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CONVERSION OF AN EXPERIMENTAL TURBOJET COMBUSTOR FROM ASTM A-1 FUEL TO NATURAL GAS FUEL

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16. Abstract

A side-entry turbojet combustor previously developed with ASTM A-1 fuel was redesigned to use natural gas fuel. The rectangular test section simulated a segment of an annular turbojet combustor. Five combustor liner configurations and two fuel nozzle geometries were evaluated. Natural gas fuel temperatures ranging from -259° to 1200° F (111.5 to 922 K) were investigated. The test conditions were as follows: nominally atmospheric inlet pressure; inlet air temperature of 600° F (589 K); and diffuser inlet Mach numbers of 0.24, 0.30, and 0.37 corresponding to nominal reference velocities of 77, 100, and 120 ft/sec (23.5, 30.5, and 36.3 m/sec), respectively. The combustor configurations were designed to achieve combustor exit temperatures of 2200° F (1478 K). No insurmountable fuel conversion problems were encountered. High combustion efficiency and desirable radial exit-temperature profiles having low pattern factors were achieved with only minor combustor modifications. Ignition was readily obtained with natural gas temperatures of -235° F (125 K).

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SUMMARY

A side-entry turbojet combustor previously developed with ASTM A-1 fuel was redesigned to use natural gas fuel. Tests were conducted with a rectangular test section simulating a segment of an annular turbojet combustor. Five combustor liner configurations and two fuel nozzle geometries were evaluated. Natural gas fuel temperatures ranging from -259° to 1200° F (111.5 to 922 K) were investigated. The test conditions were as follows: nominally atmospheric inlet pressure; inlet air temperatures of 600° F (589 K); and diffuser inlet Mach numbers of 0.24, 0.30, and 0.37 corresponding to nominal reference velocities of 77, 100, and 120 feet per second (23.5, 30.5, and 36.3 m/sec), respectively.

Using one combustor liner configuration for comparison, the combustion efficiency with ambient-temperature natural gas fuel was higher than that for ASTM A-1 fuel at fuel-air ratios below about 0.020. However, as the fuel-air ratio was increased above 0.020, combustion efficiency decreased to levels below that for ASTM A-1 fuel.

Improvements in combustion efficiency were obtained with a modified combustor liner configuration which increased combustor pressure loss from a reference isothermal level of 5.48 percent to 6.42 percent at an inlet Mach number of 0.259. With ambient-temperature natural gas fuel, the modified combustor liner configuration achieved an exit temperature of 2253° F (1507 K); pattern factor of 0.23; combustion efficiency of 100.6 percent; and total-pressure loss of 7.54 percent at an inlet Mach number of 0.252, and a reference velocity of 80.0 feet per second (24.4 m/sec). However, combustion efficiency decreased to 87.6 percent at a reference velocity of 120.5 feet per second (36.7 m/sec). By heating the fuel from ambient to inlet temperatures near 1200° F (922 K), the combustion efficiency was 97.6 percent at a reference velocity of 118.1 feet per second (36.0 m/sec). Ignition was readily obtained with natural gas temperatures as low as -235° F (125 K) at a combustor pressure of one atmosphere and an air temperature of 36° F (275 K).

INTRODUCTION

Liquified natural gas has good potential as a fuel for advanced turbojet aircraft (refs. 1 to 3). Its advantages include increased heat-sink capacity, higher heating value than JP fuels, less tendency to smoke, lower flame radiation, and greatly reduced tendency for fuel decomposition (ref. 2). Since experience with gaseous fuels in turbojet combustors is limited, this investigation was conducted to examine the problems that may arise in converting an experimental turbojet combustor from ASTM A-1 fuel to natural gas fuel.

A side-entry combustor design was previously developed for ASTM A-1 fuel as a short-length combustor having the characteristic of insensitivity to inlet velocity profile distortions (ref. 4). This design was revised for natural gas fuel to accommodate large fuel nozzles and alternate combustor liner configurations. Tests were conducted to determine performance with natural gas fuel and to compare the performance with previous results using ASTM A-1 fuel; to determine the effect of natural gas fuel temperature on combustor performance, including the effects at the instant of takeoff when high fuel flows may cause lowered fuel temperatures; and to examine the combustor ignition capabilities under a simulated engine cranking condition using cold fuel and cold ambient inlet airflow.

A rectangular segment apparatus designed to simulate about a one-sixth sector of a full annular combustor was used for this investigation. Nominal test conditions were maintained at 1-atmosphere inlet total pressure and 600° F (589 K) inlet total temperature. Combustion efficiency, overall total-pressure loss, and exit-temperature distribution data were obtained for various side-entry combustor configurations. Performance data are presented to show the effects of fuel-air ratio, fuel temperatures, reference velocity, and pressure loss on combustion efficiency.

APPARATUS AND PROCEDURE

Test Facility

The combustor test facility shown in figure 1 was supplied from a source of dry combustion air at a nominal air temperature of 50° F (283 K). The orifice was sized to measure flow rates up to 5 pounds per second (2.67 kg/sec) as set with the flow control valve. Because the combustor exhausted directly to the atmosphere, combustor inlet pressures were maintained just slightly above the local barometric pressure. To attain combustor inlet air temperature of 600° F (589 K), a direct-fired (vitiating) preheater heated a portion of the air supply, which then was dumped and mixed with a bypassed portion in a large plenum chamber. The plenum chamber was 36 inches (0.914 m) in diameter and 56 inches (1.422 m) in length. A cone having a 120° included angle at the apex and a 24-inch (0.610-m) diameter at the base was mounted within the plenum chamber to aid mixing. Square-mesh wire fabric was installed at the exit of the plenum chamber to aid in obtaining uniform velocity profiles. Two layers of fabric similar to number 2 mesh with 1/2-inch (1.27-cm) wire spacing were staggered to get nominal 3/16-inch (0.5-cm) openings.

The natural gas fuel system is shown in figure 2. Natural gas fuel at near-ambient temperatures was obtained directly from a high-pressure tube-type gas trailer. Natural gas fuel temperatures near 1200° F (922 K) were obtained by passing the fuel flow from this gas trailer through a double-coil heat-exchanger system. To get natural gas fuel in the low-temperature range from ambient to -259° F (111.5 K), liquified natural gas from a self-pressurizing dewar storage trailer was passed through the heat-exchanger system to somewhat stabilize the low-temperature-fuel conditions. Nevertheless, some fuel flow fluctuations still occurred due to unavoidable liquid entrainment in the gas.

The rectangular test section assembly and the inlet and exit ducts shown in figure 3 were 15 inches (38.1 cm) wide. The inlet section was 2 inches (5.1 cm) in height and provided mounts for inlet total-pressure rakes and thermocouple probes. The exit section was 4.2 inches (10.7 cm) in height and provided mounts for exit-temperature and pressure rakes. These heights are representative of the compressor exit and turbine inlet for an experimental supersonic transport engine (ref. 5). Water sprays downstream of the exit section quenched the combustion products before they were exhausted to the atmosphere. The water sprays were shut off only when viewing the combustor flame characteristics from the window in the exhaust pipe.

Instrumentation

Airflow rates were determined from a sharp-edged orifice installed according to ASME specifications. The orifice differential pressure was measured by a strain-gage-type pressure transducer whose output was read on a digital voltmeter. Upstream orifice pressure was measured with a Bourdon-tube-type, direct-indicating gage; and orifice inlet temperature was measured with an iron-constantan thermocouple probe.

All fuel flow rates were measured with an orifice. Orifice inlet temperature and manifold fuel temperatures were measured with a thermocouple probe of a type suited to the range of the fuel temperature. Ambient fuel temperatures were measured with iron-constantan thermocouple probes, low-temperature natural gas with copper-constantan probes, and heated natural gas with Chromel-Alumel probes.

The locations of the combustor inlet and exit instrumentation stations are shown in figure 3, and the details at these stations are shown in figure 4. At station A, six iron-constantan thermocouples provided a measurement of inlet temperature. At station B, seven rakes, each having three total-pressure-sensing points, provided measurement of inlet total pressure. At station C, eight water-cooled thermocouple rakes, each having five temperature-sensing points, were installed to measure the combustor exit-temperature distribution. The thermocouple wire was 24-gage platinum - 13-percent-rhodium/platinum (ISA calibration R). These thermocouples were the exposed junction type having a 0.5-inch (1.3-cm) extension of bare wire from the support tubing to minimize conduction errors. At station D, seven water-cooled total-pressure rakes, each having five total-pressure-sensing points, provided measurement of exit total pressure. The instrumentation rakes are shown in figure 5.

The iron-constantan and Chromel-Alumel thermocouples were read from indicating-type, continuous-balance potentiometers. The copper-constantan thermocouples were read with a millivolt indicator. The platinum - 13-percent-rhodium/platinum thermocouples were read from a multipoint, strip-chart-recording, continuous-balance potentiometer. Pressures were connected to scanivalve strain-gage pressure transducers, one for inlet pressures and one for exit pressures. The pressures were read from a paper-type printout of transducer output voltages.

Probable accuracy of exit thermocouple readings was $\pm 20^{\circ}$ F (11.1 K) prior to any adjustment for radiation. The temperature adjustment for radiation was based on the method of reference 6. An unshielded-wedge-type exit thermocouple probe and a platinum wire emissivity of 0.3 were assumed. The typical adjustment amounted to 115° F (64 K) at an exit-temperature reading of 2081° F (1412 K) and an exit Mach number of 0.22. Other values of radiation correction are plotted against wire temperature at typical exit Mach numbers in reference 7. Probable accuracy of inlet-temperature readings was $\pm 10^{\circ}$ F (5.6 K).

Combustor Design

Side-entry combustor Model II, previously developed with ASTM A-1 fuel, is described in reference 4. The final Model II configuration, which is shown in figure 6, had an inner diffuser wall angle of about 24°, and diffuser inlet- to exit-area ratio of about 1.7 with a 7° included diffuser angle. Radial swirlers were used with liquid-fuel nozzles which required 1.12-inch (2.84-cm) diameter openings in the firewall. In order to convert this combustor to a design using natural gas fuel, 2.0-inch (5.08-cm) diameter openings in the firewall were required to accommodate larger gas-fuel nozzles with matching axial swirlers. It was also decided to make an arbitrary change in diffuser design to allow testing outer combustor liners of longer length and revised slot patterns. This required a steeper inner diffuser wall angle of about 35° and also resulted in a shorter diffuser length. The effects of other diffuser designs on side-entry combustor performance, including the effect of diffuser length, were investigated separately and are described in reference 8.

Another change from the Model II configuration was in the design of the lower (inner) liner. This was to provide increased film cooling with a design similar to that used for transition liners in annular turbojet combustors such as that described in reference 5. The liner sections are formed and welded so that the film-cooling slot can be supplied from inclined metering holes which aid cooling of the overlapping edge trailing each cooling slot. A slight revision in combustor airsplits resulted from this change. Thus, the modifications for converting to natural gas fuel were significant enough to warrant a separate combustor designation, namely, the Model VI side-entry combustor.

As in the previous investigation, a rectangular combustor housing 15 inches (38.1 cm) wide and 10 inches (25.4 cm) high was used to simulate a sector of an annular-type combustor. The diffuser inlet height was 2 inches (5.1 cm) and the combustor exit height was 4.2 inches (10.7 cm). The length of the combustor test section was 22 inches (55.9 cm).

Similarly, five fuel nozzle locations were provided and positioned between the four inlet chutes. The first gas-fuel nozzle that was tested is shown in figure 7(a) and is designated FN-1. This nozzle had an internal set of eight flow orifices and an external nozzle face with six flow orifices. The total internal flow area was approximately one-third of the total external flow area. Thus, the internal orifices provided a pressure drop so as to obtain a nearly equal fuel flow to each nozzle. The external orifices provided a low injector pressure drop to obtain low-velocity fuel entry into the combustion zone. The air swirlers which surround each fuel nozzle were an axial type, having 16 vanes inclined at a 45° helix angle. Dimensions are shown in figure 7(b). This fuel nozzle and swirler assembly is shown in figure 8. Figure 9 shows the swirlers attached to the firewall and also the assembly of the inlet chutes to the inner diffuser wall.

