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EFFECTS OF FUEL NOZZLE DESIGN ON PERFORMANCE OF AN EXPERIMENTAL ANNULAR COMBUSTOR USING NATURAL GAS FUEL

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16. Abstract

Tests of various fuel nozzles were conducted with natural gas fuel in a full-annulus combustor. The nozzles were designed to provide either axial, angled, or radial fuel injection. Each fuel nozzle was evaluated by measuring combustion efficiency at relatively severe combustor operating conditions. Combustor blowout and altitude ignition tests were also used to evaluate nozzle designs. Results indicate that angled injection gave higher combustion efficiency, less tendency toward combustion instability, and altitude relight characteristics equal to or superior to those of the other fuel nozzles that were tested.

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SUMMARY

Tests of various designs of fuel nozzles with natural gas fuel were conducted in an advanced-design full-annulus combustor. Various fuel nozzles were screened in an attempt to find a design that would show improved combustion efficiency and altitude relight. Severe combustor operating conditions were used to accentuate possible combustion efficiency differences resulting from the various nozzle designs. Three basic designs of nozzles were tested having either axial, angled, or radial injection of the fuel. Nozzle injection area and axial injection position were also varied. Test results indicate that angled-injection nozzles exhibited the highest overall combustion efficiency and had the least tendency for combustion instability. These nozzles also had altitude relight characteristics equal to or superior to those of the other nozzles.

INTRODUCTION

The purpose of this investigation was to optimize the design of a fuel nozzle for natural gas to obtain improved combustion efficiency at off-design conditions and to extend the altitude blowout and relight limits. Liquefied natural gas used as a fuel for turbojet engines powering a supersonic transport has been shown to have many advantages over the conventional ASTM A-1 kerosene-type fuel (refs. 1 to 3). Some of the reported advantages are increased heat-sink capacity, higher heating value on a weight basis, low flame radiation, low smoke levels, and a reduced tendency for fuel decomposition.

Previous tests with combustors designed for a supersonic engine have demonstrated combustion efficiency with natural gas fuel equal to that of ASTM A-1 liquid fuel at simulated takeoff and cruise conditions (ref. 4). However, at off-design conditions, combustion efficiency decreased at a greater rate with decreasing combustor pressure and was particularly sensitive to decreasing inlet-air temperature. Of particular importance were the very poor altitude blowout and relight limits obtained with natural gas fuel. For every operating condition, the blowout and relight pressures were significantly higher than those obtained with ASTM A-1. Similar results are indicated by data presented in reference 5.

Previous investigations have indicated that the method of gaseous fuel injection into the combustor is of primary importance on combustion efficiency (refs. 6 to 9). In spite of the many different fuel injector geometries used in these tests, no single method or design seemed to excel.

For the tests described in this report, no attempt was made to alter the basic combustor geometry, which was designed for use with kerosene-type fuel (ASTM A-1). Instead, all attempts at combustion efficiency improvement were focused on the method of natural gas fuel injection.

Several different designs of fuel nozzles were investigated. Three basic modes of fuel injection were evaluated: axial, radial, and angled injection. Several variations of each type were also evaluated to determine effects of orifice size, injected gas velocity, sheet or jet injection, and axial position.

The combustion efficiency test conditions simulate engine idle conditions and were also intended to be severe enough so that possible combustion efficiency differences between nozzles would be evident. The nominal conditions were as follows: inlet pressure, 13.8 and 17.2 newtons per square centimeter (20 and 25 psia); combustor reference velocity, 32.3 and 40.5 meters per second (106 and 133 ft/sec); and inlet air temperature, 422 K (300° F).

The altitude relight and blowout test conditions were obtained from a windmilling-flight-Mach-number - altitude envelope. The conditions included two combustor reference Mach numbers, 0.08 and 0.10, and two inlet air temperatures, 300 and 425 K (80° and 305° F).

APPARATUS

Test Facility

The fuel nozzle investigation was conducted in a full-scale experimental annular ram-induction combustor installed in a closed-duct test facility at the Lewis Research Center (ref. 10). An overall view of the test section is shown in figure 1. Airflows are available for combustion up to 136 kilograms per second (300 lb/sec) at pressures from below atmospheric to 10 atmospheres. The air is heated by indirectly fired heat exchangers.

Figure 2 shows the combustor test section and the connected inlet and outlet ducting. Flow straighteners installed in the air ducting (fig. 1) were followed by about $4\frac{1}{2}$ pipe diameters of constant-area inlet ducting leading to the test section. Following the inlet ducting was the combustor housing, which included the diffuser inlet duct and the diffuser. The combustor housing measured 106.3 centimeters (41.85 in.) at the maximum diameter and was 95.9 centimeters (37.75 in.) long. Following the combustor housing was the outlet or exhaust instrumentation section. Following this section and downstream, the combustor exhaust gases were cooled by a water-injection spray system. Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section.

Combustor

The combustor used for these tests was a full-scale, full-annulus ram-induction combustor designed for operation at Mach 3 cruise conditions with ASTM A-1 liquid fuels. This combustor is the same as the one used in references 11 and 12, designated as model F. Figure 3 is a cross-sectional sketch of the ram-induction combustor with pertinent dimensions. Figure 4 is an upstream view of a portion of the combustor and shows original dual-orifice liquid fuel nozzles, air swirlers, and the combustor headplate. More complete details of the combustor and its performance are given in references 11 and 12.

Fuel Nozzles

Figure 5(a) shows a portion of the fuel strut with the original dual-orifice liquid fuel nozzle installed and the position relative to the headplate of the combustor. Pertinent dimensions are included. The air swirler screws onto the fuel strut and acts as a retainer for the fuel nozzles. The fuel strut with nozzle cannot be inserted into the combustor housing if any part of the fuel nozzle extends downstream of the air swirler, as shown in figure 5(a), because the downstream face of the air swirler engages the upstream face of the headplate swirl cup at assembly. Nozzles that did extend past this plane had to be installed in the fuel strut after the strut was mounted in the combustor. These nozzles were installed through the air swirler by being screwed into a threaded insert that was retained by the air swirler. No change was made to the air swirler to facilitate installation of the gaseous fuel nozzles.

The three nozzles that generally gave the best combustion efficiency values for each of the three basic injection schemes were nozzles 13, 2, and 4. Nozzle 13, shown in figure 5(b), was designed to provide downstream axial injection. The nozzle had the largest feasible injection area without redesign of the air swirler. The injection area was 0.811 square centimeter (0.1257 in.^{2}). Nozzle 2, shown in figure 5(c), was designed to provide injection of the fuel at an included angle of 27°. Each nozzle had six holes and a total injection area of 1.068 square centimeters (0.1656 in.^{2}). Nozzle 4, shown in figure 5(d), was designed to provide fuel injection normal to the combustor axis. The injection location was farther downstream than that of the previous nozzle. The nozzle had two rows of five holes each and a total injection area of 3.576 square centimeters (0.5542 in.^{2}). The injection area of all nozzles is presented in table I.

Fuels

The chemical and physical properties of the natural gas fuel are presented in table II. The natural gas composition reported is representative of the natural gas used during the test program. The gas composition did vary slightly and was dependent upon the season, demand, and gas field from which it was obtained. The variations in composition were accounted for in calculations of fuel-air ratio and theoretical temperature rise.

Instrumentation

Combustion air and natural gas flow rates were measured by square-edge orifice plates installed according to ASME specifications. Combustor-inlet-air total and static pressures were measured at the plane of the diffuser inlet (station 3, fig. 2). Combustor-outlet total and static pressures and total temperatures were measured at the turbine-inlet plane (station 5, fig. 2). Combustor-exhaust total pressures and temperatures were measured at 3° increments around the exhaust circumference. At each point, five temperature and pressure readings were obtained across the radius. Exhaust thermocouples were platinum-plus-13-percent-rhodium/platinum and were of the high-recovery aspirating type. The indicated readings of all thermocouples were taken as true values of the total temperatures. More detail of the instrumentation construction, dimensions, and readout capability is given in references 10 and 12.

PROCEDURE

Combustion Efficiency Tests

Table III presents the various values for three operating conditions used for performance comparisons of the nozzles. These include inlet pressures, temperatures, mass flows, reference velocities, and values of a correlating parameter PT/V, where P is inlet total pressure, T is inlet total temperature, and V is combustor reference velocity. The different operating conditions are designated as conditions 1, 2, and 3. The severity of the conditions increases from 1 to 3. Conditions 1 and 2 compare a change in reference velocity at the same inlet pressure. Conditions 2 and 3 compare a change in inlet pressure at constant reference velocity.

After ignition, the inlet conditions of pressure, temperature, and airflow were adjusted to desired values. An approximate fuel-air ratio of 0.008 was chosen for the lean operating limit. At constant conditions, fuel flow was increased and data were taken at several fuel-air ratios. A rich fuel-air ratio limit of approximately 0.02 was arbitrarily selected. However, in many of the tests, audible instability and/or erratic combustion was encountered before this value was reached. When this situation occurred, the fuel flow was slightly reduced so that a complete set of data could be obtained without damage to the combustor. This reduced fuel-air ratio was considered to be the rich limit of the curve. No attempt was made to go through the unstable combustion to possible blowout. Previous tests had indicated that, when the fuel-air ratio was increased during unstable combustion, combustion that may be described in one of the following ways would occur:

(1) Blowout would occur with increased fuel-air ratio after unstable combustion was encountered.

(2) The pressure amplitude would remain at about the same level of intensity as fuel-air ratio was increased.

(3) Combustion would become violently unstable with an increase in fuel-air ratio, and severe combustor damage would occur in a very short time.

Altitude Limit Relight and Blowout

The altitude relight and blowout characteristics of the various fuel nozzles are compared by two criteria: (1) the minimum combustor-inlet total pressure at which ignition occurred and stable combustion was maintained at the ignition fuel-air ratio, and (2) the pressure at combustion blowout. These tests were conducted at reference Mach numbers of 0.08 and 0.10 and at inlet-air temperatures of 300 and 425 K (80° and 305° F). No change was made to the igniter position or type for these tests (fig. 5(a)).

The altitude relight data were determined as follows. At the desired inlet conditions, the fuel-air ratio was slowly varied up and down from about 0.005 to 0.015 (during a maximum time period of 60 sec). If ignition occurred and combustion was stable at the ignition fuel-air ratio, the inlet pressure was recorded as an ignition pressure. After a successful ignition, inlet conditions were adjusted to desired values if they had varied at all during the start, and the fuel-air ratio values decreased or increased to a value of about 0.01.

The altitude blowout data were obtained as follows. After ignition at a combustion pressure value considerably higher than the blowout pressure, the values of inlet-air temperature and combustion reference Mach number were adjusted to their desired values and then maintained constant. A fuel-air ratio of about 0.01 was held while making combustor pressure changes. At a fixed inlet-pressure condition, fuel flow was increased to a value that resulted in a fuel-air ratio of 0.012 to 0.013 (theoretical temperature rise of approximately 556 K or 1000° F). The fuel-flow increase was over a time period of 6 to 8 seconds. If the monitored exhaust temperature indicated an increase during the fuel flow increase, the fuel-air ratio was reduced to about 0.01, combustor pressure was decreased, and the series of steps was repeated. This procedure was repeated until combustor blowout was encountered.

CALCULATIONS

Combustion Efficiency

Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. Exit temperatures were measured with five-point traversing aspirated thermocouple probes and were mass-weighted for the efficiency calculation. The inlet temperature was the arithmetic average of readings of eight single-point thermocouples around the inlet circumference. The theoretical temperature rise was computed as a function of fuel (heat of formation and hydrogen-carbon weight ratio), inlet-air pressure, inlet-air temperature, and fuel-air ratio.

Chromatographic analysis of the natural gas indicated about 98 percent hydrocarbons, as shown in table II. The heating value and fuel-air ratios used for theoretical temperature rise and other calculations and figures were based on actual hydrocarbons in the gas. The nonhydrocarbons were considered as air.

Inlet-Air Total Pressure

The inlet total-pressure average was obtained by mass-weighting values from eight five-point pressure rakes around the diffuser inlet. Static pressures, used in the mass-weighting calculations, were measured around the circumference on both the inner and outer wall of the inlet annulus.

Combustor Reference Mach Number

The reference Mach number was computed from the total airflow, inlet total pressure and temperature, and reference area (maximum cross-sectional area between inner and outer shrouds, 4484 cm^2 or 695 $in.^2$) (fig. 3).

Combustor Reference Velocity

Reference velocity for the combustor was calculated from the reference Mach number and sonic velocity at the combustor-inlet conditions.

Diffuser-Inlet Mach Number

This Mach number was computed from total airflow, diffuser-inlet area, and diffuser-inlet static pressure and total temperature.

Total-Pressure Loss

The total-pressure loss is defined as the difference between diffuser-inlet and turbine-inlet mass-weighted total-pressure averages. The total-pressure loss, therefore, includes the diffuser loss.

Fuel Nozzle Injection Velocity

The injection area of the gaseous fuel nozzles was considerably larger than upstream restrictions between the nozzle and the fuel manifold. The actual pressure differential across the injection area of the various designs of nozzles was determined by air calibration of the nozzles. These values, after adjustment for density (differences between air and natural gas), were used to obtain fuel injection velocity.

Units

The U.S. customary system of units was used for primary measurements and calculations. Conversion to SI units (Systems International d'Unites) is done for reporting purposes only. In making the conversion, consideration is given to implied accuracy and may result in rounding off the values expressed in SI units.

RESULTS AND DISCUSSION

Combustion Efficiency Tests

Test results of all fuel nozzles are presented in table IV. As previously mentioned, nozzles 13, 2, and 4 generally gave the best combustion efficiency for each of the three basic injection schemes. Details of these nozzles are given in the APPARATUS section. Pertinent details and dimensions of the additional nozzles tested are listed in appendix A. A discussion of test results obtained with these additional nozzles is given in appendix B.

Figure 6 shows the effect of fuel-air ratio on combustion efficiency for nozzles 13, 2, and 4 at the three nominal operating conditions. As previously mentioned, the combustion efficiency test conditions were chosen to represent engine idle conditions. A range of conditions was chosen in order to have conditions severe enough to indicate possible efficiency differences between nozzles. At test condition 1 (fig. 6(a)) there was a general increase in efficiency with all nozzles as fuel-air ratio was increased. At lean fuel-air ratios, nozzles 2 and 4 gave slightly higher efficiency values, while at higher fuel-air ratios, nozzles 13 and 2 showed better efficiency. At test conditions 2 and 3 (figs. 6(b) and (c), respectively) and low fuel-air ratios, nozzle 4 permitted as high or higher efficiency values than nozzle 13 or 2; however, as fuel-air ratio increased, the efficiency for nozzle 4 fell off quite rapidly to values lower than those for the other nozzles. Unstable combustion was encountered by nozzles 4 and 13 at successively lower fuel-air ratios as test conditions varied from 1 to 3.

Nozzle 2, which injected the natural gas as six discrete jets at an included angle of 27°, clearly exhibited higher efficiencies and a wider operating fuel-air-ratio range. Nozzle 4, which gave the lowest efficiencies at the higher fuel-air ratios, injected the fuel normal to the combustor centerline. With this nozzle, the injection plane was farther downstream than that of the other two nozzles.

Results of investigations at the Lewis Research Center (unpublished data) indicate that combustion efficiency values obtained with ASTM A-1 liquid fuel and the dual orifice nozzles were 8 to 12 percentage points higher (test condition 3) than values obtained with natural gas and nozzle 2.

The variation of combustor temperature rise with fuel-air ratio for nozzles 13, 2, and 4 at the three test conditions is shown in figure 7. At test condition 1 (fig. 7(a)), temperature rise values greater than 800 K (1440° F) were obtained with all nozzles. As the test condition was varied from 1 to 3, the values obtained with nozzle 2 were somewhat greater than 750 K (1350° F). However, with nozzles 13 and 4, the maximum temperature rise values dropped sharply to 550 and 430 K (990° and 774° F), respectively, for condition 2 (fig. 7(b)) and to 380 and 325 K (684° and 585° F), respectively, for condition 3 (fig. 7(c)).

Altitude Limit Tests

Test results for altitude limit ignition and blowout obtained with all nozzles are summarized in table V. Discussion of test results of nozzles other than 13, 2, and 4 is presented in appendix B.

The inlet-air temperatures and reference Mach numbers listed in table V varied slightly from test to test. The Mach number variations were considered to be small enough so that no correction of the recorded blowout pressures was required. However, as indicated in reference 4, small variations of the inlet-air temperature, particularly at values near 300 K (80° F), had a large effect on measured altitude limits. In order to make valid comparisons at the desired nominal temperature values of 300 and 425 K (80° and 305° F), the measured pressures were adjusted for any variation in inlet-air temperatures. The correction was made by making plots of the ignition or blowout pressure against the inlet-air temperature and determining the proper pressure at the desired nominal value of temperatures. These corrected data are presented in figure 8 for ignition limits and figure 9 for blowout limits for nozzles 13, 2, and 4.

Data in figure 8 show that nozzle 13 (axial injection) provided ignition at the lowest pressure at an inlet-air temperature of 300 K (80° F) at both combustor reference Mach numbers. However, as the inlet-air temperature increased, this no longer held true. Nozzle 2 was better at the low reference Mach number and 4 was best at the higher Mach number. Minimum ignition pressures obtained with nozzle 2 were as low or lower than those obtained with nozzles 13 and 4 at the low Mach number. However, at the higher Mach number, the values obtained with nozzle 2 were considerably higher, at both inlet-air temperatures. Nozzle 2 was more sensitive to variation of combustor reference Mach number than were the other two nozzles.

