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FULL-SCALE TESTS OF A SHORT-LENGTH, DOUBLE-ANNULAR RAM-INDUCTION TURBOJET COMBUSTOR FOR SUPERSONIC FLIGHT

by Porter J. Perkins, Donald F. Schultz, and Jerrold D. Wear

*Lewis Research Center
Cleveland, Ohio 44135*

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16. Abstract

A 40-in. (102-cm) diameter combustor $20\frac{1}{4}$ in. (51.5 cm) in length gave performance equalling or exceeding that of a similar combustor 50 percent longer. Tests were with inlet-air at 1150° F (895 K) and 90 psia (62.0 N/cm^2), at 1050° F (839 K) and 60 psia (41.4 N/cm^2), and at 600° F (589 K) and 90 psia (62.0 N/cm^2), with 2200° F (1478 K) exit temperatures. Combustion efficiency was 100 percent, exit temperature profiles were good, and no visible smoke was measured. At cruise and takeoff, pattern factors were 0.20 and 0.25, and pressure loss 8.4 percent and 6.2 percent, respectively. Blowout limits, altitude relight, and response to rapid increase in fuel flow were measured over a wide operating range. Durability was satisfactory for 100 hr although some metal burning occurred at the 1150° F (895 K) inlet temperature.

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SUMMARY

Full-scale tests were conducted to determine the performance of a short-length, 40-inch (102-cm) diameter turbojet combustor. The combustor was designed for a large turbofan engine operating at flight speeds up to Mach 3.0. The short overall diffuser-combustor length of $20\frac{1}{4}$ inches (51.5 cm) was achieved by using both the double-annulus and the ram-induction concepts. Single annular combustors for the same airflow are longer by 50 percent, or more, than the combustor described herein. The double-annulus concept reduces combustor length while maintaining an adequate ratio of length to annulus height in each combustion zone. Ram induction reduces overall length by using more of the high velocity in the compressor discharge air. This shortens the diffuser by not diffusing to as high a static pressure and shortens the combustor by promoting rapid mixing in the primary and secondary zones.

Combustor performance was satisfactory in equalling or exceeding that of a similar ram-induction combustor that had a single annulus and was 50 percent longer. Combustion efficiency at design conditions was 100 percent, but at off-design conditions of low temperature and pressure was less than 100 percent.

The exit radial average temperature profile was in good agreement with the design profile. Exit temperature pattern factors measured 0.20 and 0.25 at cruise and takeoff conditions, respectively.

The overall diffuser-combustor total pressure loss was 6.2 percent and 8.4 percent for the takeoff and cruise conditions.

During 100 hours of operation at variable operating conditions, the durability appeared satisfactory except at the Mach 3.0 cruise condition (1150° F (895 K) inlet temperature) where some burning occurred.

Combustor blowout limits and altitude relight were determined. The exit temperature response to a rapid step increase in fuel flow was also evaluated. Smoke measurements indicated no visible smoke at the cruise and takeoff conditions.

INTRODUCTION

A shorter length combustor is desired in advanced jet engines on supersonic aircraft. The shorter length will reduce engine size and weight and improve combustor life. Supersonic speeds impose high inlet-air temperatures (about 1000° F) (811 K) on the combustor which requires large amounts of air to cool the metal surfaces. Less liner area in the shorter length can reduce the amount of inlet air required for cooling or increase the cooling capability thereby providing longer life. An increase in the amount of air available for dilution can also be provided. The Lewis Research Center is, therefore, engaged in research to develop short-length combustors.

The combustor development reported herein has double-annular and ram-induction concepts to achieve short length. The double annulus is used to provide the necessary length-to-height ratio but over a reduced length. The ram-induction principle is used to shorten the diffuser and to promote rapid mixing within a short length. The length of this combustor is compared with conventional can-annular and full-annular combustors in figure 1. For the same airflow, single annular combustors are about 65 percent longer and can-annular about 130 percent longer. The design operating requirements for the short combustor are the same as those for the combustor used in the Pratt & Whitney candidate supersonic transport engine primary combustor. The photograph in figure 2 shows the comparative length of the two combustors without exit transition liners which were the same length in both combustors.

Sector testing described in references 1 and 2 aided in the development of the double-annular combustor (sometimes referred to as the Twin Ram-Induction Combustor). The investigation reported herein, was conducted in a full-scale engine component, connected-duct research facility at Lewis. The combustor operating environment such as inlet-air temperatures, pressures, and airflows was simulated and detailed instrumentation, not possible in an engine installation, was used. Details of the test facility and instrumentation are contained in appendixes A and B.

The purpose of this investigation was to determine the performance characteristics of the full-scale double-annular combustor designed from the Pratt & Whitney sector studies (refs. 1 and 2). The fuel used for the tests was ASTM A-1 at ambient temperatures.

COMBUSTOR DESIGN

The Double-Annular Concept

The combustor used in this investigation is referred to as a double-annular, ram-induction combustor. Constructing the combustion zone as a double annulus permits the reduction of overall combustor length while maintaining an adequate ratio of length to annulus height in each combustion zone. This feature allows a considerable reduction in length to be made over a single annulus with the same overall height.

Individual control of the inner and outer annulus fuel systems of the double-annular combustion zone provides a useful method for adjusting the outlet radial temperature profile.

The Ram-Induction Concept

The ram-induction combustor differs from the more conventional combustors in that the compressor discharge air is allowed to penetrate into the combustion and mixing zones without diffusing to as high a static pressure. The kinetic energy of the inlet air is thereby used to promote rapid mixing of air and fuel in the primary zone and diluent air and burned gases in the mixing zone. The airflow is efficiently turned into the combustor by two rows of vaned turning scoops that penetrate into the combustor.

The ram-induction combustor has several advantages over conventional static pressure-fed combustors. These are

(1) A shorter length combustor is obtained because more controlled mixing can be established in the combustion zone. This is achieved by better control of the airflow injection angle with the vaned turning scoops.

(2) Diffuser length can be shortened since diffusion to very low Mach numbers is no longer needed or desired. The overall diffuser-combustor length can, therefore, be reduced. The small area ratio diffuser in the shorter length could have less pressure loss since it is not as prone to flow separation. However, this advantage can be offset by the increased turning losses associated with spreading the relatively high velocity flow evenly around the combustor.

(3) The high velocity flow over the exterior surfaces of the combustor provides substantial convective cooling of these walls. This reduces the film cooling air requirements. Thus more air is available for mixing and temperature profile control.

A more detailed discussion of the ram-induction concept is provided in reference 3.

Combustor Design Details

The double-annular ram-induction combustor and associated diffuser design used for this investigation is shown in cross section in figure 3. Forward airflow spreaders in the diffuser split the inlet airflow into three passages leading into the combustor. These are the inside liner passage, the outside liner passage, and the center passage. The airflow around the outside and inside of the diffuser is ducted by shrouds surrounding the outside of both the outer and inner liners of the combustor. The high airflow velocity which is maintained from the diffuser inlet through this ducting is turned into the combustor burning zones by means of the scoops. The first row of scoops supplies air to the primary zone while the second row supplies diluent air to the secondary zone.

Basic dimensions for this combustor are shown in figure 3. The diameters are essentially those of the combustor for the Pratt & Whitney Aircraft experimental supersonic transport engine (JTF17 (ref. 4)). However, the diffuser-combustor overall length of the double-annular combustor is about 30 percent shorter than that used in the JTF17 engine.

Photographs of the combustor are given in figure 4. Figure 4(a) shows the downstream end with the two circumferential rows of scoops attached to the inner and outer liners and to the center section. Figure 4(b) is a closeup of this same view showing more detail of the scoop arrangement. The fuel nozzles and associated swirlers are removed, but the deflectors for cooling the inner and outer headplates are shown at the nozzle locations. A side view of the combustor with the upstream diffuser airflow spreaders and inner exit transition liner added to the combustor is shown in figure 4(c). The notches in the airflow spreaders fit around the diffuser struts. The combustor is pin mounted through the struts using tangs attached to the inner and outer headplates that extend forward into the airflow spreaders.

Fuel nozzles. - Simplex fuel nozzles were used for the investigation. Two sets of nozzles were used to cover the range of high fuel flows for simulated takeoff conditions to low flows for altitude relight. Curves of total fuel flow for the combustor (sum of 64 nozzles) as a function of pressure drop across these nozzles are shown in figure 5.

Combustor design specifications. - The major items of the combustor design are tabulated in table I. The circumferential locations of combustor components such as scoops, fuel nozzles, and diffuser struts are shown in figure 6. The flow areas as distributed among the many openings (scoops, film cooling, swirlers, etc.) are given on the combustor sketch of figure 7. The scoop discharge areas with length and width dimensions are listed in table II.

CALCULATIONS

Combustion Efficiency

Efficiency was determined by dividing the measured temperature rise across the combustor by the theoretical temperature rise. The theoretical rise is calculated from the fuel-to-air ratio, fuel properties, inlet air temperature, and the amount of water vapor present in the inlet airflow. The exit temperatures were measured with five-point traversing aspirated thermocouple probes and were mass-weighted for the efficiency calculation. The indicated readings of all thermocouples were taken as true values of the total temperatures. The mass-weighting procedure is given in reference 2. In each mass-weighted average, 585 individual exit temperatures were used.

Reference Velocity and Diffuser Inlet Mach Number

Reference velocity V_{ref} for the combustor was computed from the total airflow, the maximum cross-sectional area between the inner and outer shrouds (see table I), and the air density based on the total pressure and temperature at the diffuser inlet. Diffuser inlet Mach number was calculated from the total airflow, the total temperature, static pressure measured at the diffuser inlet, and the inlet annulus area.

Total Pressure Loss

The total pressure loss $\Delta P/P_{t3}$ was calculated by mass-averaging total pressures measured upstream of the diffuser inlet and at the combustor exit. The total pressure loss, therefore, includes the diffuser loss.

Exit Temperature Profile Parameters

Three parameters of interest in evaluating the quality of exit temperature profile are considered. Figure 8 is a graphical explanation of these parameters.

Exit temperature pattern factor $\overline{\delta}$ is one parameter which is defined as

$$\overline{\delta} = \frac{T_{t4, max} - \overline{T}_{t4}}{\overline{T}_{t4} - \overline{T}_{t3}}$$

where $\overline{T}_{t4}$ and $\overline{T}_{t3}$ are averages of temperatures measured at the exit and inlet and where $T_{t4, max} - \overline{T}_{t4}$ is the maximum temperature occurring anywhere in the combustor exit plane minus the average exit temperature. (Symbols are defined in appendix C.) This is a useful parameter for preliminary screening, but it does not take into account the desired radial temperature profile for which the combustor was designed. The desired average radial distribution of temperature at the combustor exit plane is determined by the stress and cooling characteristics of the turbine. For purposes of evaluating the double-annular combustor, an exit radial temperature profile was selected for conditions that are typical of advanced engines.

The two other parameters take the design profile into account. These parameters are

$$\delta_{stat} = \frac{\left[T_{t4j(loc)} - T_{t4j(des)}\right]_{max}}{T_{t4} - T_{t3}}$$

$$\delta_{rot} = \frac{\left[T_{t4j} - T_{t4j(des)}\right]_{max}}{T_{t4} - T_{t3}}$$

where $\left[T_{t4j(loc)} - T_{t4j(des)}\right]_{max}$ for δ_{stat} is the maximum positive temperature difference between the highest local temperature at any given radius and the design temperature for that same radius (subscript j refers to any radial location in the radial temperature profile) and where $\left[T_{t4j} - T_{t4j(des)}\right]_{max}$ for δ_{rot} is the maximum temperature difference between the average temperature at any given radius around the circumference and the design temperature for that same radius (see fig. 8). The term $T_{t4} - T_{t3}$ used in all three parameters is the average temperature rise across the combustor ΔT.

The parameter δ_{stat} is a measure of the quality of the exit temperature profile on the turbine stator, and δ_{rot} is a measure of the quality of the exit temperature profile on the turbine rotor.

RESULTS AND DISCUSSION

The double-annular ram-induction combustor was tested at inlet-air pressures up to 90 psia (62.0 N/cm^2), inlet-air temperature up to 1150° F (894 K), and exit temperatures up to 2200° F (1476 K). The test data and performance of the combustor at design conditions are given in table III and for all other conditions in table IV. Combustion efficiency was 100 percent for the takeoff and cruise conditions. Exit temperature profiles were satisfactory and equalled or exceeded those for a single-annular ram-induction combustor that was 50 percent longer (ref. 4). Exit temperature pattern factors measured 0.20 and 0.25 for the cruise and takeoff conditions. These compare to 0.21 and 0.29 for the same conditions measured in the 50-percent longer single-annular combustor. Exit temperature radial profiles came very close to the design profile. The average circumferential temperature at any of the five radii traversed was less than 75° F (42 K) above the design objective. The pressure loss was higher than desired, being 6.2 and 8.4 percent of the diffuser inlet total pressure for the takeoff and cruise conditions, respectively. For the same conditions in the single-annular combustor which had a larger open hole area (289 sq in. (1865 cm^2)), the losses were 4.5 and 5.4 percent.