Several alternate fuel nozzle concepts were screened in preliminary testing to determine their effects on combustion efficiency. A typical design is shown in figure 10 and is designated FN-2. This design has a 2-inch (5.08-cm) outer diameter. Fuel was injected from a torus of about 30 closely spaced fuel holes of 3/16-inch (0.48-cm) diameter. The central 1-inch (2.54-cm) diameter was hollow for air passage. Further fuel dispersion was provided by a ring that extended from the face of the nozzle. One combustor configuration, called VI-A2(FN-2), was evaluated with this type fuel nozzle. Otherwise, fuel nozzle FN-1 was used.

Several outer-liner configurations were investigated with the Model VI combustor. A reference outer-liner configuration corresponding to the final Model II design shown in figure 6 was fabricated to establish a basis for performance comparison. This reference configuration is designated VI-A1. Other combustor configurations differed in airflow apportionment and pressure loss. These were designated as follows: VI-A2, VI-A2 (FN-2), VI-B1, VI-B2, and VI-C. Liner configuration B2, shown in figure 11, is a typical arrangement of slots and scoops. Details of all the liner configurations are presented in table I. The individual liners are shown in figure 12. Liner configuration B1 was the same as B2, except for the slot sizes. Thus, slot blockage strips were utilized to modify the B1 liner configuration to the B2 liner configuration. An assembly sketch showing the Model VI-B2 combustor airsplits is shown in figure 13. Liner configuration C was designed with 55-percent primary air to investigate very short length air entry for possible extended-temperature application.

Due to a lack of sufficient film cooling with liner configuration A1, perforated liner material was used for the other liners to get additional cooling. The perforated liners had about 4.8 percent open area before fabrication. This was assumed to allow about 2.2 percent airflow for liner cooling. Some liner warpage did occur but did not cause problems with combustor operation.

Test Conditions

The data used to determine the performance of combustor configurations included exit-temperature distribution, total-pressure loss, and combustion efficiency. Two nominal test conditions were generally used: one an inlet Mach number near 0.24 and another a Mach number near 0.30, at an inlet temperature of 600° F (589 K). Limited data were obtained at a supplementary test condition corresponding to an inlet Mach number of 0.37. Fuel-air ratios were set to approach design objective average exit temperature of 2200° F (1478 K). Nominal test conditions are listed in table II.

Uniform inlet velocity profiles were maintained for evaluation of combustor modifications. The inlet Mach number was calculated by the compressible flow expression using the average inlet static pressure and the measured total airflow. Natural gas fuel containing approximately 94 percent methane by volume was used. Its heating value was calculated to be 20 531 Btu per pound (47 800 J/g) based on a representative fuel composition analysis.

Ignition was provided by a capacitor-type ignitor system with an available energy of 20 joules. The ignitor boss was located on a side wall of the diffuser housing.

RESULTS AND DISCUSSION

Performance data for the Model VI side-entry combustor using natural gas fuel were obtained for five combustor liner configurations. Two natural gas fuel nozzle designs were also investigated. The effects of fuel-air ratio, reference velocity, total-pressure loss, and fuel temperature on combustion efficiency were determined. Other combustor performance data obtained were radial exit temperature profiles, ignition data using cold fuel temperatures with cold ambient inlet air, and total-pressure loss. The reference liner configuration was also tested using ASTM A-1 fuel to establish a basis of comparison with the previous data of reference 4. Tables III to VI contain the data which are discussed in the following paragraphs.

Combustion Efficiency

Combustion efficiency was defined as the percentage ratio of actual enthalpy rise to theoretical enthalpy rise. It was calculated by the procedures described in reference 4. The accuracy of the combustion efficiency calculation is believed to be of the order of ±5 percent. Except when determining the effect of inlet fuel temperature, the combustion efficiency characteristics were obtained with ambient natural gas fuel.

Effect of fuel-air ratio. - Each combustor configuration was tested over a range of fuel-air ratios, as shown in figure 14. The design fuel-air ratio for a 1600° F (888.8 K) temperature rise to an exit temperature of 2200° F (1478 K) using typical natural gas fuel was calculated to be 0.0235. At ambient natural gas fuel temperatures and a reference velocity of 77 feet per second (23.5 m/sec), four combustor configurations (VI-A1, VI-A2, VI-B1, and VI-B2) exhibited combustion efficiencies of 100 percent at fuel-air ratios of about 0.015. Beyond 0.015 fuel-air ratio, the respective efficiencies tended to drop, except for combustor configuration VI-B2 which maintained its level of efficiency even at a fuel-air ratio of 0.028. The fifth configuration, VI-C, achieved 89.1-percent combustion efficiency at a fuel-air ratio of 0.0157 and increased to a level of 100.9 percent at a fuel-air ratio of 0.0266.

Effect of reference velocity. - As also shown in figure 14, there was a noticeable decrease in combustion efficiency when the combustor reference velocity was increased nominally from 77 feet per second (23.5 m/sec) to 100 feet per second (30.5 m/sec). The best combustor configuration, VI-B2, maintained a combustion efficiency level of about 95 percent at a reference velocity of 102 feet per second (31.1 m/sec) over the range of fuel-air ratios from 0.017 to 0.028.

Effect of total-pressure loss. - There was a noticeable improvement in combustion efficiency for configuration VI-B2, for which the combustor pressure loss was slightly increased by proportionally reducing the slot sizes of the VI-B1 liner configuration. Combustor configuration VI-B1 at an inlet Mach number of 0.248 and a fuel-air ratio of 0.0220 had a combustor pressure loss of 5.88 percent and 91.1-percent combustion efficiency (run 20, table III). Combustor configuration VI-B2 at an inlet Mach number of 0.245 and a fuel-air ratio of 0.0225 had a combustor pressure loss of 6.93 percent and 102.9-percent combustion efficiency (run 32, table III). Thus, a small increase in combustor pressure loss resulted in a significant increase in combustion efficiency.

Effect of fuel nozzle geometry. - The test results with combustor configuration VI-A2(FN-2) using the alternate fuel nozzles are also shown in figure 14. Configuration VI-A2(FN-2) did not show an improvement in combustion efficiency compared to configuration VI-A2. Other fuel nozzle modifications of FN-1 and FN-2 to effect better fuel-air mixing were screened in preliminary tests, but produced no improvements. One nozzle using a simple 1/8-inch (0.32-cm) diameter fuel orifice at each fuel nozzle position was particularly difficult to ignite.

Effect of fuel inlet temperature. - Combustor configurations VI-B2 and VI-A2(FN-2) were tested over a range of fuel temperatures and reference velocities at a nominally constant fuel-air ratio of 0.020. The data in figure 15 show that combustion efficiency was significantly improved to levels near 100 percent by heating the natural gas fuel from ambient to temperatures near 1200° F (922 K). For configuration VI-B2 (fig. 15(a)) at a reference velocity of 77 feet per second (23.5 m/sec), combustion efficiency was at the 100-percent level even with ambient fuel temperature. At a reference velocity of 119 feet per second (36.3 m/sec), combustion efficiency increased from 87.6 percent with a fuel temperature of 6° F (259 K) to 97.6 percent with a fuel temperature of 1110° F (872 K). For configuration VI-A2(FN-2) (fig. 15(b)) at a reference velocity of 77 feet per second (23.5 m/sec), combustion efficiency increased from 88.7 percent with a fuel temperature of 11° F (261 K) to 103.4 percent with a fuel temperature of 1075° F (853 K). At a reference velocity near 105 feet per second (32.0 m/sec), combustion efficiency increased from 73.3 percent with a fuel temperature of 16° F (264 K) to 93.8 percent with a fuel temperature of 1095° F (864 K). Thus, by heating the fuel from ambient to near 1200° F (922 K), the gain in combustion efficiency was most significant at high reference velocities and with nonoptimized configurations such as the VI-A2(FN-2) configuration. Similar results were obtained with U-gutter flameholders, as reported in reference 7.

Additional combustion efficiency data were obtained with configurations VI-B2 and VI-A2(FN-2) using low-temperature fuel from a source of liquified natural gas. These data are not included in figure 15 because the calculated combustion efficiencies were a little higher than those with the ambient fuel supply. As the fuel temperatures were lowered to -200° F (144 K), additional increases in combustion efficiency were measured which seemed to indicate that there was unavoidable liquid entrainment in the gas. Thus, it is believed that no drastic dropoff in combustion efficiency occurs with very low fuel temperatures. However, at the coldest manifold fuel temperatures, near -259° F (111 K), when some liquid fuel may have actually entered the combustor, flames and burning downstream of the combustor were visually observed through the exhaust viewing port. Obviously, such burning could cause problems under such severe operating conditions. This condition may be prevented by the use of an appropriate heat exchanger to maintain the minimum fuel temperatures above such conditions.

Comparison of results to those with ASTM A-1 fuel. - Figure 16 shows the combustion efficiency characteristics previously obtained for the Model II combustor using ASTM A-1 fuel and also the characteristics of Model VI combustor configurations VI-A1 and VI-B2 using natural gas fuel. Checkpoints of Model VI-A1 using ASTM A-1 fuel (table IV) show a higher level of combustion efficiency compared to the Model II data. This may be attributed to the use of different fuel nozzles with the Model VI combustor, as well as to other design differences between the two models. However, similar variations in combustion efficiency with fuel-air ratio would be expected.

The combustion efficiency of Model VI-A1 with ambient natural gas fuel was substantially higher than that of the Model II combustor at fuel-air ratios below 0.020. The Model VI-A1 configuration exhibited a dropoff in combustion efficiency at a fuel-air ratio of 0.022, whereas the Model II combustor efficiency tended to its maximum at this fuel-air ratio. By increasing combustor pressure loss with the VI-B2 configuration--from a reference isothermal level of 5.48 percent to an isothermal level of 6.42 percent at an inlet Mach number of 0.259 (table V)--good combustion efficiency was obtained at fuel-air ratios from 0.020 to 0.028.

Exit-Temperature Profiles

The radial exit-temperature profile is established from the average of the temperatures at each radial position and is plotted as a deviation from average exit temperature against radial position. To eliminate any sidewall effects, the end-wall thermocouple readings were deleted from profile calculations. The design profile used for these tests is typical of ones required in advanced high-temperature engines.

To detect temperature nonuniformities which may not be evident in the average radial profiles, three temperature-profile quality factors were calculated. The temperature pattern factor $\bar{\delta}$ is a ratio which reflects the magnitude of nonuniformity caused by the maximum local temperature. This factor is calculated as follows:

$$\bar{\delta} = \frac{T_{max} - T_{av}}{T_{av} - T_{in}} \tag{1}$$

where T_{max} is the maximum individual temperature at any point, T_{av} is the average exit temperature, and T_{in} is the average inlet temperature.

The factor δ_{stator} is a measure of the magnitude of temperature nonuniformity which affects turbine stator blades. This factor is calculated as follows:

$$\delta_{stator} = \frac{(T_{R,local} - T_{R,design})_{max}}{\Delta T_{av}} \tag{2}$$

where $T_{R,local}$ is the individual temperature at a particular radial height which yields the maximum positive temperature difference with respect to the design temperature $T_{R,design}$ at that radial height, and ΔT_{av} is the temperature difference between the average exit temperature and the average inlet temperature.

The factor δ_{rotor} is a measure of the magnitude of temperature nonuniformity which affects turbine rotor blades. This factor is calculated as follows:

$$\delta_{rotor} = \frac{(T_{R,av} - T_{R,design})_{max}}{\Delta T_{av}} \tag{3}$$

where $T_{R,av}$ is the average radial temperature at a particular radial height which yields the maximum positive temperature difference with respect to the design average radial temperature at the respective radial height position. Values for temperature-profile quality factors are listed in tables III and IV for all combustor liner configurations.