The blowout results given in figure 9 show that radial injection of the fuel, nozzle 4, gives the highest blowout pressure. Angled fuel injection, nozzle 2, produces the lowest blowout pressure at elevated air temperatures and is not greatly inferior to axial injection, nozzle 13, at the lower temperature.

Complete altitude limit data were not obtained with the nozzles at all test conditions. In some cases, facility limitations of flow or pressure limited tests. In other situations, previous results indicated that further tests would not be informative.

Altitude limit ignition and blowout data obtained with nozzles other than 13, 2, and 4 are presented in appendix B. The data include results from tests of nozzles of the same injection scheme, but with variations in nozzle size and injection area. The results are somewhat inconclusive in that no one type of nozzle design is clearly superior for both relight and blowout. For example, the minimum ignition pressures obtained with nozzle 2 are considerably higher than those obtained with several other nozzles. However, blowout pressures with nozzle 2 were as low or nearly as low as those obtained with any of the other nozzles.

SUMMARY OF RESULTS

The wide variation in combustion efficiencies, stability range, and altitude ignition and blowout pressures obtained with different nozzle designs indicates that the method of gaseous fuel injection is an important step in the combustion process. However, the results are somewhat inconclusive in that no one type of nozzle design is clearly superior at all test conditions. Fuel nozzles that gave good altitude relight often had a narrow range of fuel-air ratios for stable combustion. Conversely, nozzles that demonstrated high combustion efficiency and stable combustion were often inferior in some aspects of altitude limit performance. From examination of the data, the following results were obtained.

1. Gaseous fuel injected at a slight angle to the combustor axis (angled fuel injection) generally gave better combustion efficiency, combustion stability, and lower altitude ignition and blowout pressures.

2. Radial injection of the gaseous fuel generally gave the lowest efficiencies at the high fuel-air ratio values and also the narrowest range of stable combustion of the three injection methods. Radial injection results compare more favorably with results of other injection methods from altitude ignition tests than with those from altitude blowout tests.

3. Axial injection of fuel gave combustion efficiencies approaching those of angled injection, although the useful fuel-air ratio range of axial injection was reduced by combustion instability.

4. Combustion instability was common to all nozzles. The effect of the combustion instability was to narrow the range of fuel-air ratios where satisfactory combustion could be maintained.

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APPENDIX A

DETAILS OF GASEOUS FUEL NOZZLES

Axial Injection

Nozzle 11, shown in figure 10, was the same as nozzle 13, except that the injection area was smaller. This nozzle was the threaded insert, described previously, that the other natural gas nozzles screwed into. The injection area was 0.199 square centimeter (0.0308 in.^{2}). Later this nozzle was drilled out, and the injection area was enlarged to 0.811 square centimeter (0.1257 in.^{2}) to make nozzle 13.

Angled Injection

Nozzle 1, shown in figure 11, was designed as a replacement for the usual liquid fuel nozzles. This nozzle did not extend downstream of the swirler. The natural gas was metered through six angled holes in the nozzle body. These jets of fuel then converged around the pintle on the nozzle axis which later served to spread the jet as a sheet as it was injected into the combustor. The injection area of this nozzle was taken to be the difference in areas of the swirler minimum area minus the area of the pintle stem. The injection area was 0.773 square centimeter (0.1198 in.^{2}).

Nozzle 6, shown in figure 12, had a slightly larger injection area than nozzle 1 and injected the fuel at a 27° included angle, but 1.5 centimeters (0.6 in.) downstream from the usual injection position at the swirler face. The injection area was 0.888 square centimeter (0.1377 in.^{2}). The gas was injected as a sheet.

Nozzle 8, shown in figure 13, had the injection plane, which included 10 injection holes, moved farther downstream and the physical size of the nozzle was substantially increased. The injection area was 3.576 square centimeters (0.5542 in.^{2}). The included angle of injection was 27°. The fuel issued more as discrete jets than as a sheet as in nozzles 1 and 6. With the physical size of the nozzle increased, the fuel jets could penetrate closer to the combustor walls than in previous angled-injection type nozzles. The large size of this nozzle body, required in order to obtain increased injection area, could change the airflow patterns from the air swirler.

Nozzle 9, shown in figure 14, was similar to nozzle 8 but had a smaller total injection area and only six injection holes. It had the same injection area as nozzle 2, 1.068 square centimeters (0.1656 in.^{2}).

Radial Injection

Nozzle 3, shown in figure 15, was a shorter length version of nozzle 4, shown in figure 5(d). The first of two rows of radial injection holes (five in each row) was much closer to the swirler face. The open or injection area of this nozzle was the same as for nozzle 4, 3.576 square centimeters (0.5542 in.^{2}).

Nozzle 5, shown in figure 16, injected the fuel as a radial sheet. The injection slot was located 1.5 centimeters (0.6 in.) downstream of the swirler face, and the injection flow area was 2.445 square centimeters (0.3790 in.^{2}).

Nozzle 7, shown in figure 17, radially injected the natural gas from a set of eight longitudinal slots. The injector flow area was 2.140 square centimeters (0.3317 in.^{2}).

APPENDIX B

COMBUSTION EFFICIENCY AND ALTITUDE LIMIT IGNITION AND BLOWOUT PRESSURES

Combustion Efficiency

The combustion efficiency obtained with the fuel nozzles described in appendix A, as affected by fuel-air ratio, is presented in figures 18 to 21. Data are presented for each nozzle at the three test conditions. Also included in these figures are results obtained with nozzles previously described in the APPARATUS section.

Axial injection. - Nozzles 13 and 11, figures 5(b) and 10, were two nozzles designed for axial injection that differed only in injection area. As shown in figure 18, nozzle 11, with the smaller injection area, had slightly higher combustion efficiencies, particularly at the lower fuel-air ratios. However, combustion instability was encountered at lower fuel-air ratios than with nozzle 13.

The somewhat more limited stability range of nozzle 11 led to the choice of nozzle 13 as the better performing axial injection nozzle.

Angled injection. - Combustion efficiencies as affected by fuel-air ratio for nozzles 1 and 6, are shown in figure 19; data for nozzles 8 and 9 are presented in figure 20. The efficiencies obtained with these nozzles were clearly inferior to that obtained with nozzle 2. Generally, the combustion efficiencies were low, even for the least severe operating conditions. Nozzles 6 and 9 had a very limited operational range before unstable combustion occurred. Comparing the performance of nozzles 8 and 9 shows that injection of fuel at a low velocity enhanced the combustion stability range. The differences in fuel injection position and angle may have also been responsible for differences in performance, but the effect of each variable in this instance was not clear.

Radial injection. - The variation in combustion efficiency with fuel-air ratio and fuel injection velocity with the radial injection fuel nozzles is shown in figure 21. A distinctive characteristic of these nozzles was the rapid decrease in combustion efficiency as fuel-air ratio increased at the more severe operating conditions. Efficiency results indicated that radial jet injection close to the air swirler (nozzle 3) should be avoided. When the injection position was moved farther downstream, as in the case of nozzle 4, there was a slight increase in the stable combustion range, and combustion efficiency did not decrease as rapidly with increasing fuel-air ratio. Radial sheet injection close to the air swirler (nozzle 5) gave slightly better combustion efficiencies at the more severe operating conditions than did nozzle 3 (radial jet injection close to the air swirler).

Summary. - Results obtained with the two axial injection nozzles were quite similar;

nozzle 13 was considered slightly better because of a somewhat wider stable combustion range at the most severe operating condition.

Nozzle 2 was clearly superior to the other angle injection nozzles tested. The various nozzles included types that inject the fuel as jets or sheet, vary the injection plane, and vary the injection velocity.

Radial injection nozzle 4 gave as high or higher combustion efficiencies and as wide a stable combustion range as the other radial-injection nozzles.

Altitude Limit Ignition and Blowout Pressures

Altitude limit ignition and blowout data, of all fuel nozzles, are shown in figures 22 and 23, respectively. They include the data from nozzles 13, 2, and 4, which were previously discussed.

Ignition. - The radial injection nozzles 3, 4, 5, and 7 were designed to bring a high fuel concentration near the igniter. This should have enhanced altitude ignition limits. As shown in figure 22, some of the radial injection nozzles did show good relight characteristics, although some other nozzles permitted lower ignition pressures. A study of figure 22 indicates that angled injection, typified by nozzles 1 and 9, gave the lowest ignition pressures at all operating conditions except the severest, low air temperature and high combustor reference Mach number. At this severe condition, axial injection nozzle 13 gave the lowest ignition pressure. Also, nozzle 13 was least sensitive to variation in combustor reference Mach number. Axial injection nozzle 11, with a smaller injection area than 13, gave about the highest ignition pressure of all the nozzles. The disparity in minimum ignition pressure of the nozzles indicates that none of these designs are optimum.

Blowout. - Data shown in figure 23 indicate that no one nozzle or nozzle type permits the lowest blowout pressure at all operating conditions. Angled-injection nozzles 2 and 9 had the lowest pressures at low Mach number and both inlet-air temperature conditions; axial-injection nozzle 13 permitted the lowest pressure at the high-Mach-number - low-temperature condition; and radial-injection nozzle 5 showed the lowest ignition pressure at the high-Mach-number - high-temperature condition. However, the pressure values obtained with nozzles 13 and 5 were only slightly lower than values obtained with nozzle 2.

Summary. - Results of altitude limit ignition and blowout tests indicate that angled-injection fuel nozzles generally permitted the lowest or nearly lowest pressures. The large radial-injection area nozzle 13 permitted the lowest pressure for both ignition and blowout tests at the most severe operating condition.

Several nozzle designs would ignite at fuel-air ratios as low as 0.004. In some cases, as fuel-air ratio was increased, after ignition, combustion was satisfactory; in other cases, combustion blowout would occur before the fuel-air ratio reached a value of about 0.010.

During blowout tests, there generally was a range of pressures over which the exhaust temperatures would remain constant or decrease, but not enough for blowout to occur as the fuel-air ratio was increased to the desired value. Further decrease in pressure would result in blowout.

Complete altitude limit data were not obtained with the nozzles at all test conditions. In some cases, facility limitations of flow or pressure limited tests. In other situations, previous results indicated that further tests would not be informative.

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TABLE I. - NOZZLE INJECTION AREAS

Nozzle	Injection area		Type of injection
	cm^2	$in.^2$	
11	0.199	0.0308	Axial
13	.811	.1257	Axial
1	0.773	0.1198	Angled
6	.888	.1377	
2	1.068	.1656	
9	1.068	.1656	
8	3.576	.5542	
7	2.140	0.3317	Radial
5	2.445	.3790	
3	3.576	.5542	
4	3.576	.5542	

TABLE II. - PHYSICAL PROPERTIES OF NATURAL GAS

Density,[a] kg/m^3 (lb/ft^3)	0.7320 (0.0457)
Calculated net heat of combustion, J/kg (Btu/lb)	49 770×10^3 (21 397)
Normalized chromatographic analysis, vol. %	
Methane	93.50
Ethane	3.53
Propane	0.53
C_4, C_5, and C_6 hydrocarbons	0.32
Nitrogen	1.05
Carbon dioxide	1.07
Oxygen	trace

[a]At temperature of 289 K (60° F) and pressure of 10.159 N/cm^2 (30.00 in. Hg at 32° F).

TABLE III. - COMBUSTOR NOMINAL OPERATING CONDITIONS

Operating condition	Pressure		Temperature		Airflow rate		Reference velocity		PT/V		Diffuser-inlet Mach number
	N/cm^2	psia	K	$^\circ F$	kg/sec	lb/sec	m/sec	ft/sec	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^\circ R)(sec)}{ft^3}$	
1	17.2	25.0	422	300	20.6	45.5	32.3	106	22.53×10^5	25.81×10^3	0.326
2	17.2	25.0	422	300	25.9	57.0	40.5	133	17.95	20.57	.415
3	13.8	20.0	422	300	20.7	45.6	40.5	133	14.36	16.46	.415

TABLE IV. - COMBUSTOR EFFICIENCY

Combustor-inlet-air conditions										Fuel temperature	
Total pressure		Total temperature		Flow		Reference velocity		PT/V		K	°F
N/cm^2	psia	K	°F	kg/sec	lb/sec	m/sec	ft/sec	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^oR)(sec)}{ft^3}$		
										Nozzle	
17.2	25.0	419	294	20.5	45.1	31.7	104	22.76×10^5	26.08×10^3	284	52
17.2	25.0	422	300	20.6	45.5	32.3	106	22.56	25.85	286	55
17.0	24.7	416	290	20.6	45.5	32.0	105	22.19	25.43	287	57
17.2	24.9	416	290	20.5	45.3	31.7	104	22.50	25.78	290	62
17.2	25.0	416	289	20.5	45.3	31.4	103	22.76	26.08	290	63
17.2	24.9	429	312	25.6	56.4	40.2	132	18.24	20.90	276	37
17.2	25.0	426	307	25.5	56.3	39.9	131	18.36	21.04	276	37
17.2	24.9	426	307	25.5	56.2	39.9	131	18.33	21.00	277	39
17.2	24.9	428	310	25.7	56.6	40.5	133	18.12	20.76	279	43
17.1	24.8	428	311	25.4	56.0	40.2	132	18.27	20.93	284	51
13.7	19.9	417	291	20.9	46.0	39.9	131	14.31	16.40	288	59
13.8	20.0	415	288	20.9	46.1	39.9	131	14.41	16.51	288	59
13.8	20.0	417	291	20.8	45.9	39.9	131	14.49	16.60	288	59
13.7	19.9	416	290	20.8	45.9	39.9	131	14.26	16.34	289	60
										Nozzle	
16.8	24.4	424	303	19.8	43.7	31.7	104	22.40×10^5	25.67×10^3	294	70
16.8	24.4	425	305	19.8	43.6	31.7	104	22.45	25.72	295	71
17.0	24.6	425	305	19.7	43.5	31.4	103	23.01	26.37	296	73
17.0	24.6	424	304	19.7	43.4	31.4	103	22.96	26.31	296	73
16.9	24.5	424	303	19.7	43.5	31.4	103	22.75	26.07	298	77
16.8	24.4	424	304	23.7	52.3	37.8	124	18.84	21.59	295	72
16.8	24.4	425	305	23.8	52.5	38.1	125	18.74	21.47	298	76
17.0	24.6	424	304	23.9	52.7	37.8	124	19.02	21.79	300	81
16.9	24.5	425	306	24.1	53.1	38.4	126	18.66	21.38	302	84
13.5	19.6	423	301	20.1	44.3	39.6	130	14.38	16.48	285	54
13.4	19.5	425	305	20.0	44.2	40.2	132	14.20	16.27	286	56
13.4	19.5	425	305	19.8	43.6	39.6	130	14.42	16.52	289	61
13.5	19.6	423	301	19.8	43.6	39.3	129	14.53	16.65	296	73
										Nozzle	
17.3	25.1	421	299	20.9	46.0	32.3	106	22.60×10^5	25.90×10^3	286	56
17.3	25.1	421	299	20.8	45.9	32.3	106	22.60	25.90	287	57
17.2	24.9	421	299	20.8	45.8	32.6	107	22.21	25.45	289	61
17.3	25.1	421	299	20.8	45.9	32.3	106	22.52	25.80	292	66
17.2	24.9	423	301	20.8	45.8	32.6	107	22.31	25.56	294	69
17.2	25.0	423	301	25.6	56.4	39.6	130	18.29	20.96	293	68
17.2	24.9	423	302	25.4	56.0	39.6	130	18.43	21.12	293	68
17.2	25.0	423	301	25.6	56.4	39.6	130	18.35	21.03	296	73
17.2	25.0	423	302	25.5	56.3	39.6	130	18.39	21.07	295	72
13.9	20.1	421	298	21.1	46.5	40.5	133	14.35	16.44	285	54
13.9	20.1	422	300	21.0	46.4	40.5	133	14.38	16.48	287	57
13.8	20.0	421	299	21.1	46.5	40.8	134	14.24	16.32	286	56
13.9	20.2	422	300	21.1	46.5	40.5	133	14.49	16.60	288	59