Total Pressure Loss

The combustor total pressure loss (overall diffuser-combustor) expressed as the percent of the average diffuser inlet total pressure is shown as a function of the diffuser inlet Mach number in figure 9. The two curves shown are data obtained without combustion (isothermally) and with a combustor temperature rise of approximately 1100° F (639 K). The test conditions were total pressures of 60 and 90 psia (41.4 and 62.0 N/cm^2) and inlet air temperatures of 600°, 1050°, and 1150° F (589, 839, and 894 K). The diffuser inlet velocity profile was uniform (±1 percent of average velocity) across the inlet annulus for these tests. The diffuser inlet Mach numbers for the sea level takeoff and cruise conditions are noted on the abscissa. At these conditions the total pressure loss of the double-annular combustor is considered to be high, compared to that of the state-of-the-art for longer combustors. The total pressure losses for the single-annular ram-induction combustor were about 1.5 to 3.0 percentage points below the values for the double-annular combustor at the takeoff and cruise conditions.

Exit Temperature Profile

The measured average radial temperature profile is compared with the design radial profile in figures 10(a) to (c) for the sea level takeoff, Mach 2.7 cruise, and Mach 3.0 cruise conditions. Also shown are the maximum temperatures measured at any point around the circumference for five radial positions. This provides an indication of the hot spots in the exit temperature. The agreement with the design profile is very good for all three conditions. The measured average temperature profile did not exceed the design profile by more than 60° F (33 K) at the maximum temperature rise (takeoff) condition. At the cruise conditions, the deviation was considerably less, not exceeding the design profile by more than 40° F (22 K) for the Mach 2.7 condition and 30° F (17 K) for the Mach 3.0 condition.

The double-annulus combustor and associated dual fuel systems allow adjustments to be made in the exit temperature profile. An example of this capability is shown in figure 11. An even fuel flow split in each annulus is compared with one in which the fuel split is greater in the inner annulus than in the outer annulus. An increase in the inner to outer annulus fuel split ratio from 1.00 to 1.19 increased the exit temperatures toward the inner diameter and decreased the temperatures toward the outer diameter.

Off-Design Combustion Efficiency

The effect on efficiency of inlet-air pressures below 60 psia (41.4 N/cm^2) and a constant inlet-air temperature of 600° F (589 K) with variable fuel-to-air ratios and reference velocities is shown in figure 12. The following results were obtained:

(1) Efficiency dropped from 100 percent with low fuel-to-air ratios (0.010) at inlet-air pressure below 30 psia (20.6 N/cm^2) but held at 100 percent at higher fuel-to-air ratios (>0.015) at inlet air pressures down to 15 psia (10.3 N/cm^2) before dropping off.

(2) Efficiency improved substantially with increasing fuel-to-air ratio from 0.010 to 0.022 at pressures below 30 psia (20.6 N/cm^2).

(3) There was only a slight improvement of efficiency with reduced reference velocity (150 to 100 ft/sec (45.7 to 30.5 m/sec)) at various fuel-to-air ratios and pressures.

(4) The best efficiency at low pressure was 97 percent at a total pressure of 10 psia (6.9 N/cm^2), the reference velocity of 100 feet per second (30.5 m/sec), and a fuel-to-air ratio of 0.022.

The effect on efficiency of low inlet-air temperatures (below 600° F (589 K)) at a constant inlet-air pressure of 30 psia (20.6 N/cm^2) with variable fuel-to-air ratios and reference velocities is shown in figure 13. The following results were obtained:

(1) Efficiency fell off rapidly at temperatures below 600° F (589 K) except for low reference velocities (100 ft/sec or 30.5 m/sec) and for fuel-to-air ratios of about 0.015 where efficiency fell off rapidly at temperatures below 400° F (477 K).

(2) At inlet-air temperatures below 400° F (477 K), operation at 100 percent efficiency with high fuel-to-air ratios (>0.015) was limited because of the onset of acoustic instability.

(3) The efficiency at low temperatures was 30 percentage points lower than that for the single-annular ram-induction combustor (53 percent compared to 83 percent at an inlet-air temperature of 300° F (422 K), an inlet-air pressure of 30 psia (20.6 N/cm^2), a fuel-to-air ratio of 0.015, and a reference velocity of 150 ft/sec (45.7 m/sec)). The short combustor length which reduces residence time is probably the reason for the relatively lower efficiency at conditions of temperature and pressure which characteristically produce low efficiency. No attempt was made to improve the efficiency.

The data of figures 12 and 13 are used in the combustion efficiency correlating parameter $P_{t3}T_{t3}/V_{ref}$ shown plotted in figure 14. This parameter was developed for combustor inlet variables with the simplifying assumptions noted in reference 5. Reasonable correlation is apparent between this parameter and efficiency for two constant fuel-to-air ratios. Combustion efficiency drops from 100 percent at $P_{t3}T_{t3}/V_{ref} = 30\times10^3$ pound-second-$^{\circ}$R per cubic foot (2.62×10^6 N-K-sec/m^3).

Combustor Exit Temperature Response to Rapid Increase in Fuel Flow

Special tests were conducted to determine how well the combustor would react to rapid increase in fuel flow. For these transient tests, a special 0.005-inch (0.127-mm) diameter platinum - 13-percent-rhodium/platinum wire thermocouple was mounted in the combustor exhaust plane. The measured temperatures were corrected for a time constant of 0.0412 second determined for this thermocouple. The test conditions were for a 30-psia (20.6-N/cm^2) combustor pressure, a 66-foot-per-second (20.1-m/sec) reference velocity, and a 350° F (451 K) inlet-air temperature.

The test was started with the combustor operating at an initial exit temperature of 1500° F (1090 K) as measured by the thermocouple. Several step increases in fuel flow were then made to produce temperatures up to about 2400° F (1590 K). At each step increase, a steady-state temperature and a corresponding fuel flow were measured. The transient response to a rapid increase in fuel flow was made through this fuel flow range by starting again at 1500° F (1090 K) initial temperature level and increasing the fuel flow in about 1.4 seconds to a value which should produce 2400° F (1590 K). The fuel flow increase during this period was converted to an exit temperature based on the steady-state fuel flow exit temperature relation determined from the initial steady-state step increases. This temperature increase is plotted against fuel burst time in figure 15 as a dashed line. The measured temperature increase corresponding to this same time interval is also plotted on this figure. The temperature increase, as shown in figure 15, lags behind that expected from the fuel flow increase. After about 3.4 seconds the temperature rise had caught up with the rapid increase in fuel flow. This lag in temperature may be caused by the low efficiency of the combustor at the low inlet-air pressure and temperature and the initial fuel-to-air ratio at which these tests were conducted (as shown in fig. 13). The combustor temperature response is considered within the controlled acceleration limits for an engine.

Combustor Blowout and Altitude Relight

To obtain blowout data, the combustor was first ignited at moderate inlet-air pressure and temperature. Then the pressure was lowered in steps while the inlet-air temperature, fuel-to-air ratio, and reference Mach number were held constant. After each change in pressure a fuel burst test (rapid increase in fuel-to-air ratio) was made to determine whether the combustor would produce a corresponding temperature rise. This procedure indicated whether an engine would accelerate at these conditions. The fuel-to-air ratio would then be returned to the original value, the pressure reduced a further step, and the procedure repeated. Finally, at some pressure level, the combustor would blow out. Relight was then attempted at successively increased pressure levels. If relight occurred, a fuel burst test was conducted at that condition to determine again if engine acceleration would occur. These procedures were repeated at a lower inlet-air temperature.

The facility limited testing to a minimum inlet-air temperature of 65° F (292 K). Tests were conducted at reference Mach numbers of 0.1, 0.075, and 0.050 with a fuel-to-air ratio of 0.01. This corresponded to a temperature rise of about 700° F (389 K). The fuel burst tests increased the fuel-to-air ratio sufficiently to give a temperature rise of 1000° F (555 K).

Figure 16 presents the results of these tests. The limit lines shown are for combustor blowout noted by the solid symbols. Relight followed by successful temperature rise is shown by the open symbols. A significant effect of reference Mach number is apparent. The lower reference Mach numbers (<0.1) significantly improved the blowout and, to some extent, the relight characteristics of the combustor. At an inlet-air temperature of 75° F (297 K), blowout occurred at inlet-air pressures as low as 9 psia (6.2 N/cm^2). This was obtained, however, only at the low reference Mach number of 0.05. Under these same conditions, relight was possible only at inlet-air pressures of 14 psia (9.6 N/cm^2). The blowout limit line at a reference Mach number of 0.05 follows about the same trend with pressure and temperature as that for relight in the single annular combustor at a higher Mach number of 0.10. No attempt was made to improve the relight characteristics of the double-annular combustor.

Durability

A total of about 100 hours of operation was accumulated on the combustor during the performance evaluation testing. The combustor showed deterioration after approximately 1 hour of operation at the most severe Mach 3.0 cruise condition of an 1150° F (894 K) inlet-air temperature and a 90-psia (62-N/cm^2) inlet-air pressure. Some burning of the center scoops and inner lip of the outside headplate occurred. At the Mach 2.7 cruise condition (1050° F (839 K) inlet-air temperature and 60-psia (41.2-N/cm^2) inlet-air pressure), however, very little deterioration occurred after 15 hours of operation. The center scoops did not burn, and the headplate areas were affected only slightly. No durability problems were evident for the sea-level takeoff condition.

Smoke Density Evaluations

Measurements were made to determine the general level of smoke density in the combustor exhaust gases at design operating conditions.

Smoke numbers (defined in appendix B) obtained at conditions simulating takeoff, Mach 2.7, and 3.0 cruise were 4 or less. These values are very low, being well below the threshold of visible smoke. The very low smoke number at the simulated takeoff pressure of 90 psia (62 N/cm^2) would probably prevent reaching the visible smoke level at the higher normal takeoff pressure of 180 psia (124 N/cm^2).

SUMMARY OF RESULTS

A full-scale short-length turbojet combustor designed for Mach 3 cruise conditions was tested at the Lewis Research Center. This high performance short length combustor was achieved by using both the double annulus and the ram-induction concepts. The following results were obtained:

1. Combustor performance except for durability at the Mach 3.0 cruise conditions was satisfactory. The performance equalled or exceeded that of a similar ram-induction combustor designed for the same supersonic conditions having a single annulus and being 50 percent longer.

2. The combustor total pressure loss, including the diffuser, was 6.1, 8.4, and 9.1 percent at the simulated sea-level takeoff, Mach 2.7 cruise, and Mach 3.0 cruise conditions, respectively. At these conditions, the diffuser inlet Mach numbers were 0.249, 0.300, and 0.313, respectively. These pressure losses are about 1.5 to 3.0 percentage points greater than those of the single annular combustor for the same range of conditions.

3. Combustion efficiencies were 100 percent for the simulated takeoff and cruise conditions. At off-design conditions (low inlet-air temperature and pressures) the combustion efficiency was considerably less (53 percent at 300° F (923 K), 30 psia (20.6 N/cm^2), 0.015 fuel-to-air ratio, and reference velocity of 150 ft/sec (45.7 m/sec)).

4. The exit radial average temperature profile was in good agreement with the design profile. The largest positive temperature differences between the circumferentially average temperature on any radius and the design temperature for that same radius were only 60° F (33 K) and 30° F (17 K) for the sea-level takeoff and Mach 3 cruise conditions, respectively.

5. Exit temperature pattern factors were 0.20 to 0.25 at all design conditions. These compare to 0.21 and 0.29 for the same conditions in a single annular combustor 50 percent longer.

6. Combustor exit temperature response to a rapid step increase in fuel-to-air ratio was good. The temperature increased not quite as rapidly as the fuel flow during the 3.4 seconds when the temperature rise was increased from 1500° F (1090 K) to 2400° F (1590 K). The combustor response is considered to be within the controlled acceleration limits for an engine.

7. Combustor blowout limit was 9.0 psia (6.2 N/cm^2) at 75° F (297 K) at a reference Mach number of 0.05 and a fuel-to-air ratio of 0.01. The minimum pressure for blowout increased sharply at temperatures near 75° F (297 K). The minimum pressure for relight at these same conditions was 14 psia (9.6 N/cm^2). No attempt was made to improve the relight characteristics of this combustor.