Radial exit-temperature profiles at a nominal reference velocity of 77 feet per second (23.5 m/sec) are shown in figure 17. The profiles for the Model VI-A1 configuration using natural gas and ASTM A-1 fuel are shown in figure 17(a), along with the reference profile from the Model II combustor. The differences between Model VI-A1 and Model II profiles were slight and are attributed to outer-liner fabrication tolerances and to the increased fraction of airflow supplied to the inner liner for cooling. Using ASTM A-1 fuel, the reference combustor liner configuration VI-A1 had a pattern factor of 0.30 at an average exit temperature of 2200° F (1478 K) and a diffuser inlet Mach number of 0.253. With natural gas fuel, this configuration had a pattern factor of 0.34 at an average exit temperature of 2025° F (1380 K) and a diffuser inlet Mach number of 0.231. The radial exit-temperature profiles were nearly identical for both fuels at the above conditions.

The radial exit-temperature profiles obtained with the other Model VI combustor configurations using ambient natural gas fuel are shown in figures 17(b) to (f). Of these, combustor configuration VI-B2 produced the best profile, with a pattern factor of 0.23

at an average exit temperature of 2253° F (1507 K).

Total-Pressure Loss

Combustor total-pressure loss is defined by the following expression:

$$\frac{\Delta P}{P_3} = \frac{(\text{Average diffuser inlet total pressure}) - (\text{Average combustor exit total pressure})}{\text{Average diffuser inlet total pressure}}$$

Total-pressure-loss data at isothermal conditions are listed in table V and shown in figure 18(a) for comparison with pressure loss data from the Model II combustor (ref. 4). Pressure loss data from table III at exit- to inlet-temperature ratios near 2.5 are shown in figure 18(b) with reference pressure loss data from the Model II combustor, and with checkpoint data from the Model VI-A1 configuration using ASTM A-1 fuel (table IV).

The best configuration with natural gas fuel, VI-B2, gave the following results. At a diffuser inlet Mach number of 0.252 and an exit- to inlet-temperature ratio of 2.54, the pressure loss was about 7.54 percent. At a diffuser inlet Mach number of 0.317 and an exit- to inlet-temperature ratio of 2.30, the pressure loss was 11.33 percent. For comparison, using ASTM A-1 fuel, the reference combustor configuration, VI-A1, produced a total-pressure loss of 6.46 percent with a temperature ratio of 2.50 at a diffuser inlet Mach number of 0.253 and a total-pressure loss of 10.02 percent with a temperature ratio of 2.46 at a diffuser inlet Mach number of 0.317. Thus, the level of pressure loss with the Model VI combustor was higher than the level with the Model II combustor, as shown in figure 18. This was attributed mostly to the differences in the diffuser designs used for each model. Model VI had a shorter diffuser with a steeper inner diffuser wall angle.

Cold-Flow Ignition

In order to simulate engine ground start conditions, cold-flow ignition data were obtained with combustor configuration VI-A2(FN-2), as shown in table VI. At reference velocities of 35 and 45 feet per second (10.7 and 13.7 m/sec) with a combustor inlet air temperature of 36° F (275 K), ignition was easily obtained at fuel-air ratios of 0.006 and 0.005 with natural gas fuel temperatures as low as -230° F (127 K) and -235° F (125 K), respectively. Ignition at altitude conditions was not investigated.

SUMMARY OF RESULTS

Five side-entry combustor liner configurations and two fuel nozzle geometries were tested at fuel-air ratios from about 0.005 to 0.028 using natural gas fuel. The combustor had a short diffuser with four inlet chutes to supply airflow for swirler mixing and for cooling of the firewall and inner liner. The test conditions were as follows: nominally atmospheric inlet pressure, inlet air temperature of 600° F (589 K), and inlet Mach numbers of 0.24, 0.30, and 0.37 corresponding to nominal reference velocities of 77, 100, and 120 feet per second (23.5, 30.5, and 36.6 m/sec). The combustor configurations were designed to achieve combustor exit temperatures of 2200° F (1478 K). The following results were obtained:

1. Only combustor configurations VI-B2 and VI-C exhibited high efficiencies at fuel-air ratios above 0.024. Other configurations (VI-A1, VI-A2, VI-A2(FN-2), and VI-B1) showed a drop in combustion efficiency at fuel-air ratios near 0.020.

2. At reference velocities of 100 feet per second (30.5 m/sec), combustion efficiency for each configuration was lower than that at 77 feet per second (23.5 m/sec) by about 5 to 14 percentage points.

3. For configuration VI-B2, total-pressure loss increased about 1.2 percentage points, as compared to configuration VI-B1, at an inlet Mach number of 0.26. This brought a corresponding increase in combustion efficiency of about 12 percentage points, to a level of 101.8 percent at a fuel-air ratio of about 0.022.

4. Increased combustion efficiencies were obtained for configurations VI-B2 and VI-A2(FN-2) by heating the fuel from ambient to near 1200° F (922 K). With configuration VI-B2, the efficiency improvement amounted to an increment of 10 percentage points, to a level of 97.6 percent at a reference velocity of 118.1 feet per second (36.0 m/sec). With configuration VI-A2(FN-2) the efficiency improvement amounted to an increment of 20 percentage points, to a level of 93.8 percent at a reference velocity of 103.4 feet per second (31.5 m/sec). Very cold gaseous fuel did not produce drastic reductions in combustion efficiency below the levels obtained with ambient fuel temperatures.

5. The combustion efficiency characteristics of Model VI natural gas configurations VI-B2 and VI-A1 compared favorably to the results previously obtained with ASTM A-1 fuel with the Model II combustor. Combustion efficiencies were generally higher, even using ambient-temperature natural gas fuel. However, combustor configuration VI-A1 showed a decrease in combustion efficiency at a fuel-air ratio of about 0.022.

6. With Model VI-A1, using the identical outer liner for natural gas and ASTM A-1 fuels, the radial exit-temperature profiles were nearly identical, with pattern factors of 0.34 and 0.30, respectively.

7. Combustor configuration VI-B2 produced the best radial exit-temperature profile, having a pattern factor of 0.23 at an average exit temperature of 2253° F (1507 K).

8. Combustor configuration VI-B2 exhibited a pressure loss of 7.54 percent at a diffuser inlet Mach number of 0.252 and an absolute temperature ratio of 2.5. At a diffuser inlet Mach number of 0.317 and an absolute temperature ratio of 2.3, the pressure loss was about 11.33 percent.

9. No difficulties were encountered with ignition tests using cold ambient inlet air and cold gaseous fuel.

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Cleveland, Ohio, December 23, 1970,
720-03.

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TABLE I. - LINER CONFIGURATIONS FOR MODEL VI COMBUSTOR

Combustor liner configuration	Design airsplit (nominal)			Primary scoop				Primary slot				Secondary scoop				Secondary slot 1				Secondary slot 2				Slot-locating dimension (see fig. 11)					
	Primary, percent	Secondary, percent	Secondary ratio, slot 1:slot 2	Width		Length		Width		Length		Width		Length		Width		Length		Width		Length		X_1		X_2		X_3	
				in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm
A1[a]	20.6	60.0	78:22	0.75	1.91	1.38	3.50	2.00	5.08	2.75	6.98	2.50	6.35	4.50	11.44	0.87	2.21	4.50	11.44	0.75	1.91	5.50	13.96	2.6	6.7	6.4	16.2	6.4	16.2
A2	25.0	55.0	60:40	1.00	2.54	4.80	12.18	1.25	3.18	4.50	11.44	2.00	5.08	4.80	12.18	.75	1.91	↓	↓	1.00	2.54	4.50	11.44	.9	2.3	↓	↓	6.4	16.2
B1	35.0	45.0	75:25	1.38	3.50	3.00	7.62	2.00	5.08	2.75	6.98	2.62	6.65	4.80	12.18	.94	2.39	↓	↓	.50	1.27	4.50	11.44	2.6	6.7	↓	↓	6.4	16.2
B2	35.0	45.0	75:25	1.38	3.50	3.00	7.62	1.00	2.54	2.75	6.98	2.62	6.65	4.80	12.18	.75	1.91	↓	↓	.50	1.27	2.25	5.72	2.6	6.7	↓	↓	8.6	21.8
C	55.0	25.0	75:25	2.00	5.08	2.50	6.35	1.31	3.33	2.50	6.35	2.75	6.98	2.50	6.35	.50	1.27	2.50	6.35	.25	.64	2.00	5.08	1.0	2.5	4.5	11.4	5.0	12.7

[a]Combustor configuration A1 is a replica of the final liner design developed in Model II testing.

TABLE II. - NOMINAL TEST CONDITIONS

[Nominal inlet temperature, 600° F (589 K).]

Test condition	Diffuser inlet Mach number, M_3	Inlet total pressure, P_3		Airflow rate, W		Reference velocity[a], V_R		Combustor reference Mach number, M_R
		psia	N/m^2	lb/sec	kg/sec	ft/sec	m/sec	
A	0.24	16.0	1.103×10^5	3.17	1.44	77.8	23.7	0.049
B	.30	17.0	1.172	4.12	1.87	97.4	29.7	.061

[a]Computed from airflow rate, diffuser inlet static pressure and temperature, and maximum cross-sectional area of combustor housing ($1.04\ ft^2$, $0.097\ m^2$).

TABLE III. - PERFORMANCE DATA FOR

[Combustor pressure

Combustor configuration	Run	Diffuser inlet Mach number, M_3	Airflow rate, W		Inlet total temperature, T_3		Total-pressure loss, $\Delta P/P_3$, percent	Exit- to inlet-temperature ratio, T_4'/T_3	Fuel-air ratio, f/a	Combustion efficiency, η, percent
			lb/sec	kg/sec	$^{\circ}F$	K				
A1	1	0.232	2.81	1.27	614	596	Questionable data	----	0.0119	105.8
	2	.230	2.81	1.27	612	595		----	.0180	102.7
	3	.231	2.81	1.27	624	602		----	.0222	94.2
	4	.298	3.66	1.66	611	595		----	.0092	101.5
	5	.295	3.66	1.66	606	592		----	.0137	100.2
	6	.299	3.69	1.67	620	600		----	.0169	97.6
	7	.297	3.70	1.68	612	595		----	.0205	83.5
A2	8	0.228	2.83	1.28	620	600	Questionable data	----	0.0179	99.9
	9	.226	2.84	1.29	616	598		----	.0225	98.3
	10	.290	3.65	1.66	620	600		----	.0138	98.6
	11	.287	3.65	1.66	619	599		----	.0197	94.9
A2(FN-2)	12	0.262	3.26	1.48	593	585	5.81	----	0.0158	86.0
	13	.259	3.25	1.47	585	580	6.38	----	.0209	82.6
	14	.266	3.34	1.52	580	578	6.28	----	.0204	88.7
	15	.266	3.41	1.55	561	567	7.08	----	.0263	80.4
	16	.348	4.38	1.99	624	602	10.98	----	.0130	81.2
	17	.345	4.38	1.99	614	596	11.17	----	.0129	86.0
	18	.338	4.36	1.98	607	593	11.86	----	.0204	73.3
B1	19	0.253	3.12	1.42	595	586	5.77	----	0.0164	103.0
	20	.248	3.08	1.40	595	586	5.88	----	.0220	91.1
	21	.321	4.03	1.83	612	595	9.46	----	.0172	93.8
	22	.317	4.01	1.82	613	596	9.46	----	.0217	83.7
B2	23	0.253	3.18	1.44	600	589	7.18	----	0.0218	103.2
	24	.252	3.17	1.44	609	594	7.54	2.54	.0247	100.6
	25	.246	3.11	1.41	614	596	6.81	----	.0201	103.2
	26	.253	3.22	1.46	603	590	7.14	----	.0229	101.8
	27	.251	3.20	1.45	603	590	7.29	----	.0256	101.4
	28	.249	3.19	1.45	604	591	7.45	----	.0280	102.9
	29	.316	4.07	1.85	626	603	11.11	----	.0168	95.5
	30	.319	4.12	1.87	624	602	11.20	----	.0198	96.4
	31	.317	4.12	1.87	626	603	11.33	2.30	.0221	95.5
	32	.245	3.04	1.38	620	600	6.93	----	.0225	102.9
	33	.316	4.06	1.84	616	598	11.29	----	.0197	95.2
	34	.375	4.96	2.25	632	606	16.04	----	.0198	87.6
C	35	0.251	3.13	1.42	644	613	9.62	----	0.0157	89.1
	36	.247	3.10	1.41	638	610	9.46	----	.0199	96.3
	37	.246	3.10	1.41	647	615	9.99	----	.0228	97.9
	38	.242	3.15	1.43	607	593	9.10	2.50	.0241	100.2
	39	.244	3.18	1.44	610	594	9.78	----	.0266	100.9
	40	.304	4.08	1.85	608	593	13.95	----	.0186	85.1
	41	.300	4.06	1.84	610	594	14.05	2.32	.0233	90.4
B2	42	0.307	4.02	1.82	622	601	11.72	----	0.0268	95.2
	43	.311	4.10	1.86	621	600	11.68	----	.0283	96.0
	44	.237	2.98	1.35	610	594	6.89	----	.0224	103.8
	45	.241	3.04	1.38	609	594	6.86	----	.0220	104.7
	46	.310	3.98	1.81	631	606	10.88	----	.0195	101.8
	47	.309	3.98	1.81	634	608	11.23	----	.0195	97.9
	48	.368	4.92	2.23	641	611	15.75	----	.0198	93.5
	49	.366	4.94	2.24	639	610	16.01	----	.0217	97.6
A2(FN-2)	50	0.243	3.06	1.39	603	590	6.57	----	0.0216	89.2
	51	.242	3.07	1.39	609	594	6.56	2.45	.0214	103.4
	52	.238	3.00	1.36	604	591	5.88	----	.0219	96.7
	53	.236	2.98	1.35	607	593	6.40	----	.0222	93.4
	54	.322	4.14	1.88	630	605	10.65	2.21	.0199	93.8

