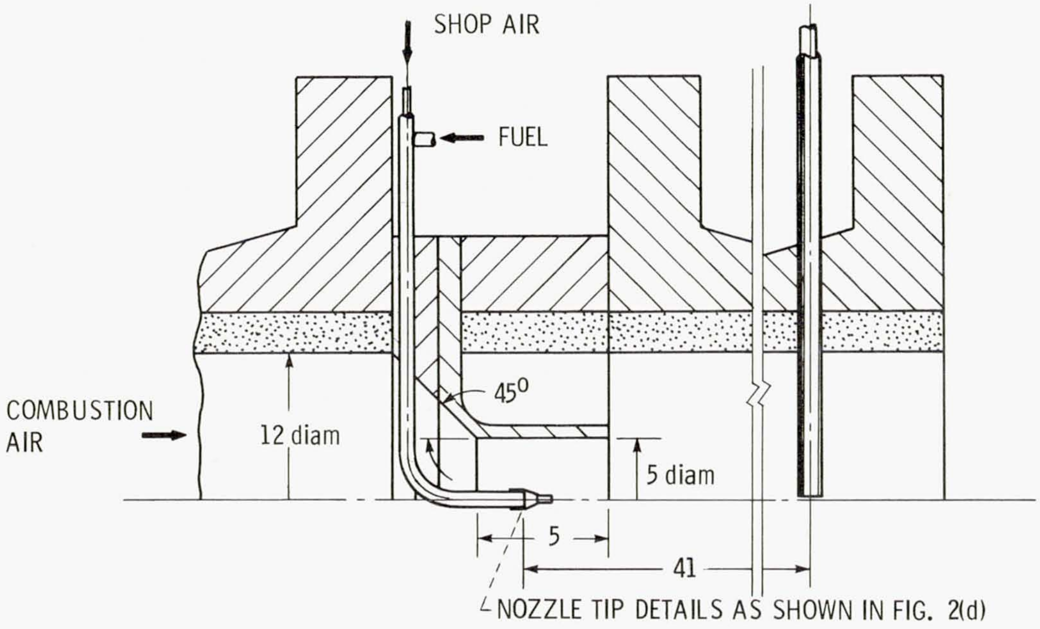
(d) SINGLE-AIR-ASSIST FUEL INJECTOR.



NOZZLE TIP DETAILS AS SHOWN IN FIG. 2(d)

(e) SINGLE-AIR-ASSIST FUEL INJECTOR WITH 7.5-cm-diameter DUCT RESTRICTION.

Figure 2. - Continued.



(f) SINGLE-AIR-ASSIST FUEL INJECTOR WITH 5-cm-diameter DUCT RESTRICTION.

Figure 2. - Concluded.

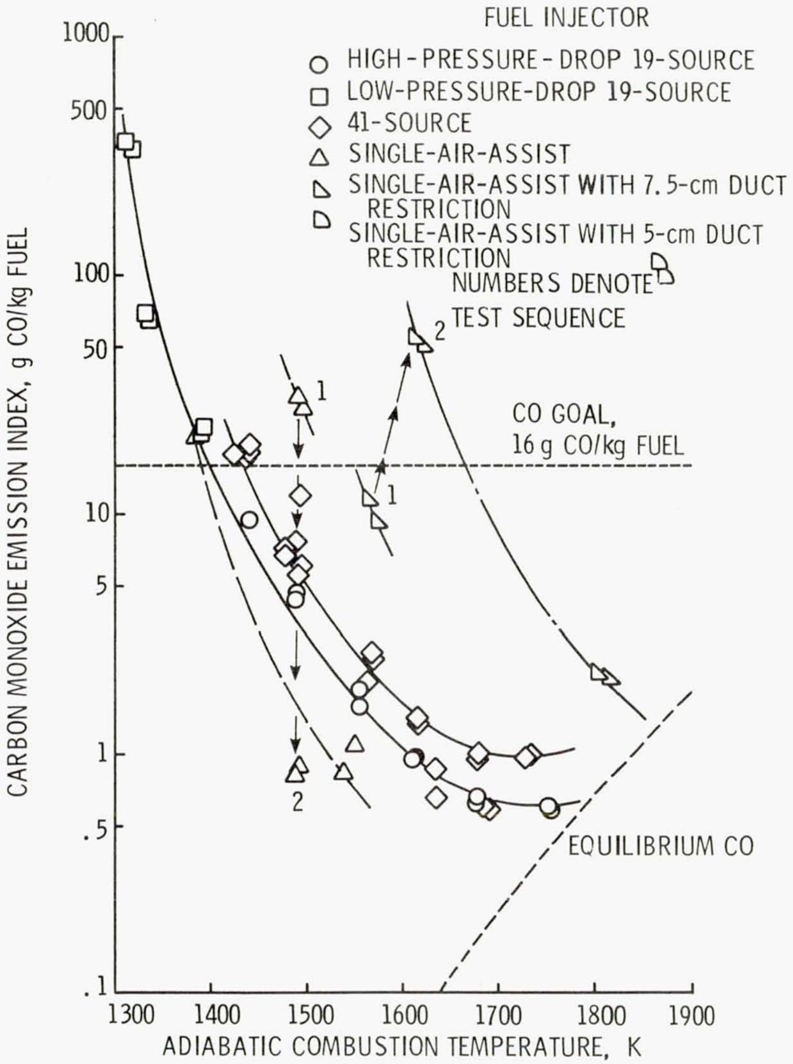


Figure 3. - Carbon monoxide emissions at duct centerline. Inlet-air temperature, 1200 K; reference velocity, 32 m/s; pressure, 250 kPa.