8. Durability evaluated during 100 hours at variable operating conditions (including 15 hr at Mach 2.7 cruise condition) was satisfactory except at the Mach 3.0 cruise condition. Here burning of center scoops and liner areas near the headplate occurred in less than 1 hour of operation.

9. Exhaust gas smoke numbers obtained to evaluate smoke density at the operating conditions measured 4 or less. These values are well below the threshold of visible smoke.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 1, 1970,
720-03.

APPENDIX A

TEST FACILITY

The full-scale double-annular ram-induction combustor investigation was conducted in a closed-duct test facility of the Engine Components Research Laboratory at Lewis. A sketch of this facility is shown in figure 17. Airflows for combustion up to 300 pounds per second (136 kg/sec) at pressures from below atmospheric to 10 atmospheres could be heated to 1200° F (922 K) without vitiation before entering the combustor under test.

Figure 18 shows the combustor test section and the connected inlet and outlet ducting. About $4\frac{1}{2}$ pipe diameters of constant-area duct was ahead of the test section. Following the inlet ducting was the combustor housing which included the diffuser inlet and diffuser as part of the housing. The combustor housing measured 42 inches (1.07 m) at the maximum diameter and was 37.75 inches (0.96 m) long including the inlet section. Following the combustor housing was the outlet instrumentation section. At this section and downstream, the combustor exhaust gases were cooled by a water-injection spray system. The exposed surfaces downstream of the combustor were cooled by two methods: (1) circulating water in passages adjacent to the hot surfaces and (2) water sprays impinging directly on the exposed surfaces. Photographs of the test section installation are shown in figure 19.

For combustor inlet-air temperatures of 600° F (589 K) or less, an indirect-fired heat exchanger was used. For higher inlet temperatures (to 1200° F, 922 K), a second-stage of indirect heating was used. Heat for the second stage was provided by a natural-gas-fueled J-57 jet engine with an afterburner. The engine exhaust gases were passed through a heat exchanger of special design shown in figure 20.

Airflow rates and combustor pressures were regulated by remotely controlled valves upstream and downstream of the test section. Flow straighteners were used to evenly distribute the airflow entering the combustor (see fig. 17).

APPENDIX B

INSTRUMENTATION

Measurements to determine combustor operation and performance were recorded by the Lewis Central Automatic Data Processing System (ref. 6). Control room readout instrumentation (indicating and recording) was used to set and monitor the test conditions and the operation of the combustor. Pressures were measured and recorded by the central digital automatic multiple pressure recorder (DAMPR) and by strain-gage pressure transducers (ref. 7). Temperatures were measured by iron-constantan and Chromel-Alumel thermocouples for low- and medium-temperature conditions and by platinum - 13-percent-rhodium/platinum thermocouples for high temperatures. The indicated readings of all thermocouples were taken as true values of the total temperatures. The platinum - 13-percent-rhodium/platinum thermocouples were of the high-recovery aspirating type (ref. 8, type 6).

Airflow rates were measured by square-edged orifices installed according to ASME specifications. Fuel flow rates were measured by turbine flowmeters using frequency-to-voltage converters for readout and recording.

The locations of the combustor instrumentation stations axially along the test section are shown in figure 18. Instrumentation at inlet station 3 is shown in figure 21. Inlet-air temperature was measured by eight Chromel-Alumel thermocouples that were equally spaced around the inlet at station 3. Inlet air total pressure was measured by eight five-point total pressure rakes equally spaced around the inlet at station 3. The pressure rakes measured the total pressure profile at centers of equal areas across the inlet annulus. Static pressure at the inlet was measured by 16 wall static pressure taps with eight on the outside and eight on the inside walls of the annulus.

Combustor outlet total temperature and pressure at instrumentation station 4 were measured at 3° increments around the exit circumference. At each 3° increment, five temperature and pressure points were measured across the annulus. These points were located at centers of equal areas across the annulus. The water-cooled probe assembly containing the five temperature and pressure sensors is shown in figure 22. Three of these probes, each on an arm 120° apart, rotated 120° providing full coverage of the circumference. Water-cooled shields protected these probes when they were not in use at three fixed points in the exhaust stream. At these points, temperature and pressure were not measured. The probes were made of platinum-rhodium alloy where exposed to the hot exhaust gases. Also located at station 4 were eight wall static pressure taps.

A schematic of the equipment used to obtain the smoke density or smoke number (SN) is shown in figure 23. Combustor exhaust gas samples were picked up by the aspirating thermocouple probes and cooled to room temperature by a heat exchanger. A portion of these gases, which was used to obtain the smoke number, was piped into a plenum chamber. The chamber was continuously purged by these gases and maintained at about 2 psi (1.4 N/cm^2) above atmospheric pressure. A Von Brand Smokemeter was used to obtain the smoke stain on Whatman No. 4 filter tape. To obtain a smoke stain, the vacuum pump was started, and the gas flow adjusted to 0.6 standard cubic feet per minute (2.83×10^{-4} m^3/sec) as measured by the calibrated rotameter. A pressure drop across the filter tape of about 5 inches (12.7 cm) of mercury was maintained for all the tests. The tape speed was 4 inches per minute (0.17 cm/sec) which gave a sample flow rate of 0.3 standard cubic feet per minute per square inch (2.19×10^{-5} $m^3/sec\text{-}cm^2$) of tape. Two moisture traps were used between the plenum chamber and the heated head on the smokemeter. During a test, some moisture was carried into the first trap; however, none was ever evident in the second trap.

The absolute reflectivity of the stained filter tape was measured with a Welsh Densichron using a gray background. The Densichron was calibrated with a Welsh Gray Scale.

The smoke number was determined from the following equation:

$$SN = 100\left[1 - \left(\frac{\text{Percent absolute reflectivity of sample}}{\text{Percent absolute reflectivity of clean paper}}\right)\right]$$

APPENDIX C

SYMBOLS

C_d	discharge coefficient
F/A	fuel-to-air ratio
P_t	total pressure
T_t	total temperature
W_a	mass airflow rate
V_{ref}	reference velocity
ΔP	total pressure drop across combustor $(P_{t3} - P_{t4})$
M	Mach number
W_f	mass fuel flow rate
ΔT_{stat}	$\left[T_{t4j(loc)} - T_{t4j(des)}\right]$
ΔT_{rot}	$\left[T_{t4j} - T_{t4j(des)}\right]$
ΔT	temperature rise across combustor $(T_{t4} - T_{t3})$
P_s	static pressure
SN	smoke number

Subscripts:

ref	reference
3	diffuser inlet
4	combustor exit
j	radial location

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TABLE I. - DOUBLE-ANNULAR RAM-INDUCTION

COMBUSTOR DIMENSIONS AND SPECIFICATIONS

Lengths	
Compressor exit to turbine inlet, in. (cm)	20.25 (51.5)
Fuel nozzle face to turbine inlet, in. (cm)	12.00 (30.5)
Diameters	
Inlet outside diameter, in. (cm)	31.80 (80.77)
Inlet inside diameter, in. (cm)	28.00 (71.1)
Outlet outside diameter, in. (cm)	35.38 (89.9)
Outlet inside diameter, in. (cm)	27.50 (69.9)
Shroud	
Outside diameter, in. (cm)	37.09 (94.2)
Inside diameter, in. (cm)	22.52 (57.2)
Reference area (between shrouds), in.^{2} (cm^2)	663 (4270)
Diffuser inlet area, in.^{2} (cm^2)	182.5 (1177)
Open hole area (including cooling), in.^{2} (cm^2)	200 (1291)
Flow spreader inlet areas, in.^{2} (cm^2)	
Outside diameter passage, in.^{2} (cm^2)	54.0 (348)
Center passage, in.^{2} (cm^2)	121.5 (785)
Inside diameter passage, in.^{2} (cm^2)	52.5 (339)
Exit area, in.^{2} (cm^2)	388 (2503)
Number of fuel nozzles and swirlers	64
Number of diffuser struts	16
Number of ram-induction scoops	512
Rows, primary zone	1
Rows, secondary zone	1
Ratio length to annulus height	
Outer annulus	4.8
Inner annulus	3.9

TABLE II. - SCOOP AREAS[a] AND SIZES FOR DOUBLE-ANNULAR RAM-INDUCTION COMBUSTOR[b]

Type of scoop	Discharge area		Length		Width	
	in.^{2}	cm^2	in.	cm	in.	cm
Outer liner primary	12.480	80.516	0.458	1.163	0.458	1.163
Outer liner secondary	22.144	142.864	.614	1.560	.614	1.560
Outer centershroud primary	12.480	80.516	.458	1.163	.458	1.163
Outer centershroud secondary	11.072	71.432	.614	1.560	.306	.803
Inner centershroud primary	12.480	80.516	.458	1.163	.458	1.163
Inner centershroud secondary	11.072	71.432	.614	1.560	.306	.803
Inner liner primary	12.544	80.929	.481	1.222	.438	1.112
Inner liner secondary	22.720	146.580	.773	1.963	.490	1.245

[a]All areas are actual area for a full annulus.
[b]See fig. 3.

TABLE III. - COMBUSTOR PERFORMANCE DATA FOR DOUBLE-ANNULAR RAM-INDUCTION

COMBUSTOR-PERFORMANCE AT DESIGN CONDITIONS

Engine condition	Inlet air conditions							Combustor operating conditions				
	Total pressure, P_{t3}		Total temperature, T_{t3}		Air flow, W_a		Diffuser inlet Mach number, M_3	Reference velocity, V_{ref}		Fuel-air ratio, W_f	Average exit temperature, T_{t4}	
	psia	N/cm^2	^oF	K	lbm/sec	kg/sec		ft/sec	m/sec		^oF	K
Takeoff	89.7	61.9	602	590	111.2	50.4	0.252	105.5	32.2	0.0250	2219	1488
Mach 2.7 cruise	61.8	42.6	1053	841	73.4	33.3	.296	144.2	44.0	.0186	2203	1479
Mach 3.0 cruise	89.2	61.5	1147	892	104.4	47.4	.302	150.8	46.0	.0173	2192	1473

Engine condition	Combustor performance characteristics														
	Maximum exit hot spot temperature, $(T_{t4})_{max}$		Exit temperature parameters							Temperature rise across combustor, ΔT		Combustor pressure loss, $\Delta P/P_{t3}$, percent	Combustion efficiency, percent	$\frac{P_{t3}T_{t3}}{V_{ref}}$	
			Pattern factor, δ	Profile parameters											
				δ_{stat}	$\Delta T_{stat(max)}$		δ_{rot}	$\Delta T_{rot(max)}$						$\frac{lbs\text{-}^oR\text{-}sec}{ft^3}$	$\frac{N\text{-}K\text{-}sec}{m^3}$
	^oF	K			^oR	K		^oR	K	^oR	K				
Takeoff	2630	1717	0.254	0.249	403	224	0.044	72	40	1617	898	6.28	104.2	130.2×10^3	11.35×10^6
Mach 2.7 cruise	2440	1611	.206	.202	232	129	.024	25	14	1150	639	8.24	102.1	93.4	8.14
Mach 3.0 cruise	2447	1615	.244	.239	250	139	.027	28	15	1045	581	8.74	100.6	136.9	11.92