[a]Average of central 30 exit temperatures used to calculate the exit temperature profile quality factors $\bar{\delta}$, δ_{stator},

[b]Average of 40 exit temperatures with adjustment for radiation.

COMBUSTORS WITH NATURAL GAS FUEL

nominally atmospheric.]

Reference velocity, V_R		Average exit temperature,[a] T_4		Exit-temperature-profile quality factors			Average exit temperature,[b] T'_4		Fuel temperature			
									Manifold		Orifice	
ft/sec	m/sec	°F	K	$\bar{\delta}$, eq. (1)	δ_{stator}, eq. (2)	δ_{rotor}, eq. (3)	°F	K	°F	K	°F	K
74.0	22.6	1587	1137	----	----	----	1518	1098	18	265	8	260
73.4	22.4	1970	1350	----	----	----	1888	1304	10	261	3	257
74.0	22.6	2114	1430	0.34	0.33	0.05	2025	1380	2	256	-6	252
94.8	28.9	1340	1000	----	----	----	1297	976	14	263	5	258
93.7	28.6	1661	1178	----	----	----	1584	1136	4	258	-2	254
95.6	29.2	1869	1294	.42	.37	.08	1768	1238	0	255	-6	252
94.4	28.8	1889	1305	----	----	----	1786	1248	-4	253	-10	250
72.8	22.2	1787	1248	----	----	----	1858	1288	34	274	32	273
72.3	22.0	2027	1381	0.38	0.35	0.16	2113	1429	---	---	12	262
92.6	28.2	1557	1120	----	----	----	1595	1142	34	274	32	273
91.8	28.0	1841	1278	.46	----	----	1908	1316	32	273	30	272
82.8	25.2	1612	1151	0.28	----	----	1554	1119	18	265	16	264
81.4	24.8	1812	1262	.28	----	----	1771	1240	11	261	10	261
83.4	25.4	1864	1291	.24	0.30	0.10	1825	1269	11	261	10	261
82.6	25.2	2014	1374	.29	----	----	2002	1368	6	259	4	258
111.3	33.9	1454	1063	.43	----	----	1377	1020	22	268	21	267
110.0	33.5	1483	1080	.40	----	----	1409	1038	23	268	21	267
107.3	32.7	1708	1204	.30	----	----	1636	1164	16	264	16	264
79.9	24.4	1859	1288	0.28	----	----	1776	1242	---	---	34	274
78.3	23.9	2043	1390	.34	0.39	0.23	1951	1340	---	---	33	274
102.2	31.2	1832	1273	.38	----	----	1732	1218	---	---	34	274
101.2	30.9	1953	1340	.42	----	----	1845	1280	---	---	32	273
80.1	24.4	2170	1461	0.26	----	----	2114	1430	---	---	-16	246
80.0	24.4	2321	1545	.23	0.22	0.04	2253	1507	---	---	-22	243
78.6	24.0	2027	1382	.19	----	----	2023	1380	---	---	-13	248
80.2	24.4	2171	1462	.19	.15	.06	2163	1457	---	---	-20	244
79.5	24.2	2300	1533	.22	----	----	2313	1540	---	---	-20	244
78.9	24.0	2450	1616	.20	----	----	2476	1631	---	---	-20	244
101.4	30.9	1796	1253	.23	----	----	1740	1222	---	---	-8	251
102.1	31.1	1985	1358	.24	----	----	1923	1324	---	---	-11	249
101.8	31.0	2101	1422	.25	----	----	2044	1391	---	---	-12	249
78.4	23.9	2157	1454	.16	----	----	2168	1460	14	263	2	256
101.1	30.8	1953	1340	.23	----	----	1897	1310	10	261	0	255
120.5	36.7	1895	1308	.31	----	----	1817	1265	6	259	-5	253
81.2	24.8	1676	1186	0.44	----	----	1622	1157	101	311	116	320
79.6	24.3	1965	1347	.43	----	----	1941	1334	100	311	114	319
79.8	24.3	2127	1437	.33	----	----	2136	1442	107	315	120	322
77.1	23.5	2182	1468	.37	0.33	0.12	2212	1484	48	282	50	283
77.6	23.7	2294	1530	.28	----	----	2368	1571	48	282	49	283
96.5	29.4	1772	1240	.51	----	----	1704	1202	49	283	50	283
95.6	29.1	2045	1392	.39	----	----	2023	1380	46	281	48	282
98.2	29.9	2332	1551	0.25	----	----	2291	1528	50	283	36	275
99.5	30.3	2421	1600	.24	----	----	2385	1580	48	282	37	276
75.3	23.0	2169	1460	.19	----	----	2193	1474	590	583	29	271
76.7	23.4	2173	1462	.22	----	----	2220	1489	1190	916	31	273
99.5	30.3	2055	1397	.22	----	----	2035	1386	1160	900	30	272
99.8	30.4	2004	1369	.16	----	----	1956	1342	610	594	30	272
118.9	36.2	1994	1363	.19	----	----	1919	1322	585	580	28	271
118.1	36.0	2165	1458	.21	----	----	2114	1430	1110	872	31	273
77.1	23.5	1958	1343	0.18	----	----	1908	1316	100	311	2	256
76.9	23.4	2173	1463	.24	----	----	2154	1452	1075	853	5	258
75.7	23.1	2090	1417	.26	----	----	2052	1396	590	583	-16	246
75.2	22.9	2061	1400	.26	----	----	2022	1379	458	510	-17	246
103.4	31.5	2026	1381	.30	----	----	1947	1337	1095	864	8	260

and δ_{rotor}. Does not include adjustment for radiation.

TABLE IV. - PERFORMANCE DATA FOR THE VI-A1 COMBUSTOR CONFIGURATION WITH ASTM A-1 FUEL

[Combustor pressure nominally atmospheric.]

Run	Diffuser inlet Mach number, M_3	Airflow rate, W		Inlet total temperature, T_3		Total-pressure loss, $\Delta P/P_3$, percent	Exit- to inlet-temperature ratio, T_4'/T_3	Fuel-air ratio, f/a	Combustion efficiency, η, percent	Reference velocity, V_R		Average exit temperature,[a] T_4		Exit-temperature-profile quality factors			Average exit temperature,[b] T_4'	
		lb/sec	kg/sec	^{o}F	K					ft/sec	m/sec	^{o}F	K	$\bar{\delta}$, eq. (1)	δ_{stator}, eq. (2)	δ_{rotor}, eq. (3)	^{o}F	K
1	0.253	3.17	1.44	603	590	6.46	2.50	0.0267	97.0	80.7	24.6	2257	1510	0.30	0.22	0.06	2200	1478
2	.317	4.10	1.86	594	585	10.02	2.46	.0256	97.4	100.2	30.6	2204	1480	.25	.25	.03	2137	1443

[a]Average of central 30 exit temperatures used to calculate the exit-temperature profile quality factors $\bar{\delta}$, δ_{stator}, and δ_{rotor}. Does not include adjustment for radiation.
[b]Average of 40 exit temperatures with adjustment for radiation.

TABLE V. - TOTAL-PRESSURE-LOSS DATA AT ISOTHERMAL CONDITIONS

[Combustor pressure nominally atmospheric.]

Combustor configuration	Run	Diffuser inlet Mach number, M_3	Airflow rate, W		Inlet total temperature, T_3		Total-pressure loss, $\Delta P/P_3$, percent	Reference velocity, V_R	
			lb/sec	kg/sec	^{o}F	K		ft/sec	m/sec
C	1	0.251	3.08	1.40	644	613	8.79	81.2	24.8
B2	2	0.259	3.17	1.44	607	593	6.42	82.3	25.1
	3	.258	3.18	1.44	616	598	6,35	82.2	25.1
B1	4	0.259	3.13	1.42	602	590	5.23	82.0	25.0
	5	.327	3.99	1.81	614	596	8.59	104.4	31.8
A2(FN-2)	6	0.356	4.41	2.00	613	596	10.44	113.3	34.5
	7	.342	4.22	1.91	618	599	10.44	109.3	33.3
	8	.276	3.42	1.55	577	576	6.37	86.5	26.4
A1	9	0.259	3.17	1.44	603	590	5.48	82.5	25.2

TABLE VI. - COLD-FLOW-IGNITION DATA

[Combustor pressure nominally atmospheric. Inlet total temperature, 36° F (275 K).]