DATA WITH NATURAL GAS FUEL

Fuel pressure differential between manifold and combustor, N/cm^2	Fuel pressure differential between manifold and combustor, psi	Calculated fuel injection velocity, m/sec	Calculated fuel injection velocity, ft/sec	Fuel-air ratio	Combustor average exhaust total temperature, K	Combustor average exhaust total temperature, ^oF	Combustor temperature rise, K	Combustor temperature rise, ^oF	Combustion efficiency, percent	Remarks
1										
23.8	34.5	71.0	233	0.0079	728	850	309	556	86.0	----------------------
33.5	48.6	86.9	285	.0099	800	981	378	681	85.6	----------------------
48.3	70.1	109.1	358	.0129	896	1154	480	864	85.0	----------------------
69.4	100.7	134.4	441	.0173	1094	1509	677	1218	92.6	----------------------
82.2	119.2	146.9	482	.0199	1215	1728	799	1439	96.6	High-frequency audible combustion resonance (buzz), erratic outlet temperature
34.2	49.6	89.3	293	.0082	724	843	295	531	79.7	----------------------
43.3	62.8	102.1	335	.0097	758	904	332	598	76.4	----------------------
55.2	80.1	117.7	386	.0117	769	924	343	617	66.7	----------------------
71.5	103.7	136.9	449	.0144	831	1036	403	726	65.2	----------------------
80.1	116.1	147.5	484	.0158	893	1147	464	836	69.0	Erratic outlet temperature
28.7	41.6	95.1	312	.0081	697	795	279	503	75.7	----------------------
37.2	53.9	110.9	364	.0098	714	826	299	538	68.3	----------------------
51.7	74.9	135.6	445	.0128	739	870	322	579	57.5	----------------------
69.3	100.6	158.2	519	.0164	827	1029	411	739	58.9	Erratic outlet temperature
2										
18.1	26.3	41.8	137	0.0062	658	725	234	422	82.3	----------------------
38.6	56.0	68.0	223	.0104	832	1038	407	733	88.3	----------------------
62.4	90.6	93.9	308	.0152	1029	1392	604	1087	93.0	----------------------
81.5	118.2	113.1	371	.0189	1188	1678	763	1374	96.7	----------------------
87.8	127.4	120.7	396	.0201	1235	1764	812	1461	97.5	----------------------
43.5	63.1	75.3	247	.0094	751	892	327	588	77.5	----------------------
77.0	111.6	111.6	366	.0148	929	1213	504	907	79.2	----------------------
100.4	145.6	136.6	448	.0187	1103	1525	678	1221	86.9	----------------------
119.1	172.7	153.3	503	.0212	1203	1705	778	1400	89.0	Erratic outlet temperature
35.2	51.1	76.8	252	.0094	703	806	281	505	66.6	----------------------
51.4	74.6	99.4	326	.0125	778	941	353	636	64.5	----------------------
78.8	114.2	133.8	439	.0180	984	1312	559	1007	74.1	----------------------
104.0	150.8	163.4	536	.0226	1184	1671	761	1369	82.5	----------------------
3										
23.2	33.6	14.6	48	0.0069	703	806	282	507	89.4	----------------------
37.0	53.6	20.4	67	.0096	815	1008	394	709	91.6	----------------------
53.3	77.3	26.5	87	.0127	887	1137	466	838	83.9	----------------------
76.5	110.9	35.4	116	.0169	1050	1431	629	1132	87.8	----------------------
98.5	142.8	43.3	142	.0211	1239	1771	817	1471	94.2	Erratic outlet temperature
31.6	45.9	18.9	62	.0068	679	763	257	462	82.4	----------------------
50.4	73.1	26.8	88	.0097	766	920	344	619	79.0	----------------------
60.0	87.1	30.8	101	.0111	750	890	327	589	66.8	----------------------
71.5	103.6	35.1	115	.0129	733	859	309	557	55.2	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
26.6	38.6	18.9	62	.0068	675	756	254	458	81.9	----------------------
40.1	58.1	26.5	87	.0095	733	860	311	560	73.4	----------------------
52.0	75.4	32.3	106	.0116	669	745	248	446	48.7	----------------------
57.8	83.8	35.1	115	.0126	637	687	215	387	38.9	Low-frequency audible combustion resonance (rumble), erratic outlet temperature

TABLE IV. - Continued. COMBUSTOR

Combustor-inlet-air conditions										Fuel temperature	
Total pressure		Total temperature		Flow		Reference velocity		PT/V			
N/cm^2	psia	K	^oF	kg/sec	lb/sec	m/sec	ft/sec	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^oR)(sec)}{ft^3}$	K	^oF
Nozzle											
17.0	24.6	426	307	20.1	44.4	32.3	106	22.43×10^5	25.70×10^3	279	43
17.0	24.6	426	307	20.0	44.2	32.0	105	22.51	25.79	278	41
16.9	24.5	427	309	20.1	44.3	32.3	106	22.42	25.69	280	44
17.0	24.6	426	308	20.2	44.5	32.3	106	22.42	25.69	281	47
17.0	24.6	428	310	20.2	44.6	32.3	106	22.46	25.74	283	50
16.9	24.5	426	307	24.7	54.4	39.3	129	18.32	20.99	284	51
16.9	24.5	426	308	24.7	54.4	39.3	129	18.29	20.96	285	53
16.9	24.5	427	309	24.6	54.3	39.3	129	18.35	21.03	288	58
17.0	24.7	428	310	24.6	54.3	39.3	129	18.53	21.23	291	64
13.5	19.6	427	309	20.4	44.9	40.5	133	14.18	16.25	290	63
13.5	19.6	426	307	20.6	45.5	41.1	135	13.94	15.97	290	63
13.5	19.6	426	307	20.6	45.4	40.8	134	14.06	16.11	290	62
13.5	19.6	427	309	20.6	45.4	41.1	135	14.08	16.13	292	66
13.4	19.5	427	309	20.6	45.4	41.5	136	13.84	15.86	291	65
Nozzle											
17.3	25.1	429	312	20.8	45.8	32.6	107	22.64×10^5	25.94×10^3	284	51
17.4	25.2	429	312	20.8	45.8	32.6	107	22.79	26.11	286	56
17.3	25.1	428	310	20.8	45.8	32.6	107	22.66	25.97	288	59
17.2	25.0	428	310	20.8	45.8	32.6	107	22.52	25.80	291	64
17.3	25.1	428	311	20.7	45.7	32.6	107	22.69	26.00	294	69
17.3	25.1	428	311	25.4	56.1	39.6	130	18.67	21.39	293	67
17.4	25.2	428	311	25.4	56.1	39.6	130	18.70	21.43	293	68
17.3	25.1	428	311	25.4	56.1	39.9	131	18.62	21.34	295	71
17.3	25.1	429	313	25.5	56.2	39.9	131	18.51	21.21	296	74
13.9	20.1	425	306	21.2	46.8	41.1	135	14.26	16.34	281	47
13.8	20.0	428	311	21.2	46.8	41.5	136	14.21	16.28	282	48
13.9	20.1	428	311	21.2	46.7	41.5	136	14.37	16.47	284	52
Nozzle											
17.2	25.0	428	311	20.3	44.7	32.0	105	22.96×10^5	26.31×10^3	275	35
17.2	25.0	429	312	20.4	44.9	32.3	106	22.98	26.33	276	37
17.3	25.1	426	307	20.3	44.8	32.0	105	23.10	26.47	276	37
17.2	25.0	426	307	20.3	44.8	32.0	105	22.89	26.23	277	39
17.2	25.0	427	309	24.8	54.6	38.7	127	19.00	21.77	278	41
17.2	25.0	427	309	25.4	56.0	39.6	130	18.54	21.24	280	45
17.3	25.1	427	309	25.4	56.1	39.6	130	18.56	21.27	282	48
17.2	25.0	427	309	25.4	56.0	39.6	130	18.56	21.27	285	53
13.9	20.1	427	309	21.3	46.9	41.5	136	14.27	16.35	284	52
13.8	20.0	427	309	21.3	46.9	41.5	136	14.17	16.24	284	52
13.8	20.0	426	308	21.3	46.9	41.5	136	14.22	16.29	285	54
13.8	20.0	426	308	21.2	46.8	41.5	136	14.24	16.32	286	56

EFFICIENCY DATA WITH NATURAL GAS FUEL

Fuel pressure differential between manifold and combustor, N/cm^2	Fuel pressure differential between manifold and combustor, psi	Calculated fuel injection velocity, m/sec	Calculated fuel injection velocity, ft/sec	Fuel-air ratio	Combustor average exhaust total temperature, K	Combustor average exhaust total temperature, ^oF	Combustor temperature rise, K	Combustor temperature rise, ^oF	Combustion efficiency, percent	Remarks
4										
27.3	39.5	16.8	55	0.0083	750	891	325	585	86.5	------------------------
36.0	52.3	20.4	67	.0101	825	1025	399	718	88.4	------------------------
52.3	75.8	26.8	88	.0133	957	1263	530	954	92.1	------------------------
73.6	106.7	35.1	115	.0174	1104	1528	678	1220	92.7	------------------------
96.7	140.3	44.2	145	.0218	1265	1818	838	1509	94.0	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
37.1	53.9	21.6	71	.0082	711	821	286	514	76.9	------------------------
48.6	70.5	26.2	86	.0100	771	928	345	621	77.6	------------------------
61.5	89.2	31.4	103	.0120	833	1039	405	729	77.0	------------------------
78.7	114.1	38.1	125	.0146	860	1088	433	779	68.9	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
30.3	43.9	22.3	73	.0079	686	775	259	466	71.9	------------------------
41.1	59.6	27.7	91	.0098	729	852	303	546	69.0	------------------------
41.1	59.6	27.7	91	.0099	731	856	306	550	69.3	------------------------
58.0	84.1	36.6	120	.0130	743	878	316	568	55.8	------------------------
63.9	92.7	40.2	132	.0141	698	796	271	487	44.6	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
5										
28.0	40.7	25.0	82	0.0082	753	895	324	583	87.8	------------------------
36.8	53.4	30.5	100	.0097	805	989	376	677	86.6	------------------------
53.6	77.7	39.6	130	.0128	870	1106	442	796	79.2	------------------------
74.0	107.4	51.2	168	.0166	1028	1390	600	1080	85.4	------------------------
90.5	131.2	60.0	197	.0196	1183	1669	754	1358	92.8	------------------------
39.1	56.7	32.6	107	.0081	737	867	309	556	84.1	------------------------
51.7	74.9	39.9	131	.0100	776	938	348	627	78.4	------------------------
64.3	93.3	47.5	156	.0119	768	922	339	611	65.1	------------------------
83.3	120.8	58.2	191	.0146	795	971	366	659	58.2	Erratic outlet temperature
31.5	45.7	32.6	107	.0080	715	827	289	521	79.9	------------------------
40.6	58.9	39.3	129	.0096	746	884	318	573	74.3	------------------------
55.5	80.5	50.3	165	.0123	678	760	249	449	46.3	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
6										
27.0	39.1	59.1	194	0.0083	732	858	304	547	80.7	------------------------
35.9	52.1	70.4	231	.0100	799	978	370	666	82.9	------------------------
37.3	54.1	71.9	236	.0104	801	983	376	676	81.5	------------------------
54.8	79.4	91.1	299	.0138	940	1232	514	925	86.4	Erratic outlet temperature and inlet pressure
37.2	54.0	73.5	241	.0083	684	772	258	464	68.5	------------------------
47.7	69.1	87.9	287	.0096	714	825	287	516	66.9	------------------------
60.0	87.1	101.2	332	.0115	753	895	325	585	64.2	------------------------
73.5	106.6	115.8	380	.0135	796	973	369	664	63.0	Erratic outlet temperature and inlet pressure
30.5	44.3	76.2	250	.0078	638	689	211	380	59.8	------------------------
40.5	58.7	91.4	300	.0095	661	731	234	422	54.9	------------------------
55.4	80.4	113.1	371	.0122	695	792	269	484	50.2	------------------------
63.0	91.4	124.4	408	.0137	724	844	298	537	50.4	Erratic outlet temperature

Combustor-inlet-air conditions										Fuel temperature	
Total pressure		Total temperature		Flow		Reference velocity		PT/V			
N/cm^2	psia	K	^oF	kg/sec	lb/sec	m/sec	ft/sec	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^oR)(sec)}{ft^3}$	K	^oF
											Nozzle
17.2	24.9	421	299	21.0	46.4	32.9	108	22.10×10^5	25.32×10^3	289	61
17.2	25.0	422	300	20.5	45.3	32.0	105	22.74	26.06	290	63
17.2	25.0	421	298	20.5	45.3	32.0	105	22.67	25.98	292	66
17.2	25.0	422	300	20.5	45.3	32.0	105	22.74	26.06	295	72
17.3	25.1	422	300	20.5	45.3	31.7	104	22.96	26.31	293	68
17.3	25.0	420	297	20.6	45.5	32.0	105	22.71	26.02	294	70
17.2	25.0	421	299	25.5	56.3	39.3	129	18.43	21.12	290	63
17.2	25.0	420	297	25.8	56.8	39.6	130	18.33	21.00	288	58
17.2	24.9	420	296	25.7	56.6	39.6	130	18.20	20.85	288	58
17.2	24.9	421	298	25.8	56.8	39.9	131	18.15	20.80	289	61
13.9	20.1	422	300	20.9	46.1	40.2	132	14.46	16.57	292	66
13.9	20.1	423	301	21.0	46.3	40.2	132	14.51	16.63	293	67
13.8	20.0	423	301	21.0	46.3	40.5	133	14.33	16.42	294	70
13.9	20.1	422	300	21.0	46.2	40.2	132	14.46	16.57	294	70
											Nozzle
17.1	24.8	418	293	20.9	46.0	32.6	107	21.98×10^5	25.19×10^3	275	36
17.1	24.8	425	306	20.6	45.4	32.6	107	22.37	25.63	275	35
17.0	24.6	425	305	21.0	46.3	33.5	110	21.59	24.74	276	37
17.0	24.7	420	297	21.0	46.3	32.9	108	21.70	24.87	279	43
17.0	24.6	419	295	21.0	46.2	33.2	109	21.47	24.60	281	47
17.1	24.8	421	298	25.0	55.2	39.0	128	18.40	21.08	282	48
17.0	24.7	420	297	25.0	55.2	39.0	128	18.31	20.98	283	49
17.0	24.7	420	297	25.1	55.3	39.3	129	18.25	20.91	284	52
17.0	24.6	422	300	25.1	55.3	39.6	130	18.06	20.69	288	58
17.2	24.9	421	299	25.0	55.2	39.0	128	18.61	21.32	289	60
13.7	19.8	420	297	21.3	47.0	41.5	136	13.79	15.80	288	59
13.7	19.9	421	298	21.2	46.7	41.1	135	14.03	16.08	286	55
13.6	19.7	421	299	21.1	46.6	41.5	136	13.85	15.87	287	57
13.7	19.8	418	292	21.2	46.7	40.8	134	13.96	16.00	290	62
											Nozzle
17.0	24.7	424	304	20.8	45.9	32.9	108	21.86×10^5	25.05×10^3	274	34
17.0	24.6	426	308	20.8	45.9	33.2	109	21.67	24.83	277	29
17.0	24.6	423	302	21.0	46.2	33.2	109	21.61	24.76	274	33
17.0	24.6	421	298	21.0	46.3	33.2	109	21.50	24.64	275	36
16.9	24.5	420	296	25.1	55.3	39.3	129	18.02	20.65	275	35
16.8	24.4	418	293	25.1	55.3	39.6	130	17.86	20.47	277	39
17.0	24.7	420	296	25.0	55.2	39.0	128	18.29	20.96	278	41
17.0	24.6	420	297	25.0	55.2	39.0	129	18.12	20.76	279	43
13.5	19.6	421	298	20.9	46.1	41.1	135	13.78	15.79	280	45
13.4	19.5	421	298	20.9	46.0	41.5	136	13.68	15.68	279	43
13.4	19.5	419	295	20.8	45.9	41.1	135	13.68	15.68	280	45

EFFICIENCY DATA WITH NATURAL GAS FUEL

Fuel pressure differential between manifold and combustor		Calculated fuel injection velocity		Fuel-air ratio	Combustor average exhaust total temperature		Combustor temperature rise		Combustion efficiency, percent	Remarks
N/cm^2	psi	m/sec	ft/sec		K	°F	K	°F		
7										
29.2	42.3	30.2	99	0.0082	738	868	317	570	85.7	----------------------
38.2	55.4	36.3	119	.0100	802	984	380	684	85.0	----------------------
57.3	83.1	48.8	160	.0136	853	1076	432	778	73.4	----------------------
80.9	117.3	63.1	207	.0180	1081	1486	659	1186	87.5	----------------------
84.3	122.3	64.9	213	.0187	1124	1563	702	1263	89.8	----------------------
98.5	142.8	73.2	240	.0212	1224	1743	803	1445	92.3	----------------------
46.3	67.1	43.0	141	.0092	731	856	310	558	74.9	----------------------
37.1	53.9	35.7	117	.0077	703	805	282	507	80.3	----------------------
63.5	92.1	53.6	176	.0118	669	745	249	449	48.3	----------------------
71.7	104.0	59.4	195	.0130	636	686	216	388	38.3	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
33.1	48.0	39.6	130	.0082	704	808	282	508	75.7	----------------------
41.6	60.3	44.8	147	.0098	693	787	271	487	61.8	----------------------
47.4	68.7	52.4	172	.0108	648	706	226	406	47.3	----------------------
54.6	79.2	58.5	192	.0121	596	614	174	314	32.8	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
8										
27.7	40.2	16.8	55	0.0083	686	776	269	484	71.2	----------------------
36.7	53.2	19.5	64	.0102	782	948	356	641	78.3	----------------------
54.2	78.6	25.3	83	.0132	895	1152	471	848	82.0	----------------------
77.8	112.8	32.3	106	.0176	1086	1495	666	1199	89.9	----------------------
87.6	127.1	35.4	116	.0194	1158	1625	739	1330	91.4	High-frequency audible combustion resonance (buzz)
38.2	55.4	21.0	69	.0084	658	725	237	427	62.2	----------------------
49.3	71.5	24.4	80	.0101	696	794	276	496	61.2	----------------------
61.5	89.2	28.3	93	.0119	756	902	336	605	64.2	----------------------
83.1	120.6	35.1	115	.0151	878	1121	456	821	70.5	----------------------
95.1	137.9	39.0	128	.0171	978	1300	556	1001	76.9	Erratic outlet temperature
30.2	43.8	21.6	71	.0079	630	674	210	378	58.5	----------------------
42.3	61.4	26.2	86	.0100	639	690	218	392	48.7	----------------------
58.1	84.3	32.6	107	.0128	676	758	256	460	45.6	----------------------
82.4	119.5	42.4	139	.0172	937	1227	408	735	56.2	Erratic outlet temperature
9										
28.4	41.2	55.5	182	0.0086	716	830	292	526	75.5	----------------------
37.7	54.7	64.3	211	.0103	786	955	359	647	78.8	----------------------
52.3	75.8	78.3	257	.0130	895	1152	472	850	83.6	----------------------
57.4	83.3	83.5	274	.0138	926	1207	506	910	84.4	Erratic outlet temperature and inlet pressure
36.2	52.6	64.3	211	.0082	643	698	223	402	60.1	----------------------
47.9	69.5	76.5	251	.0100	698	796	279	503	62.6	----------------------
62.3	90.3	90.5	297	.0123	784	951	364	655	67.4	----------------------
69.1	100.3	96.0	315	.0133	831	1037	412	741	71.4	Erratic outlet temperature and inlet pressure
30.3	43.9	68.9	226	.0080	614	645	192	346	52.7	----------------------
39.9	57.8	80.5	264	.0098	635	683	214	385	49.0	----------------------
54.5	79.0	98.5	323	.0125	713	823	294	529	53.6	Low-frequency audible combustion resonance (rumble), erratic outlet temperature