TABLE IV. - COMBUSTOR PERFORMANCE DATA FOR

Run no.	Inlet air conditions: Total pressure, P_{t3}, psia	Total pressure, P_{t3}, N/cm^2	Total temperature, T_{t3}, ^oF	Total temperature, T_{t3}, K	Air flow, W_a, lbm/sec	Air flow, W_a, kg/sec	Diffuser inlet Mach number, M_3	Combustor operating conditions: Reference velocity, V_{ref}, ft/sec	Reference velocity, V_{ref}, m/sec	Fuel-air ratio, W_f	Average exit temperature, T_{t4}, ^oF	Average exit temperature, T_{t4}, K
222	10.0	6.9	584	580	12.8	5.8	0.258	108.0	32.9	0.0092	1055	841
223	10.1	7.0	581	578	12.9	5.8	.254	106.4	32.4	.0149	1486	1081
224	10.1	7.0	576	575	12.8	5.8	.252	105.2	32.1	.0203	1829	1272
214	14.9	10.3	598	588	18.0	8.1	.243	102.7	31.3	.0100	1210	928
215	15.2	10.5	598	588	18.0	8.2	.239	100.8	30.7	.0158	1631	1162
216	15.2	10.5	594	585	17.9	8.1	.238	100.3	30.6	.0220	1983	1357
208	20.0	13.8	598	588	23.5	10.7	.237	100.2	30.5	.0100	1245	947
209	20.0	13.8	598	588	23.5	10.7	.236	99.9	30.4	.0163	1674	1185
210	19.9	13.7	596	586	23.5	10.6	.237	100.0	30.5	.0228	2047	1392
203	25.1	17.3	600	589	29.1	13.2	.234	99.0	30.2	.0101	1280	966
204	25.1	17.3	607	592	29.2	13.2	.235	99.5	30.3	.0164	1697	1198
205	25.1	17.3	606	592	29.2	13.2	.235	99.7	30.4	.0217	2005	1369
199	40.0	27.6	597	587	47.0	21.3	.238	99.7	30.4	.0100	1289	971
249	40.0	27.6	607	593	47.5	21.5	.240	101.5	30.9	.0160	1680	1189
250	50.3	34.7	607	593	58.8	26.7	.237	100.0	30.5	.0101	1294	974
252	50.0	34.4	599	588	58.9	26.7	.238	100.1	30.5	.0162	1686	1192
255	60.3	41.6	595	586	69.7	31.6	.233	97.8	29.8	.0102	1299	977
256	60.5	41.7	602	590	69.5	31.5	.232	98.0	29.9	.0164	1705	1203
217	9.9	6.9	594	585	18.0	8.2	.385	152.3	46.4	.0099	1089	860
218	10.1	7.0	591	584	18.0	8.2	.377	149.9	45.7	.0158	1505	1092
221	10.0	6.9	596	586	17.8	8.1	.381	151.4	46.1	.0220	1859	1288
211	15.0	10.4	599	588	26.4	12.0	.373	149.0	45.4	.0101	1208	927
212	15.2	10.5	599	588	26.5	12.0	.369	147.6	45.0	.0163	1640	1167
213	15.0	10.3	602	590	26.5	12.0	.376	150.3	45.8	.0223	1984	1357
206	20.0	13.8	604	591	34.7	15.7	.367	147.6	45.0	.0101	1254	952
207	19.9	13.8	601	589	34.5	15.7	.366	146.9	44.8	.0166	1683	1190
202	24.9	17.1	601	589	44.8	20.3	.385	152.7	46.5	.0099	1250	950
245	24.9	17.2	603	590	46.8	21.2	.405	159.2	48.5	.0152	1596	1142
227	30.0	20.7	597	587	54.0	24.5	.383	151.7	46.2	.0099	1258	954
247	39.8	27.5	608	593	70.6	32.0	.379	151.1	46.1	.0102	1293	974
253	50.2	34.6	580	578	88.6	40.3	.373	147.0	44.8	.0100	1254	952
229	30.0	20.7	87	303	65.6	29.8	.324	95.6	29.1	.0104	384	469
230	29.7	20.5	87	304	65.1	29.5	.325	95.8	29.2	.0149	541	556
232	29.9	20.6	285	414	50.2	22.8	.288	100.4	30.6	.0100	837	721
233	29.7	20.5	291	417	49.8	22.6	.288	100.9	30.8	.0135	1136	887
236	30.0	20.7	402	479	44.2	20.0	.270	101.9	31.1	.0099	1023	824
237	30.1	20.7	405	481	44.0	19.9	.268	101.4	30.9	.0159	1479	1077
238	30.0	20.7	411	484	44.0	20.0	.270	102.4	31.2	.0216	1849	1283
200	29.9	20.6	613	596	36.6	16.6	.250	105.4	32.1	.0097	1269	960
201	30.2	20.8	607	592	36.5	16.6	.247	103.9	31.7	.0156	1651	1172
244	30.1	20.7	605	592	37.3	16.9	.252	106.1	32.3	.0209	1952	1340
234	29.7	20.5	292	417	74.2	33.7	.466	149.2	45.5	.0102	713	652
235	30.0	20.7	296	420	74.4	33.7	.463	149.1	45.4	.0158	807	704
239	29.9	20.6	411	484	67.7	30.7	.451	156.9	47.8	.0098	977	798
240	30.1	20.7	406	481	67.2	30.5	.443	154.0	46.9	.0129	1153	896
241	30.1	20.8	612	595	55.7	25.3	.400	158.1	48.2	.0153	1621	1156

DOUBLE-ANNULAR RAM-INDUCTION COMBUSTOR

Combustor performance characteristics

Maximum exit hot spot temperature, $(T_{t4})_{max}$		Pattern factor, $\bar{\delta}$	Exit temperature parameters: Profile parameters						Temperature rise across combustor, ΔT		Combustor pressure loss, $\Delta P/P_{t3}$, percent	Combustion efficiency, percent	$\frac{P_{t3}T_{t3}}{V_{ref}}$	
			δ_{stat}	$\Delta T_{stat(max)}$		δ_{rot}	$\Delta T_{rot(max)}$						$\frac{lbs\text{-}^{o}R\text{-}sec}{ft^3}$	$\frac{N\text{-}K\text{-}sec}{m^3}$
^{o}F	K			^{o}R	K		^{o}R	K	^{o}R	K				
1224	935	0.359	0.482	227	126	0.134	63	35	471	262	7.17	76.1	13.9×10^{3}	1.21×10^{6}
1748	1226	.290	.237	214	119	.042	38	21	904	502	7.11	92.9	14.2	1.25
2173	1463	.274	.226	284	158	.033	41	23	1253	696	7.27	97.2	14.4	1.25
1376	1020	.270	.275	168	94	.054	33	18	612	340	6.09	91.0	22.1	1.93
1934	1330	.294	.245	254	141	.023	23	13	1033	574	6.01	100.7	22.9	2.00
2404	1591	.303	.260	361	201	.056	78	43	1389	772	6.05	100.4	23.1	2.00
1407	1037	.251	.252	163	90	.032	21	11	647	359	5.77	96.5	30.3	2.65
2003	1368	.307	.261	281	156	.031	33	18	1076	598	5.85	102.0	30.5	2.66
2553	1674	.349	.315	458	254	.071	104	58	1451	806	5.97	101.7	30.3	2.64
1459	1066	.265	.236	160	89	.022	15	8	679	377	5.45	100.6	38.6	3.38
2010	1372	.287	.265	289	161	.035	38	21	1090	606	5.68	102.9	38.7	3.38
2459	1622	.325	.290	405	225	.068	95	52	1399	777	5.74	102.8	38.6	3.37
1460	1066	.247	.231	160	89	.020	14	8	692	385	5.47	103.3	61.0	5.33
2025	1380	.321	.317	340	189	.025	27	15	1073	596	5.61	103.0	60.4	5.29
1499	1088	.300	.293	201	112	.022	15	8	687	382	5.44	101.5	77.0	6.75
2023	1379	.310	.306	332	185	.026	29	16	1087	604	5.66	103.4	76.0	6.64
1508	1093	.298	.291	205	114	.021	15	8	704	391	5.28	102.6	93.7	8.17
2023	1379	.288	.283	312	174	.026	28	16	1103	613	5.30	103.7	94.5	8.23
1251	950	.327	.419	207	115	.100	50	28	495	275	15.34	74.6	10.0	.86
1798	1254	.320	.271	248	138	.050	46	25	914	508	14.96	89.0	10.2	.89
2274	1519	.328	.289	365	203	.040	51	28	1263	702	15.63	91.3	9.9	.87
1384	1024	.288	.295	180	100	.053	32	18	609	339	14.00	90.5	23.9	1.34
1921	1323	.270	.261	272	151	.024	25	14	1041	579	13.89	98.7	15.8	1.37
2372	1573	.281	.257	356	198	.032	44	24	1382	768	14.59	99.1	15.3	1.33
1431	1050	.282	.253	164	91	.034	22	12	650	361	13.23	96.2	20.8	1.81
1999	1366	.292	.277	300	167	.029	32	18	1083	601	13.36	100.9	20.6	1.81
1418	1043	.259	.252	163	91	.032	21	11	649	361	14.40	97.9	24.8	2.17
1596	1142	.287	.272	270	150	.028	27	15	993	552	16.07	100.1	24.0	2.09
1421	1045	.247	.240	159	88	.026	17	9	661	367	14.00	99.8	30.1	2.63
1493	1085	.291	.284	195	108	.021	14	8	685	381	13.58	99.9	40.5	3.54
1459	1066	.304	.297	200	111	.019	13	7	674	374	13.01	99.4	51.2	4.46
523	546	.472	.588	175	97	.150	45	24	297	165	10.01	39.3	24.8	2.16
816	709	.606	.498	226	126	.031	14	8	454	252	10.33	43.2	24.4	2.13
1085	836	.376	.403	223	124	.083	46	26	552	307	8.19	78.2	32.0	2.79
1390	1028	.300	.312	264	146	.066	55	31	845	470	8.53	90.8	31.9	2.78
1231	940	.376	.360	223	124	.057	35	20	621	345	7.19	90.2	36.6	3.19
1825	1270	.323	.267	287	159	.032	34	19	1073	596	7.34	100.6	36.9	3.22
2389	1583	.375	.334	480	267	.049	71	40	1439	799	7.57	102.8	36.7	3.20
1425	1047	.237	.229	150	83	.020	13	7	656	365	6.09	101.3	43.8	3.83
1955	1341	.291	.266	278	154	.032	33	18	1044	580	6.09	103.3	44.5	3.89
2390	1583	.326	.281	378	210	.045	60	33	1347	748	6.59	101.6	43.5	3.80
875	741	.384	.536	226	126	.060	25	14	421	234	20.34	58.5	21.5	1.88
1042	834	.460	.363	186	103	.006	3	2	511	284	20.51	47.6	21.9	1.91
1135	886	.278	.380	215	120	.049	28	15	566	314	19.15	83.4	23.9	2.09
1388	1027	.316	.271	202	112	.031	23	13	747	415	18.89	85.0	24.3	2.12
1919	1322	.296	.269	271	151	.024	25	14	1009	561	15.50	101.1	29.4	2.57

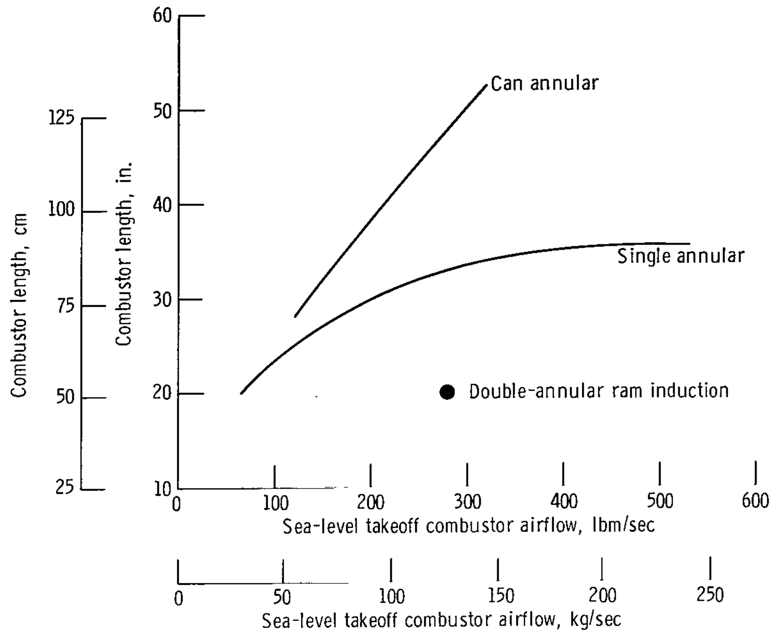


Figure 1. - Comparison of short-length ram-induction combustor with conventional combustors.

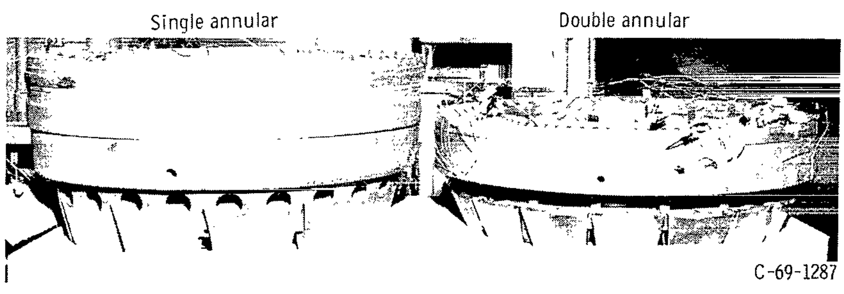


Figure 2. - Short-length double-annular combustor compared to length of single annular combustor for same operating conditions. (Exit transition liners removed).