Combustor configuration	Run	Diffuser inlet Mach number, M_3	Airflow rate, W		Reference velocity, V_R		Fuel temperature		Fuel-air ratio, f/a
			lb/sec	kg/sec	ft/sec	m/sec	°F	K	
A2(FN-2)	1	0.18	3.28	1.49	35	11	-230	127	0.0060
	2	.23	4.18	1.90	45	14	-235	125	.0051

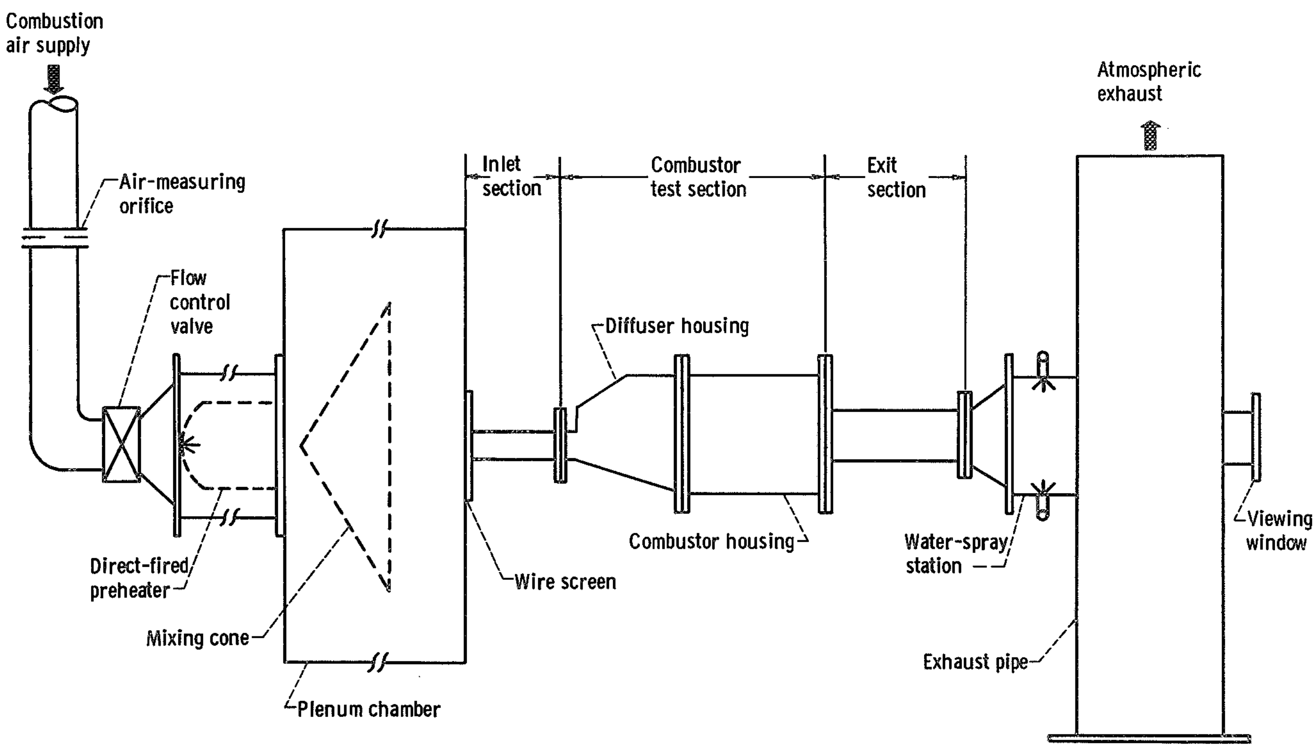


Figure 1. - Schematic diagram of combustor test facility

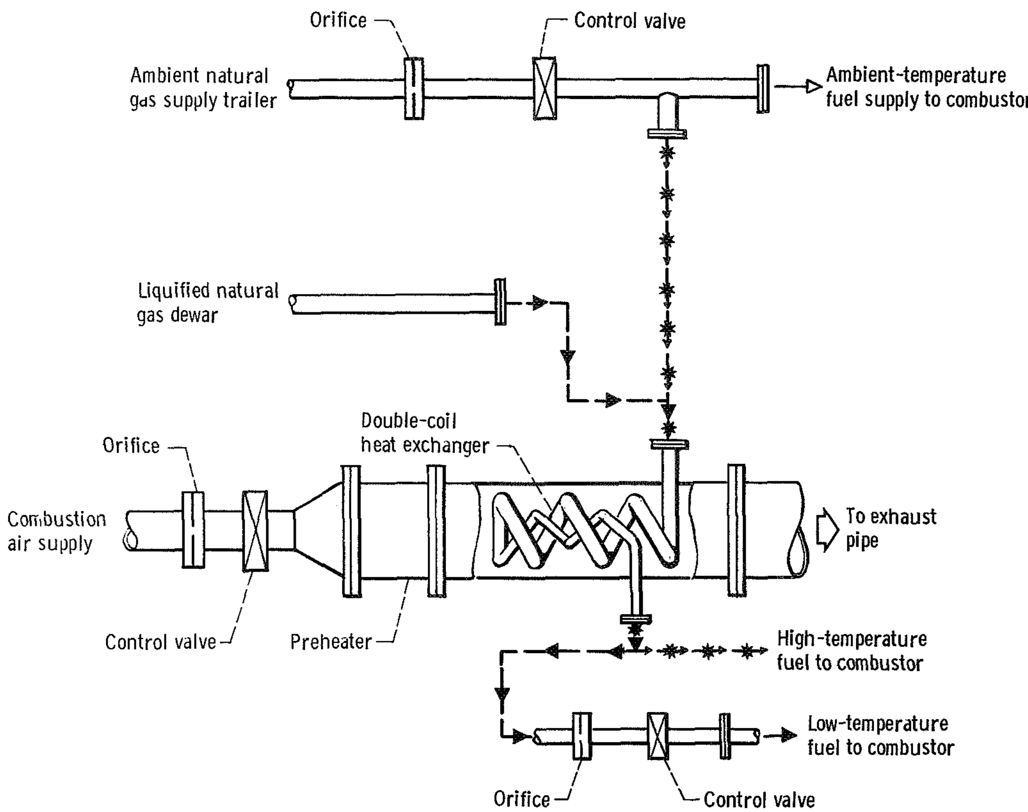


Figure 2. - Natural gas fuel supply system.

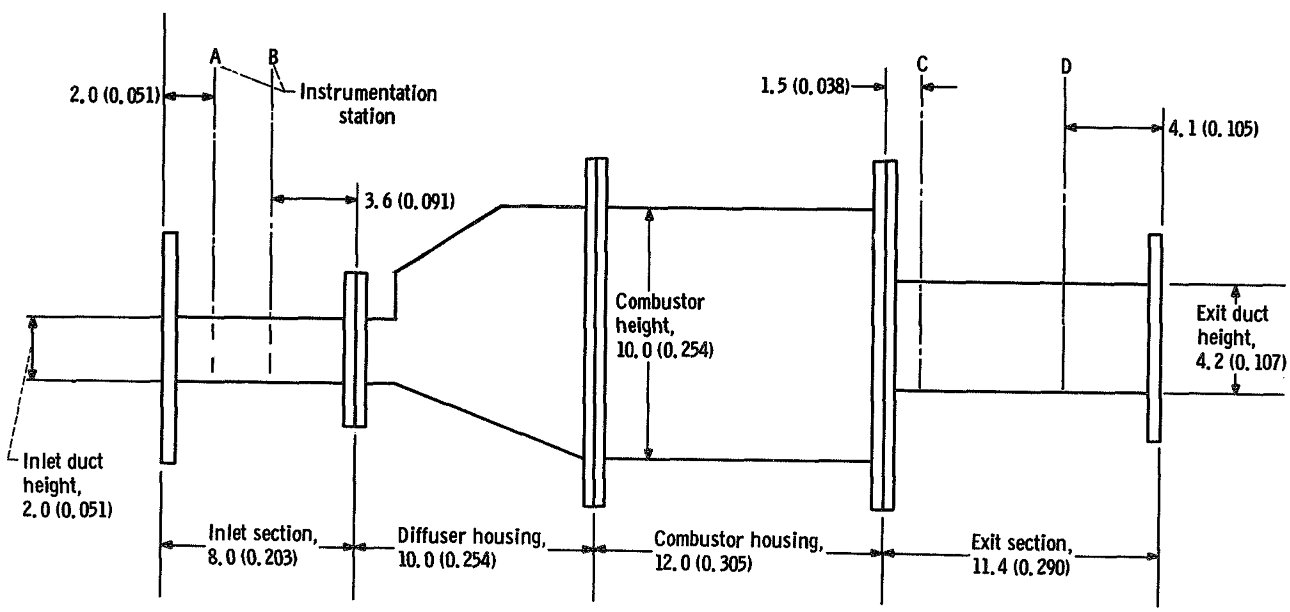


Figure 3. - Test sections and instrumentation stations. Dimensions are in inches (m).

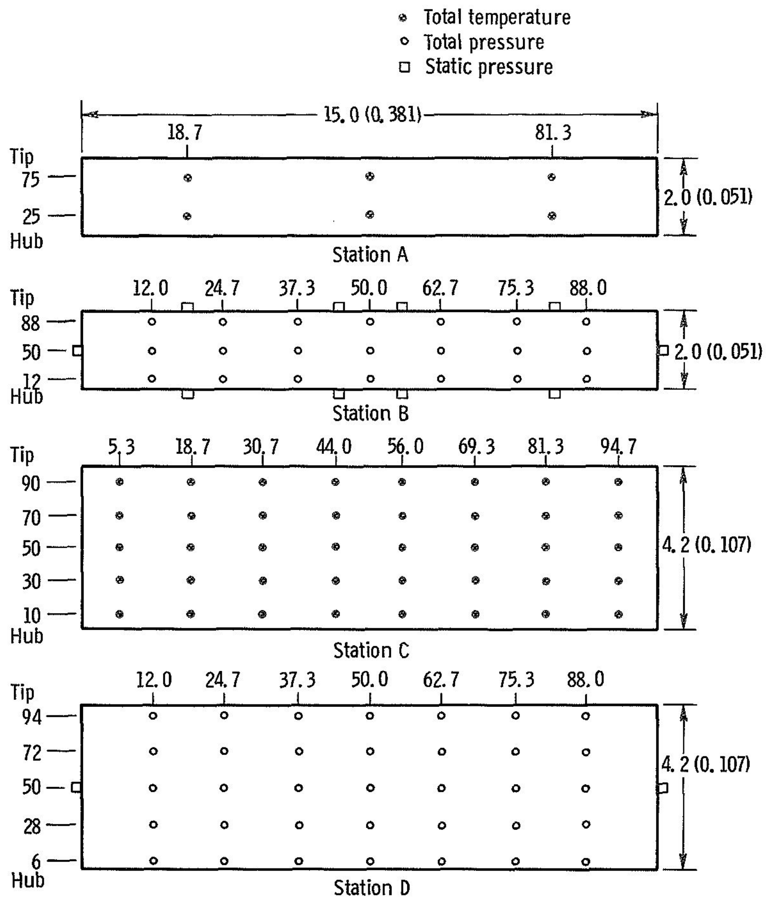
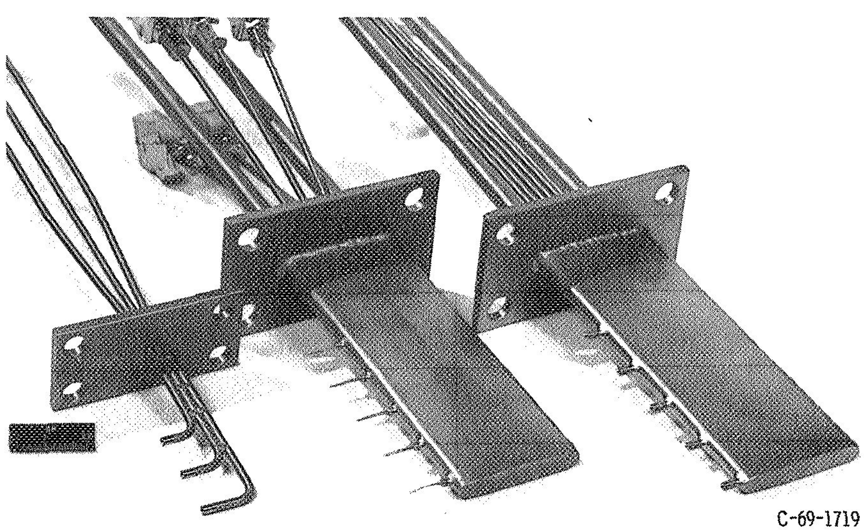


Figure 4. - Location of temperature and pressure probes, in percentage of duct height and width. Dimensions are in inches (m). Views are looking downstream. See figure 3 for station locations.



(a) Inlet total pressure, P_3. (b) Exit total temperature, T_4. (c) Exit total pressure, P_4.

Figure 5. - Instrumentation rakes.