TABLE IV. - Concluded. COMBUSTOR

Combustor-inlet-air conditions										Fuel temperature	
Total pressure		Total temperature		Flow		Reference velocity		PT/V			
N/cm^2	psia	K	°F	kg/sec	lb/sec	m/sec	ft/sec	$\frac{(N)(K)(sec)}{m^3}$	$\frac{(lb)(^oR)(sec)}{ft^3}$	K	°F
											Nozzle
17.0	24.7	424	304	20.9	46.1	33.2	109	21.66×10^5	24.82×10^3	294	70
17.0	24.6	424	304	21.0	46.2	33.5	110	21.47	24.61	293	68
17.0	24.6	423	302	20.8	45.9	33.2	109	21.65	24.81	295	71
17.0	24.7	424	304	21.0	46.3	33.5	110	21.67	24.83	295	71
17.0	24.6	424	303	21.0	46.4	33.5	110	21.36	24.48	298	77
17.0	24.7	423	301	20.8	45.8	32.9	108	21.83	25.01	298	77
17.0	24.7	430	314	25.4	56.1	40.8	134	17.88	20.49	292	66
16.9	24.5	428	311	25.6	56.4	41.5	136	17.48	20.03	293	68
17.0	24.7	427	309	25.8	56.9	41.1	135	17.72	20.30	293	68
17.0	24.6	426	307	25.5	56.3	40.8	134	17.74	20.32	293	68
17.0	24.6	423	302	25.6	56.4	40.8	134	17.62	20.19	295	71
13.4	19.5	424	303	21.0	46.3	42.1	138	13.58	15.56	298	76
13.5	19.6	423	301	20.9	46.1	41.5	136	13.78	15.79	296	74
13.4	19.5	422	300	20.8	45.9	41.5	136	13.69	15.69	296	73
13.5	19.6	423	302	20.8	45.9	41.5	136	13.82	15.84	297	75
											Nozzle
17.3	25.1	426	307	22.1	48.8	34.7	114	21.17×10^5	24.26×10^3	295	71
17.2	25.0	424	304	22.0	48,6	34.4	113	21.23	24.33	296	74
17.2	24.9	424	304	22.1	48,7	34.7	114	20.92	23.97	295	72
17.2	24.9	423	302	22.0	48.6	34.7	114	20.94	23.99	297	75
17.2	24.9	424	303	22.1	48.7	34.7	114	21.03	24.10	299	78
17.1	24.8	423	301	22.1	48.8	34.7	114	20.78	23.81	299	79
17.3	25.1	424	303	22.1	48.7	34.4	113	21.31	24.42	301	83
17.2	25.0	424	303	22.0	48.6	34.4	113	21.12	24.20	302	84
17.0	24.7	425	305	25.6	56.5	40.6	133	17.93	20.55	289	61
17.0	24.7	425	306	25.5	56.2	40.2	132	17.99	20.61	291	65
17.1	24.8	421	298	25.5	56.3	39.9	131	18.03	20.66	292	66
17.2	24.9	421	299	25.4	56.1	39.6	130	18.34	21.02	291	65
17.2	25.0	423	301	25.5	56.2	39.6	130	18.37	21.05	294	69
13.7	19.9	423	302	22.0	48.6	43.0	141	13.46	15.43	298	77
13.7	19.9	423	302	22.0	48.6	43.0	141	13.47	15.43	296	74
13.7	19.8	425	306	22.1	48.7	43.6	143	13.38	15.33	296	73
13.7	19.9	425	305	22.0	48.6	43.0	141	13.53	15.50	297	75
13.7	19.9	424	304	22.0	48.4	43.0	141	13.56	15.54	296	74

EFFICIENCY DATA WITH NATURAL GAS FUEL

Fuel pressure differential between manifold and combustor		Calculated fuel injection velocity		Fuel-air ratio	Combustor average exhaust total temperature		Combustor temperature rise		Combustion efficiency, percent	Remarks
N/cm^2	psi	m/sec	ft/sec		K	^{o}F	K	^{o}F		
11										
28.8	41.8	222.5	730	0.0081	734	862	310	558	86.1	------------------------
40.0	58.0	249.3	818	.0100	821	1019	398	716	90.4	------------------------
49.9	72.3	264.3	867	.0119	903	1166	480	864	93.1	------------------------
67.2	97.4	284.1	932	.0150	1025	1385	601	1081	95.0	------------------------
85.4	123.9	296.9	974	.0181	1137	1587	713	1284	95.8	------------------------
97.9	142.0	302.1	991	.0205	1231	1757	809	1456	97.0	High-frequency audible combustion resonance (buzz)
38.7	56.1	249.9	820	.0080	703	805	273	491	76.3	------------------------
50.0	72.6	270.4	887	.0096	754	898	326	587	77.0	------------------------
60.2	87.2	282.2	926	.0111	800	981	373	672	77.7	------------------------
71.0	102.9	289.6	950	.0129	838	1049	413	743	74.7	------------------------
93.0	134.8	304.8	1000	.0159	910	1179	487	877	73.1	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
32.5	47.1	269.1	883	.0080	673	752	249	449	70.0	------------------------
42.7	61.9	289.9	951	.0098	726	847	303	546	70.3	------------------------
52.0	75.5	306.6	1006	.0115	758	905	336	605	67.3	------------------------
55.6	80.6	310.0	1017	.0122	768	922	344	619	65.6	Low-frequency audible combustion resonance (rumble), erratic outlet temperature
13										
24.7	35.9	59.1	194	0.0074	702	804	276	497	82.5	------------------------
33.3	48.2	73.2	240	.0091	767	921	343	617	84.1	------------------------
43.0	62.4	86.9	285	.0110	837	1047	412	742	85.5	------------------------
52.5	76.1	100.6	330	.0127	910	1179	487	877	88.1	------------------------
60.2	87.4	110.9	364	.0142	975	1295	551	992	90.5	------------------------
69.1	100.2	123.4	405	.0158	1047	1425	625	1125	93.1	------------------------
82.0	118.9	137.8	452	.0182	1161	1630	737	1327	96.9	------------------------
93.0	134.9	149.7	491	.0203	1246	1783	822	1480	98.2	High-frequency audible combustion resonance (buzz), erratic outlet temperature
34.2	49.5	75.6	248	.0082	705	810	281	505	76.1	------------------------
44.5	64.6	91.4	300	.0098	745	882	320	576	73.5	------------------------
55.6	80.6	107.3	352	.0117	799	979	379	682	73.8	------------------------
64.9	94.2	118.9	390	.0133	861	1091	441	793	76.4	------------------------
82.4	119.5	139.0	456	.0161	974	1294	552	993	81.0	Erratic outlet temperature
30.2	43.7	82.3	270	.0078	657	723	234	421	66.3	------------------------
39.0	56.5	100.0	328	.0095	685	774	262	472	61.8	------------------------
47.6	69.1	117.0	384	.0113	711	820	286	514	57.7	------------------------
55.9	81.1	130.8	429	.0128	750	890	325	585	58.3	------------------------
67.8	98.3	150.0	492	.0151	803	985	378	681	58.5	Low-frequency audible combustion resonance (rumble), erratic outlet temperature

TABLE V. - COMBUSTOR ALTITUDE LIMIT DATA WITH NATURAL GAS FUEL

Combustor inlet-air conditions							Rating criteria	
Total pressure		Total temperature		Flow		Reference Mach number	Ignition - stable combustion at ignition fuel-air ratio	Combustion - blowout as fuel-air ratio increased above 0.010; stable combustion at fuel-air ratio of 0.010 or less
N/cm^2	psia	K	^{o}F	kg/sec	lb/sec			
Nozzle 1								
8.3	12.0	299	78	11.9	26.2	0.080	---	No
7.0	10.1	295	72	10.0	22.0	.079	Yes	No
5.6	8.1	292	66	8.0	17.6	.078	---	Yes
4.8	7.0	290	62	7.1	15.7	.081	Yes	Yes
4.1	6.0	289	61	6.0	13.3	.080	Yes	Yes
3.6	5.2	288	59	5.2	11.5	.079	No	---
13.8	20.0	301	82	24.0	54.9	.101	Yes	No
12.4	18.0	301	82	22.4	49.3	.100	Yes	Yes
11.0	16.0	300	81	19.8	43.6	.100	Yes	Yes
9.7	14.0	287	57	17.7	39.1	.100	Yes	Yes
9.0	13.0	288	58	16.5	36.3	.100	No	---
8.3	12.0	287	57	15.2	33.6	.100	No	---
2.8	4.0	416	289	3.4	7.5	.081	Yes	No
2.8	4.0	416	289	3.4	7.5	.081	---	Yes
2.1	3.0	412	282	2.5	5.6	.080	No	Yes
6.9	10.0	422	300	10.5	23.2	.101	Yes	No
5.6	8.1	425	305	8.4	18.5	.100	Yes	No
4.8	7.0	426	308	7.3	16.1	.101	Yes	Yes
4.1	6.0	427	309	6.3	13.8	.101	Yes	Yes
3.4	5.0	425	306	5.2	11.5	.101	Yes	---
2.8	4.0	423	302	4.2	9.3	.101	No	---
Nozzle 2								
9.7	14.0	299	78	14.0	30.8	0.080	Yes	No
8.3	12.0	298	77	11.8	26.0	.079	Yes	No
7.6	11.0	296	74	10.8	23.7	.078	No	No
7.0	10.1	297	75	10.0	22.1	.080	No	No
17.9	26.0	300	80	31.8	70.0	.099	Yes	No
15.2	22.0	296	73	27.6	60.8	.100	No	No
12.4	18.0	304	88	22.2	49.0	.100	No	No
11.0	16.0	305	89	19.7	43.5	.100	No	No
9.7	14.1	304	88	17.3	38.1	.100	---	No
8.3	12.0	301	82	14.7	32.5	.099	---	Yes
7 6	11.0	300	80	13.5	29.7	.099	---	Yes
7.6	11.0	416	290	9.3	20.6	.081	Yes	No
4.8	7.0	416	289	5.9	13.1	.081	Yes	No
4.2	6.1	408	274	5.1	11.3	.079	Yes	No
3.4	5.0	408	275	4.2	9.3	.080	No	No
2.8	4.0	410	278	3.4	7.4	.079	No	Yes
8.3	12.1	418	293	12.6	27.8	.100	No	No
7.6	11.0	416	290	11.7	25.8	.102	No	No
6.3	9.1	421	298	9.5	20.9	.100	No	No
5.5	8.0	419	295	8.4	18.6	.101	No	No
4.8	7.0	416	290	7.4	16.3	.101	---	Yes
Nozzle 3								
15.2	22.0	293	68	27.7	61.0	0.100	Yes	No
13.8	20.0	294	70	25.2	55.5	.101	Yes	Yes
13.1	19.0	294	70	23.9	52.7	.101	Yes	Yes
12.5	18.1	294	70	22.7	50.0	.100	No	---
4.8	7.0	422	300	7.3	16.2	.101	Yes	Yes
4.2	6.1	419	295	6.3	13.9	.099	Yes	Yes
4.1	6.0	419	295	6.3	13.9	.101	Yes	---
3.8	5.5	419	295	5.8	12.7	.100	No	---

TABLE V. - Continued. COMBUSTOR ALTITUDE LIMIT DATA WITH NATURAL GAS FUEL

Combustor inlet-air conditions							Rating criteria	
Total pressure		Total temperature		Flow		Reference Mach number	Ignition - stable combustion at ignition fuel-air ratio	Combustion - blowout as fuel-air ratio increased above 0.010; stable combustion at fuel-air ratio of 0.010 or less
N/cm^2	psia	K	^oF	kg/sec	lb/sec			
Nozzle 4								
17.2	25.0	304	88	24.5	54.0	0.079	Yes	No
15.9	23.1	304	88	23.1	51.0	.081	Yes	No
11.7	17.0	306	92	16.9	37.2	.081	No	---
11.7	17.0	306	92	16.9	37.2	.081	Yes	---
16.6	24.1	304	88	29.0	64.0	.098	Yes	No
15.9	23.0	300	88	27.7	61.0	.098	Yes	Yes
15.2	22.0	305	89	27.2	60.0	.101	Yes	Yes
13.8	20.0	306	91	24.7	54.5	.101	Yes	---
12.5	18.1	306	92	22.3	49.2	.101	Yes	---
11.7	17.0	306	92	21.1	46.5	.101	No	---
6.9	10.0	419	294	10.5	23.2	.101	Yes	Yes
5.6	8.1	418	293	8.4	18.6	.100	Yes	Yes
4.8	7.0	420	296	7.3	16.2	.101	Yes	Yes
3.5	5.1	419	295	5.3	11.6	.099	Yes	---
3.3	4.8	418	293	4.1	9.0	.081	No	---
Nozzle 5								
12.4	18.0	313	103	17.5	38.6	0.080	Yes	No
9.7	14.0	312	102	13.6	30.0	.080	---	No
6.9	10.0	311	101	9.8	21.5	.080	Yes	Yes
5.6	8.1	307	93	7.9	17.4	.079	Yes	Yes
4.1	6.0	306	92	6.0	13.2	.081	Yes	---
3.4	5.0	305	90	4.9	10.9	.080	No	---
17.3	25.1	309	96	30.8	68.0	.101	Yes	No
16.5	24.0	310	98	29.8	65.6	.102	Yes	Yes
15.9	23.0	311	101	28.3	62.5	.101	Yes	Yes
15.2	22.0	314	105	27.0	59.5	.101	No	---
3.4	5.0	416	289	4.2	9.3	.080	No	No
7.0	10.1	421	298	10.5	23.2	.100	Yes	No
5.5	8.0	420	297	8.4	18.6	.101	Yes	No
4.2	6.1	420	296	6.3	13.9	.099	Yes	Yes
3.4	5.0	418	293	5.3	11.6	.101	No	Yes
Nozzle 6								
8.3	12.0	304	88	11.7	25.8	0.079	Yes	No
6.9	10.0	304	87	9.8	21.5	.079	Yes	Yes
5.5	8.0	303	86	7.8	17.2	.079	Yes	Yes
4.8	7.0	301	83	6.9	15.2	.080	No	---
4.1	6.0	303	85	5.9	13.0	.079	No	---
16.5	24.0	293	68	30.2	66.5	.100	Yes	No
15.2	22.0	294	70	27.7	61.0	.101	Yes	No
13.8	20.0	295	72	25.2	55.5	.101	Yes	Yes
12.4	18.0	299	78	22.1	48.7	.099	Yes	Yes
11.7	17.0	299	78	20.9	46.0	.099	No	---
11.0	16.0	299	78	19.6	43.3	.099	No	---
7.0	10.1	419	294	10.8	23.7	.102	Yes	No
6.2	9.0	421	298	9.5	20.9	.101	Yes	No
5.5	8.0	422	300	8.4	18.6	.101	Yes	Yes
4.8	7.0	423	301	7.3	16.2	.101	Yes	Yes
4.1	6.0	422	300	6.3	13.9	.101	No	---