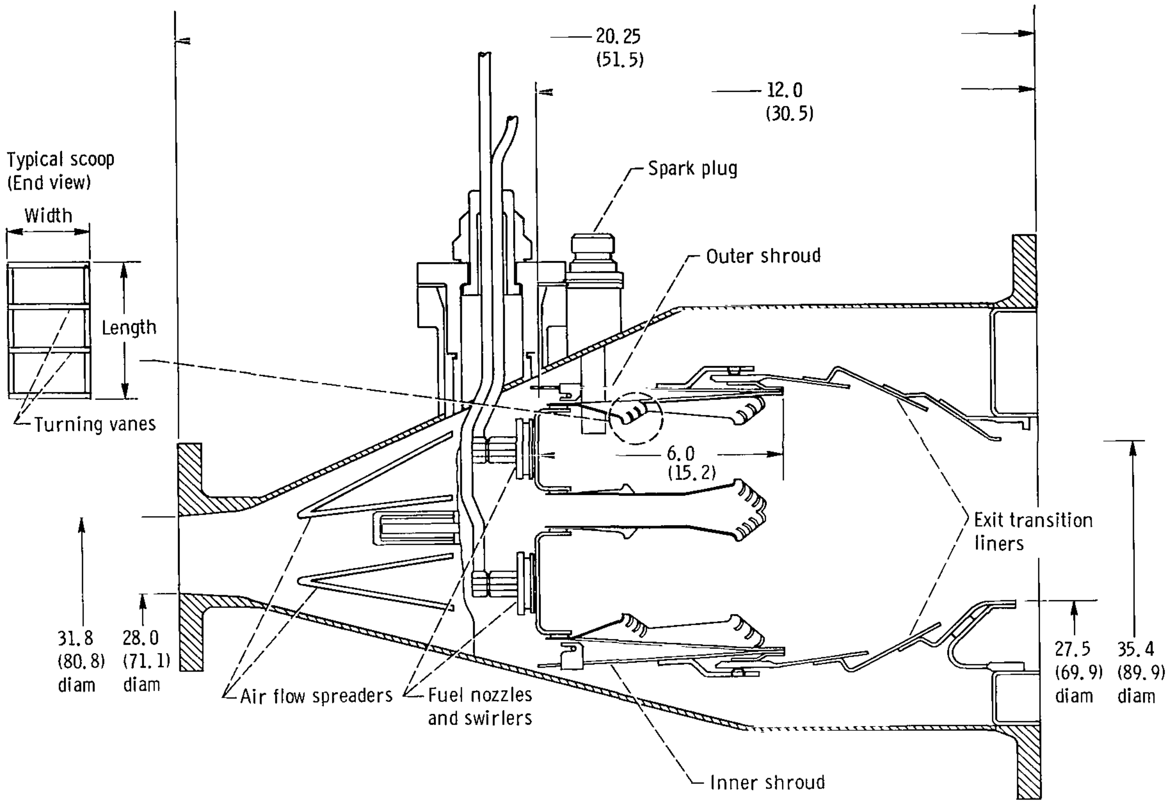
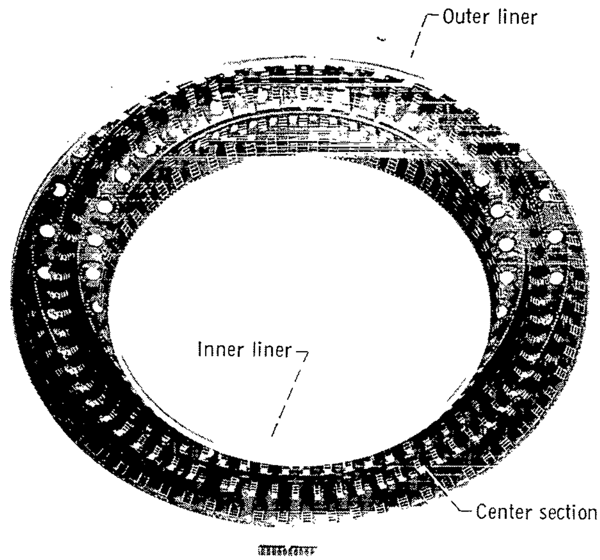


Figure 3. - Cross-section of double-annular ram induction combustor. Dimensions are in inches (cm).



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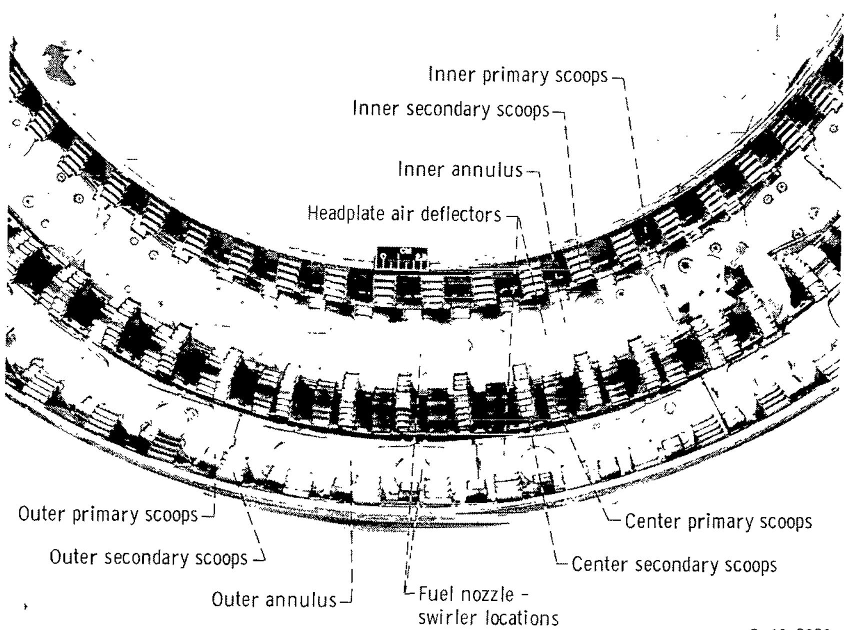
(a) Viewed from downstream (fuel nozzles removed).



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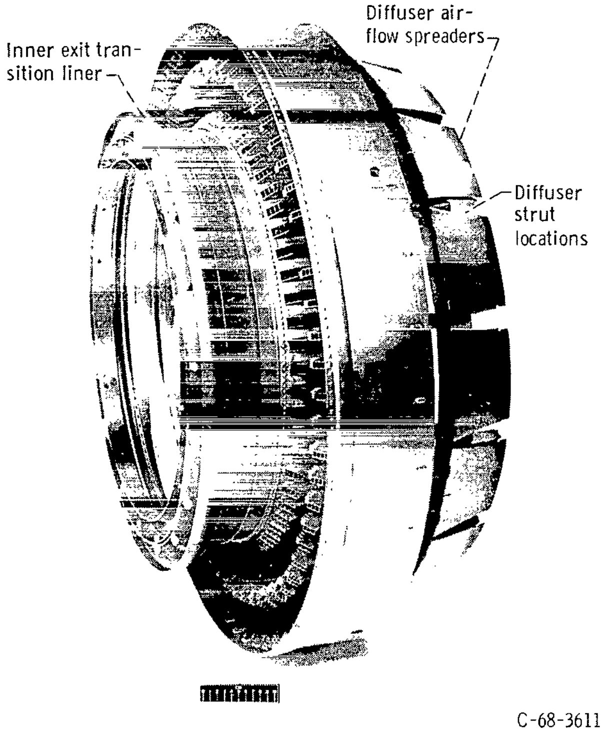
(b) Close-up view.

Figure 4. - Double-annular ram-induction combustor.



(c) Side view (outer transition liner removed).
Figure 4. - Concluded.

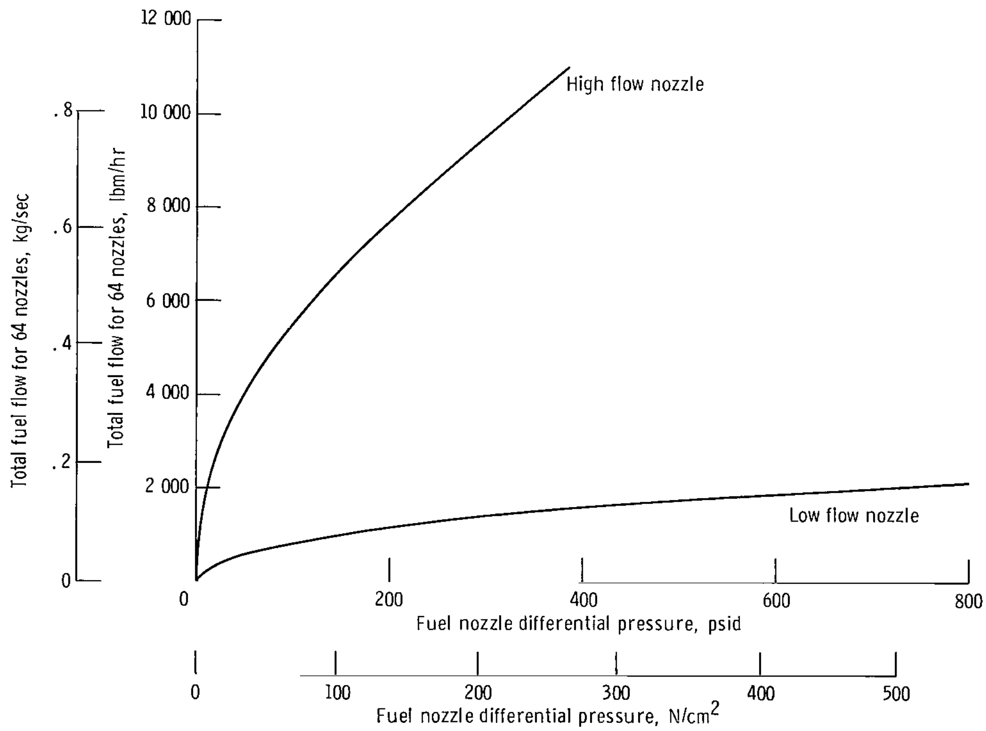


Figure 5. - Fuel flow as function of pressure drop across fuel nozzles of double-annular combustor.

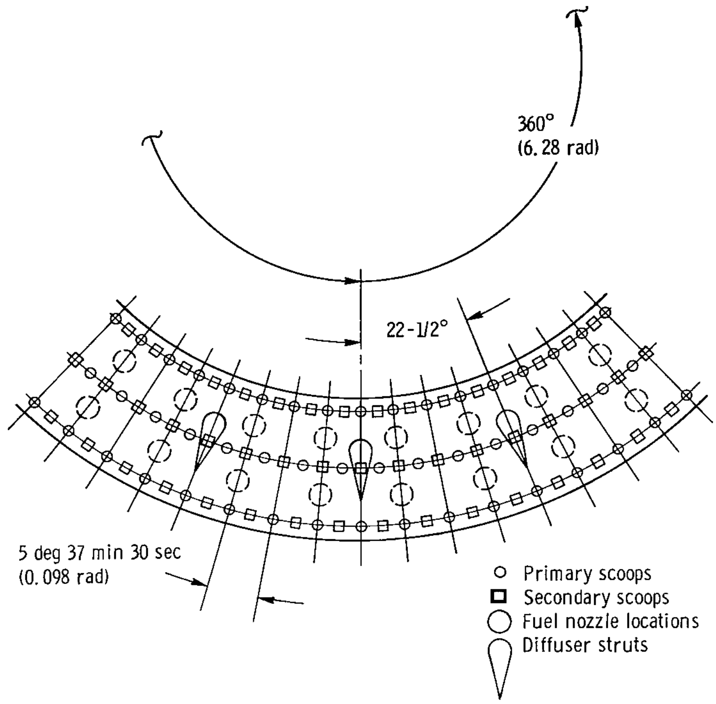


Figure 6. - Circumferential arrangement of combustor scoops and fuel nozzles.