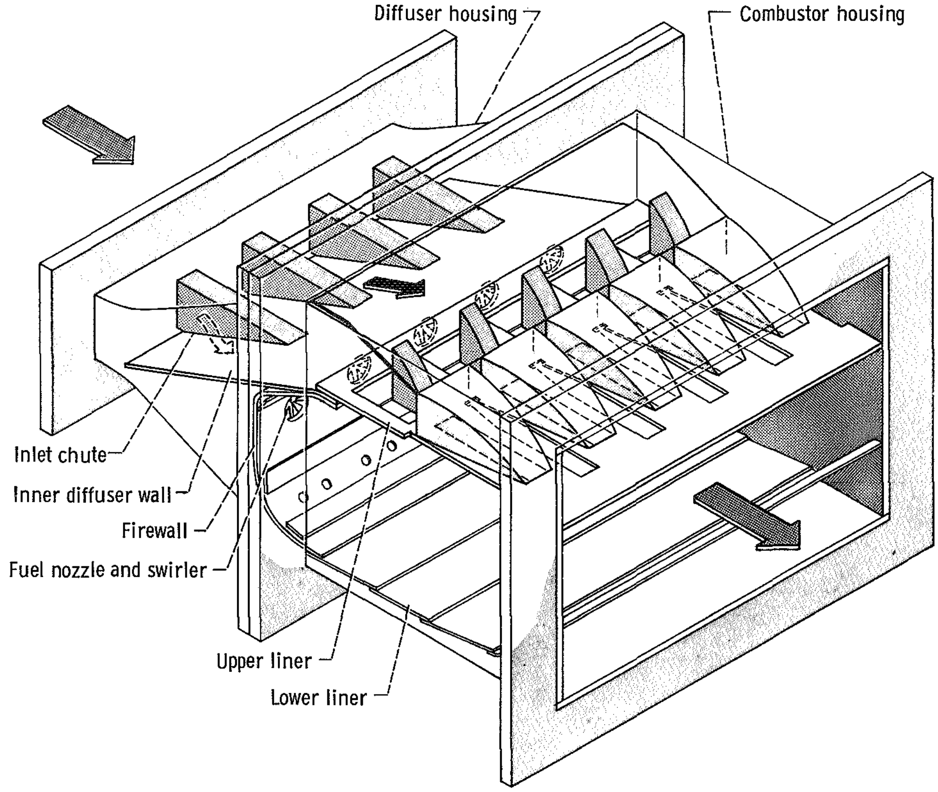


Figure 6. - Final Model II rectangular combustor and housing; type A1 upper (outer) liner configuration.

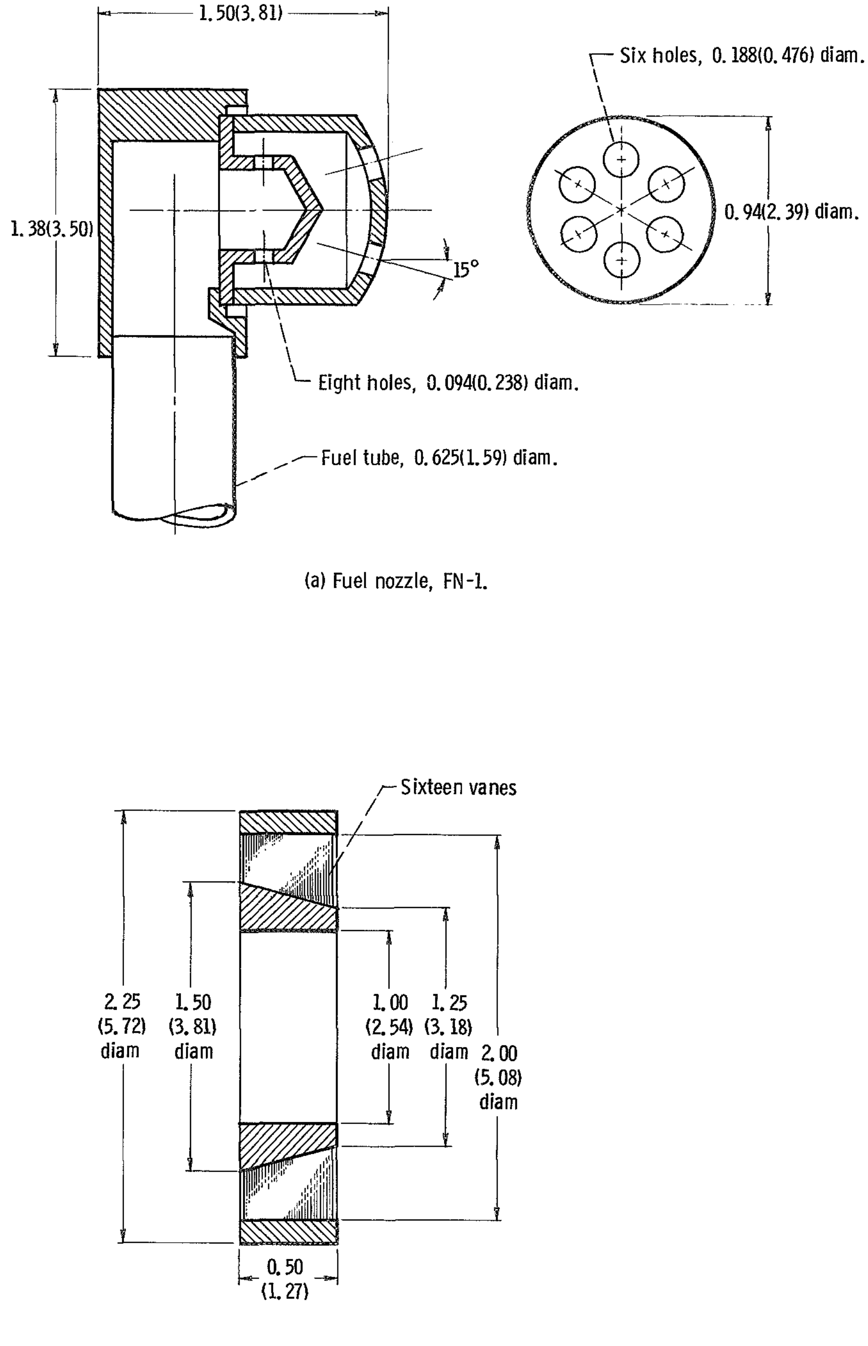
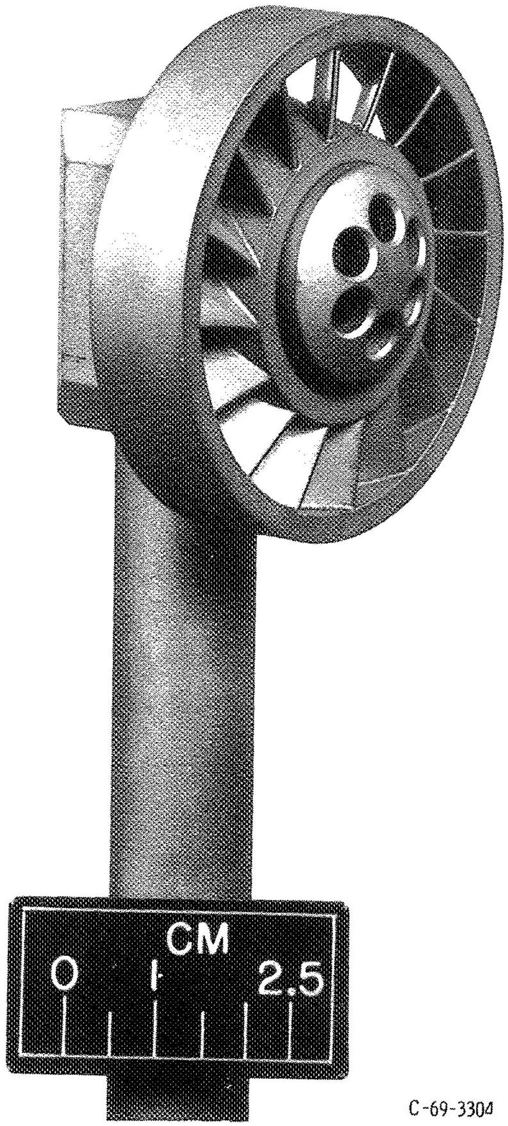
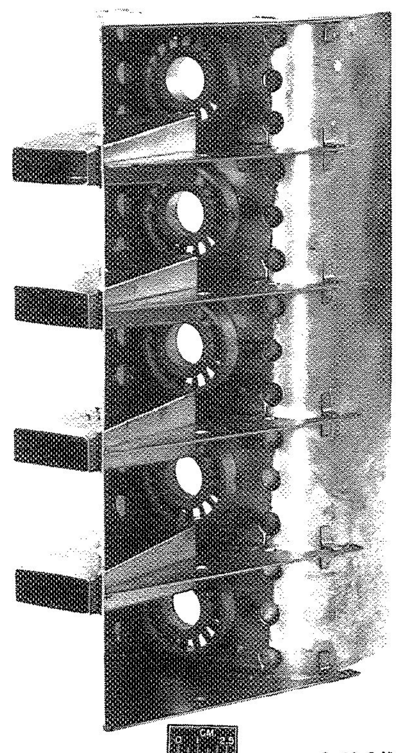


Figure 7. - Schematic drawing of FN-1 natural gas fuel nozzle and axial swirler. Dimensions are in inches (cm).



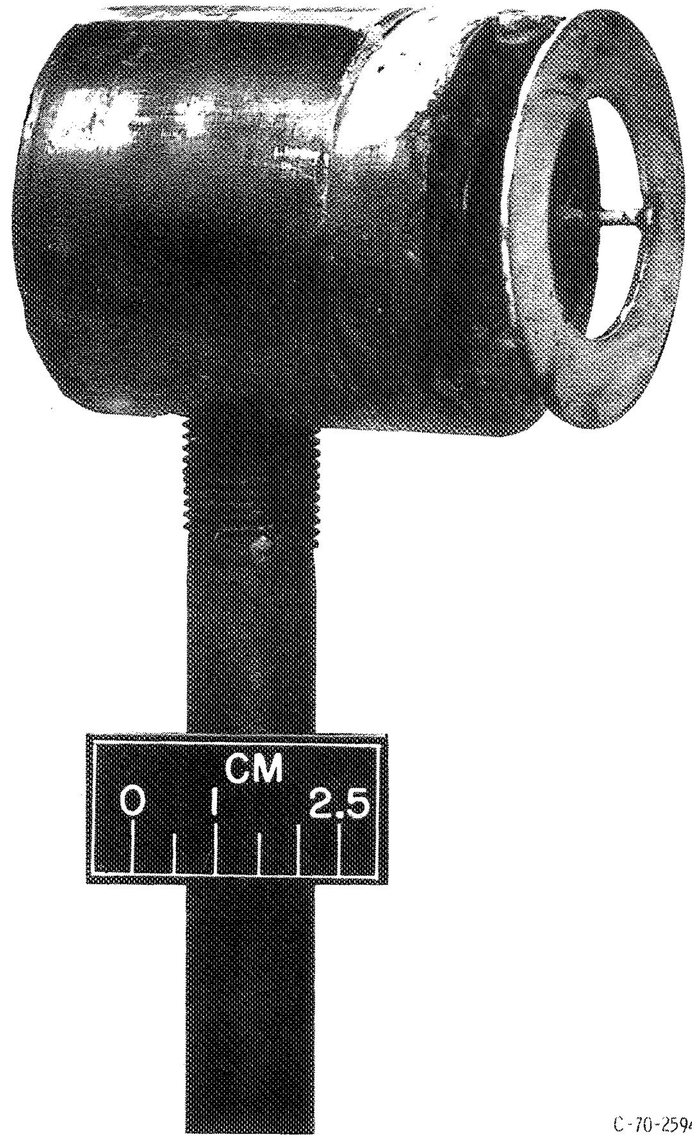
C-69-3304

Figure 8. - FN-1 natural gas fuel nozzle and axial swirler.