TABLE V. - Continued. COMBUSTOR ALTITUDE LIMIT DATA WITH NATURAL GAS FUEL

Combustor inlet-air conditions							Rating criteria	
Total pressure		Total temperature		Flow		Reference Mach number	Ignition - stable combustion at ignition fuel-air ratio	Combustion - blowout as fuel-air ratio increased above 0.010; stable combustion at fuel-air ratio of 0.010 or less
N/cm^2	psia	K	^oF	kg/sec	lb/sec			
Nozzle 7								
13.8	20.0	309	96	24.0	53.0	0.098	Yes	Yes
12.4	18.0	311	100	22.0	48.5	.100	Yes	Yes
11.0	16.0	309	96	19.5	43.0	.100	Yes	Yes
10.3	15.0	307	93	18.2	40.2	.099	Yes	---
9.7	14.0	306	92	17.1	37.7	.100	No	---
4.1	6.0	419	295	5.0	11.1	.080	Yes	No
7.6	11.0	419	295	11.7	25.7	.101	Yes	No
5.5	8.0	420	297	8.4	18.6	.101	Yes	No
4.8	7.0	419	295	7.3	16.2	.101	Yes	No
4.1	6.0	420	296	6.3	13.9	.101	No	No
Nozzle 8								
13.8	20.0	301	83	19.8	43.6	0.080	Yes	No
12.4	18.0	301	83	17.9	39.4	.080	Yes	Yes
11.7	17.0	301	83	16.9	37.2	.080	Yes	Yes
11.0	16.0	300	81	15.9	35.0	.080	No	Yes
16.6	24.1	300	80	29.9	66.0	.100	Yes	Yes
16.5	24.0	297	75	30.1	66.4	.101	Yes	No
15.2	22.0	297	75	27.4	60.4	.100	No	Yes
Nozzle 9								
9.7	14.0	304	87	13.8	30.5	0.080	Yes	No
8.3	12.0	303	85	11.8	26.1	.080	Yes	No
7.0	10.1	303	86	9.9	21.8	.079	Yes	Yes
5.5	8.0	302	84	7.9	17.4	.080	Yes	Yes
17.2	25.0	298	76	31.2	68.7	.100	Yes	No
16.5	24.0	294	70	29.7	65.5	.099	Yes	Yes
2.8	4.0	403	265	3.4	7.5	.080	Yes	No
2.1	3.0	403	265	2.5	5.6	.079	No	Yes
8.3	12.0	420	296	12.6	27.8	.101	Yes	No
7.0	10.1	420	296	10.5	23.2	.100	Yes	No
6.2	9.0	419	295	9.5	20.9	.101	Yes	Yes
5.5	8.0	419	294	8.4	18.6	.101	Yes	Yes
4.8	7.0	418	293	7.4	16.4	.102	Yes	---
3.4	5.0	415	288	5.3	11.7	.101	Yes	---
2.8	4.0	414	285	4.3	9.4	.101	Yes	---
2.1	3.0	411	280	3.2	7.0	.100	No	---

TABLE V. - Concluded. COMBUSTOR ALTITUDE LIMIT DATA WITH NATURAL GAS FUEL

Combustor inlet-air conditions							Rating criteria	
Total pressure		Total temperature		Flow		Reference Mach number	Ignition - stable combustion at ignition fuel-air ratio	Combustion - blowout as fuel-air ratio increased above 0.010; stable combustion at fuel-air ratio of 0.010 or less
N/cm^2	psia	K	^oF	kg/sec	lb/sec			
Nozzle 11								
11.0	16.0	299	78	16.1	35.5	0.081	Yes	No
9.7	14.1	299	78	14.2	31.2	.081	Yes	No
9.0	13.0	296	73	13.2	29.0	.081	No	No
8.3	12.0	297	75	12.2	26.8	.081	No	No
6.9	10.0	297	75	10.0	22.0	.080	No	No
6.2	9.0	300	80	9.1	20.0	.081	---	Yes
19.0	27.5	295	72	34.0	75.0	.099	Yes	No
19.0	27.5	294	70	34.1	75.1	.099	No	Yes
17.2	25.0	296	73	30.8	68.0	.099	No	Yes
6.2	9.0	425	305	7.6	16.7	.081	Yes	No
4.1	6.0	429	313	5.0	11.1	.081	Yes	Yes
3.4	5.0	432	318	3.9	8.5	.075	No	Yes
9.7	14.0	423	302	14.7	32.4	.101	Yes	No
8.3	12.0	423	302	12.6	27.8	.101	Yes	No
6.9	10.0	423	301	10.5	23.2	.101	Yes	Yes
6.2	9.0	417	291	9.5	20.9	.101	No	Yes
5.5	8.0	418	292	8.4	18.6	.101	No	---
Nozzle 13								
7.6	11.0	301	82	11.0	24.2	0.080	No	No
6.9	10.0	297	75	10.0	22.0	.080	No	No
5.5	8.0	301	82	7.9	17.5	.080	No	Yes
10.3	15.0	291	65	18.9	41.6	.100	Yes	No
8.3	12.0	290	63	15.1	33.3	.100	No	No
6.9	10.0	297	75	12.6	27.8	.101	No	Yes
5.5	8.0	303	85	9.9	21.8	.100	No	Yes
8.3	12.0	422	300	10.1	22.2	.080	Yes	No
5.5	8.0	417	291	6.8	14.9	.081	Yes	No
4.8	7.0	418	292	6.2	13.6	.084	No	Yes
4.1	6.0	416	290	5.0	11.1	.080	No	Yes
8.3	12.0	422	300	12.6	27.8	.101	Yes	No
6.9	10.0	421	299	10.5	23.2	.101	Yes	No
5.5	8.0	421	298	8.4	18.6	.101	No	Yes
4.8	7.0	420	296	7.7	17.0	.106	No	Yes
4.1	6.0	420	297	6.3	13.9	.101	No	---

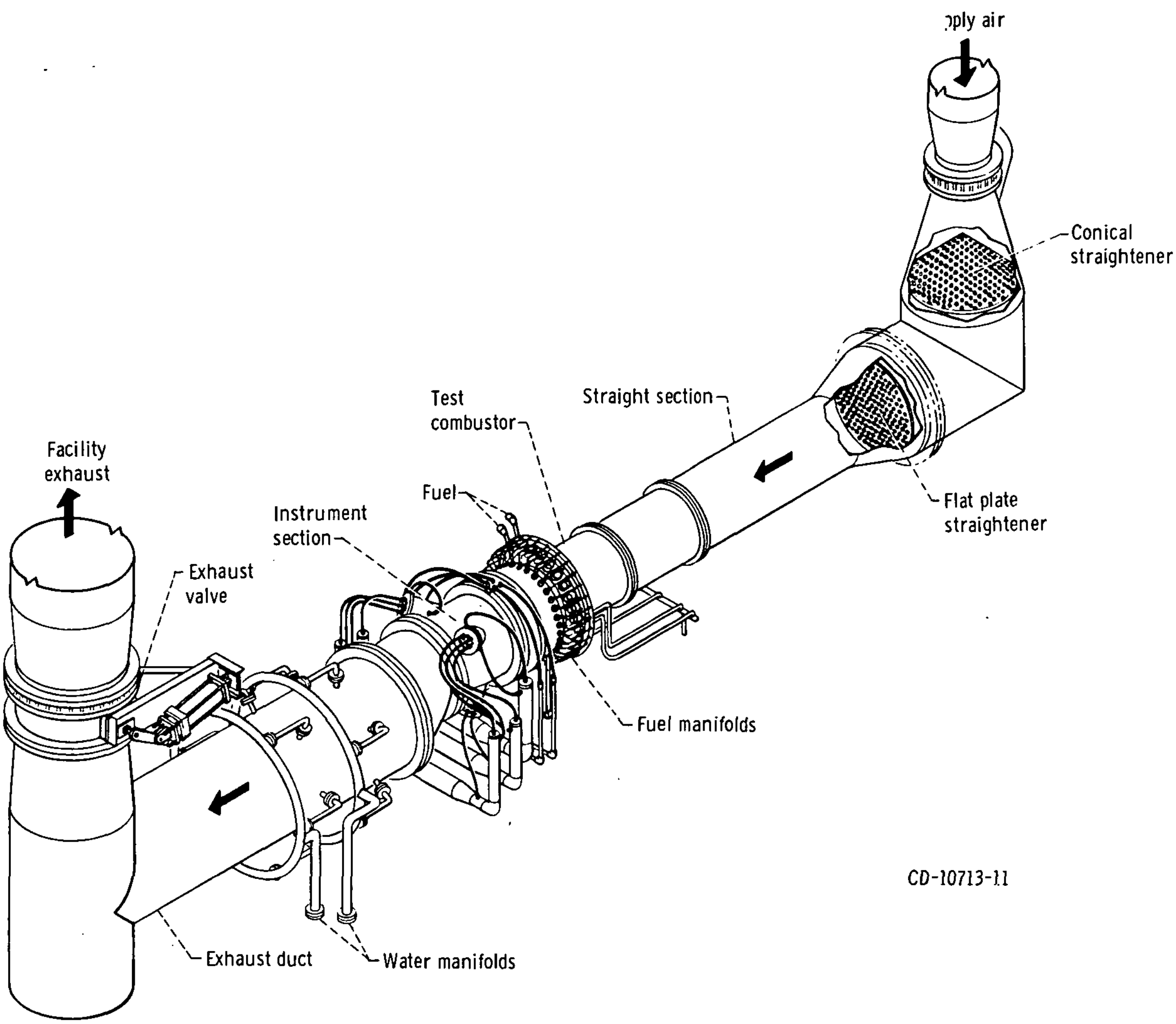


Figure 1. - Test section overall view.

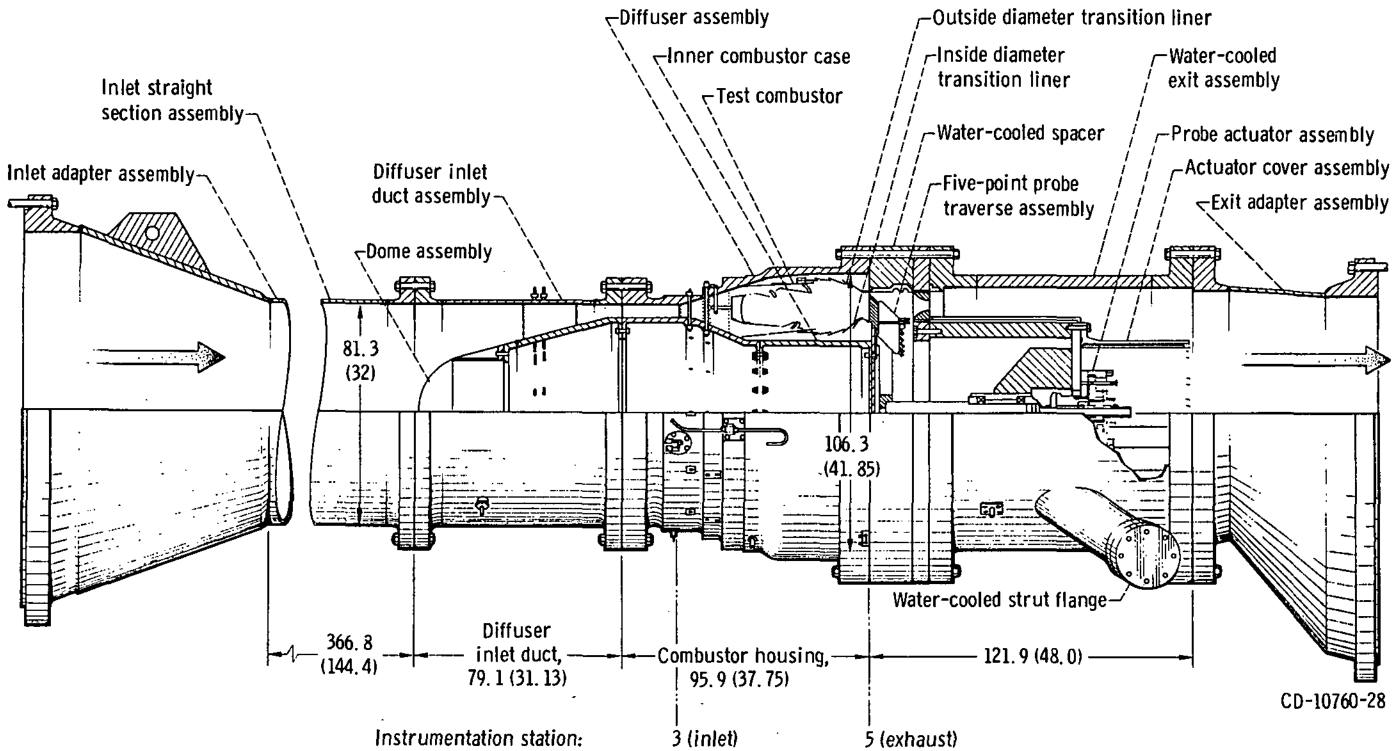


Figure 2. - Test section for full-scale annular combustor. (Dimensions are in centimeters (in.).)

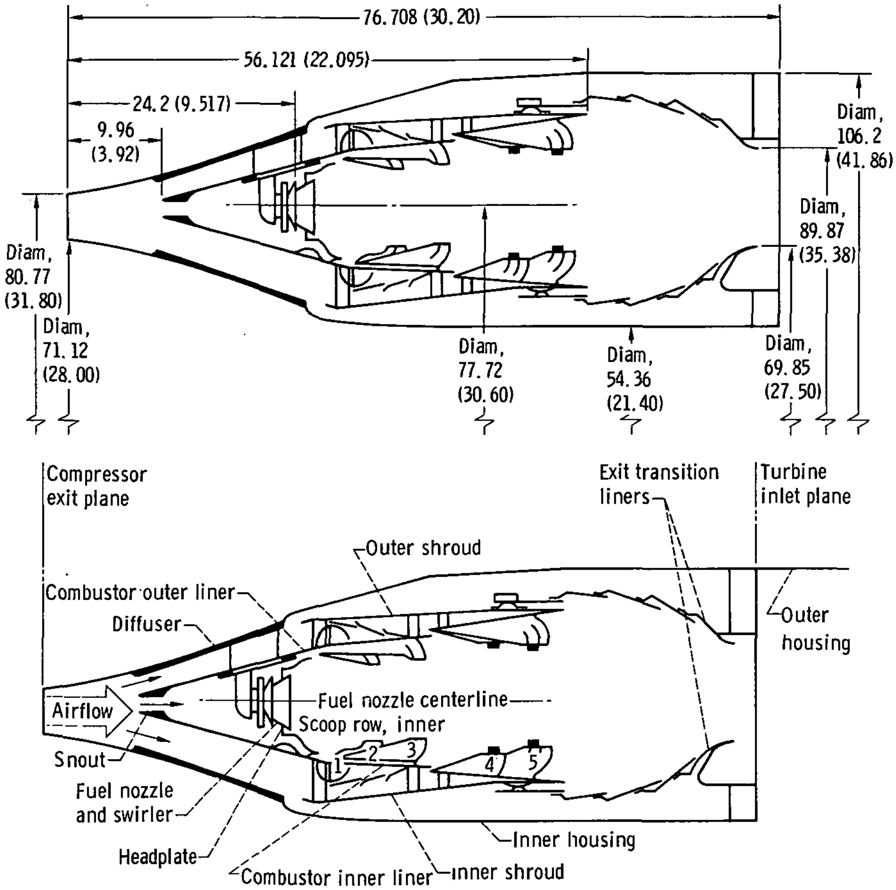


Figure 3. - Cross-sectional sketch of ram-induction annular combustor, model F. (Dimensions are in centimeters (in.).)