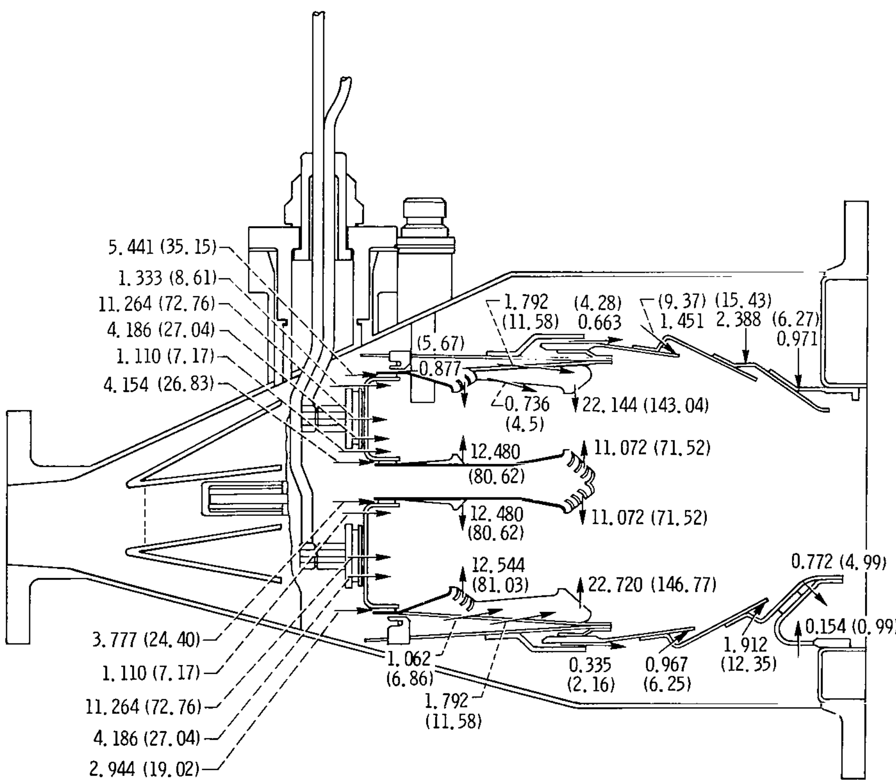


Figure 7. - Effective flow area distribution for double-annular ram-induction combustor. Swirler discharge coefficient, 0.50; hole discharge coefficient, 0.62; scoops and slot discharge coefficient, 1.00; total area, (effective), 183.374 square inches (1184.547 cm^2). All areas are based on a full annulus with units of square inches (cm^2).

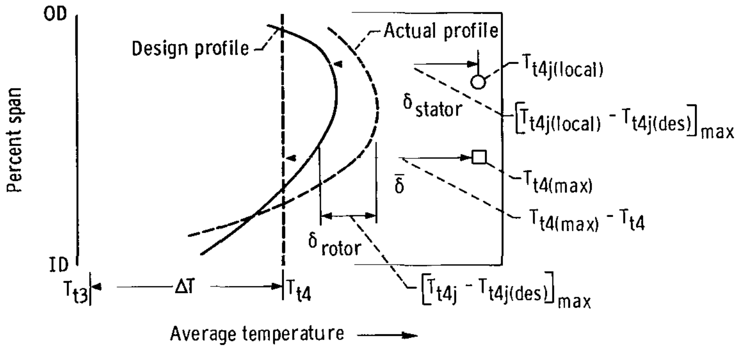


Figure 8. - Explanation of terms in exit temperature profile parameters.

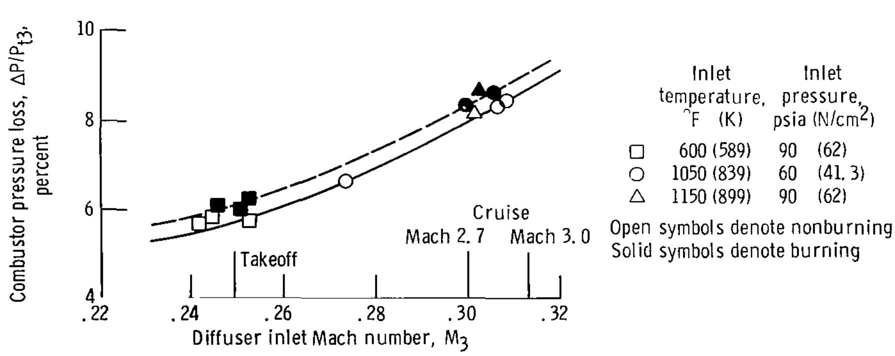
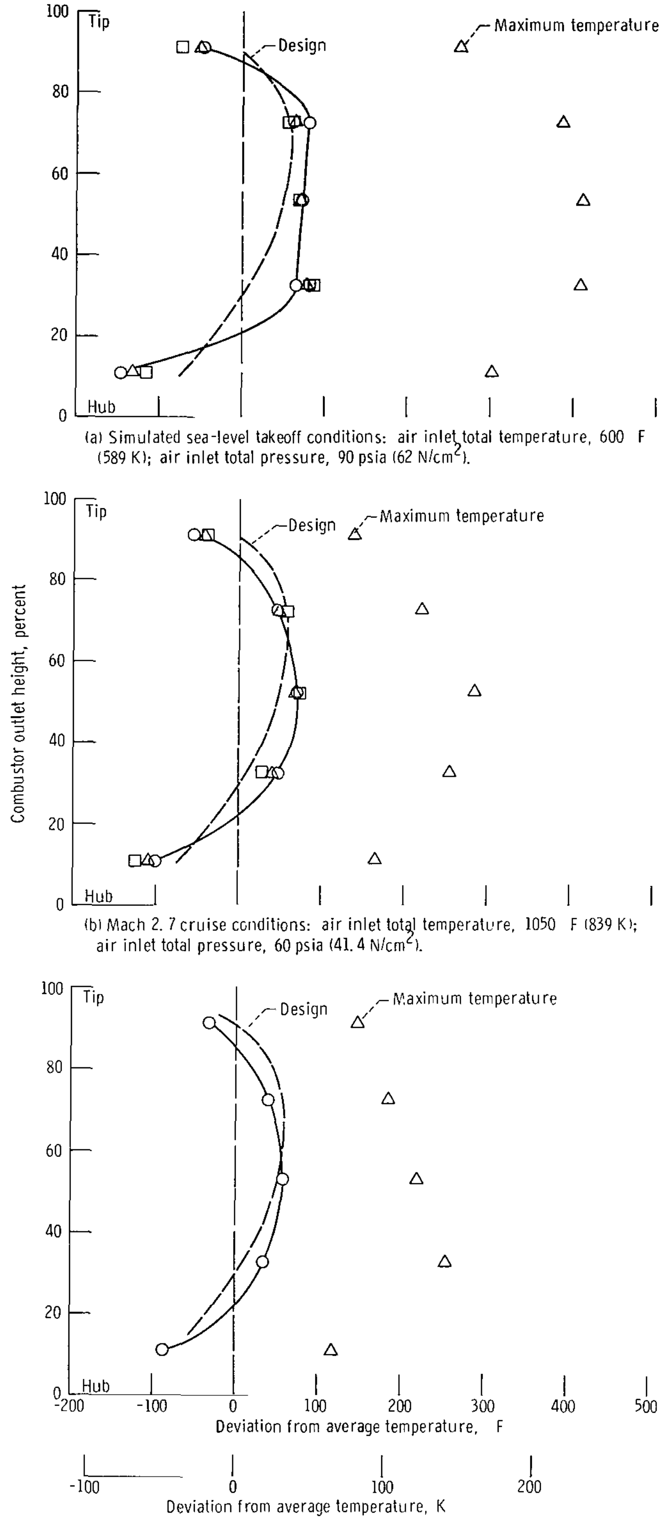


Figure 9. - Overall diffuser-combustor pressure loss as function of diffuser inlet Mach number.



(a) Simulated sea-level takeoff conditions: air inlet total temperature, 600 F (589 K); air inlet total pressure, 90 psia (62 N/cm^2).

(b) Mach 2.7 cruise conditions: air inlet total temperature, 1050 F (839 K); air inlet total pressure, 60 psia (41.4 N/cm^2).

(c) Mach 3.0 cruise conditions: air inlet total temperature, 1150° F (894 K); air inlet total pressure, 90 psia (62 N/cm^2).

Figure 10. - Average radial exit temperature profiles. Exit average temperature, 2200° F (1478 K).

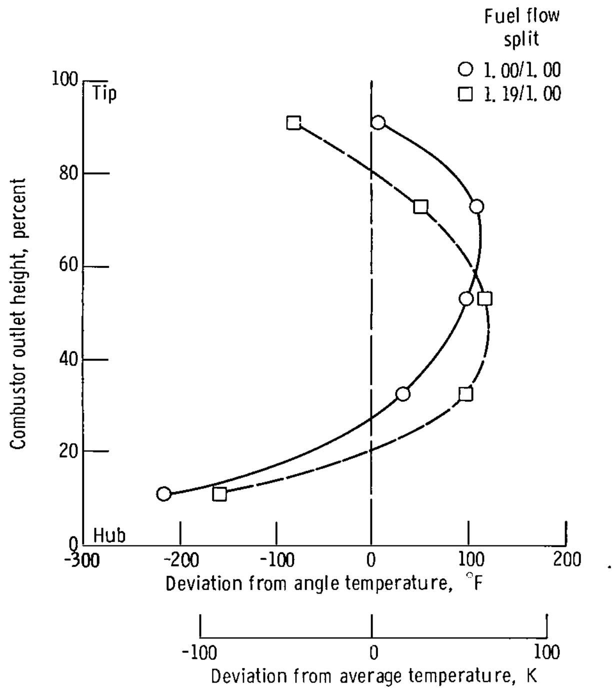


Figure 11. - Effect of fuel flow split between inside-diameter and outside-diameter annuli on average radial exit temperature profile.

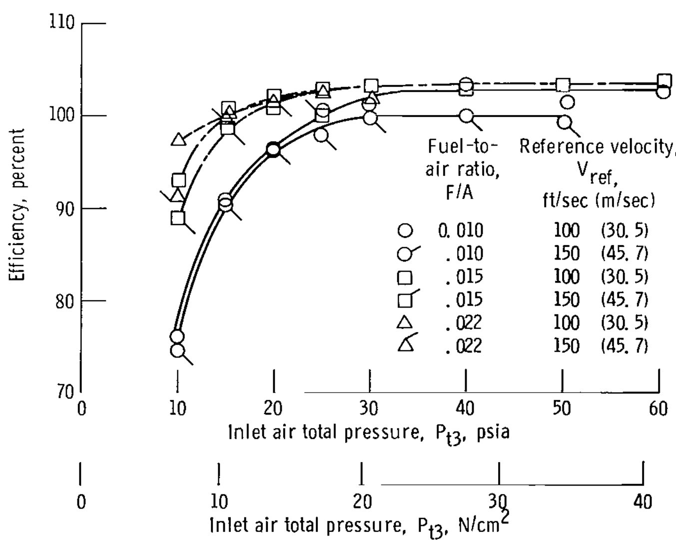


Figure 12. - Combustion efficiency at low inlet-air pressures for variable fuel-to-air ratios and reference velocities. Inlet-air temperature, 600° F (589 K).

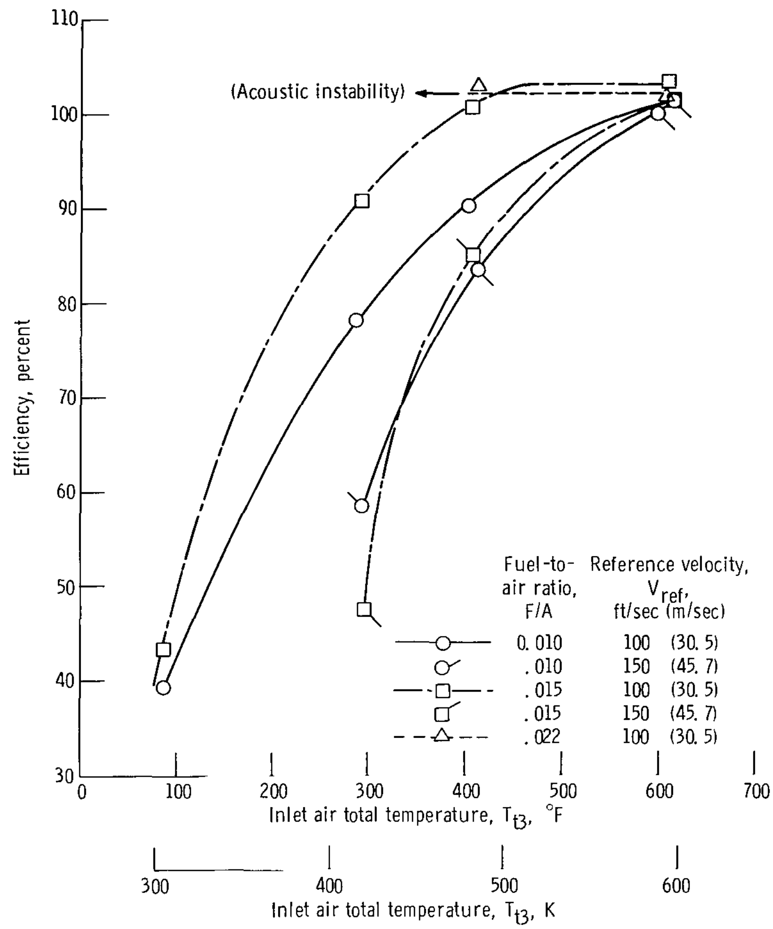


Figure 13. - Combustor efficiency at low inlet-air temperatures for variable fuel-to-air ratios and reference velocities. Inlet-air pressure, 30 psia (20.6 N/cm^2).