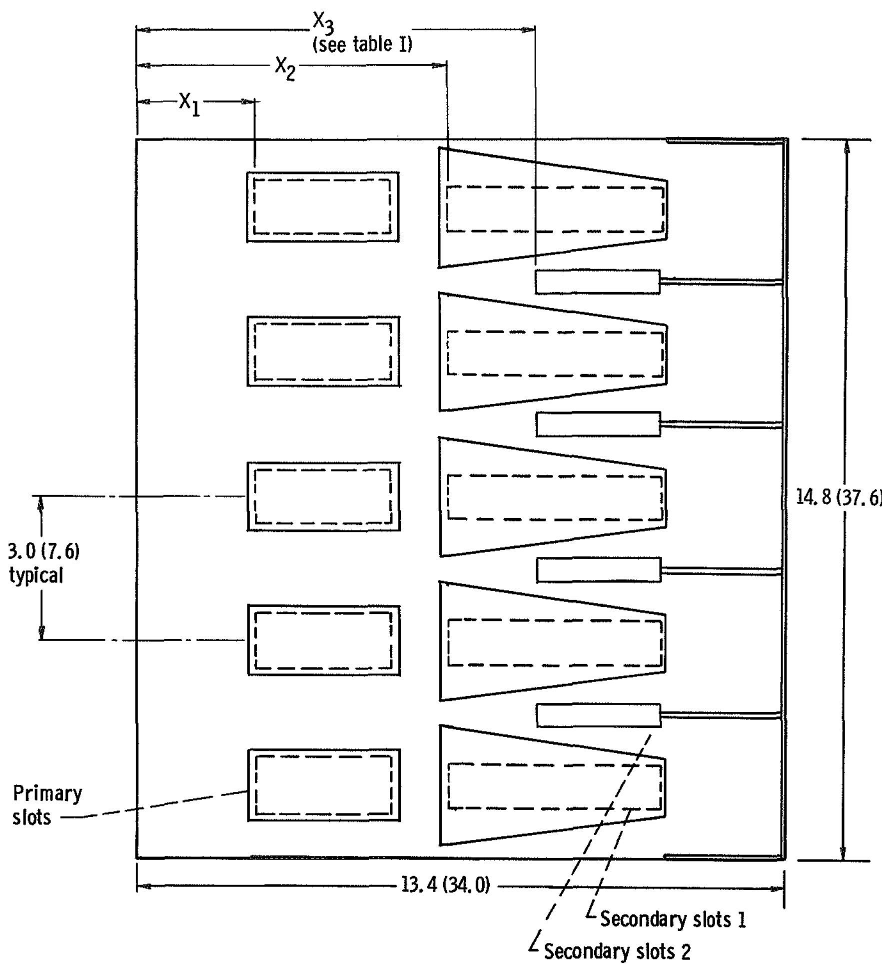
C-69-3414

Figure 9. - Firewall assembly with inlet chutes and swirlers.

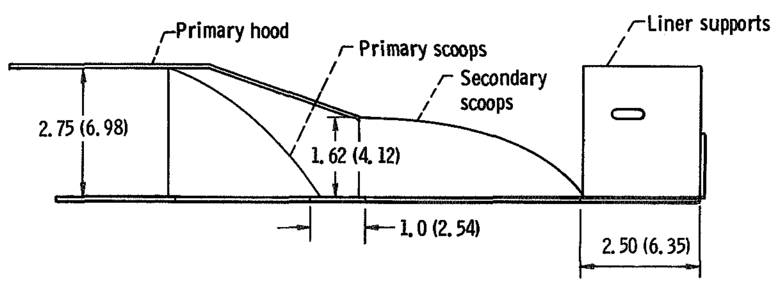


C-70-2594

Figure 10. - Alternate fuel nozzle, FN-2.

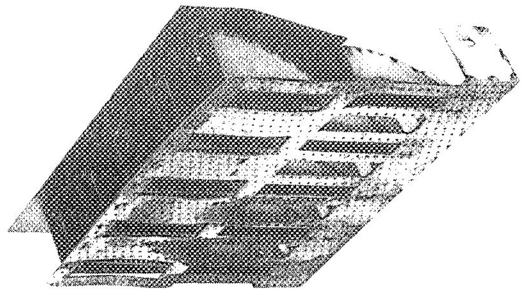


(a) Top view without hood.

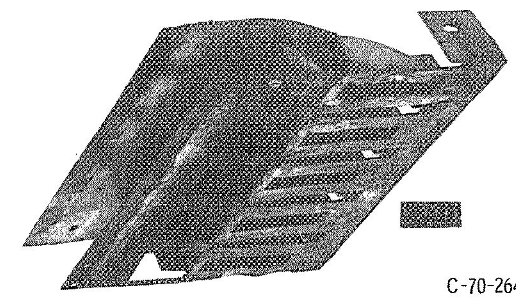


(b) Side view.

Figure 11. - Liner B2 slot and scoop arrangement. Dimensions are in inches (cm). For slot and scoop dimensions see table I.

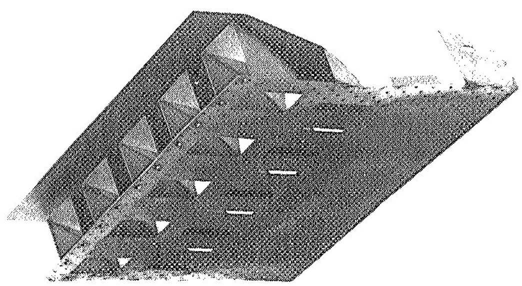


(a) Liner A2.

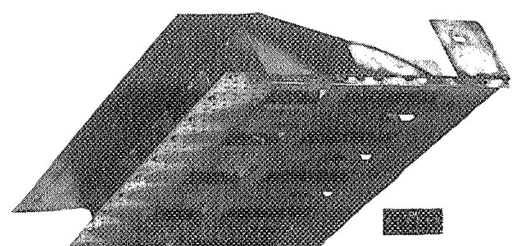


C-70-2642

(b) Liner A1.



(c) Liner C.



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(d) Liner B2 (liner B1 is identical except that it has no blockage strips).

Figure 12. - Combustor liner configurations.

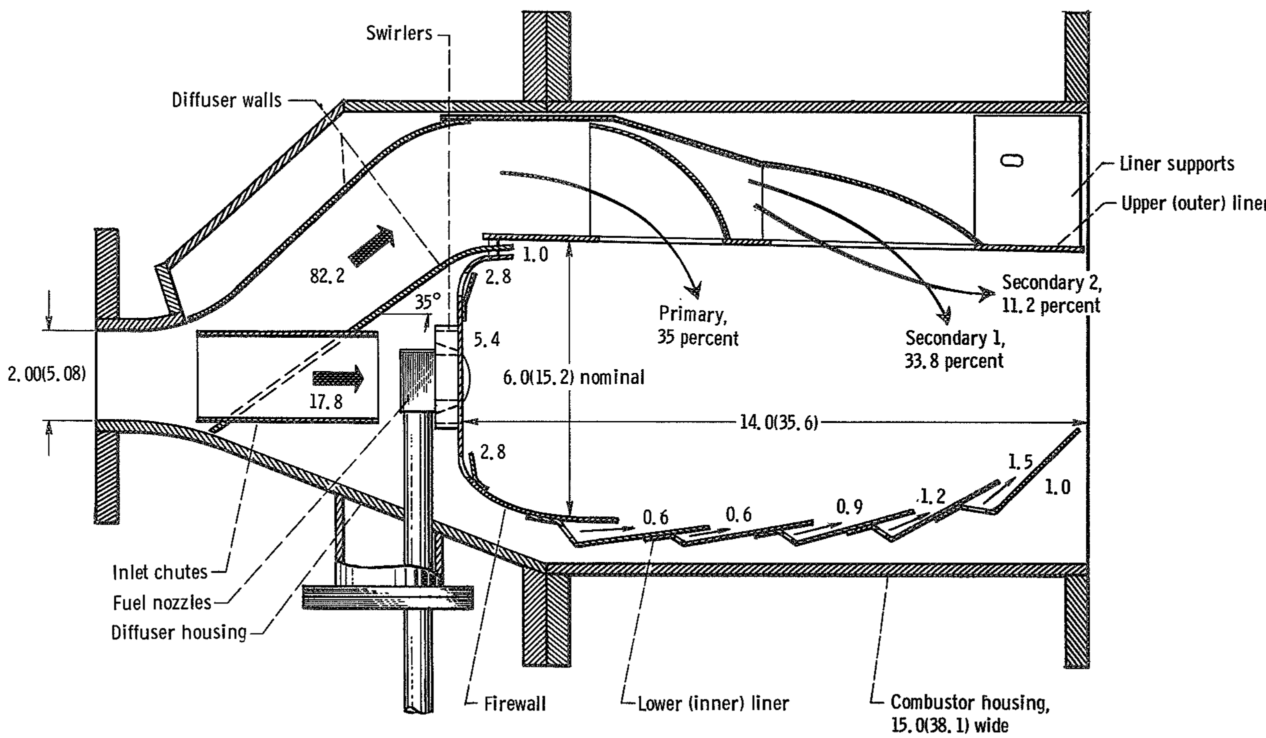
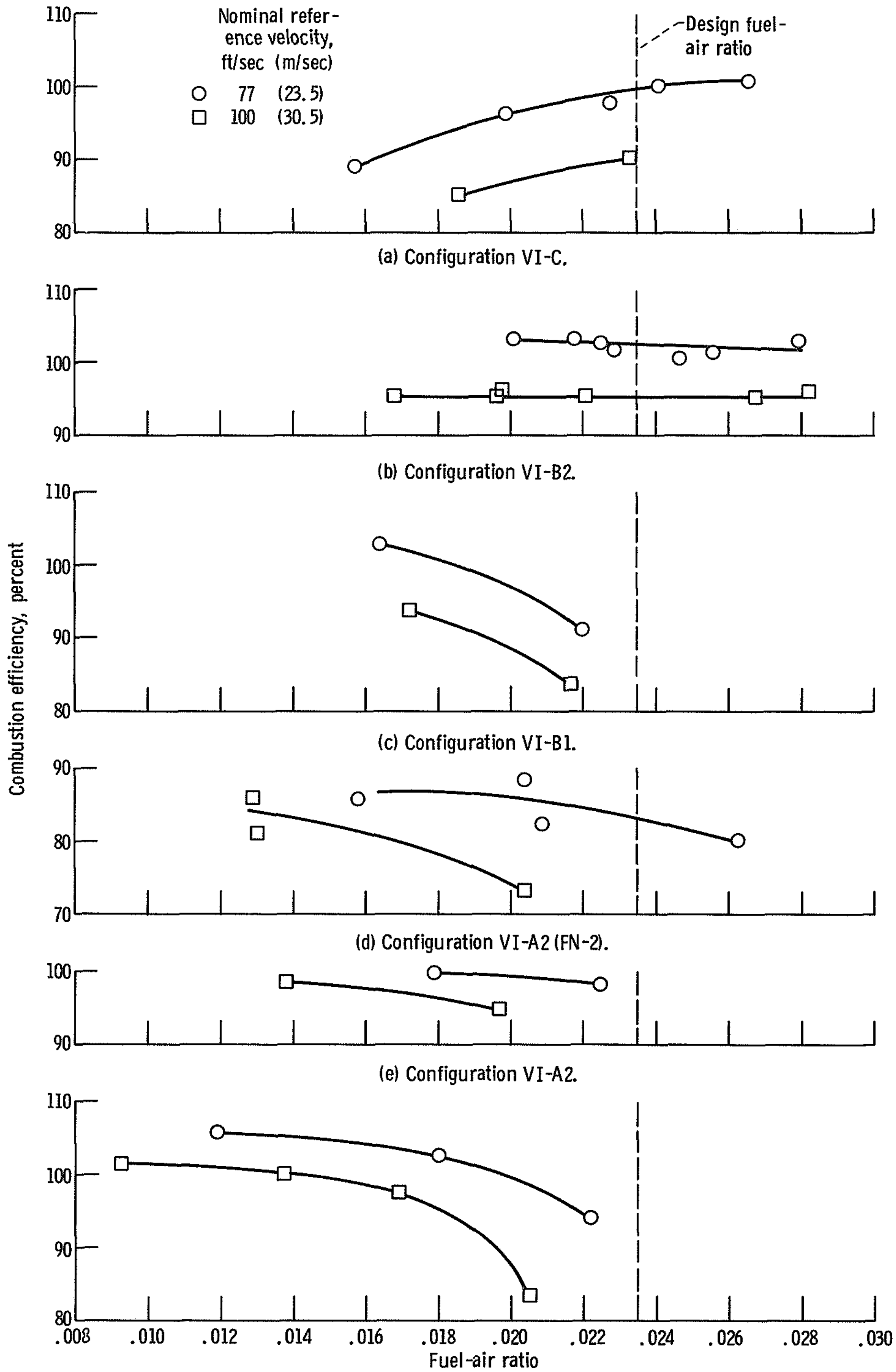


Figure 13. - Model VI-B2 combustor assembly. Dimensions are in inches (cm). Airflow splits in percent.