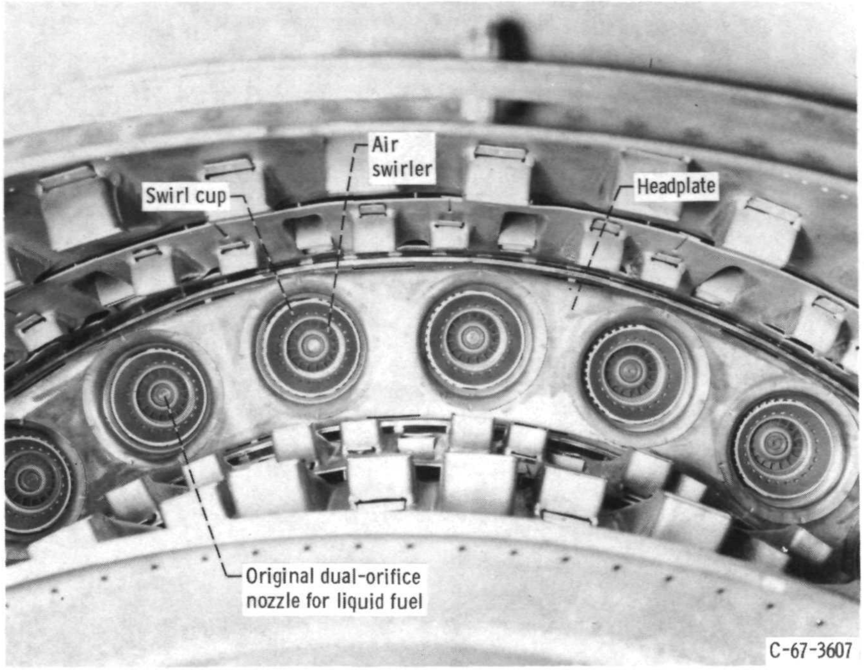
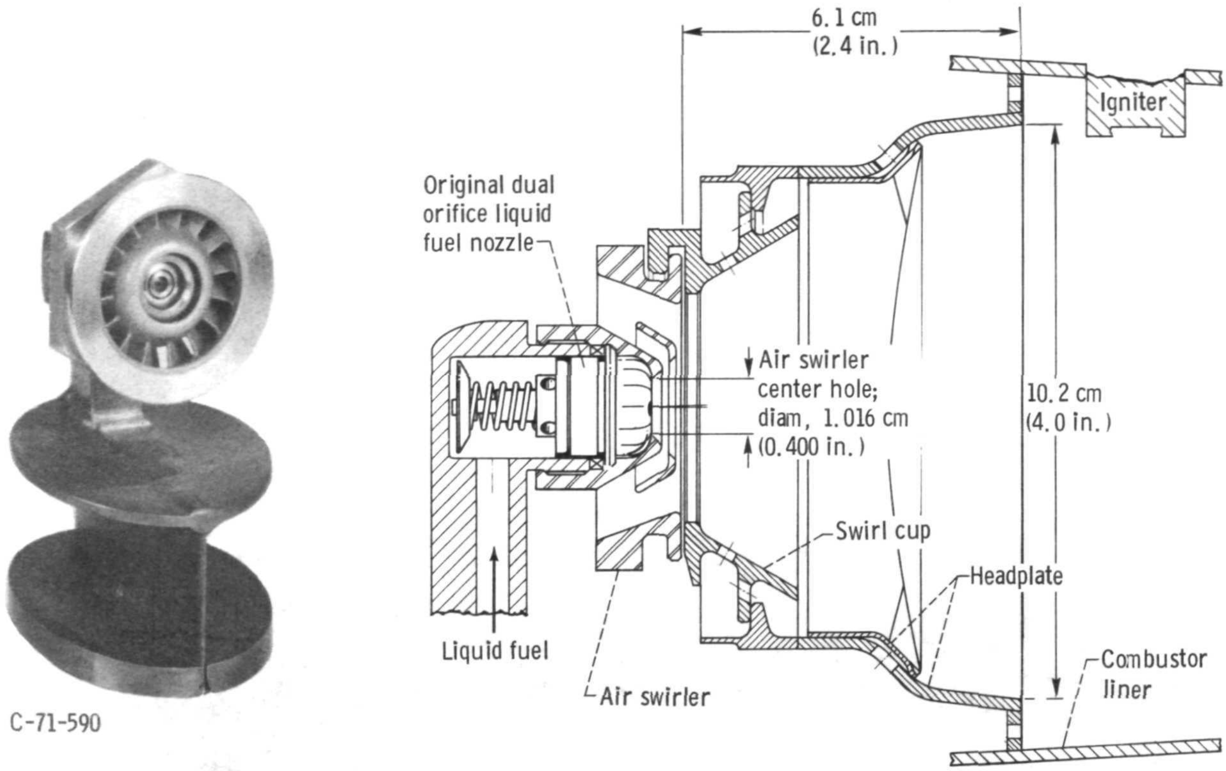
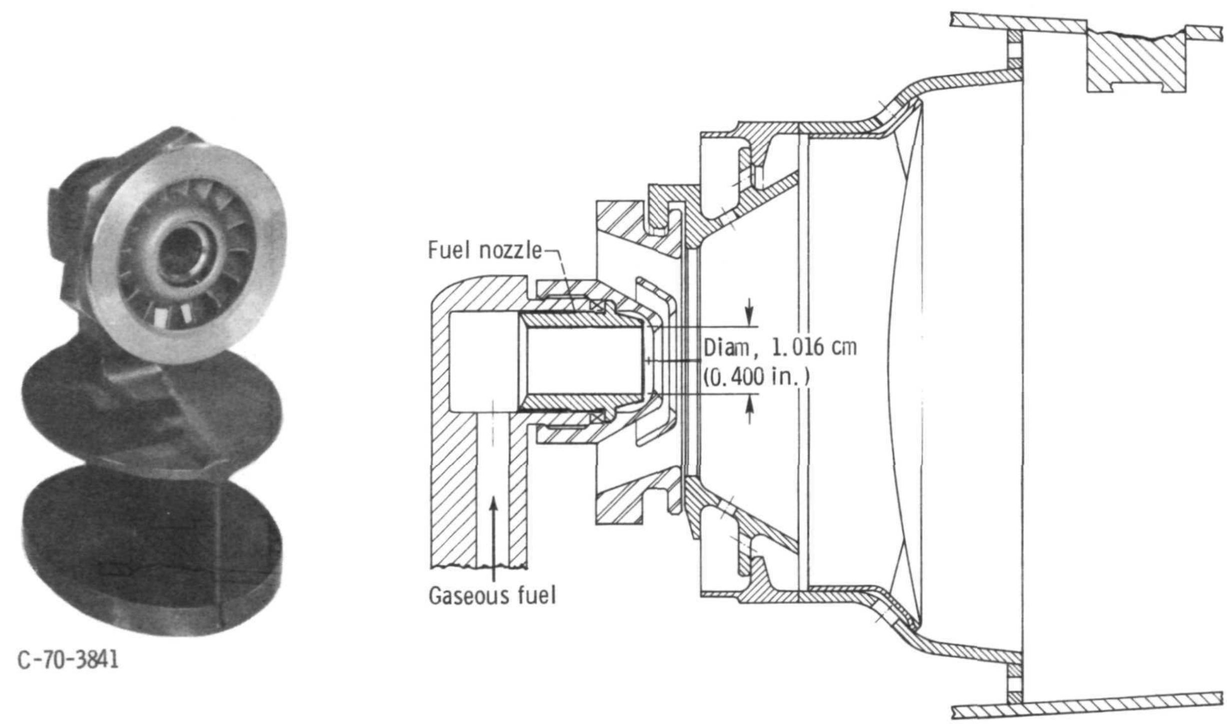


Figure 4. - View of ram-induction combustor looking upstream.

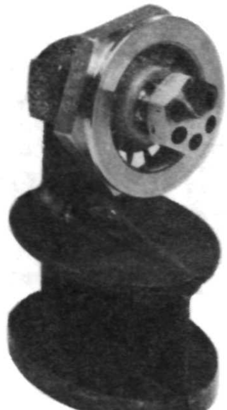


(a) Original dual-orifice fuel nozzle, for liquid fuel.



(b) Nozzle 13.

Figure 5. - Fuel strut installed in combustor.



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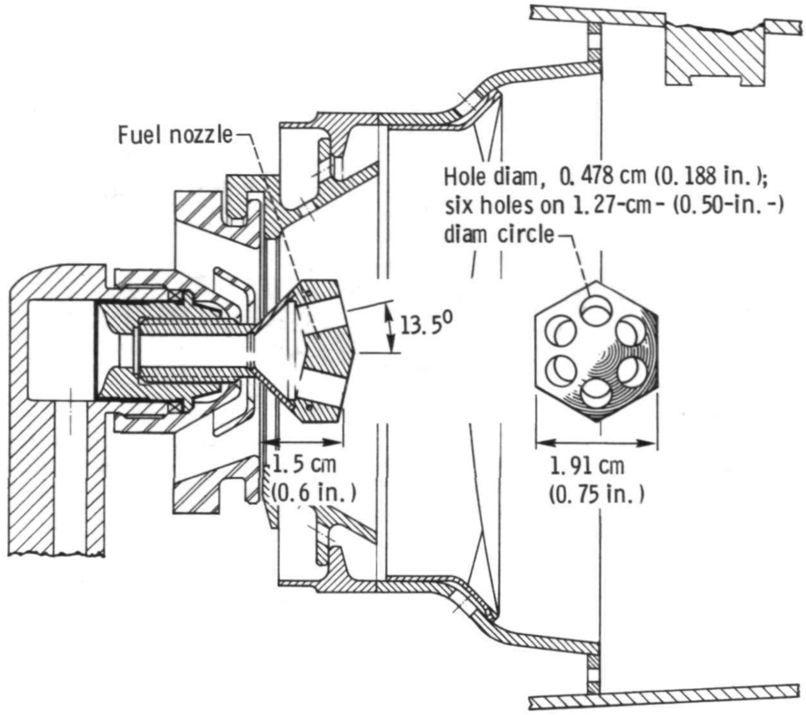
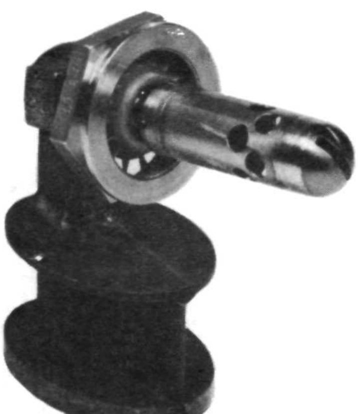
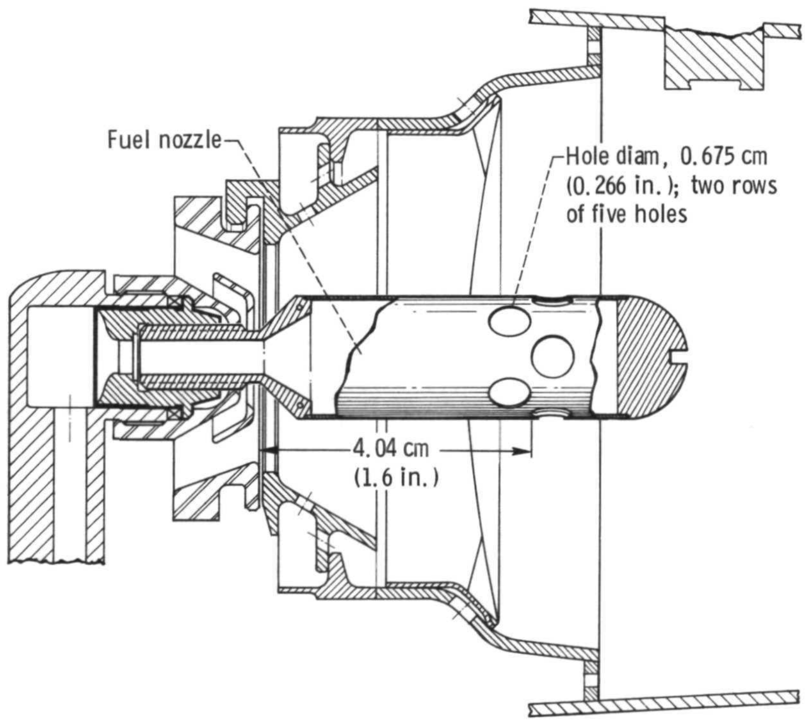


(c) Nozzle 2.

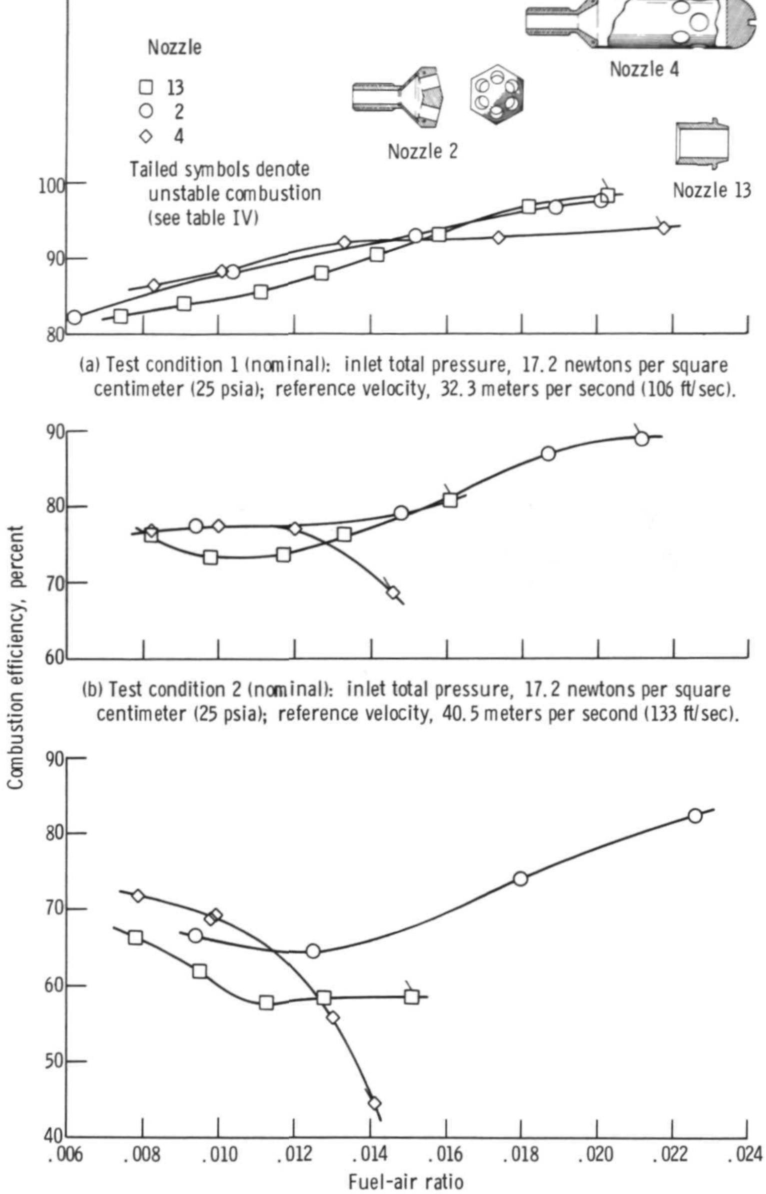


C-69-3935



(d) Nozzle 4.

Figure 5. - Concluded.

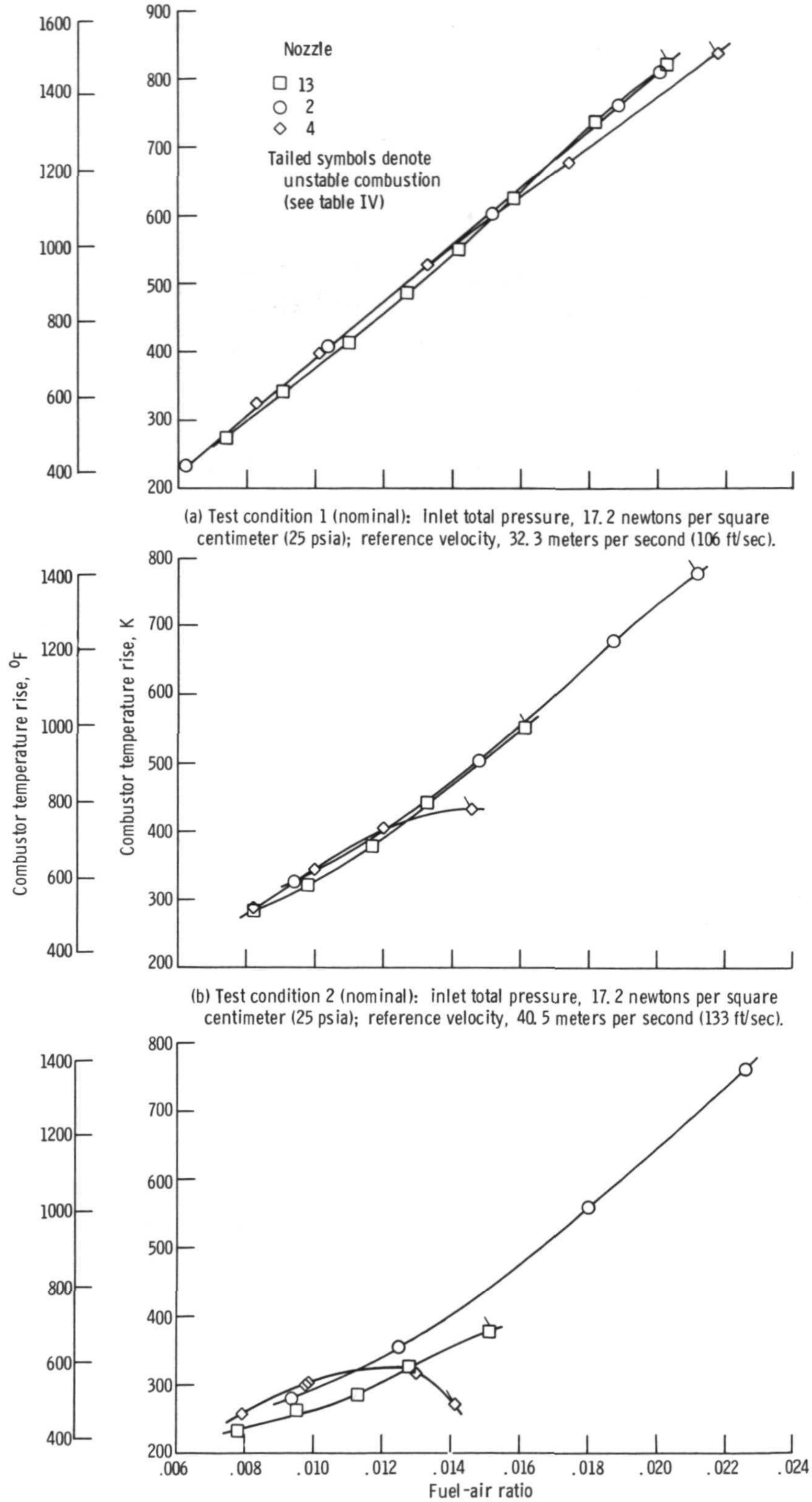


(a) Test condition 1 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

Figure 6. - Combustion efficiency as affected by fuel-air ratio for various fuel nozzles. Inlet-air total temperature, 422 K (300° F).



(a) Test condition 1 (nominal): Inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

Figure 7. - Combustor temperature rise as affected by fuel-air ratio for various fuel nozzles. Inlet-air total temperature, 422 K (300° F).