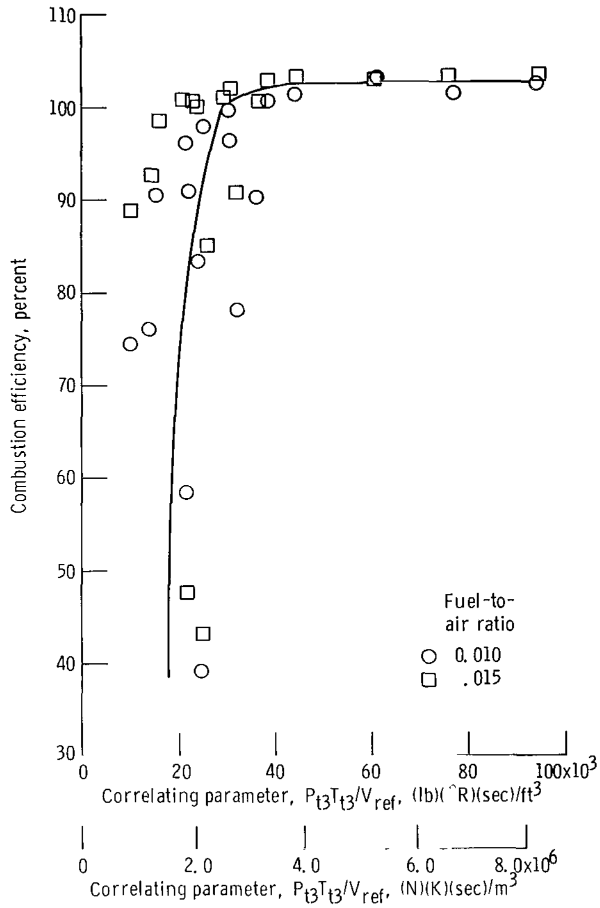


Figure 14. - Correlation between combustion efficiency and $P_{t3}T_{t3}/V_{ref}$ for data obtained at low inlet-air temperatures (<600° F (589 K)) and pressures (<60 psia (41.4 N/cm²)).

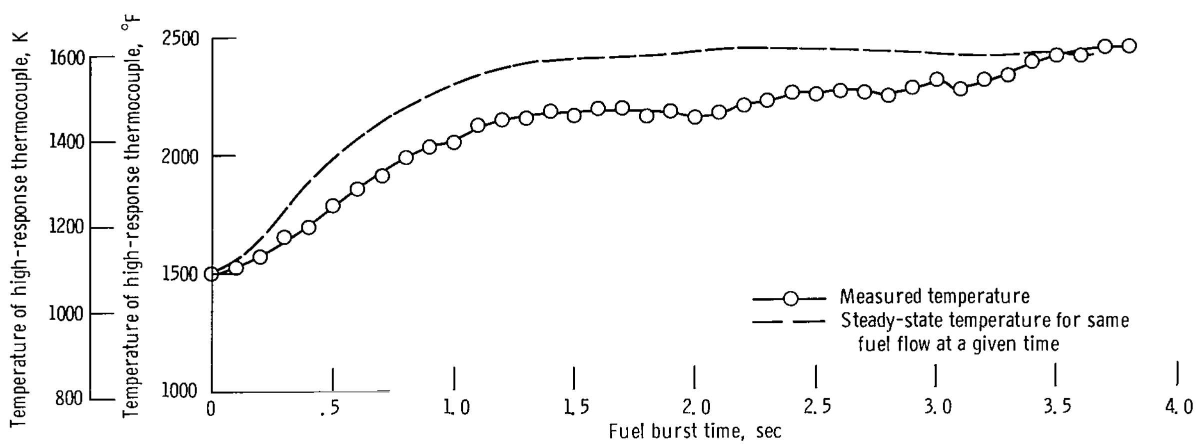


Figure 15. - Temperature response of double-annular combustor to rapid fuel flow increase. Exit temperature measured at only one spot in exit plane. Inlet-air temperature, 350° F; inlet-air total pressure, 30 psia (20.6 N/cm^2); reference velocity, 66 ft/sec (20 m/sec).

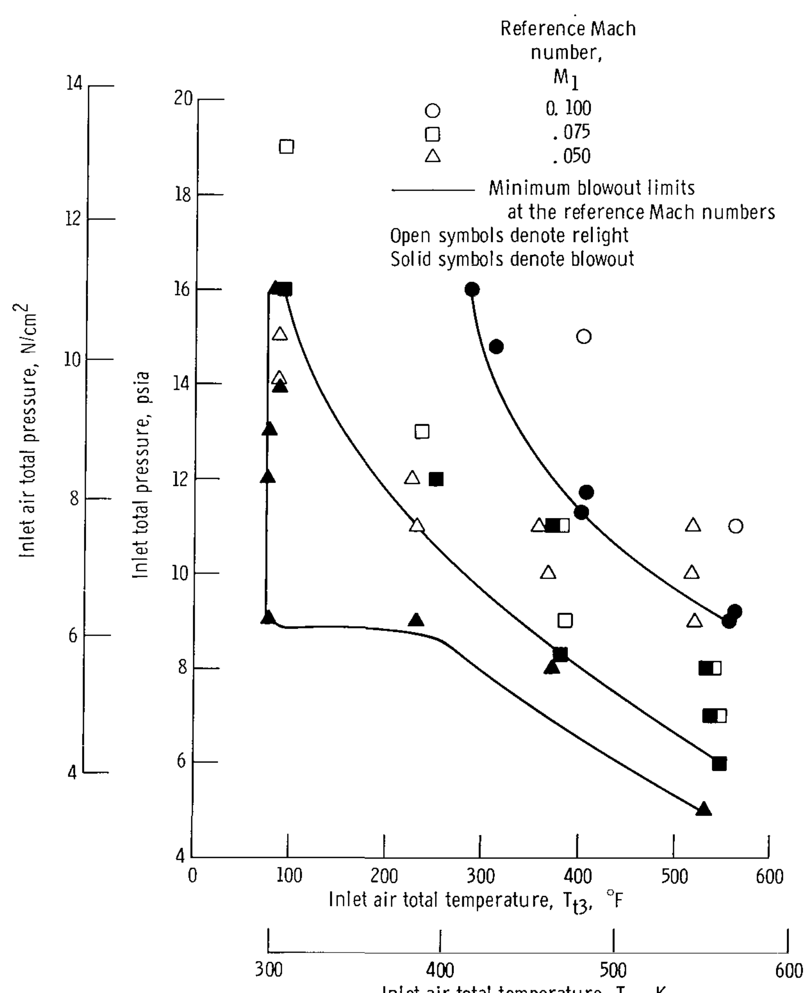


Figure 16. - Blowout and altitude relight characteristics of double-annular ram-induction combustor.

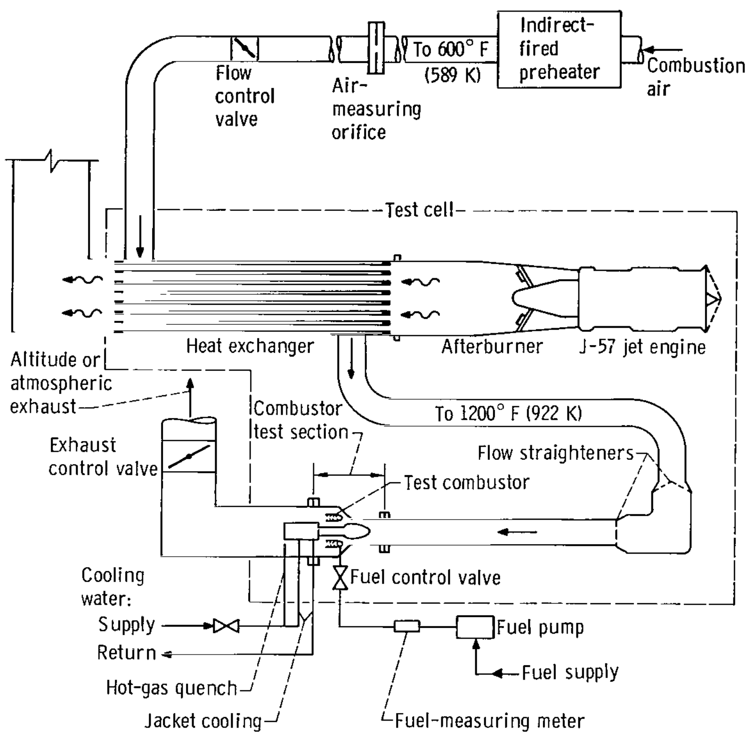


Figure 17. - Test facility and associated systems for full-scale advanced annular combustor tests.

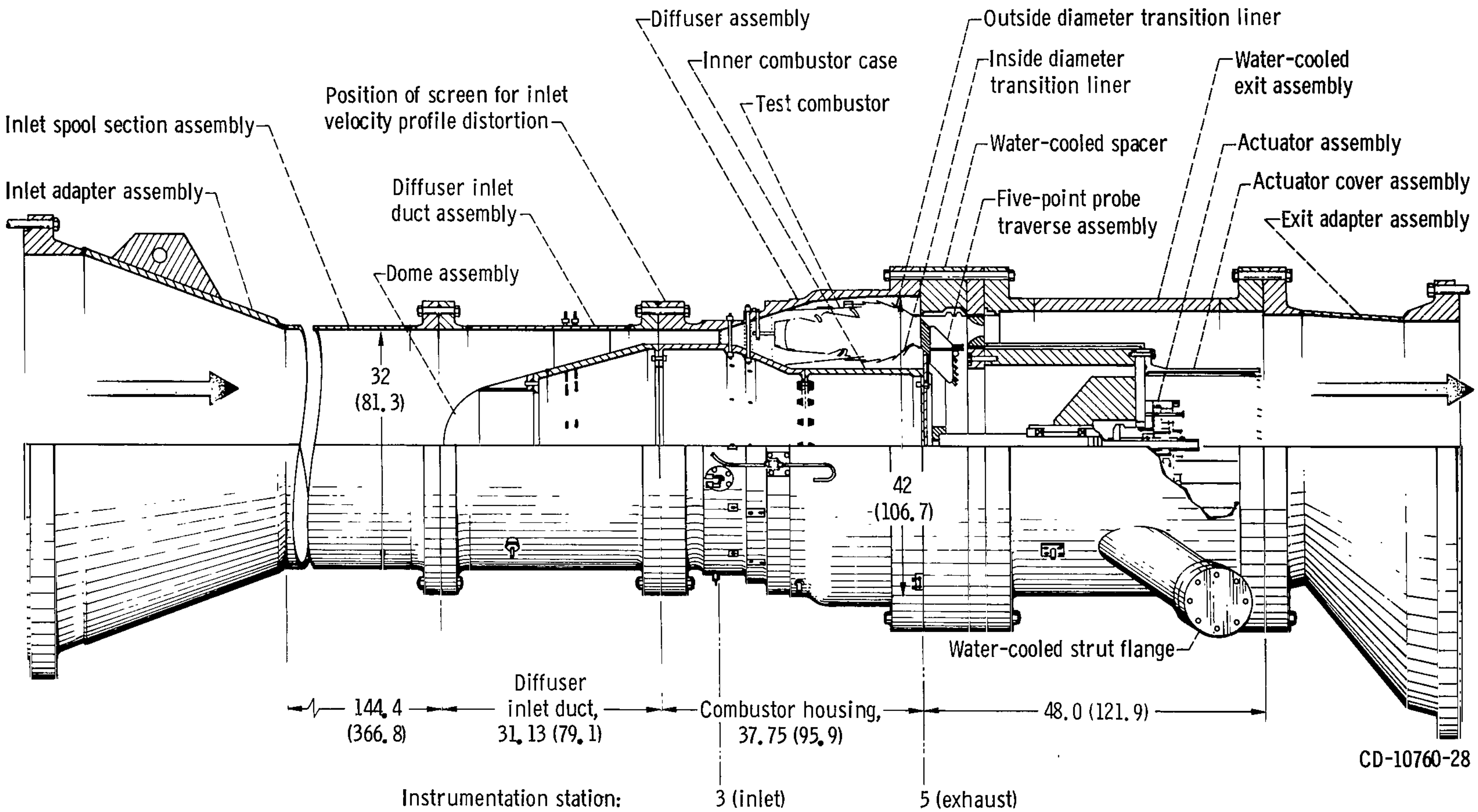
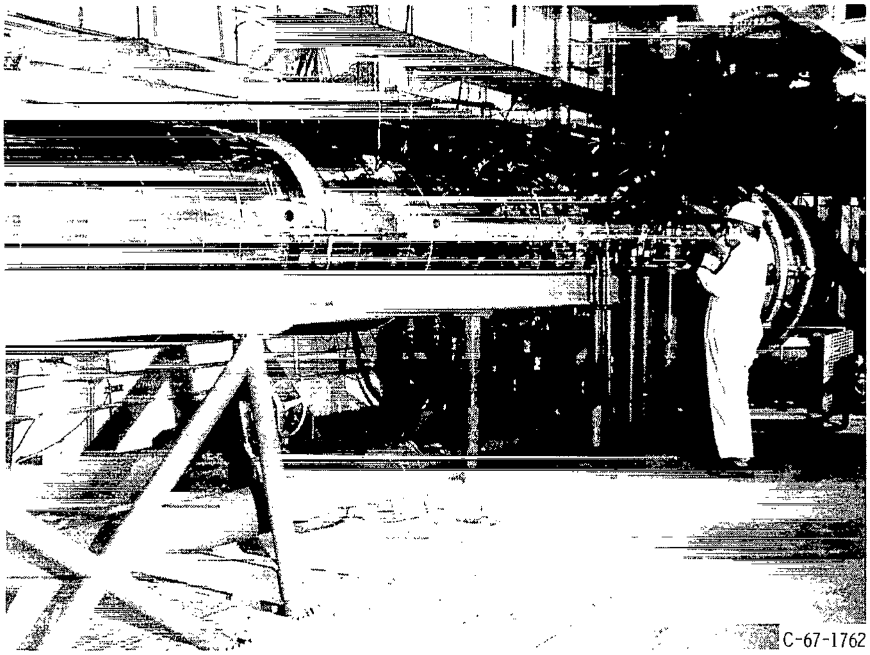
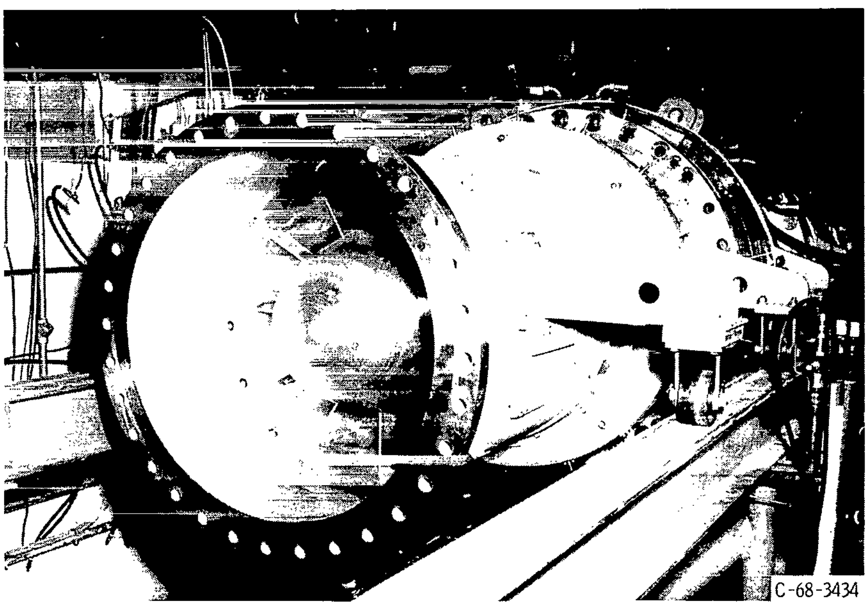