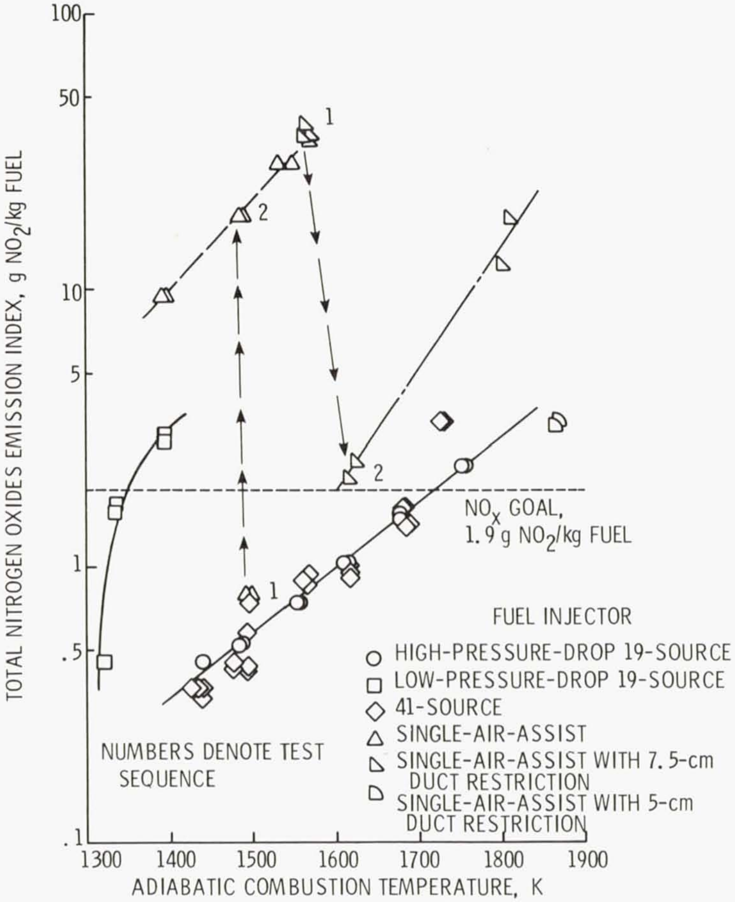


Figure 4. - Nitrogen oxides emissions at duct centerline. Inlet-air temperature, 1200 K; reference velocity, 32 m/s; pressure, 250 kPa.

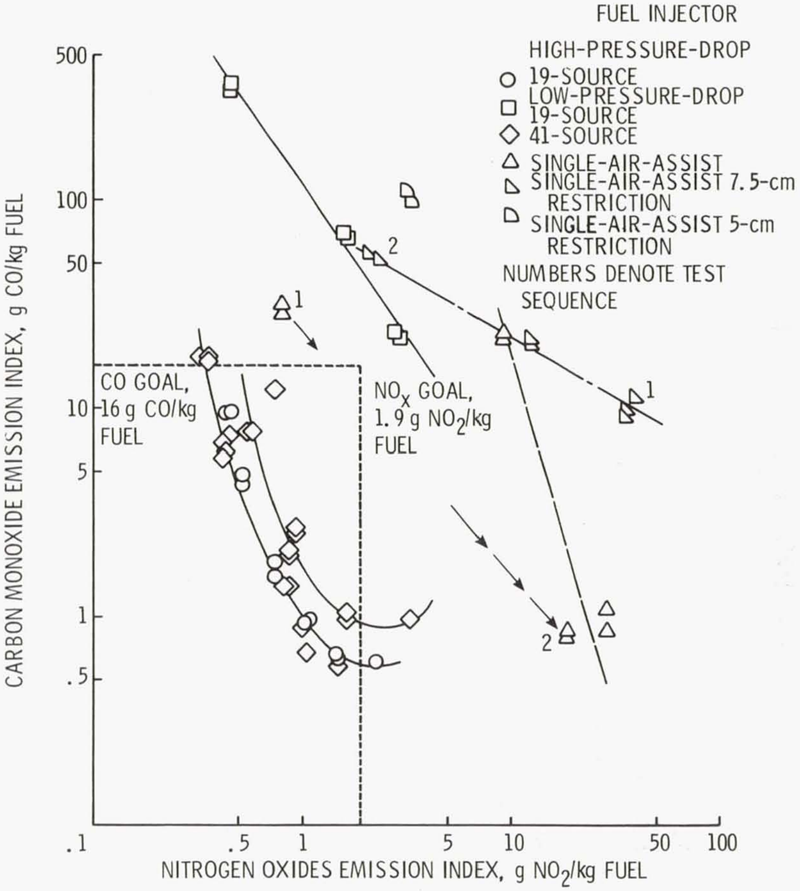


Figure 5. - Trade-off between carbon monoxide and nitrogen oxides emissions at duct centerline. Inlet-air temperature, 1200 K; reference velocity, 32 m/s; pressure, 250 kPa.

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16. Abstract
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