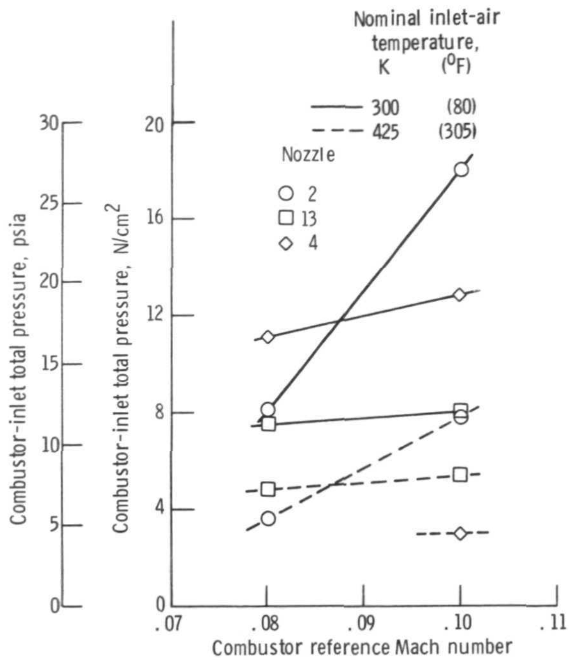


Figure 8. - Variation of minimum ignition pressure with combustor reference Mach number.

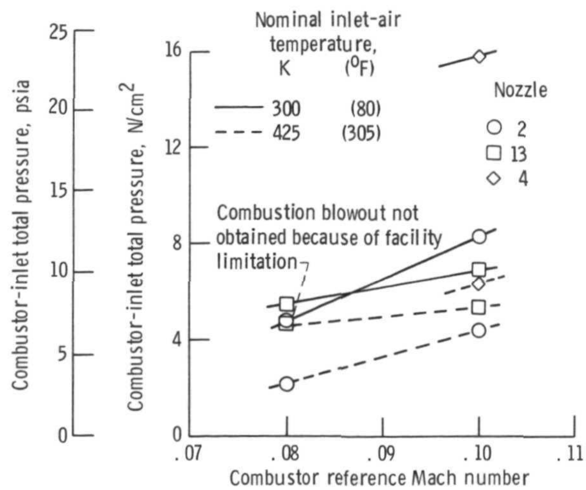


Figure 9. - Variation of combustor blowout pressure with combustor reference Mach number.

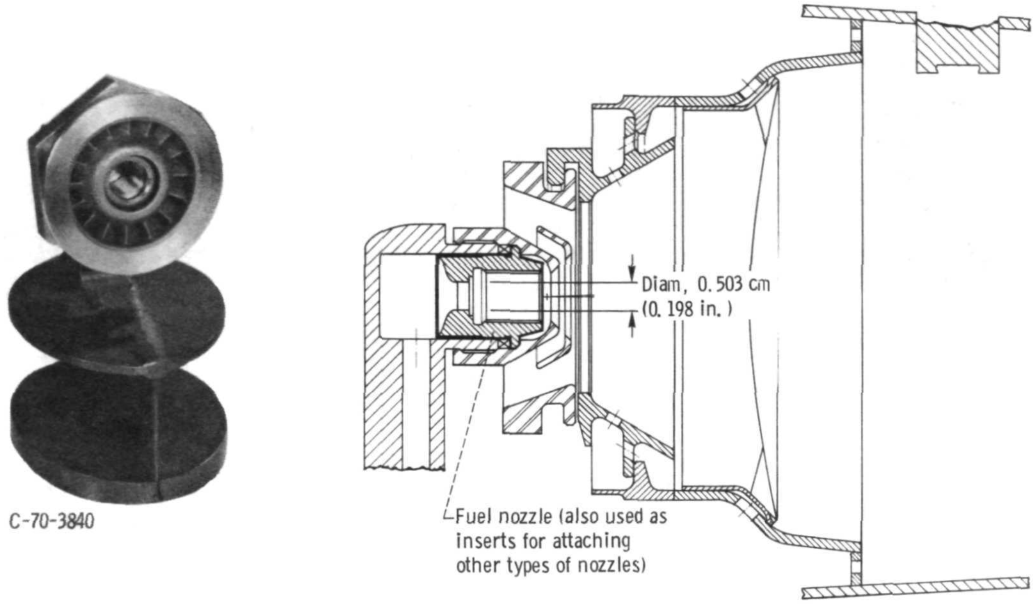


Figure 10. - Nozzle 11.

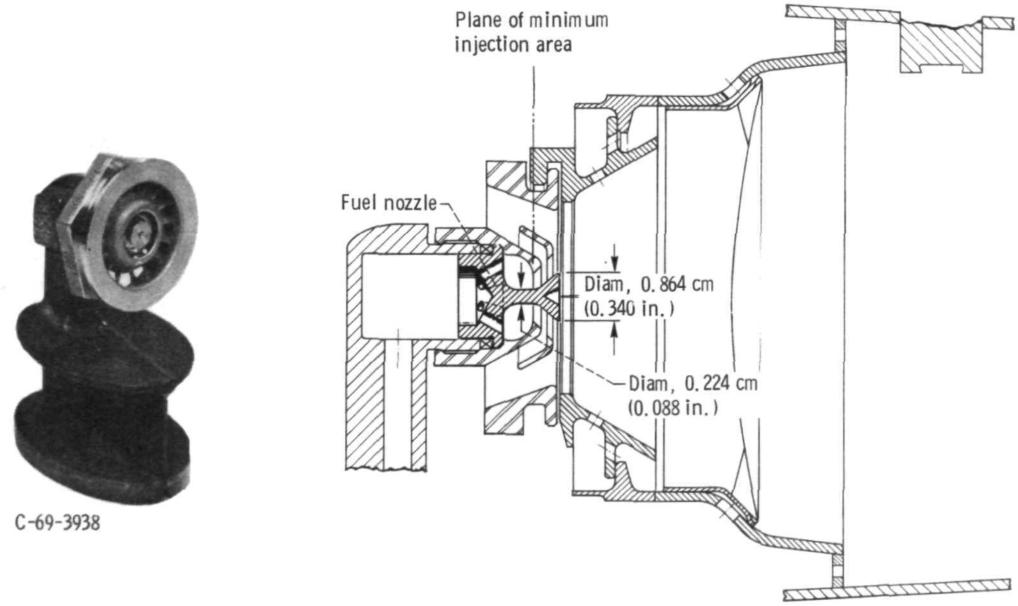


Figure 11. - Nozzle 1.

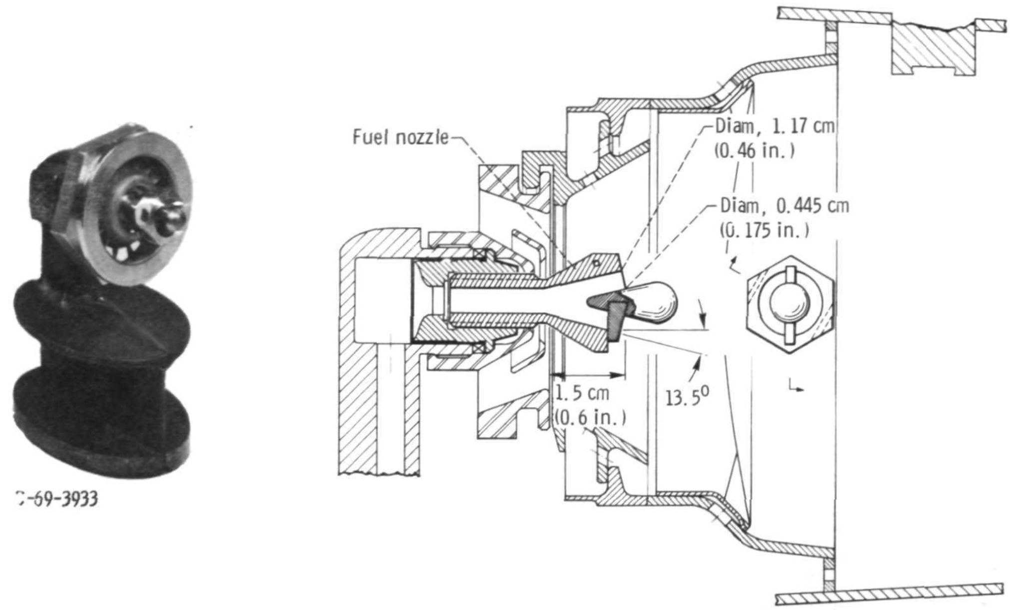


Figure 12. - Nozzle 6.

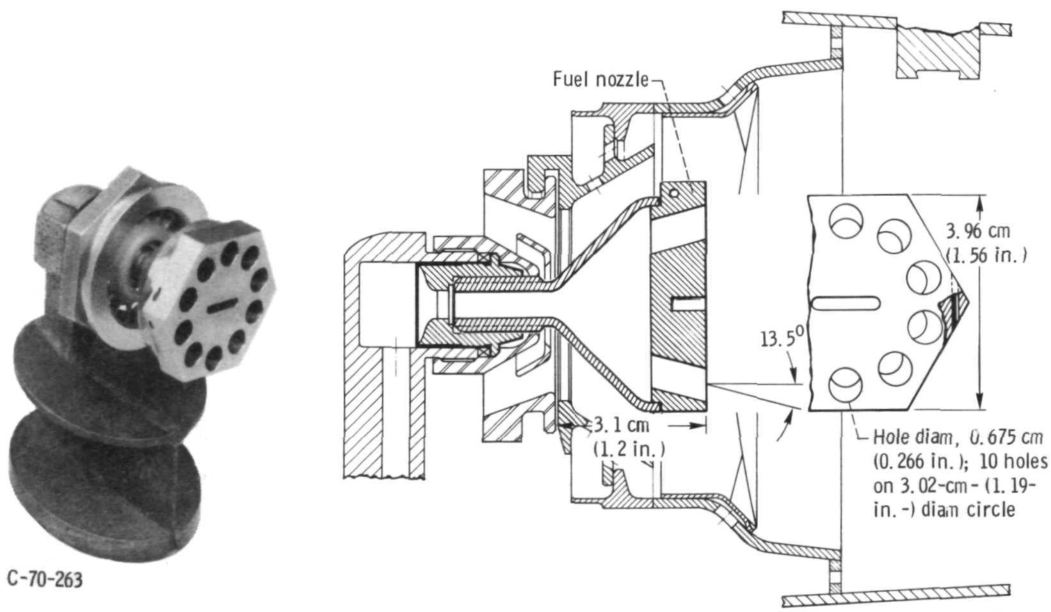


Figure 13. - Nozzle 8.

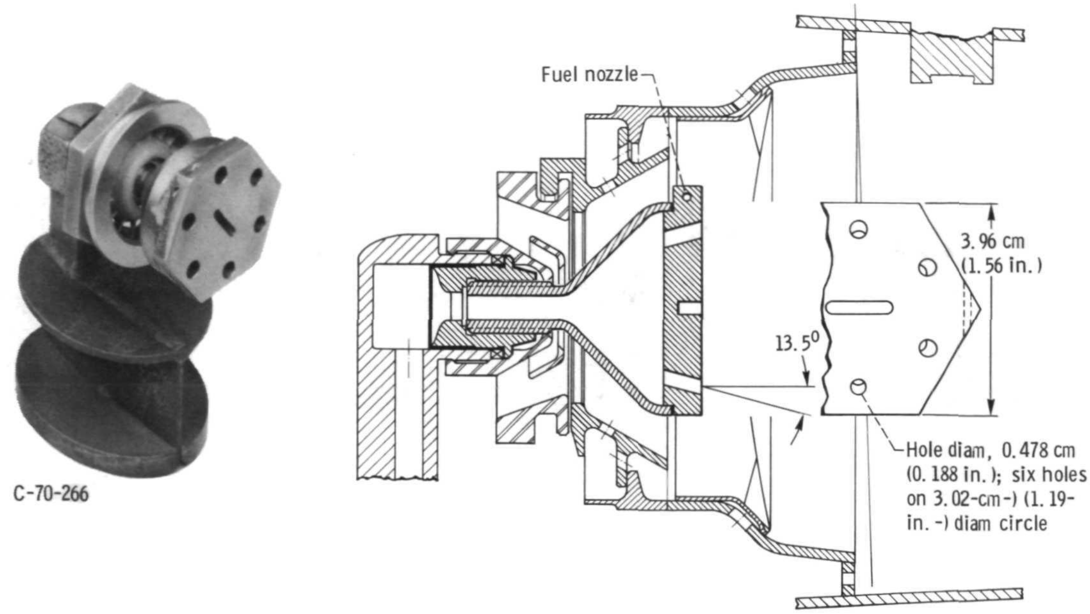


Figure 14. - Nozzle 9.

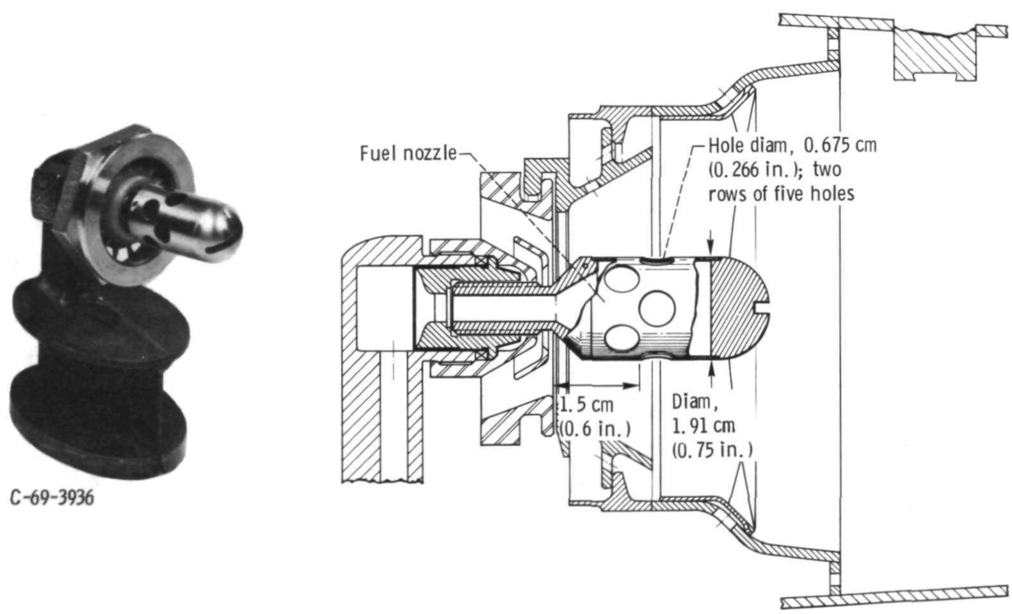
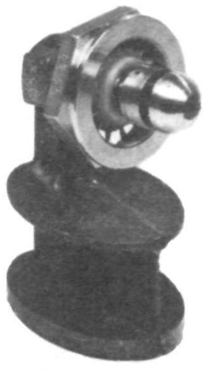


Figure 15. - Nozzle 3.



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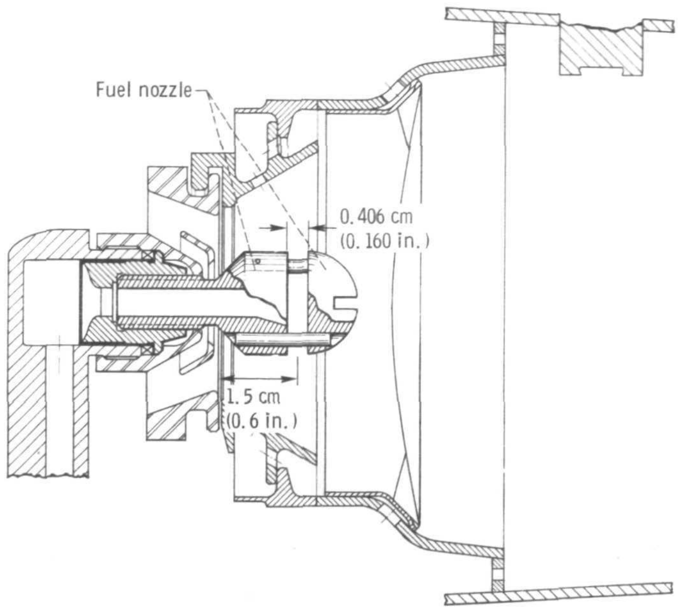
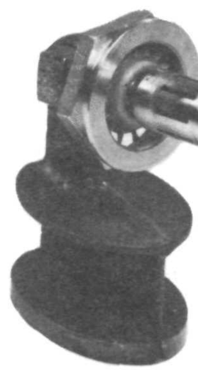


Figure 16. - Nozzle 5.