(a) Configuration VI-C.

(b) Configuration VI-B2.

(c) Configuration VI-B1.

(d) Configuration VI-A2 (FN-2).

(e) Configuration VI-A2.

(f) Configuration VI-A1.

Figure 14. - Combustion efficiencies with ambient natural gas fuel temperatures.

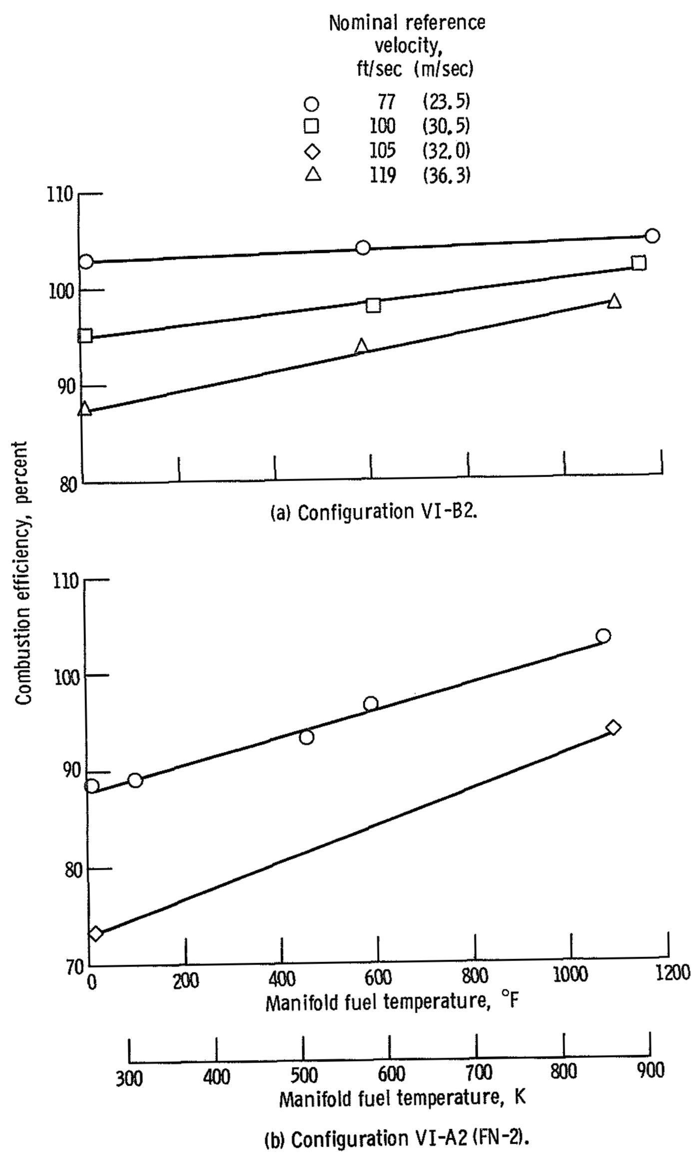


Figure 15. - Effect of fuel temperature and reference velocity on combustion efficiency.

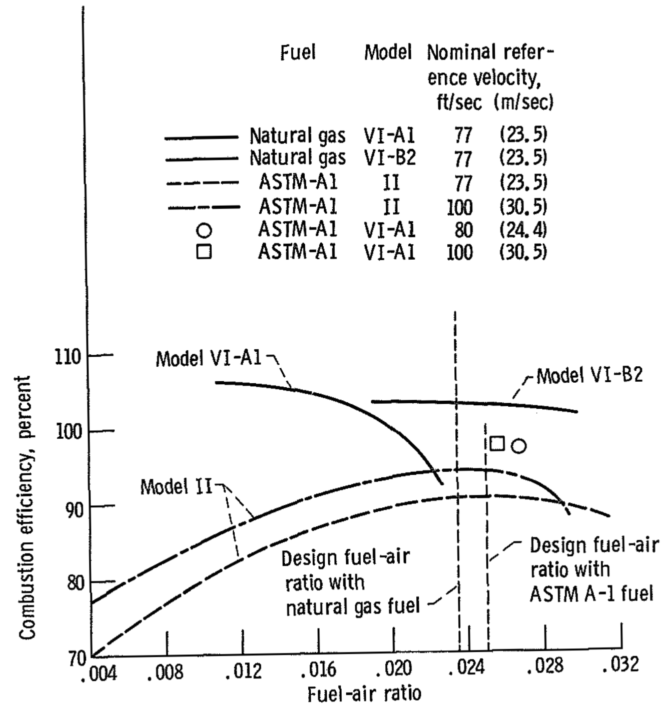
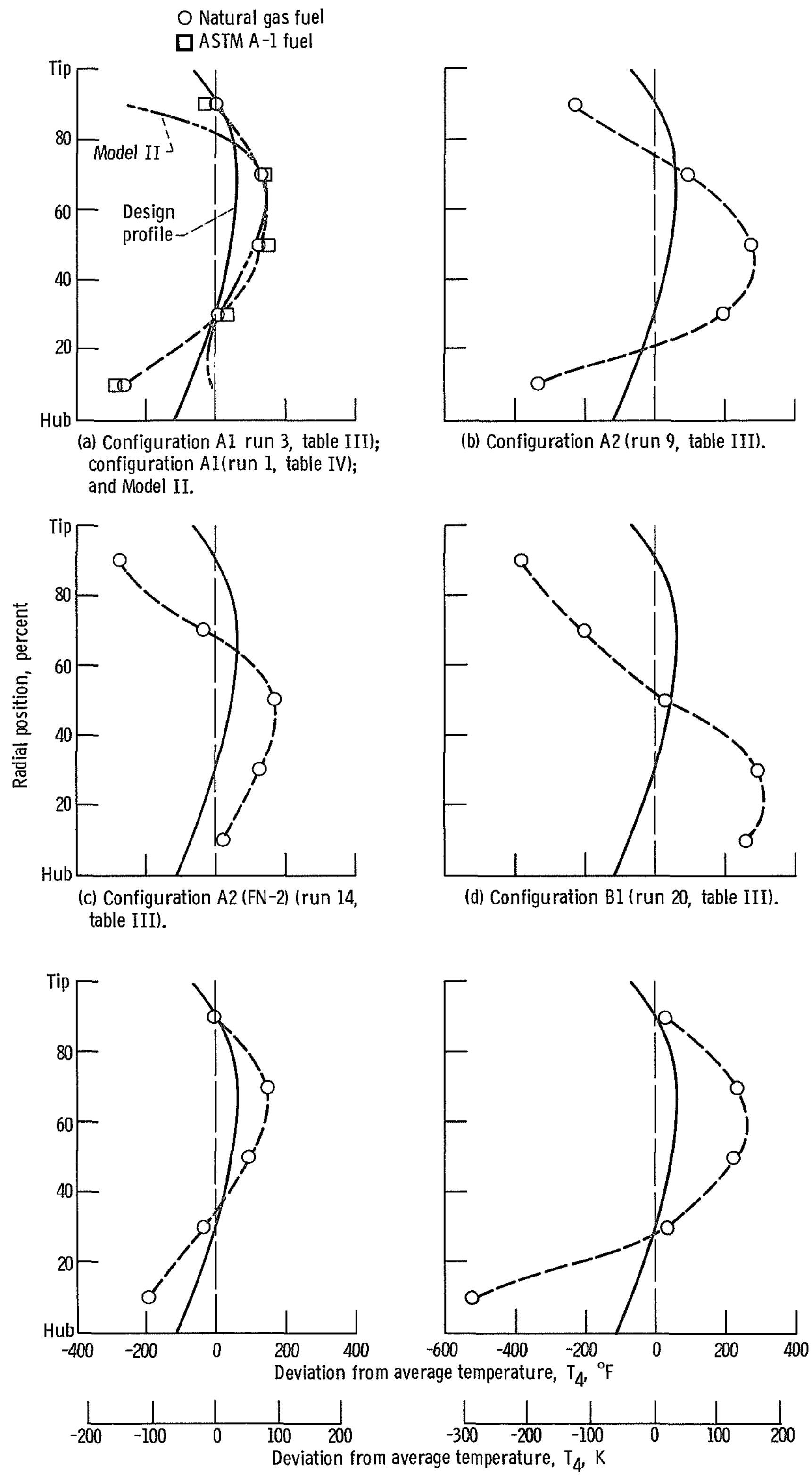


Figure 16. - Combustion efficiency characteristics; natural gas fuel compared to ASTM A-1 fuel.



(a) Configuration A1 run 3, table III); configuration A1(run 1, table IV); and Model II.

(b) Configuration A2 (run 9, table III).

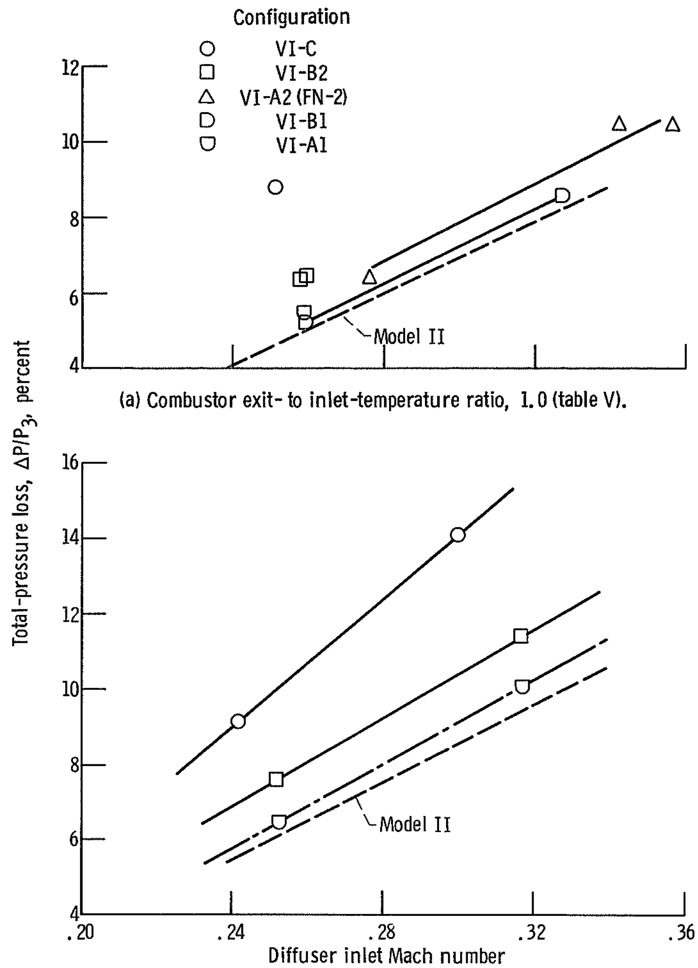
(c) Configuration A2 (FN-2) (run 14, table III).

(d) Configuration B1 (run 20, table III).

(e) Configuration B2 (run 26, table III).

(f) Configuration C (run 38, table III).

Figure 17. - Radial exit-temperature profile characteristics; nominal reference velocity, 77 feet per second (23.5 m/sec).



(a) Combustor exit- to inlet-temperature ratio, 1.0 (table V).

(b) Combustor exit- to inlet-temperature ratio, 2.5 (tables III and IV).

Figure 18. - Comparison of total-pressure losses.

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