Figure 18. - Test section for full-scale advanced annular combustor. (Dimensions are in inches (cm).)

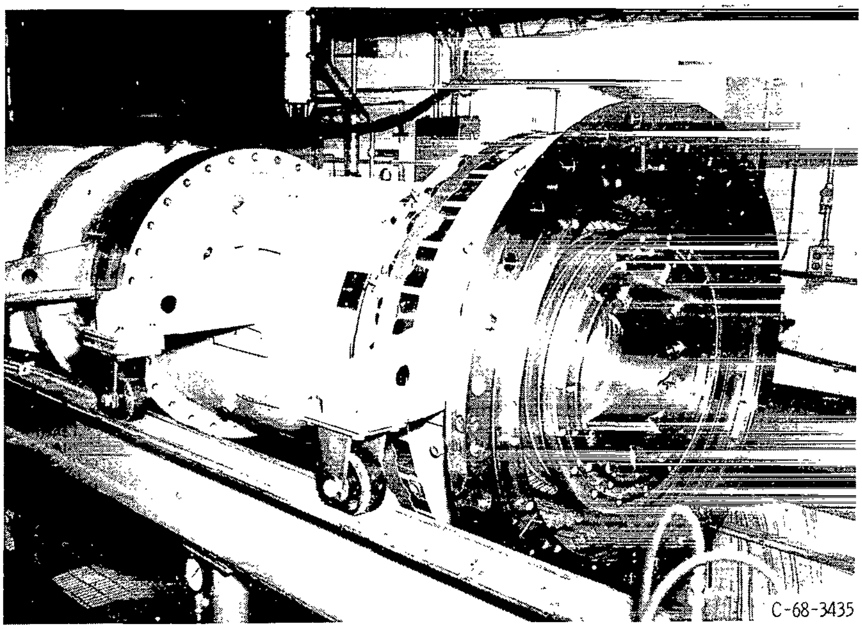


(a) Overall view looking downstream.



(b) Test section inlet (upstream pipe section removed).

Figure 19. - Test section for advanced annular combustor.



(c) Test section outlet (downstream pipe section removed).

Figure 19. - Concluded.

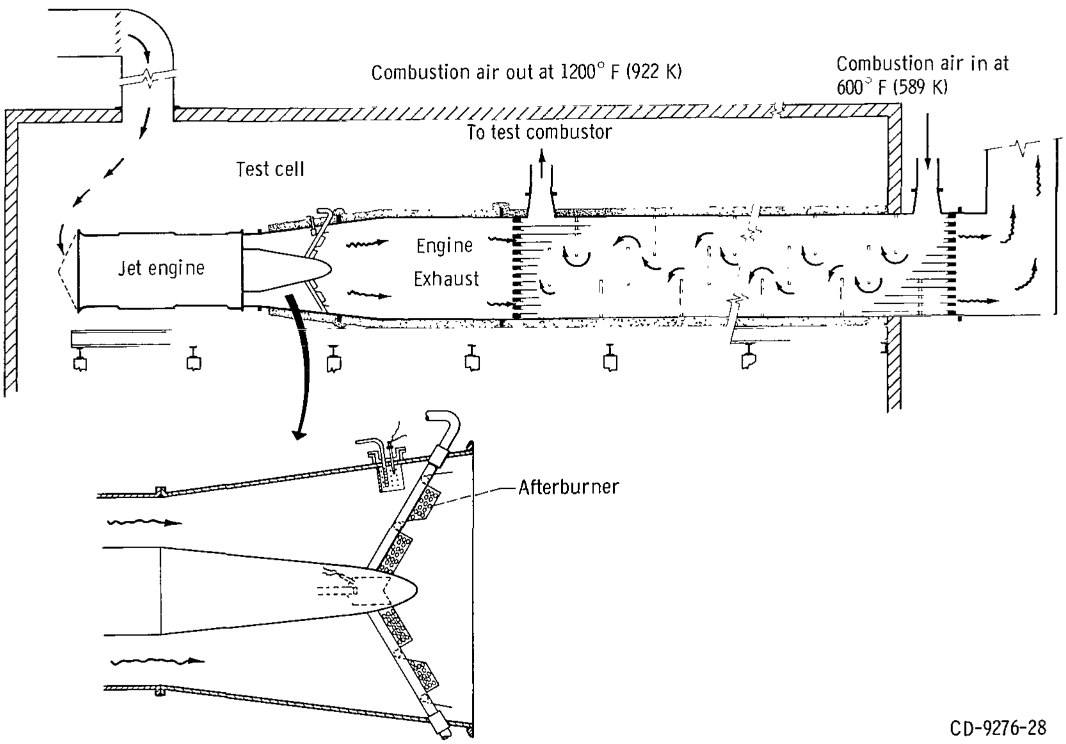


Figure 20. - Heat exchanger in exhaust of jet engine to provide high-temperature inlet air for test combustor.

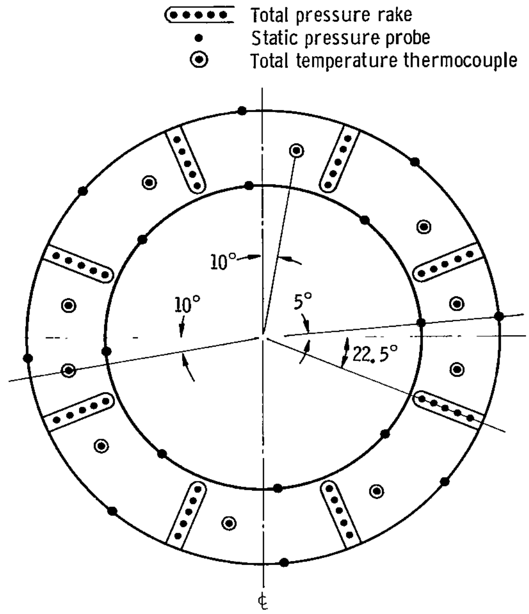


Figure 21. - Diffuser inlet instrumentation at station 3. View looking downstream.

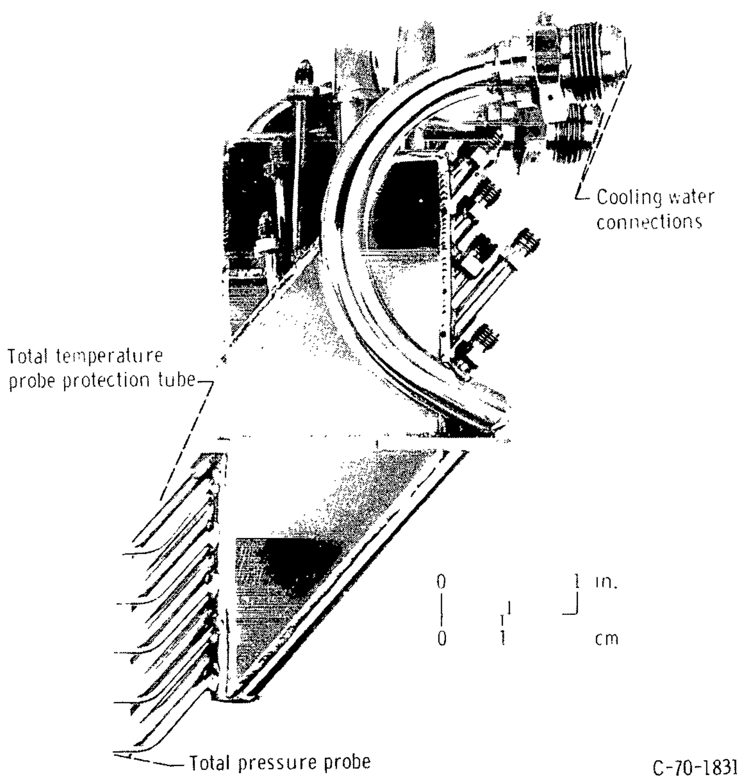


Figure 22. - Five-point total temperature and total pressure water-cooled probe assembly.

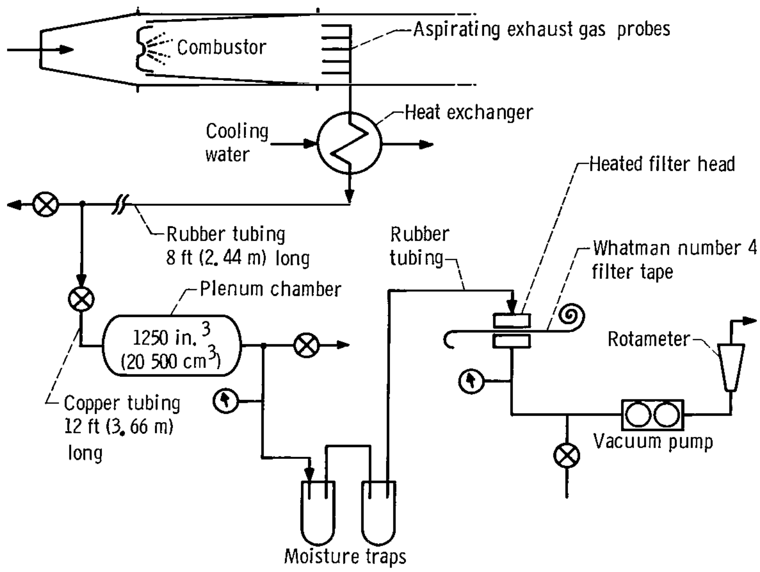


Figure 23. - Schematic of apparatus used to obtain smoke number data.

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