C-69-3932

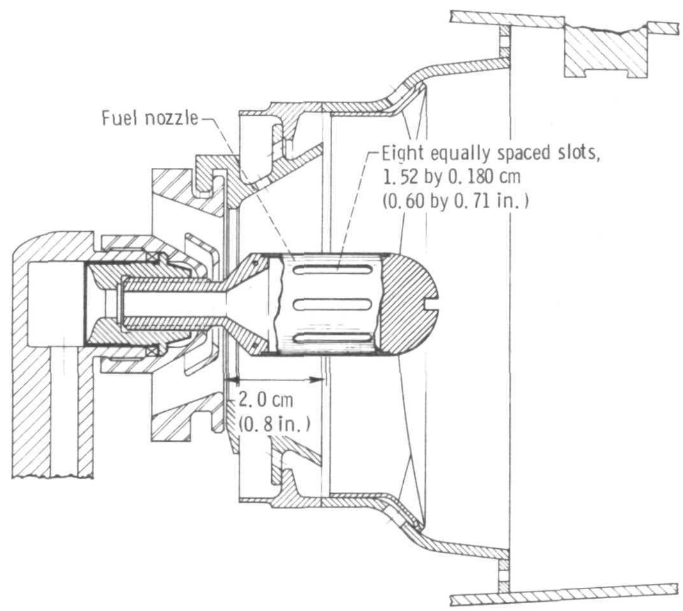
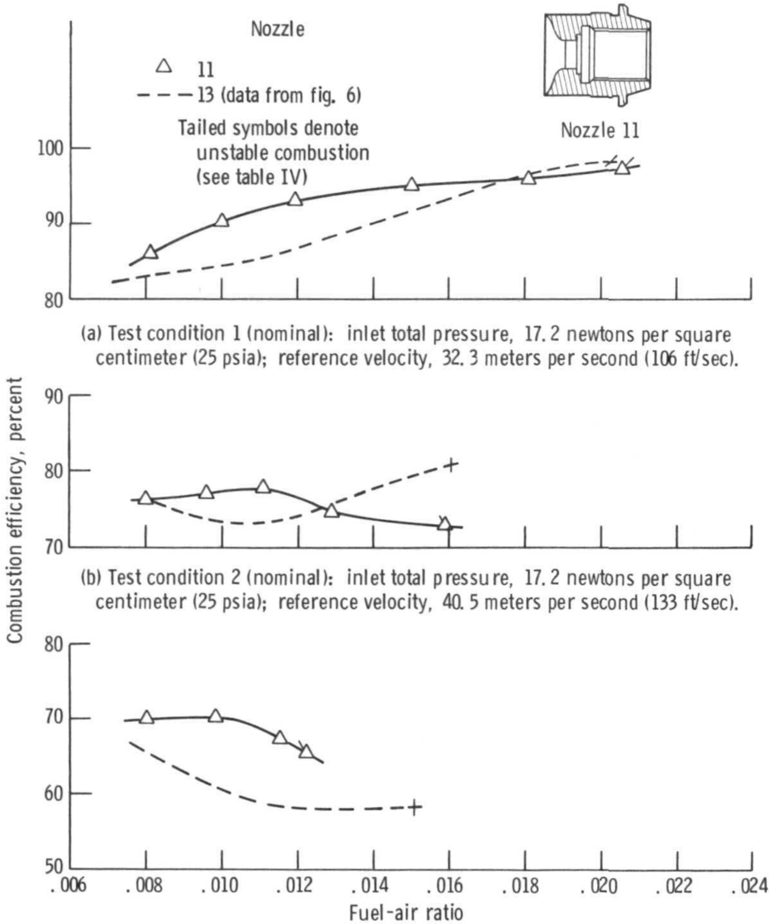


Figure 17. - Nozzle 7.

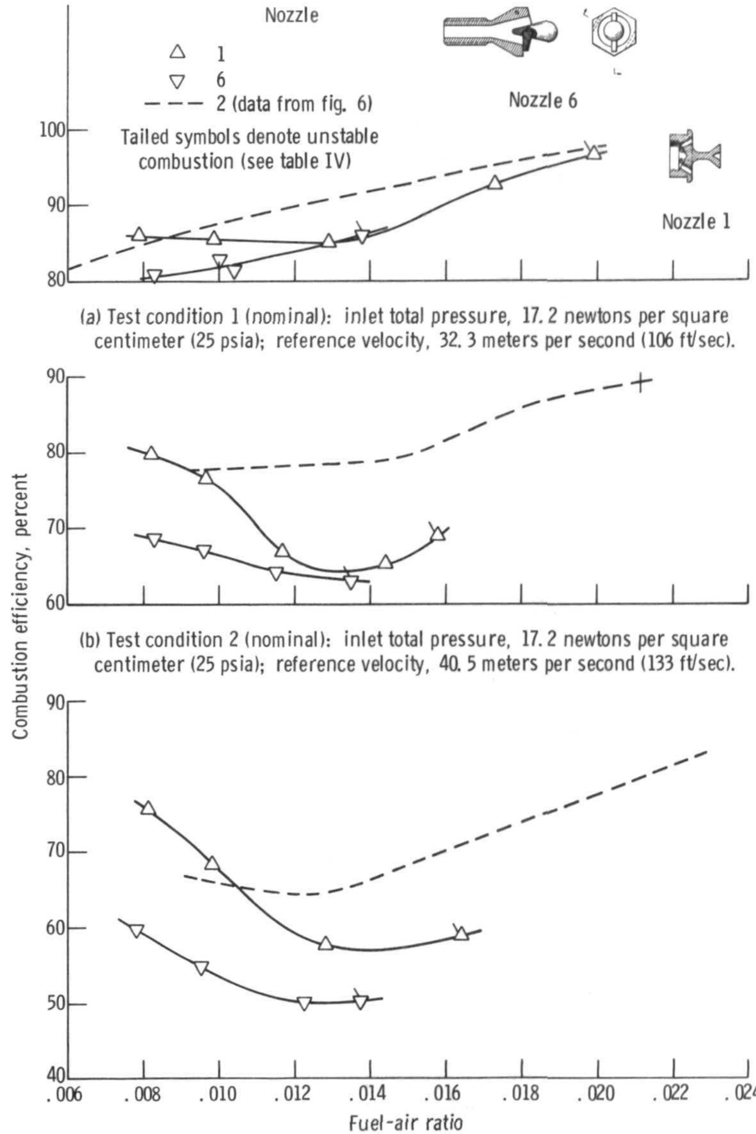


(a) Test condition 1 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

Figure 18. - Combustion efficiency as affected by fuel-air ratio for two types of axial-injection fuel nozzles. Inlet-air total temperature, 422 K (300° F).

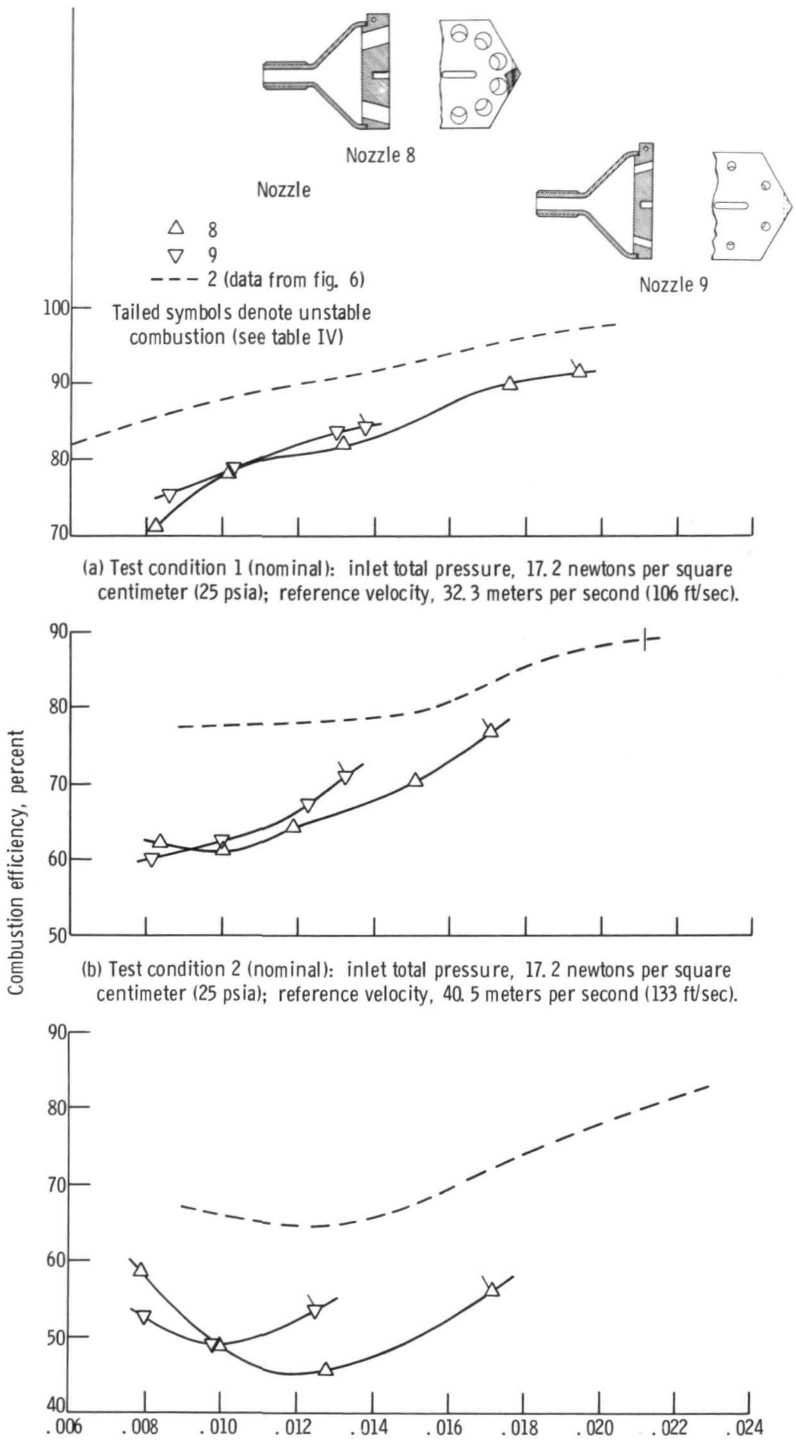


(a) Test condition 1 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

Figure 19. - Combustion efficiency as affected by fuel-air ratio for three types of angled-injection fuel nozzles. Inlet-air total temperature, 422 K (300° F).

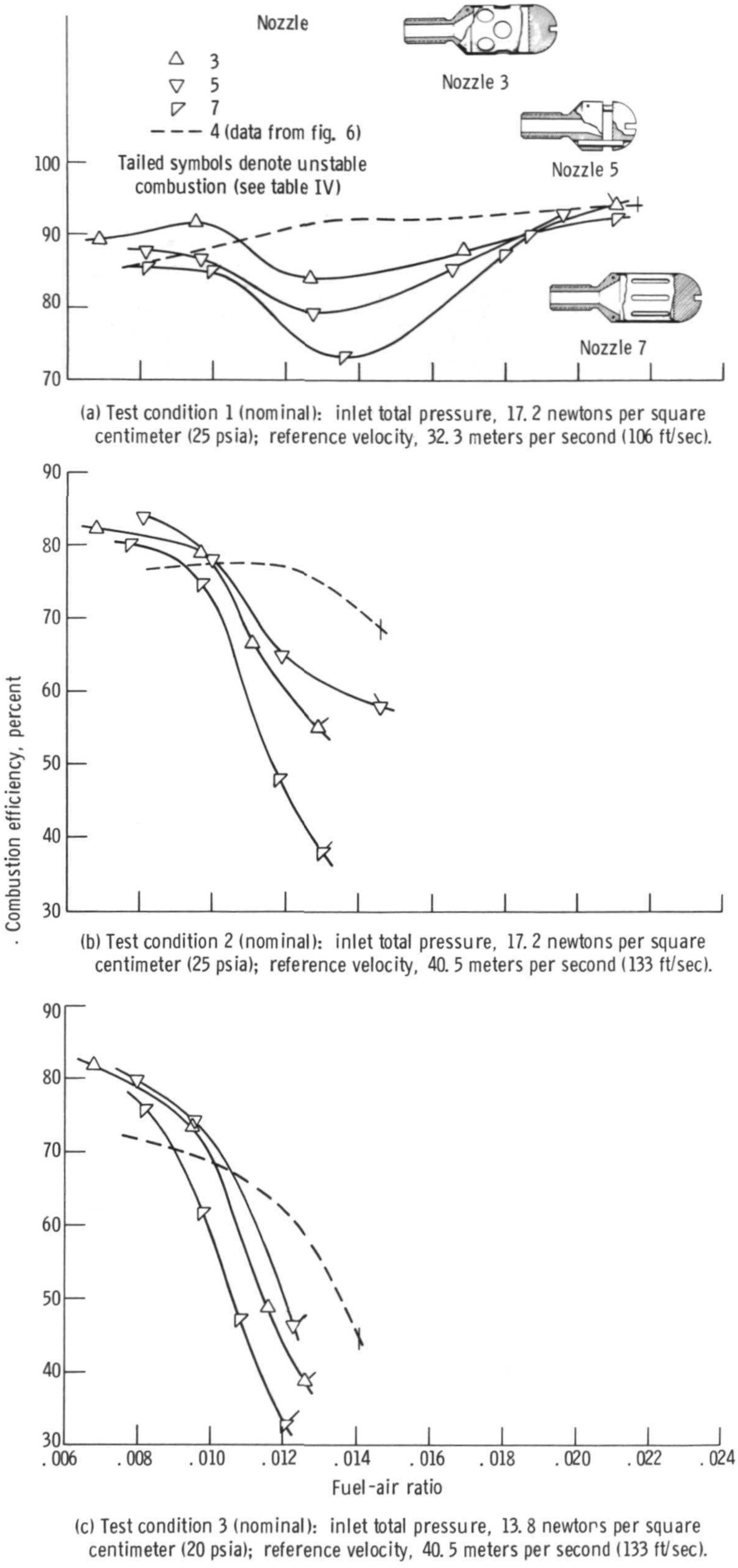


(a) Test condition 1 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

Figure 20. - Combustion efficiency as affected by fuel-air ratio for three types of angled-injection fuel nozzles. Inlet-air total temperature, 422 K (300^0 F).

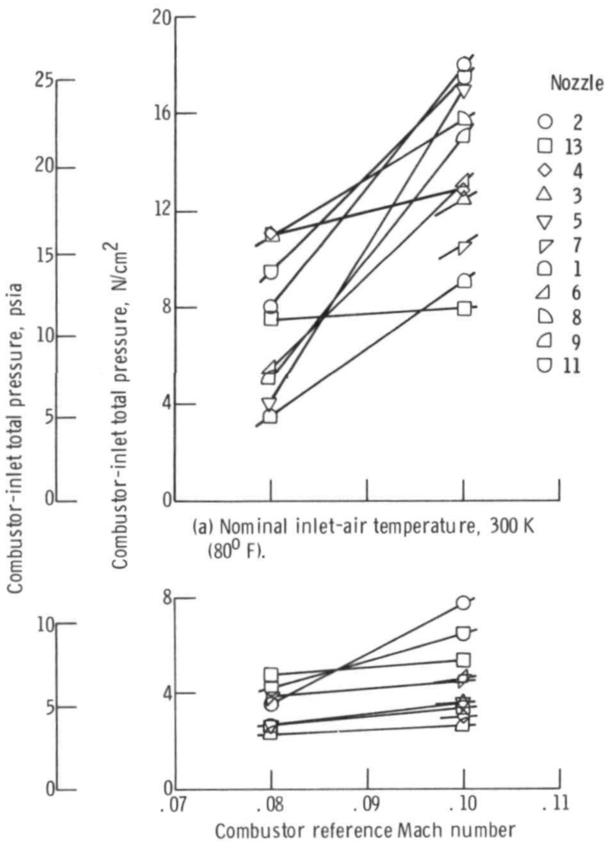


(a) Test condition 1 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 32.3 meters per second (106 ft/sec).

(b) Test condition 2 (nominal): inlet total pressure, 17.2 newtons per square centimeter (25 psia); reference velocity, 40.5 meters per second (133 ft/sec).

(c) Test condition 3 (nominal): inlet total pressure, 13.8 newtons per square centimeter (20 psia); reference velocity, 40.5 meters per second (133 ft/sec).

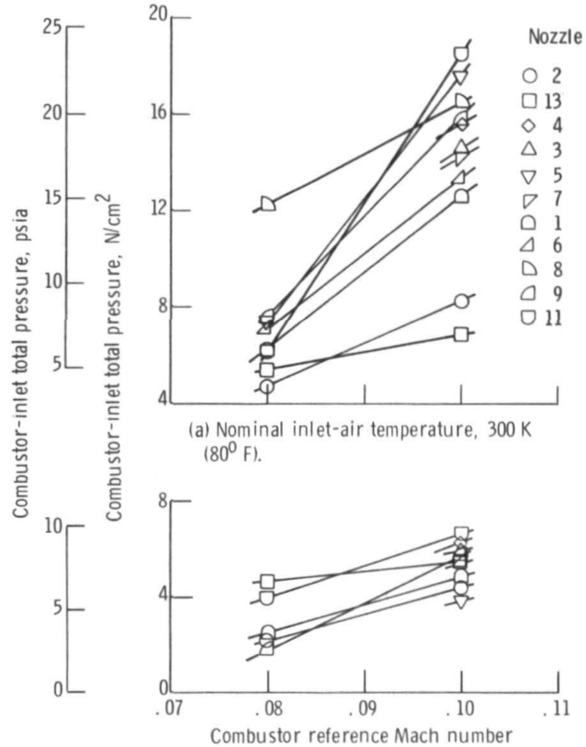
Figure 21. - Combustion efficiency as affected by fuel-air ratio for four types of radial-injection fuel nozzles. Inlet-air total temperature, 422 K (300° F).



(a) Nominal inlet-air temperature, 300 K (80° F).

(b) Nominal inlet-air temperature, 425 K (305° F).

Figure 22. - Variation of minimum ignition pressure with combustor reference Mach number for the various fuel nozzles.



(a) Nominal inlet-air temperature, 300 K (80° F).

(b) Nominal inlet-air temperature, 425 K (305° F).

Figure 23. - Variation of combustor blowout pressure with combustor reference Mach number for the various fuel nozzles.

NASA-Langley, 1972 —— 28 E-6459

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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